Lab

Flow measurement loop: *Questions 91 and 92*, **completed objectives due by the end of day 5**

Exam

Day 5 – **Complete mastery of these objectives due by the next exam date**

Specific objectives for the "mastery" exam:
- Electricity Review: Calculate voltages, currents, and phase shifts in an AC reactive circuit
- Calculate flow rate / pressure drop for a nonlinear flow element
- Determine suitability of different flow-measuring technologies for a given process fluid type
- Identify specific instrument calibration errors (zero, span, linearity, hysteresis) from data in an "As-Found" table
- Solve for a specified variable in an algebraic formula (may contain exponents or logarithms)
- Determine the possibility of suggested faults in a simple circuit given measured values (voltage, current), a schematic diagram, and reported symptoms
- Motor/relay/3phase/PLC Review: Calculate voltages and currents within balanced three-phase AC electrical circuits
- INST250 Review: Calculate split-ranged valve positions given signal value and valve calibration ranges
- INST262 Review: Determine proper AI block parameters to range a Fieldbus transmitter for a given application

Recommended daily schedule

Day 1

Theory session topic: Turbine, vortex, and positive-displacement flowmeters

Questions 1 through 20; <u>answer questions 1-9</u> in preparation for discussion (remainder for practice)

Day 2

Theory session topic: Magnetic and ultrasonic flowmeters

Questions 21 through 40; <u>answer questions 21-28</u> in preparation for discussion (remainder for practice)

Day 3

Theory session topic: True mass flowmeters, weirs and flumes

Questions 41 through 60; <u>answer questions 41-49</u> in preparation for discussion (remainder for practice)

Day 4

Theory session topic: Review for exam (site visit)

Questions 61 through 80; <u>answer questions 61-63</u> in preparation for discussion at an industrial site specified by your instructor. (All remaining questions for practice)

Feedback questions *(81 through 90)* are optional and may be submitted for review at the end of the day

Day 5

Exam

Access the worksheets and textbook: go to the *Socratic Instrumentation* website located at `http://www.ibiblio.org/kuphaldt/socratic/sinst` to find worksheets for every 2nd-year course section organized by quarter, as well as both the latest "stable" and "development" versions of the *Lessons In Industrial Instrumentation* textbook. Download and save these documents to your computer.

Maximize your learning: complete all homework *before* class starts, ready to be assessed as described in the "Inverted Session Formats" pages. Use every minute of class and lab time productively. Follow all the tips outlined in "Question 0" as well as your instructor's advice. Do not take constructive criticism personally. Make every reasonable effort to solve problems on your own before seeking help.

Identify upcoming assignments and deadlines: read the first page of each course worksheet.

Relate course days to calendar dates: reference the calendar spreadsheet file (`calendar.xlsx`), found on the BTC campus `Y:` network drive. A printed copy is posted in the Instrumentation classroom.

Locate industry documents assigned for reading: use the Instrumentation Reference provided by your instructor (on CD-ROM and on the BTC campus `Y:` network drive). There you will find a file named `00_index_OPEN_THIS_FILE.html` readable with any internet browser. Click on the "Quick-Start Links" to access assigned reading documents, organized per course, in the order they are assigned.

Study for the exams: Mastery exams assess specific skills critically important to your success, listed near the top of the front page of each course worksheet for your review. Familiarize yourself with this list and pay close attention when those topics appear in homework and practice problems. Proportional exams feature problems you haven't seen before that are solvable using general principles learned throughout the current and previous courses, for which the only adequate preparation is independent problem-solving practice every day. Answer the "feedback questions" (practice exams) in each course section to hone your problem-solving skills, as these are similar in scope and complexity to proportional exams. Answer these feedback independently (i.e. no help from classmates) in order to most accurately assess your readiness.

Calculate course grades: download the "Course Grading Spreadsheet" (`grades_template.xlsx`) from the Socratic Instrumentation website, or from the BTC campus `Y:` network drive. Enter your quiz scores, test scores, lab scores, and attendance data into this Excel spreadsheet and it will calculate your course grade. You may compare your calculated grades against your instructors' records at any time.

Identify courses to register for: read the "Sequence" page found in each worksheet.

Receive extra instructor help: ask during lab time, or during class time, or by appointment. Tony may be reached by email at `tony.kuphaldt@btc.edu` or by telephone at 360-752-8477.

Identify job openings: regularly monitor job-search websites. Set up informational interviews at workplaces you are interested in. Participate in jobshadows and internships. Apply to jobs long before graduation, as some employers take *months* to respond! Check your BTC email account daily for alerts.

Impress employers: sign the FERPA release form granting your instructors permission to share academic records, then make sure your performance is worth sharing. Document your project and problem-solving experiences for reference during interviews. Honor all your commitments.

Begin your career: participate in jobshadows and internships while in school to gain experience and references. Take the first Instrumentation job that pays the bills, and give that employer at least two years of good work to pay them back for the investment they have made in you. Employers look at delayed employment, as well as short employment spans, very negatively. Failure to pass a drug test is an immediate disqualifier, as is falsifying any information. Criminal records may also be a problem.

file `howto`

General Values, Expectations, and Standards

Success in this career requires professional integrity, resourcefulness, persistence, close attention to detail, and intellectual curiosity. If you are ever in doubt as to the values you should embody, just ask yourself what kind of a person you would prefer to hire for your own enterprise. Those same values will be upheld within this program.

Learning is the purpose of any educational program, and a worthy priority in life. Every circumstance, every incident, every day here will be treated as a learning opportunity, every mistake as a "teachable moment". Every form of positive growth, not just academic ability, will be regarded as real learning.

Responsibility means *ensuring* the desired outcome, not just *trying* to achieve the outcome. To be a responsible person means you *own* the outcome of your decisions and actions.

Integrity means being honest and forthright in all your words and actions, doing your very best every time and never taking credit for the achievement of another.

Safety means doing every job correctly and ensuring others are not endangered. Lab safety standards include wearing closed-toed shoes and safety glasses in the lab room during lab hours, wearing ear protection around loud sounds, using ladders to reach high places, using proper lock-out/tag-out procedures, no energized electrical work above 30 volts without an instructor present in the lab room, and no power tool use without an instructor present in the lab room.

Diligence in study means exercising self-discipline and persistence, realizing that hard work is a necessary condition for success. This means, among other things, investing the necessary time and effort in studying, reading instructions, paying attention to details, utilizing the skills and tools you already possess, and avoiding shortcuts. Diligence in work means the job is not done until it is done *correctly*: all objectives achieved, all problems solved, all documentation complete, and no errors remaining.

Self-management means allocating your resources (time, equipment, labor) wisely, and not just focusing on the closest deadline.

Communication means clearly conveying your thoughts and paying attention to what others convey, across all forms of communication (e.g. oral, written, nonverbal).

Teamwork means working constructively with your classmates to complete the job at hand. Remember that here the first job is *learning*, and so teamwork means working to maximize everyone's learning (not just your own). The goal of learning is more important than the completion of any project or assignment.

Initiative means recognizing needs and taking action to meet those needs without encouragement or direction from others.

Representation means your actions reflect this program and not just yourself. Doors of opportunity for all BTC graduates may be opened or closed by your own conduct. Unprofessional behavior during tours, jobshadows, internships, and/or jobs reflects poorly on the program and will negatively bias employers.

Trustworthiness is the result of consistently exercising these values: people will recognize you as someone they can rely on to get the job done, and therefore someone they would want to employ.

Respect means acknowledging the intrinsic value, capabilities, and responsibilities of those around you. Respect is gained by consistent demonstration of valued behaviors, and it is lost through betrayal of trust.

Punctuality and Attendance: late arrivals are penalized at a rate of 1% grade deduction per incident. Absence is penalized at a rate of 1% per hour (rounded to the nearest hour) except when employment-related, school-related, weather-related, or required by law (e.g. court summons). Absences may be made up by directing the instructor to apply "sick hours" (12 hours of sick time available per quarter). Classmates may donate their unused sick hours. Sick hours may not be applied to unannounced absences, so be sure to alert your instructor and teammates as soon as you know you will be absent or late. Absence on an exam day will result in a zero score for that exam, unless due to a documented emergency.

Mastery: any assignment or objective labeled as "mastery" must be completed with 100% competence (with multiple opportunities to re-try). Failure to complete by the deadline date caps your grade at a C−. Failure to complete by the end of the *next* school day results in a failing (F) grade for that course.

Time Management: Use all available time wisely and productively. Work on other useful tasks (e.g. homework, feedback questions, job searching) while waiting for other activities or assessments to begin. Trips to the cafeteria for food or coffee, smoke breaks, etc. must not interfere with team participation.

Orderliness: Keep your work area clean and orderly, discarding trash, returning tools at the end of every lab session, and participating in all scheduled lab clean-up sessions. Project wiring, especially in shared areas such as junction boxes, must not be left in disarray at the end of a lab shift. Label any failed equipment with a detailed description of its symptoms.

Independent Study: the "inverted" instructional model used in this program requires independent reading and problem-solving, where every student must demonstrate their learning at the start of the class session. Question 0 of every worksheet lists practical study tips. The "Inverted Session Formats" pages found in every worksheet outline the format and grading standards for inverted class sessions.

Independent Problem-Solving: make an honest effort to solve every problem before seeking help. When working in the lab, help will not be given to you unless and until you run your own diagnostic tests.

Teamwork: inform your teammates if you need to leave the work area for any reason. Any student regularly compromising team performance through absence, tardiness, disrespect, or other disruptive behavior(s) will be removed from the team and required to complete all labwork individually. The same is true for students found inappropriately relying on teammates.

Communication: check your email account daily for important messages from your instructor. Ask the instructor to clarify any assignment or exam question you find confusing, and express your work clearly and compellingly.

Academic Progress: your instructor will record your academic achievement, as well as comments on any negative behavior, and will share all these records with employers provided you have signed the FERPA release form. You are welcome to see these records at any time, and are encouraged to track your own academic progress using the grade spreadsheet template.

Office Hours: your instructor's office hours are by appointment, except in cases of emergency. Email is the preferred method for setting up an appointment with your instructor to discuss something in private.

Grounds for Failure: a failing (F) grade will be earned in any course if any mastery objectives are past deadline by more than one school day, or for any of the following behaviors: false testimony (lying), cheating on any assignment or assessment, plagiarism (presenting another's work as your own), willful violation of a safety policy, theft, harassment, sabotage, destruction of property, or intoxication. These behaviors are grounds for immediate termination in this career, and as such will not be tolerated here.

file `expectations`

Program Outcomes for Instrumentation and Control Technology (BTC)

| #1 | Communication |

Communicate and express concepts and ideas across a variety of media (verbal, written, graphical) using industry-standard terms.

| #2 | Time management |

Arrives on time and prepared to work; Budgets time and meets deadlines when performing tasks and projects.

| #3 | Safety |

Complies with national, state, local, and college safety regulations when designing and performing work on systems.

| #4 | Analysis and Diagnosis |

Analyze, evaluate, and diagnose systems related to instrumentation and control including electrical and electronic circuits, fluid power and signaling systems, computer networks, and mechanisms; Select and apply correct mathematical techniques to these analytical and diagnostic problems; Select and correctly use appropriate test equipment to collect data.

| #5 | Design and Commissioning |

Select, design, construct, configure, and install components necessary for the proper function of systems related to instrumentation and control, applying industry standards and verifying correct system operation when complete.

| #6 | System optimization |

Improve technical system functions by collecting data and evaluating performance; Implement strategies to optimize the function of these systems.

| #7 | Calibration |

Assess instrument accuracy and correct inaccuracies using appropriate calibration procedures and test equipment; Select and apply correct mathematical techniques to these calibration tasks.

| #8 | Documentation |

Interpret and create technical documents (e.g. electronic schematics, loop diagrams, functional diagrams, P&IDs, graphs, narratives) according to industry standards.

| #9 | Independent learning |

Select and research information sources to learn new principles, technologies, and techniques.

| #10 | Job searching |

Develop a professional resume and research job openings in the field of industrial instrumentation.

file outcomes_program

INST 241 Course Outcomes

Each and every outcome in this course is assessed at a <u>mastery</u> level (i.e. 100% competence)

- Calculate voltages and currents in an ideal AC transformer circuit. [Ref: Program Learning Outcome #4]

- Calculate voltages, currents, and phase shifts in an AC reactive circuit. [Ref: Program Learning Outcome #4]

- Sketch proper wire connections showing how to simulate an RTD or thermocouple input to a temperature transmitter using simple electronic components. [Ref: Program Learning Outcome #5]

- Calculate temperatures or voltages in thermocouple and RTD circuits given access to thermocouple and RTD tables. [Ref: Program Learning Outcome #7]

- Calculate flow rate and pressure drop for a nonlinear flow element given maximum flow specifications. [Ref: Program Learning Outcome #7]

- Determine suitability of different flow-measuring technologies for a given process fluid type. [Ref: Program Learning Outcome #4]

- Calculate instrument input and output values given calibrated ranges. [Ref: Program Learning Outcome #7]

- Solve for specified variables in algebraic formulae. [Ref: Program Learning Outcome #4]

- Identify specific instrument calibration errors (zero, span, linearity, hysteresis) from data in an "As-Found" table. [Ref: Program Learning Outcome #7]

- Determine the possibility of suggested faults in simple circuits and Wheatstone bridge circuits given measured values (voltage, current), schematic diagrams, and reported symptoms. [Ref: Program Learning Outcome #4]

- Demonstrate proper use of safety equipment and application of safe procedures while using power tools, and working on live systems. [Ref: Program Learning Outcome #3]

- Communicate effectively with teammates to plan work, arrange for absences, and share responsibilities in completing all labwork. [Ref: Program Learning Outcomes #1 and #2]

- Construct and commission a working temperature-measurement loop consisting of an electronic temperature transmitter, signal wiring, and SCADA RTU programmed in a text-based programming language. [Ref: Program Learning Outcome #5]

- Construct and commission a working flow-measurement loop consisting of an electronic flow transmitter, signal wiring, and flow computer programmed in a text-based programming language. [Ref: Program Learning Outcome #5]

- Generate accurate loop diagrams compliant with ISA standards documenting your team's systems. [Ref: Program Learning Outcome #8]

- Research equipment manuals to sketch a complete circuit connecting a loop controller to either a 4-20 mA transmitter or a 4-20 mA final control element, with all DC voltages and currents correctly annotated, all electrical sources and loads properly identified, given components randomly selected by the instructor. [Ref: Program Learning Outcomes #5 and #9]

- Calibrate an electronic RTD temperature transmitter to specified accuracy using industry-standard calibration equipment. [Ref: Program Learning Outcome #7]

- Calibrate an electronic thermocouple temperature transmitter to specified accuracy using industry-standard calibration equipment. [Ref: Program Learning Outcome #7]

- Accurately simulate a thermocouple signal using a millivoltage source. [Ref: Program Learning Outcome #7]

- Accurately simulate an RTD signal using a potentiometer. [Ref: Program Learning Outcome #7]

- Calculate flow rate and pressure drop for a nonlinear flow element given maximum flow specifications. [Ref: Program Learning Outcome #7]

- Edit text-based programming code for a flow computer. [Ref: Program Learning Outcome #5]

- Diagnose a random fault simulated by computer in a 4-wire RTD circuit, logically justifying your steps before an instructor. [Ref: Program Learning Outcome #4]
- Diagnose a random fault simulated by computer in a 4-20 transmitter circuit, logically justifying your steps before an instructor. [Ref: Program Learning Outcome #4]

file `outcomes_INST241`

Sequence of second-year Instrumentation courses

Core Electronics -- 3 qtrs
including MATH 141 (Precalculus 1)

(Only if 4th quarter was Summer: INST23x)

Prerequisite for all INST24x, INST25x, and INST26x courses

INST 200 -- 1 wk
Intro. to Instrumentation

Offered 1ˢᵗ week of Fall, Winter, and Spring quarters

Summer quarter

INST 233 -- 4 cr
Protective Relays *(elective)*

Jobshadow and/or Internship strongly recommended

Fall quarter

INST 240 -- 6 cr
Pressure/Level Measurement

INST 241 -- 6 cr
Temp./Flow Measurement

INST 242 -- 5 cr
Analytical Measurement

Winter quarter

INST 250 -- 5 cr
Final Control Elements

INST 251 -- 5 cr
PID Control

INST 252 -- 4 cr
Loop Tuning

Spring quarter

INST 260 -- 4 cr
Data Acquisition Systems

INST 262 -- 5 cr
Digital Control Systems

INST 263 -- 5 cr
Control Strategies

ENGT 134 -- 5 cr
CAD 1: Basics

Prerequisite for INST206

All courses completed? **Yes** **No**

INST 205 -- 1 cr
Job Prep I

INST 206 -- 1 cr
Job Prep II

Offered 1ˢᵗ week of Fall, Winter, and Spring quarters

Graduate!!!

8

The particular sequence of courses you take during the second year depends on when you complete all first-year courses and enter the second year. Since students enter the second year of Instrumentation at four different times (beginnings of Summer, Fall, Winter, and Spring quarters), the particular course sequence for any student will likely be different from the course sequence of classmates.

Some second-year courses are only offered in particular quarters with those quarters not having to be in sequence, while others are offered three out of the four quarters and must be taken in sequence. The following layout shows four typical course sequences for second-year Instrumentation students, depending on when they first enter the second year of the program:

Possible course schedules depending on date of entry into 2nd year

Beginning in Summer	Beginning in Fall	Beginning in Winter	Beginning in Spring
Summer quarter (July–Aug.) INST 233 -- 4 cr — Protective Relays (elective) *Jobshadow and/or Internship strongly recommended*	**Fall quarter** (Sept.–Dec.) INST 200 -- 1 wk — Intro. to Instrumentation INST 240 -- 6 cr — Pressure/Level Measurement INST 241 -- 6 cr — Temp./Flow Measurement INST 242 -- 5 cr — Analytical Measurement	**Winter quarter** (Jan.–Mar.) INST 200 -- 1 wk — Intro. to Instrumentation INST 250 -- 5 cr — Final Control Elements INST 251 -- 5 cr — PID Control INST 252 -- 4 cr — Loop Tuning	**Spring quarter** (April–June) INST 200 -- 1 wk — Intro. to Instrumentation INST 260 -- 4 cr — Data Acquisition Systems INST 262 -- 5 cr — Digital Control Systems INST 263 -- 5 cr — Control Strategies ENGT 134 -- 5 cr — CAD 1: Basics
Fall quarter (Sept.–Dec.) INST 200 -- 1 wk — Intro. to Instrumentation INST 240 -- 6 cr — Pressure/Level Measurement INST 241 -- 6 cr — Temp./Flow Measurement INST 242 -- 5 cr — Analytical Measurement	**Winter quarter** (Jan.–Mar.) INST 205 -- 1 cr — Job Prep I INST 250 -- 5 cr — Final Control Elements INST 251 -- 5 cr — PID Control INST 252 -- 4 cr — Loop Tuning	**Spring quarter** (April–June) INST 205 -- 1 cr — Job Prep I INST 260 -- 4 cr — Data Acquisition Systems INST 262 -- 5 cr — Digital Control Systems INST 263 -- 5 cr — Control Strategies ENGT 134 -- 5 cr — CAD 1: Basics	**Summer quarter** (July–Aug.) INST 233 -- 4 cr — Protective Relays (elective) *Jobshadow and/or Internship strongly recommended*
Winter quarter (Jan.–Mar.) INST 205 -- 1 cr — Job Prep I INST 250 -- 5 cr — Final Control Elements INST 251 -- 5 cr — PID Control INST 252 -- 4 cr — Loop Tuning	**Spring quarter** (April–June) INST 206 -- 1 cr — Job Prep II INST 260 -- 4 cr — Data Acquisition Systems INST 262 -- 5 cr — Digital Control Systems INST 263 -- 5 cr — Control Strategies ENGT 134 -- 5 cr — CAD 1: Basics	**Summer quarter** (July–Aug.) INST 233 -- 4 cr — Protective Relays (elective) *Jobshadow and/or Internship strongly recommended*	**Fall quarter** (Sept.–Dec.) INST 205 -- 1 cr — Job Prep I INST 240 -- 6 cr — Pressure/Level Measurement INST 241 -- 6 cr — Temp./Flow Measurement INST 242 -- 5 cr — Analytical Measurement
Spring quarter (April–June) INST 206 -- 1 cr — Job Prep II INST 260 -- 4 cr — Data Acquisition Systems INST 262 -- 5 cr — Digital Control Systems INST 263 -- 5 cr — Control Strategies ENGT 134 -- 5 cr — CAD 1: Basics	**Summer quarter** (July–Aug.) INST 233 -- 4 cr — Protective Relays (elective) *Jobshadow and/or Internship strongly recommended*	**Fall quarter** (Sept.–Dec.) INST 206 -- 1 cr — Job Prep II INST 240 -- 6 cr — Pressure/Level Measurement INST 241 -- 6 cr — Temp./Flow Measurement INST 242 -- 5 cr — Analytical Measurement	**Winter quarter** (Jan.–Mar.) INST 206 -- 1 cr — Job Prep II INST 250 -- 5 cr — Final Control Elements INST 251 -- 5 cr — PID Control INST 252 -- 4 cr — Loop Tuning
Graduation!	*Graduation!*	*Graduation!*	*Graduation!*

file sequence

Wrenches
- Combination (box- and open-end) wrench set, 1/4" to 3/4" – *the most important wrench sizes are 7/16",
  1/2", 9/16", and 5/8"; get these immediately!*
- Adjustable wrench, 6" handle (sometimes called "Crescent" wrench)
- Hex wrench ("Allen" wrench) set, fractional – 1/16" to 3/8"
- *Optional:* Hex wrench ("Allen" wrench) set, metric – 1.5 mm to 10 mm
- *Optional:* Miniature combination wrench set, 3/32" to 1/4" (sometimes called an "ignition wrench" set)

Note: *always maximize surface engagement on a fastener's head to reduce stress on that fastener. (e.g. Using box-end wrenches instead of adjustable wrenches; using the proper size and type of screwdriver; never using any tool that mars the fastener such as pliers or vise-grips unless absolutely necessary.)*

Pliers
- Needle-nose pliers
- Diagonal wire cutters (sometimes called "dikes")

Screwdrivers
- Slotted, 1/8" and 1/4" shaft
- Phillips, #1 and #2
- Jeweler's screwdriver set
- *Optional:* Magnetic multi-bit screwdriver (e.g. Klein Tools model 70035)

Electrical
- Multimeter, Fluke model 87-IV or better
- Assortment of alligator-clip style jumper wires
- Soldering iron (10 to 40 watt) and rosin-core solder
- Resistor, potentiometer, diode assortments (from first-year lab kits)
- Package of insulated compression-style fork terminals (14 to 18 AWG wire size, #10 stud size)
- Wire strippers/terminal crimpers for 10 AWG to 18 AWG wire and insulated terminals
- *Optional:* ratcheting terminal crimp tool (e.g. Paladin 1305, Ferrules Direct FDT10011, or equivalent)

Safety
- Safety glasses or goggles (available at BTC bookstore)
- Earplugs (available at BTC bookstore)

Miscellaneous
- Simple scientific calculator (non-programmable, non-graphing, no conversions), TI-30Xa or TI-30XIIS
  recommended. Required for some exams!
- Portable personal computer capable of wired Ethernet connectivity, Wi-Fi connectivity, displaying PDF
  documents, creating text documents, creating and viewing spreadsheets, running PLC programming
  software (MS Windows only), and executing command-line utilities such as `ping`.
- Masking tape (for making temporary labels)
- Permanent marker pen
- Teflon pipe tape
- Utility knife
- Tape measure, 12 feet minimum
- Flashlight

file `tools`

Methods of instruction

This course develops self-instructional and diagnostic skills by placing students in situations where they are required to research and think independently. In all portions of the curriculum, the goal is to avoid a passive learning environment, favoring instead *active engagement* of the learner through reading, reflection, problem-solving, and experimental activities. The curriculum may be roughly divided into two portions: *theory* and *practical*. All "theory" sessions follow the *inverted* format and contain virtually no lecture.

Inverted theory sessions

The basic concept of an "inverted" learning environment is that the traditional allocations of student time are reversed: instead of students attending an instructor-led session to receive new information and then practicing the application of that information outside of the classroom in the form of homework, students in an inverted class encounter new information outside of the classroom via homework and apply that information in the classroom session under the instructor's tutelage.

A natural question for instructors, then, is what their precise role is in an inverted classroom and how to organize that time well. Here I will list alternate formats suitable for an inverted classroom session, each of them tested and proven to work.

Small sessions

Students meet with instructors in small groups for short time periods. Groups of 4 students meeting for 30 minutes works very well, but groups as large as 8 students apiece may be used if time is limited. Each of these sessions begins with a 5 to 10 minute graded inspection of homework with individual questioning, to keep students accountable for doing the homework. The remainder of the session is a dialogue focusing on the topics of the day, the instructor challenging each student on the subject matter in Socratic fashion, and also answering students' questions. A second grade measures each student's comprehension of the subject matter by the end of the session.

This format also works via teleconferencing, for students unable to attend a face-to-face session on campus.

Large sessions

Students meet with instructors in a standard classroom (normal class size and period length). Each of these sessions begins with a 10 minute graded quiz (closed-book) on the homework topic(s), to keep students accountable for doing the homework. Students may leave the session as soon as they "check off" with the instructor in a Socratic dialogue as described above (instructor challenging each student to assess their comprehension, answering questions, and grading the responses). Students sign up for check-off on the whiteboard when they are ready, typically in groups of no more than 4. Alternatively, the bulk of the class session may be spent answering student questions in small groups, followed by another graded quiz at the end.

Correspondence

This format works for students unable to attend a "face-to-face" session, and who must correspond with the instructor via email or other asynchronous medium. Each student submits a thorough presentation of their completed homework, which the instructor grades for completeness and accuracy. The instructor then replies back to the student with challenge questions, and also answers questions the student may have. As with the previous formats, the student receives another grade assessing their comprehension of the subject matter by the close of the correspondence dialogue.

In all formats, students are held accountable for completion of their homework, "completion" being defined as successfully interpreting the given information from source material (e.g. accurate outlines of reading or video assignments) and constructive effort to solve given problems. It must be understood in an inverted learning environment that students *will* have legitimate questions following a homework assignment, and that it is therefore unreasonable to expect mastery of the assigned subject matter. What is reasonable to expect from each and every student is a basic outline of the source material (reading or video assignments) complete with major terms defined and major concepts identified, plus a good-faith effort to solve every problem. Question 0 (contained in every worksheet) lists multiple strategies for effective study and problem-solving.

Sample rubric for pre-assessments

- **No credit** = Any homework question unattempted (i.e. no effort shown on one or more questions); incomprehensible writing; failure to follow clear instruction(s)
- **Half credit** = Misconception(s) on any major topic explained in the assigned reading; answers shown with no supporting work; verbatim copying of text rather than written in student's own words; outline missing important topic(s); unable to explain the outline or solution methods represented in written work
- **Full credit** = Every homework question answered, with any points of confusion clearly articulated; all important concepts from reading assignments accurately expressed in the outline and clearly articulated when called upon by the instructor to explain

The minimum expectation at the start of every student-instructor session is that all students have made a good-faith effort to complete 100% of their assigned homework. This does not necessarily mean all answers will be correct, or that all concepts are fully understood, because one of the purposes of the meeting between students and instructor is to correct remaining misconceptions and answer students' questions. However, experience has shown that without accountability for the homework, a substantial number of students will not put forth their best effort and that this compromises the whole learning process. Full credit is reserved for good-faith effort, where each student thoughtfully applies the study and problem-solving recommendations given to them (see Question 0).

Sample rubric for post-assessments

- **No credit** = Failure to comprehend one or more key concepts; failure to apply logical reasoning to the solution of problem(s); no contribution to the dialogue
- **Half credit** = Some misconceptions persist by the close of the session; problem-solving is inconsistent; limited contribution to the dialogue
- **Full credit** = Socratic queries answered thoughtfully; effective reasoning applied to problems; ideas communicated clearly and accurately; responds intelligently to questions and statements made by others in the session; adds new ideas and perspectives

The minimum expectation is that each and every student engages with the instructor and with fellow students during the Socratic session: posing intelligent questions of their own, explaining their reasoning when challenged, and otherwise positively contributing to the discussion. Passive observation and listening is not an option here – every student must be an active participant, contributing something original to every dialogue. If a student is confused about any concept or solution, it is their responsibility to ask questions and seek resolution.

If a student happens to be absent for a scheduled class session and is therefore unable to be assessed on that day's study, they may schedule a time with the instructor to demonstrate their comprehension at some later date (before the end of the quarter when grades must be submitted). These same standards of performance apply equally make-up assessments: either inspection of homework or a closed-book quiz for the pre-assessment, and either a Socratic dialogue with the instructor or another closed-book quiz for the post-assessment.

Lab sessions

In the lab portion of each course, students work in teams to install, configure, document, calibrate, and troubleshoot working instrument loop systems. Each lab exercise focuses on a different type of instrument, with a limited time period typically for completion. An ordinary lab session might look like this:

(1) Start of practical (lab) session: announcements and planning
    (a) The instructor makes general announcements to all students
    (b) The instructor works with team to plan that day's goals, making sure each team member has a clear idea of what they should accomplish
(2) Teams work on lab unit completion according to recommended schedule:
    (First day) Select and bench-test instrument(s), complete prototype sketch of project
    (One day) Connect instrument(s) into a complete loop
    (One day) Each team member drafts their own loop documentation, inspection done as a team (with instructor)
    (One or two days) Each team member calibrates/configures the instrument(s)
    (Remaining days, up to last) Each team member troubleshoots the instrument loop
(3) End of practical (lab) session: debriefing where each team reports on their work to the whole class

Troubleshooting assessments must meet the following guidelines:

- Troubleshooting must be performed *on a system the student did not build themselves.* This forces students to rely on another team's documentation rather than their own memory of how the system was built.
- Each student must individually demonstrate proper troubleshooting technique.
- Simply finding the fault is not good enough. Each student must consistently demonstrate sound reasoning while troubleshooting.
- If a student fails to properly diagnose the system fault, they must attempt (as many times as necessary) with different scenarios until they do, reviewing any mistakes with the instructor after each failed attempt.

file `instructional`

Distance delivery methods

Sometimes the demands of life prevent students from attending college 6 hours per day. In such cases, there exist alternatives to the normal 8:00 AM to 3:00 PM class/lab schedule, allowing students to complete coursework in non-traditional ways, at a "distance" from the college campus proper.

For such "distance" students, the same worksheets, lab activities, exams, and academic standards still apply. Instead of working in small groups and in teams to complete theory and lab sections, though, students participating in an alternative fashion must do all the work themselves. Participation via teleconferencing, video- or audio-recorded small-group sessions, and such is encouraged and supported.

There is no recording of hours attended or tardiness for students participating in this manner. The pace of the course is likewise determined by the "distance" student. Experience has shown that it is a benefit for "distance" students to maintain the same pace as their on-campus classmates whenever possible.

In lieu of small-group activities and class discussions, comprehension of the theory portion of each course will be ensured by completing and submitting detailed answers for *all* worksheet questions, not just passing daily quizzes as is the standard for conventional students. The instructor will discuss any incomplete and/or incorrect worksheet answers with the student, and ask that those questions be re-answered by the student to correct any misunderstandings before moving on.

Labwork is perhaps the most difficult portion of the curriculum for a "distance" student to complete, since the equipment used in Instrumentation is typically too large and expensive to leave the school lab facility. "Distance" students must find a way to complete the required lab activities, either by arranging time in the school lab facility and/or completing activities on equivalent equipment outside of school (e.g. at their place of employment, if applicable). Labwork completed outside of school must be validated by a supervisor and/or documented via photograph or videorecording.

Conventional students may opt to switch to "distance" mode at any time. This has proven to be a benefit to students whose lives are disrupted by catastrophic events. Likewise, "distance" students may switch back to conventional mode if and when their schedules permit. Although the existence of alternative modes of student participation is a great benefit for students with challenging schedules, it requires a greater investment of time and a greater level of self-discipline than the traditional mode where the student attends school for 6 hours every day. No student should consider the "distance" mode of learning a way to have more free time to themselves, because they will actually spend more time engaged in the coursework than if they attend school on a regular schedule. It exists merely for the sake of those who cannot attend during regular school hours, as an alternative to course withdrawal.

file distance

Metric prefixes and conversion constants

- **Metric prefixes**
- Yotta = 10^{24} Symbol: Y
- Zeta = 10^{21} Symbol: Z
- Exa = 10^{18} Symbol: E
- Peta = 10^{15} Symbol: P
- Tera = 10^{12} Symbol: T
- Giga = 10^{9} Symbol: G
- Mega = 10^{6} Symbol: M
- Kilo = 10^{3} Symbol: k
- Hecto = 10^{2} Symbol: h
- Deca = 10^{1} Symbol: da
- Deci = 10^{-1} Symbol: d
- Centi = 10^{-2} Symbol: c
- Milli = 10^{-3} Symbol: m
- Micro = 10^{-6} Symbol: μ
- Nano = 10^{-9} Symbol: n
- Pico = 10^{-12} Symbol: p
- Femto = 10^{-15} Symbol: f
- Atto = 10^{-18} Symbol: a
- Zepto = 10^{-21} Symbol: z
- Yocto = 10^{-24} Symbol: y

METRIC PREFIX SCALE

T	G	M	k		m	μ	n	p
tera	giga	mega	kilo	(none)	milli	micro	nano	pico
10^{12}	10^{9}	10^{6}	10^{3}	10^{0}	10^{-3}	10^{-6}	10^{-9}	10^{-12}

10^{2}	10^{1}	10^{-1}	10^{-2}
hecto	deca	deci	centi
h	da	d	c

- **Conversion formulae for temperature**
- $^{o}F = (^{o}C)(9/5) + 32$
- $^{o}C = (^{o}F - 32)(5/9)$
- $^{o}R = {}^{o}F + 459.67$
- $K = {}^{o}C + 273.15$

Conversion equivalencies for distance

1 inch (in) = 2.540000 centimeter (cm)

1 foot (ft) = 12 inches (in)

1 yard (yd) = 3 feet (ft)

1 mile (mi) = 5280 feet (ft)

Conversion equivalencies for volume

1 gallon (gal) = 231.0 cubic inches (in^3) = 4 quarts (qt) = 8 pints (pt) = 128 fluid ounces (fl. oz.) = 3.7854 liters (l)

1 milliliter (ml) = 1 cubic centimeter (cm^3)

Conversion equivalencies for velocity

1 mile per hour (mi/h) = 88 feet per minute (ft/m) = 1.46667 feet per second (ft/s) = 1.60934 kilometer per hour (km/h) = 0.44704 meter per second (m/s) = 0.868976 knot (knot – international)

Conversion equivalencies for mass

1 pound (lbm) = 0.45359 kilogram (kg) = 0.031081 slugs

Conversion equivalencies for force

1 pound-force (lbf) = 4.44822 newton (N)

Conversion equivalencies for area

1 acre = 43560 square feet (ft^2) = 4840 square yards (yd^2) = 4046.86 square meters (m^2)

Conversion equivalencies for common pressure units (either all gauge or all absolute)

1 pound per square inch (PSI) = 2.03602 inches of mercury (in. Hg) = 27.6799 inches of water (in. W.C.) = 6.894757 kilo-pascals (kPa) = 0.06894757 bar

1 bar = 100 kilo-pascals (kPa) = 14.504 pounds per square inch (PSI)

Conversion equivalencies for absolute pressure units (only)

1 atmosphere (Atm) = 14.7 pounds per square inch absolute (PSIA) = 101.325 kilo-pascals absolute (kPaA) = 1.01325 bar (bar) = 760 millimeters of mercury absolute (mmHgA) = 760 torr (torr)

Conversion equivalencies for energy or work

1 british thermal unit (Btu – "International Table") = 251.996 calories (cal – "International Table") = 1055.06 joules (J) = 1055.06 watt-seconds (W-s) = 0.293071 watt-hour (W-hr) = 1.05506 x 10^{10} ergs (erg) = 778.169 foot-pound-force (ft-lbf)

Conversion equivalencies for power

1 horsepower (hp – 550 ft-lbf/s) = 745.7 watts (W) = 2544.43 british thermal units per hour (Btu/hr) = 0.0760181 boiler horsepower (hp – boiler)

Acceleration of gravity (free fall), Earth standard

9.806650 meters per second per second (m/s^2) = 32.1740 feet per second per second (ft/s^2)

Physical constants

Speed of light in a vacuum (c) = 2.9979×10^8 meters per second (m/s) = 186,281 miles per second (mi/s)

Avogadro's number (N_A) = 6.022×10^{23} per mole (mol^{-1})

Electronic charge (e) = 1.602×10^{-19} Coulomb (C)

Boltzmann's constant (k) = 1.38×10^{-23} Joules per Kelvin (J/K)

Stefan-Boltzmann constant (σ) = 5.67×10^{-8} Watts per square meter-Kelvin^4 (W/m^2·K^4)

Molar gas constant (R) = 8.314 Joules per mole-Kelvin (J/mol-K)

Properties of Water

Freezing point at sea level = 32^oF = 0^oC

Boiling point at sea level = 212^oF = 100^oC

Density of water at 4^oC = 1000 kg/m^3 = 1 g/cm^3 = 1 kg/liter = 62.428 lb/ft^3 = 1.94 slugs/ft^3

Specific heat of water at 14^oC = 1.00002 calories/g·^{o}C = 1 BTU/lb·^{o}F = 4.1869 Joules/g·^{o}C

Specific heat of ice $\approx$ 0.5 calories/g·^{o}C

Specific heat of steam $\approx$ 0.48 calories/g·^{o}C

Absolute viscosity of water at 20^oC = 1.0019 centipoise (cp) = 0.0010019 Pascal-seconds (Pa·s)

Surface tension of water (in contact with air) at 18^oC = 73.05 dynes/cm

pH of pure water at 25° C = 7.0 (*pH scale = 0 to 14*)

Properties of Dry Air at sea level

Density of dry air at 20^oC and 760 torr = 1.204 mg/cm^3 = 1.204 kg/m^3 = 0.075 lb/ft^3 = 0.00235 slugs/ft^3

Absolute viscosity of dry air at 20^oC and 760 torr = 0.018 centipoise (cp) = 1.8×10^{-5} Pascal-seconds (Pa·s)

file conversion_constants

How to get the most out of academic reading:
- <u>Outline, don't highlight!</u> Identify every major idea presented in the text, and express these ideas in your own words. A suggested ratio is one sentence of your own thoughts per paragraph of text read.

- <u>Articulate your thoughts</u> as you read (i.e. "have a conversation" with the author). This will develop *metacognition*: active supervision of your own thoughts. Note points of agreement, disagreement, confusion, epiphanies, and connections between different concepts or applications.

- <u>Work through all mathematical exercises</u> shown within the text, to ensure you understand all the steps.

- <u>Imagine explaining concepts you've just learned to someone else.</u> Teaching forces you to distill concepts to their essence, thereby clarifying those concepts, revealing assumptions, and exposing misconceptions. Your goal is to create the simplest explanation that is still technically accurate.

- <u>Create your own questions</u> based on what you read, as a teacher would to challenge students.

How to effectively problem-solve and troubleshoot:
- <u>Rely on principles, not procedures.</u> Don't be satisfied with memorizing steps – learn *why* those steps work. Each step should make logical sense and have real-world meaning to you.

- <u>Sketch a diagram</u> to help visualize the problem. <u>Sketch a graph</u> showing how variables relate. When building a real system, always prototype it on paper and analyze its function *before* constructing it.

- <u>Identify</u> what it is you need to solve, <u>identify</u> all relevant data, <u>identify</u> all units of measurement, <u>identify</u> any general principles or formulae linking the given information to the solution, and then <u>identify</u> any "missing pieces" to a solution. <u>Annotate</u> all diagrams with this data.

- <u>Perform "thought experiments"</u> to explore the effects of different conditions for theoretical problems. When troubleshooting, perform *diagnostic tests* rather than just visually inspect for faults.

- <u>Simplify the problem</u> and solve that simplified problem to identify strategies applicable to the original problem (e.g. change quantitative to qualitative, or visa-versa; substitute easier numerical values; eliminate confusing details; add details to eliminate unknowns; consider simple limiting cases; apply an analogy). Remove components from a malfunctioning system to simplify it and better identify the nature and location of the problem.

- <u>Check for exceptions</u> – does your solution work for *all* conditions and criteria?

- <u>Work "backward"</u> from a hypothetical solution to a new set of given conditions.

How to manage your time:
- <u>Avoid procrastination.</u> Work now and play later, every single day.

- <u>Consider the place you're in</u> when deciding what to do. If there is project work to do and you have access to the lab, do that work and not something that could be done elsewhere (e.g. homework).

- <u>Eliminate distractions.</u> Kill your television and video games. Turn off your mobile phone, or just leave it at home. Study in places where you can concentrate, like the Library.

- <u>Use your "in between" time productively.</u> Don't leave campus for lunch. Arrive to school early. If you finish your assigned work early, begin working on the next assignment.

Above all, cultivate <u>persistence</u>, as this is necessary to master anything non-trivial. The keys to persistence are (1) having the desire to achieve that mastery, and (2) realizing challenges are normal and not an indication of something gone wrong. A common error is to equate *easy* with *effective*: students often believe learning should be easy if everything is done right. The truth is that mastery never comes easy!

<u>file `question0`</u>

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Was the text confusing at any point(s)? If so, what was it about the text's presentation that made it difficult to understand?
- Do you see any way(s) in which the text could be improved? Articulate your ideas for improvement, and explain why those improvements are indeed better.
- Did you encounter any new concepts in the text? If so, explain each in your own words.
- Did the text apply any familiar concepts (including fundamental laws or principles) in new ways? What exactly was different about this application?
- Was the text surprising to you in any way? If so, how so?
- What background knowledge should a reader possess prior to reading this text?
- Devise a proof of concept experiment to empirically demonstrate an important principle, physical law, or technical innovation represented in the text.
- Devise your own thought experiment to virtually demonstrate the same.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Devise an experiment to clearly disprove one of these misconceptions, to show by counter-example how the misconception in question cannot be true.
- Did the text model any useful problem-solving strategies for the benefit of the reader? If so, describe one of those strategies in terms general enough to apply to some other problem.
- Devise a question of your own to challenge a reader's comprehension of the text.
- Identify where it might be easy for someone to misunderstand the text.
- Describe your own reading process. Did you skim the text first and then read it in detail from start to finish? Do you take notes are you go along, or read large sections of the text before making any notes on it? Did you identify any key words, phrases, or ideas that helped make sense of the text overall? Were there sections of the text you needed to read multiple times? How do you divide your time between examining illustrations and the reading the text accompanying those illustrations?

- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Identify where any fundamental laws or principles apply to the solution of this problem.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- Is there more than one way to solve this problem? Which method seems best to you?
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.

- For qualitative problems, try approaching it <u>quantitatively</u> instead, proposing simple numerical values for the variables.

- Were there any <u>assumptions</u> you made while solving this problem? Would your solution change if one of those assumptions were altered?

- Identify where it would be easy for someone to <u>go astray</u> in attempting to solve this problem.

- <u>Formulate your own problem</u> based on what you learned solving this one.

file `license`

Question 1

Read and outline the "Turbine Flowmeters" subsection of the "Velocity-Based Flowmeters" section of the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i04055

Question 2

Suppose a turbine flowmeter used to measure the flow of natural gas has a "K factor" equal to 37.2 pulses per standard cubic foot (SCF). Calculate the following:

The total amount of gas volume passed through the flowmeter after a digital counter circuit records 2,594,620 pulses.

The flow rate through the meter (in units of SCFM) with the pulse signal having a frequency of 94 Hz.

The amount of time required (in units of hours and minutes) to accumulate 525,000 pulses (on a digital counter circuit) give a steady flow rate of 170 SCFM.

Suppose someone entered the wrong K factor value into the digital electronic transmitter connected to the turbine meter's pickup coil. Would this cause a *zero shift*, a *span shift*, a *linearity error*, or a *hysteresis error*? Explain your reasoning.

Suggestions for Socratic discussion

- The label "Standard Cubic Feet" means one cubic foot of volume with the gas at room temperature and atmospheric (sea-level) pressure. Explain why we might use the unit of "Standard Cubic Feet" to express the flow of a gas through a pipe rather than simple "Cubic Feet".
- What advantages does a turbine meter have for measuring natural gas flow that make it well-suited for this application?
- Explain what would be necessary to make a turbine flowmeter register the true *mass flow rate* of the fluid rather than just the volumetric flow rate.
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

file i04057

Question 3

Read and outline the "Vortex Flowmeters" subsection of the "Velocity-Based Flowmeters" section of the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i04058

Question 4

Contractors install this vortex flowmeter, equipped with a pulse output (1 pulse per 25 gallons), to totalize flow through a pipe:
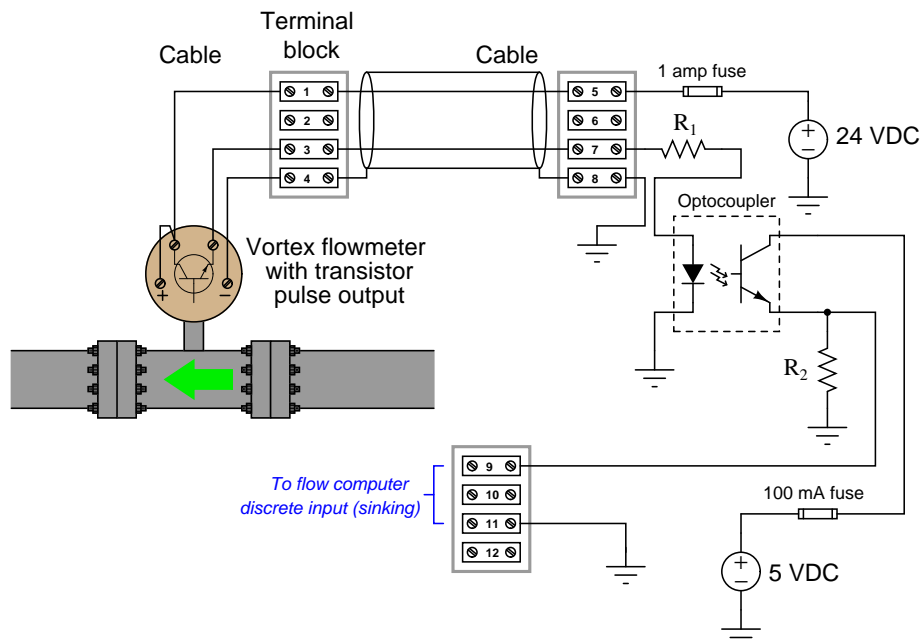
Unfortunately, the flow computer connected to this circuit is not registering any accumulated flow, even though an operator has verified flow through the pipe at approximately 370 gallons per minute. Your first step is to disconnect the flow computer input from this circuit (so it is wired exactly as shown) then to take your DC voltmeter and measure voltage between terminals 1 and 4: there, your meter registers 23.1 volts DC. Your next step is to measure DC voltage across the collector and emitter terminals of the optocoupler's transistor: there your meter registers 0 volts.

Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
R_1 failed open		
R_2 failed open		
R_1 failed shorted		
R_2 failed shorted		
1 amp fuse blown		
100 milliamp fuse blown		
24 VDC source dead		
5 VDC source dead		

Finally, identify the *next* diagnostic test or measurement you would make on this system. Explain how the result(s) of this next test or measurement help further identify the location and/or nature of the fault.

Suggestions for Socratic discussion

- Identify any other possible faults not listed in the table.

  file i00053

24

Question 5

Suppose a vortex flowmeter is used to measure the flow rate of fuel oil into a large combustion boiler. The vortex meter has a "K factor" equal to 10.344 pulses per gallon. Calculate the following:

The sensor frequency at a fuel oil flow rate of 8510 gallons per hour.

The total amount of fuel consumed by the boiler after a digital counter circuit records 800,000 pulses.

The fuel oil flow rate (in cubic feet per minute) at a sensor frequency of 35 Hz.

Suppose someone entered the wrong K factor value into the digital electronic transmitter connected to the vortex meter's sensor. Would this cause a *zero shift*, a *span shift*, a *linearity error*, or a *hysteresis error*? Explain your reasoning.

Suggestions for Socratic discussion

- Identify how we could set up this vortex flowmeter to record the total amount of fuel oil consumed by the boiler every 24 hours, and then log those values in records for operator reference.
- Explain how you could use simple test equipment to measure the frequency of the signal output by the vortex shedding sensor while the flowmeter was in operation. Note: some vortex flowmeters provide test points for you to connect electronic test equipment directly to the sensor inside the pipe!
- If the temperature of the fuel oil were to increase slightly, would it affect the vortex flowmeter's measurement accuracy? Explain why or why not.
- Explain what would be necessary to make a vortex flowmeter register the true *mass flow rate* of the fluid rather than just the volumetric flow rate.
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

file i04059

Question 6

Acetone – a valuable industrial solvent (chemical formula C_3H_6O) – may be manufactured from isopropyl alcohol (chemical formula C_3H_8O) in a chemical reaction that breaks two atoms of hydrogen away from each molecule of alcohol, leaving acetone and hydrogen gas (H_2) as byproducts:

$$C_3H_8O \rightarrow C_3H_6O + H_2$$
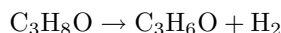
A simplified flow diagram for this process is shown here:
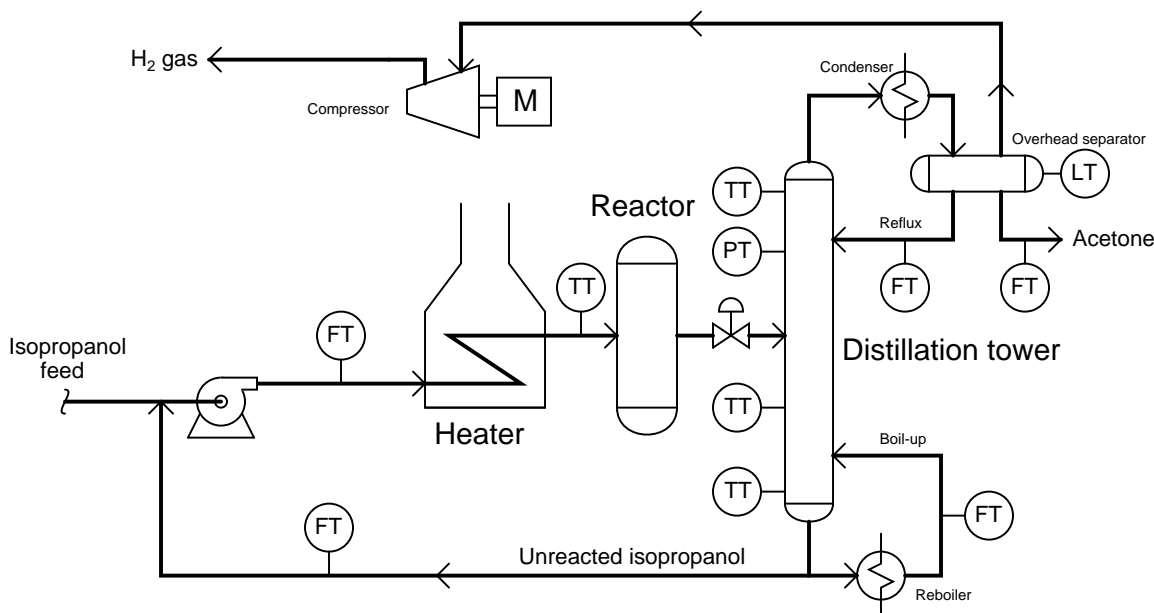
Suppose the decision is made to use a vortex flowmeter to measure acetone reflux flow into the distillation tower. This particular vortex flowmeter has a minimum Reynolds number value of 10,000 as specified by the manufacturer. Calculate the minimum flow rate of acetone at 20 ^{o}C this vortex meter will be able to measure given a schedule-40 pipe size of 1-1/2 inches (1.610 inches internal diameter). Assume a density of 49.4 pounds per cubic foot and an absolute viscosity of 0.32 centipoise for acetone at this temperature.

| Suggestions for Socratic discussion |

- Why would you as a technician (not an engineer) need to know anything about *minimum flow cutoff* for a vortex flowmeter? Identify a practical scenario where this knowledge might become important for you to do your job.
- Explain what the *Reynolds number* of a flowing fluid means in your own words. Specifically, what effects are manifest from different Reynolds number values?
- What is the purpose of a *distillation tower* in this particular process and how does it work?
- If you are familiar with distillation tower operation, identify which sunstance has the lower boiling point: acetone or isopropyl alcohol.

file i04060

Question 7

Read and outline the "Positive Displacement Flowmeters" section of the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i04061

Question 8

A manufacturing facility producing Vaseline jelly uses a positive displacement flowmeter equipped with an electronic "pickup" switch to measure the flow of jelly to a storage tank. This particular flowmeter outputs one pulse for every 20 gallons passing through. Calculate the following:

The pulse frequency given a flow rate of 310 cubic feet per minute.

The total volume of liquid passed causing an accumulation of 48,522 pulses by an electronic counter circuit connected to the meter's "pickup" switch.

The effect on measurement accuracy if the temperature of the Vaseline jelly increases enough to have a substantial effect on viscosity.

| Suggestions for Socratic discussion |

- Why do you suppose a positive displacement flowmeter is a good choice for this process fluid application?
- Are positive displacement flowmeters linear or nonlinear? Explain your answer.
- What would happen if we tried to use an orifice plate to measure the flow rate of Vaseline?
- What would happen if we tried to use a turbine flowmeter to measure the flow rate of Vaseline?
- What would happen if we tried to use a vortex flowmeter to measure the flow rate of Vaseline?
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

file i04062

Question 9

Read pages 2-3 through 2-5 of the "Rosemount Model 8800C and Model 8800A Smart Vortex Flowmeter" reference manual (publication 00809-0100-4003 Revision JA), and answer the following questions:

Explain why a vertical pipe orientation is preferred for this type of flowmeter, identifying the proper direction(s) of flow for different process fluids.

Figure 2-2 shows preferred mounting positions for hot pipes – explain why these positions are preferred to other alternative positions.

Identify the minimum upstream and downstream straight-pipe lengths for this flowmeter.

Figure 2-9 on page 2-12 shows the bolt-tightening sequence recommended for flange-mounted flowmeter installations. Examine each of the sequences shown, and explain why the sequence of bolt-tightening matters. Hint: the exact same principle is involved when tightening lug nuts on a car wheel, and it is called *cross-torquing*.

| **Suggestions for Socratic discussion** |

- Explain why the manual recommends you "install valves downstream of the meter when possible".
- This manual mentions the option of pressure and temperature compensation for the vortex flowmeter. Explain why one might choose to apply this type of compensation in a specific process application. Also, explain why compensating pressure and temperature sensors should be located downstream of the vortex flowmeter rather than upstream.
- Suppose you needed to "cross-torque" the bolts on a machine component, but did not have a manual to specify which bolts to torque in what order. Explain how you could apply a general cross-torquing procedure to *any* multi-bolt application.
- Suppose you were asked to build a circuit to interpret the pulse output from this model of vortex flowmeter, blinking an LED on and off with the pulse frequency. Sketch this circuit, being sure to note which screw terminals on the flowmeter to connect your circuit to.

file i04063

Question 10

Turbine flow meters are almost self-explanatory in their operation. Compare and contrast the turbine flow meter against the standard orifice plate flow meter as a flow-measuring device. What are some of the advantages of turbine meters over orifice plates? Are there any significant disadvantages?

Also, compare signal linearity between the two flow measurement technologies: we know that orifice plates require square-root characterization to obtain a linear response to flow rate. Is the same true for turbine meters? Why or why not?

file i00497

Question 11

A turbine flowmeter measuring cooling water for a large power generator uses an electronic circuit to convert its pickup coil pulses into a 4-20 mA analog current signal. The "K factor" for the turbine element is 99 pulses per gallon, and the 4-20 mA analog output is ranged from 0 to 500 GPM flow. Complete the following table of values for this transmitter, assuming perfect calibration (no error). Be sure to show your work!

Measured flow (GPM)	Pickup signal frequency (Hz)	Percent of output span (%)	Output signal (mA)
250			
412			
	305		
	780		
		63	
		49	
			10
			16

Suggestions for Socratic discussion

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- Suppose you were asked to check the accuracy of the frequency-to-current converter circuit for this flowmeter. What sort of test equipment would you use, and how could you perform the test with the flowmeter still installed in the cooling water pipe?
- Could the pulse output of the pickup coil be used directly as a flow signal, or is the converter circuit absolutely necessary?
- Explain how a PLC could be used to *totalize* the water flow through this flowmeter, to provide total usage values at the end of each day.

file i00101

Question 12

Suppose two water pipes of different diameter both have blunt objects ("bluff bodies") in the paths of their respective water flows. A pressure sensor device located near each of the bluff bodies measures the frequency of the vortices produced:

Small-diameter pipe

Large-diameter pipe
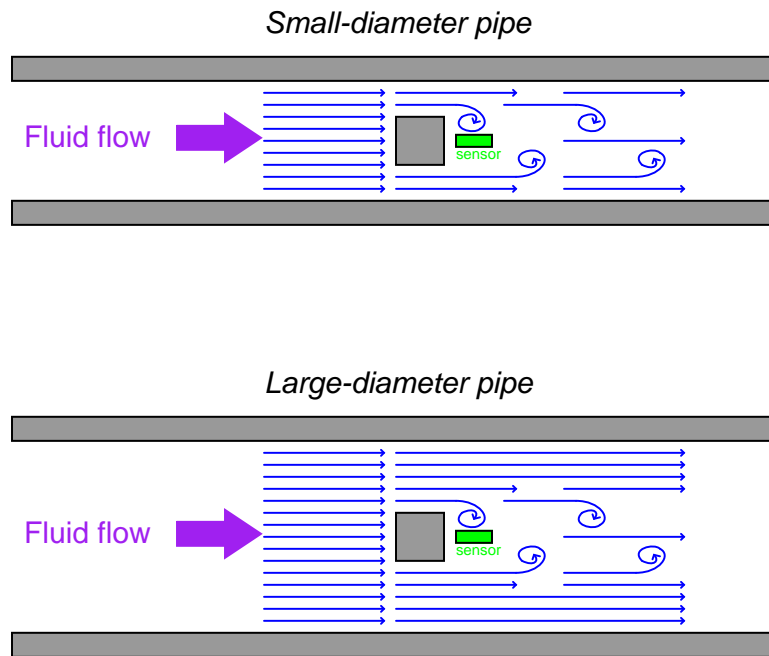
If the bluff bodies in both pipes have the same physical dimensions, and the vortex shedding frequencies are the same in both scenarios, which pipe carries a greater volumetric flow rate of water? Or, do they carry the same amount of flow? Why or why not??

file i00495

Question 13

Compare and contrast the vortex-shedding flow meter against the standard orifice plate flow meter. What are some of the advantages of vortex meters over orifice plates? Are there any significant disadvantages?

Also, compare signal linearity between the two flow measurement technologies: we know that orifice plates require square-root characterization to obtain a linear response to flow rate. Is the same true for vortex meters? Why or why not?

file i00494

Question 14

An important numerical constant related to the von Kármán effect is the *Strouhal number*. Explain what this number means, and why its constant (unchanging) value is important to flow-measuring instruments based on the von Kármán effect.

file i00492

Question 15

Suppose a stream of water flowing through a 10-inch diameter pipe passes by a 1-inch-wide blunt object installed in the middle of that pipe, and generates a series of von Kármán vortices having a frequency of 4.167 Hz. Calculate the flow rate through the pipe in gallons per minute (GPM).

file i00493

Question 16

There are several different types of flow meter devices broadly grouped under the classification of *positive displacement*. Describe the operational principle of a positive displacement flowmeter. Also, describe what physical properties of the fluid stream affect a positive displacement flowmeter's calibration.

file i00544

Question 17

What is a flow *prover*, and why is it periodically necessary to use one to re-calibrate positive-displacement flowmeters?

file i00546

Question 18

Research the necessary upstream and downstream straight-pipe requirements for vortex and turbine meters, and identify how these requirements compare against the typical requirements of orifice plates. For review's sake, why do we need a certain minimum length of straight pipe length upstream and downstream of a flow-measuring device?

file i00501

Question 19

What will be wrong with this measurement system if we connect a linear-scale indicator (an electrical meter movement responding to the transmitter's current signal) to the transmitter's output, and try to measure fluid flow along this scale? Assume the transmitter has been properly calibrated to output full current (typically 20 mA) at full flow through the orifice plate.
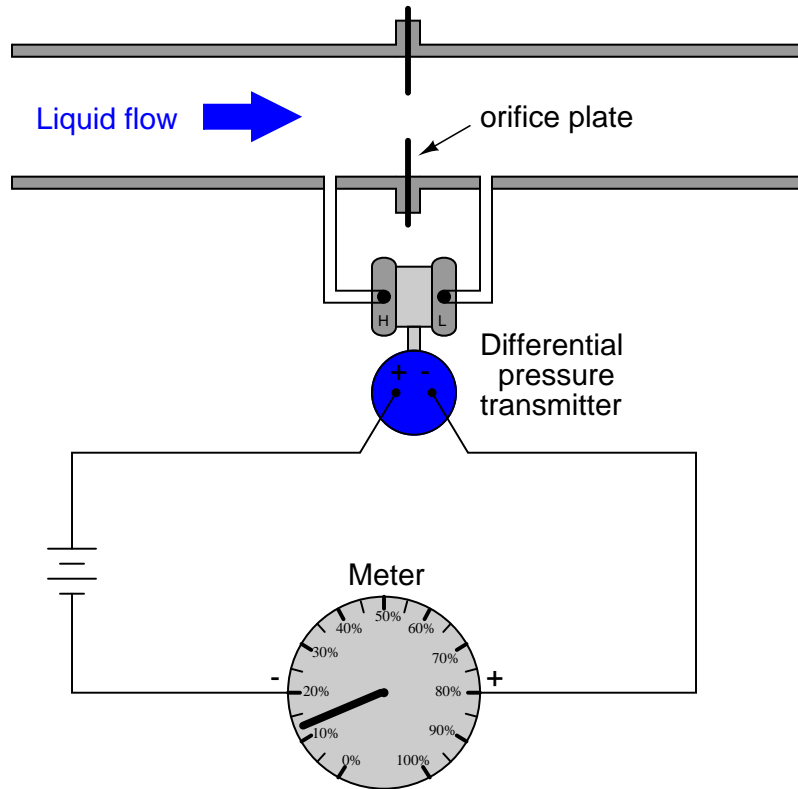
Hint: what will the meter indicate when the actual flow rate is at 0%, 50%, and 100%?
file i00483

Question 20

Question 21

Read and outline the "Magnetic Flowmeters" subsection of the "Velocity-Based Flowmeters" section of the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

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file i04064

Question 22

Read pages 2-2 through 2-18 of the "Rosemount Series 8700 Magnetic Flowmeter Flowtubes" reference manual (publication 00809-0100-4727 Revision DA), and answer the following questions:

Identify the minimum upstream and downstream straight-pipe runs necessary for reliable flow measurement using one of these magnetic flowmeters.

Two cables connect the remotely-mounted transmitter ("head") unit to the flowtube. Identify the purpose of each cable; specifically, what each one connects to inside the flowtube.

Identify the proper direction of process liquid flow when the flowtube is mounted vertically or at an angle, and explain why this is the preferred direction.

$\boxed{\textbf{Suggestions for Socratic discussion}}$

- Explain why it is important to <u>not</u> run cables from two different magnetic flow transmitters to their respective flowtube assemblies through the same electrical conduit.
- Explain why cable termination procedures must be strictly adhered to, including not stripping back the cable shield more than half an inch, and also bonding the shield conductors (only) to the flowtube case.
- Comment on the flange bolt torquing sequences shown on page 2-7. Are these sequences arbitrary, or is there some general principle we should recognize here?

file i04066

Question 23

Magnetic flowmeters exhibit special advantages and disadvantages when compared to other flow-measuring technologies. For each of the following strengths and weaknesses, explain *why* it is this way for a magnetic flowmeter:

Strengths:

- Short upstream/downstream straight-pipe requirements: 5 up and 3 down (typically)
- Output is linearly related to volumetric flow rate – no square root characterization required
- Good rangeability
- Bidirectional measurement possible

Weaknesses:

- Does not work with nonconducting fluids
- Excellent electrical grounding of the flowmeter is *essential*
- Coating of electrodes may affect performance
- Needs to be installed in pipe with electrodes horizontal, never vertical

Suppose a magflow meter is operating with a partially-filled pipe, with both electrodes still fully contacting the liquid. Will this operating condition cause a *zero shift*, a *span shift*, a *linearity error*, or a *hysteresis error*? Explain your reasoning.

Suppose the flowstream through a magflow meter contains some non-conductive solids in addition to conductive liquid. Will this affect the accuracy or reliability of the flowmeter? Explain why or why not.

<u>file i00525</u>

The *activated sludge* process is used in municipal wastewater treatment to decompose organic matter suspended in the water. A sizeable culture of naturally-occurring bacteria (the same strains at work in your own gut) eat the organic matter in the wastewater as the water passes through the aeration chamber. These bacteria are oxygen-consuming ("aerobic"), and so must be given plenty of oxygen to respirate. An air blower provides this air so the bacteria may thrive in the aeration chamber:
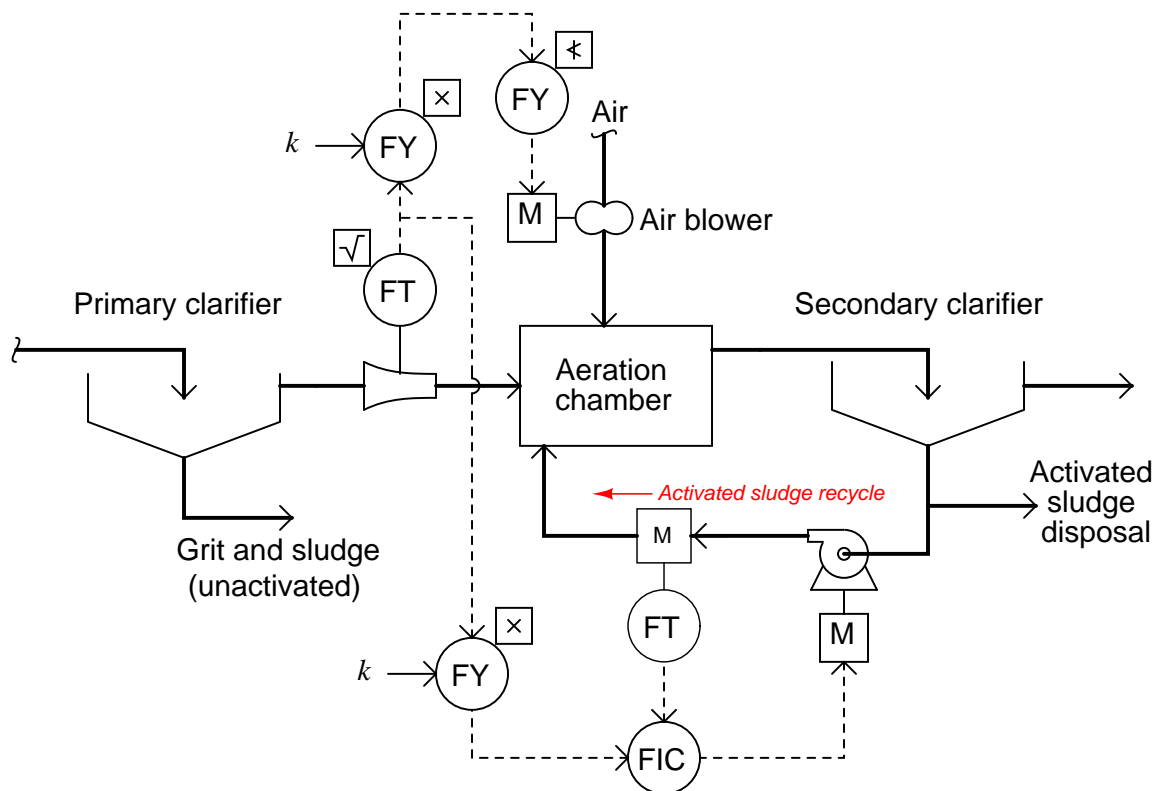
Suppose the magnetic flowmeter used to measure sludge recycle flow imparts a magnetic flux density of 0.2 Tesla across a flowtube 4 inches in diameter (10.16 centimeters, or 0.1016 meters). Calculate the amount of voltage this flowtube will generate at a sludge flow rate of 0.67 cubic meters per minute. Also, convert this sludge flow rate into units of gallons per minute.

| **Suggestions for Socratic discussion** |

- Explain why a magnetic flowmeter is ideally suited for this application, where the sludge has the approximate consistency (and appearance!) of peanut butter.
- Will a magnetic flowmeter still work well if there is a substantial amount of non-conductive matter in the flowstream (e.g. rocks or air bubbles)? Explain why or why not.
- Identify any other flowmeter types you've learned about so far which may work well in this application as an alternative to the magnetic flowmeter.
- Identify any other flowmeter types you've learned about so far which would *not* work well in this application as an alternative to the magnetic flowmeter, and explain why.
- Identify the flowmeter type used to measure influent flow, and also explain why it has a square-root symbol next to it.
- Explain what a *clarifier* vessel does, and the purposes each one serves in this process.

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

file i04067

Question 25

Read and outline the "Ultrasonic Flowmeters" subsection of the "Velocity-Based Flowmeters" section of the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

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file i04068

Question 26

Read selected portions of the "Daniel Ultrasonic Gas Flowmeter" manual for the 3400 series SeniorSonic and JuniorSonic flowmeters (part number 3-9000-740 Revision H), and answer the following questions:

Read page 3-22 and identify the minimum straight-pipe lengths upstream and downstream required for proper operation of the flowmeter.

Read page 3-22 and identify how closely the diameter of the meter flowtube must match the inside diameter of the pipe it connects to.

Read page 3-22 and identify how closely a temperature-sensing probe (i.e. thermowell with RTD) may be installed to the meter flowtube, and which side (upstream or downstream) it should be on.

Read pages 5-1 through 5-5 and identify the operating principle (Doppler or transit-time) used in both the SeniorSonic and JuniorSonic gas flowmeters.

| Suggestions for Socratic discussion |

- Why should the Senior flowmeter be installed with chords oriented horizontally?
- Why should the Junior flowmeter be installed with chords 45 degrees off vertical?
- How many paths (chords) are used in the Senior versus the Junior models?
- How does the general design of the Senior model differ from that of the Junior model?

file i04070

Question 27

Transit-time ("counterpropagation") ultrasonic flowmeters infer the flow rate of a gas or a liquid by measuring the time it takes for sound waves to travel both upstream and downstream through a moving fluid:

$$Q = k \frac{t_{up} - t_{down}}{(t_{up})(t_{down})}$$

Where,

    Q = Volumetric flow rate
    k = Constant of proportionality
    t_{up} = Time for sound pulse to travel upstream (against the flow)
    t_{down} = Time for sound pulse to travel downstream (with the flow)

Perform a "thought experiment" where the fluid inside an ultrasonic flowmeter is standing still, and demonstrate how this equation gives a value of zero for Q.

| Suggestions for Socratic discussion |

- A strong emphasis is placed on performing "thought experiments" in this course. Explain why this is. What practical benefits might students realize from regular mental exercises such as this?
- Perform a thought experiment demonstrating how the speed of sound is irrelevant for this type of flowmeter, based on an analysis of the formula shown above. Use the substitutions $t_{up} = \frac{L}{c-v}$ and $t_{down} = \frac{L}{c+v}$ to define travel time in terms of path length (L), fluid velocity (v), and speed of sound (c).

file i04071

Question 28

Ultrasonic flowmeters exhibit special advantages and disadvantages when compared to other flow-measuring technologies. For each of the following strengths and weaknesses, explain *why* it is this way for an ultrasonic flowmeter:

Strengths:

- May be attached to the *outside* of a pipe
- Relatively inexpensive on large pipes
- Work on liquids, gases, and some vapors
- Output is linearly related to volumetric flow rate – no square root characterization required
- Good rangeability
- Bidirectional measurement possible

Weaknesses:

- Calibration varies with speed of sound in fluid for some types (which?)
- Efficiently coupling sensors to pipe can be challenging
- May require long straight-pipe lengths to condition flow
- May suffer false readings from sound waves "ringing around the pipe" instead of going through the fluid

file i00529

Question 29

Explain the meaning of Faraday's Law of electromagnetic induction, shown in this familiar equation:

$$e = N\frac{d\Phi}{dt}$$

Then, explain the meaning of this *other* version of Faraday's Law of electromagnetic induction, the voltage described by it often being referred to as a *motional EMF*:

$$e = Blv$$

file i00521

Question 30

Magnetic flowmeters only function when measuring the flow of *electrically conductive* fluids. First, explain why electrical conductivity is an essential property of the fluid. Second, identify common fluids that *cannot* be detected by a magnetic flowmeter. Third, determine whether slight changes in conductivity have any effect on the accuracy of a magnetic flowmeter (e.g. if the conductivity of the fluid decreased by a factor of two, would the output voltage similarly decrease by the same factor?).
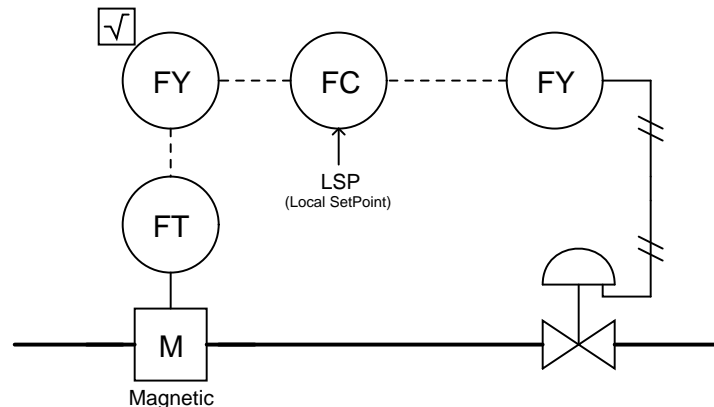file i00523

Question 31

Explain the difference(s) between an *AC* magnetic flowmeter and a *DC* magnetic flowmeter. Also, describe why there are two types (i.e. what advantages do each type of magnetic flowmeter enjoy?)
file i00524

Question 32

The following flow control system (as built) refuses to maintain process flow at a steady setpoint. It seems "sluggish" to respond to changes at high flow rates, and control at low flow rates is very erratic (rapid cycling in the measured flow). From the control scheme shown here, can you determine the problem?

file i00526

Question 33

Some animals use the principle of *echo-location* to find their way in the dark, where there is too little light to effectively use their eyes. Submarines use *sonar* to do the same thing. Explain how the same principle works to acoustically determine distance of a solid object, then determine how the same principle could be extended to determine the *speed* of a solid object.
file i00528

Question 34

Describe the operational principles of two types of *ultrasonic* flowmeter technologies: *Doppler* and *transit-time*. What physical properties of the fluid stream affect an ultrasonic flowmeter's calibration?

file i00527

Question 35

The two major types of ultrasonic flowmeters work best in different fluid streams. One type "prefers" a clean fluid stream, while the other "prefers" a flow stream containing particulate matter or bubbles. Identify which ultrasonic flowmeter type is best suited to which type of flow stream, and explain why.

file i00530

Question 36

Read the whitepaper published by Rosemount on the topic of top-mounting DP flowmeters on steam lines ("Top Mount Installation for DP Flowmeters in Steam Service", document 00870-0200-4809, copyright August 2009) and answer the following questions:

Why has the traditional recommendation for DP flow transmitter on steam lines been to locate the transmitter *below* the line?

What kind(s) of problem(s) are typically experienced with below-pipe mounting of DP flow transmitters in steam line applications?

Can DP flowmeters *always* be top-mounted? If not, what limitations dictate whether or not to top-mount?

Why shouldn't Annubar-style flow elements be mounted *vertically* in a steam pipe, but rather should be canted at least 15 degrees from vertical?

file i03488

Question 37

Question 38

Question 39

Question 40

Question 41

Read and outline the introduction of the "True Mass Flowmeters" section of the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

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Convert a volumetric flow rate of water equal to 500 CFM (cubic feet per minute) into units of pounds (mass) per second.

file i04072

Question 42

Read and outline the "Coriolis Flowmeters" subsection of the "True Mass Flowmeters" section of the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

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file i04073

Question 43

Refer to pages 4 and 5 of the "Micro Motion 'ELITE' Coriolis Flow and Density Meters" product datasheet (publication PS-00374 Revision L), and answer the following questions:

Compare the turndown performance of a Coriolis flowmeter against that of a typical orifice plate flowmeter, and identify which one has better performance. Explain *why* one has better performance than the other.

Examine the graph of accuracy versus flow rate on page 4 and explain the meaning of the "turndown ratio" limits shown on the graph (e.g. 100:1, 20:1, 2:1). Explain what *turndown* means for any measuring instrument.

Select an appropriate model of flowmeter for measuring the flow rate of water up to 25 GPM.

Select an appropriate model of flowmeter for measuring the flow rate of natural gas up to 400 SCFM (at a line pressure of 500 PSI).

| Suggestions for Socratic discussion |

- Page 10 contains tables showing the effect of process temperature and process pressure on measurement accuracy, both for flow rate and for density. Explain why changes in process pressure and/or process temperature would have this effect on a Coriolis flowmeter.
- Pages 17 through 22 show illustrations of these Coriolis flowmeters. For each of the given drawings, identify where the two vibrating tubes are located, and what shape those tubes take.

file i04076

Question 44

Read and outline the "Thermal Flowmeters" subsection of the "True Mass Flowmeters" section of the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

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file i04077

Question 45

Suppose we are measuring the flow rate of a liquid using a Coriolis flowmeter, and the volumetric flow rate of the liquid increases (with liquid density remaining the same). Will the amplitude of the meter tubes' "undulating" motion increase, decrease, or remain the same given this change in flow? Will the meter tubes' resonant frequency of vibration increase, decrease, or remain the same? Explain your answers.

Now suppose we are using the same Coriolis flowmeter to measure liquid flow, but this time the liquid's density becomes greater (i.e. the liquid becomes denser) with no change in volumetric flow. Again, qualitatively identify the change in undulation amplitude, and also in resonant frequency, for the flowmeter's metal tubes, and explain your answers.

Finally, suppose the flow through this Coriolis meter stops completely. How will changes in fluid density affect the tubes' motion, given a condition of zero flow? Again, explain your answers.

| Suggestions for Socratic discussion |

- A strong emphasis is placed on performing "thought experiments" in this course. Explain why this is. What practical benefits might students realize from regular mental exercises such as this?

  file i00728

Question 46

Perform a "thought experiment" where natural gas moves through a thermal mass flowmeter having just one (heated) RTD temperature sensing element. Explain what happens to the temperature of this element as the gas flow rate increases and decreases, and how the flowmeter's electronics would interpret this temperature change as a change in flow.

Now, perform another "thought experiment" where a constant flow of natural gas changes temperature as it moves through a thermal mass flowmeter having just one (heated) RTD temperature sensing element. Explain what happens to the temperature of this element as the incoming gas increases and decreases in temperature, and how the flowmeter's electronics would interpret this temperature change as a change in flow.

Finally, explain why all thermal flowmeters are built with *two* temperature sensors, one heated and one unheated.

| Suggestions for Socratic discussion |

- A strong emphasis is placed on performing "thought experiments" in this course. Explain why this is. What practical benefits might students realize from regular mental exercises such as this?
- Do you think a thermal mass flowmeter would be a good candidate technology for *natural gas* flow metering? Explain why or why not.

  file i04078

Question 47

Suppose both a thermal mass flowmeter and a Coriolis mass flowmeter monitor gas flow going through the exact same pipe. Normally, the gas flowing through this pipe is pure helium (specific heat $c = 1.24$ cal/g-K), and the thermal mass flowmeter has been calibrated for helium gas. Then one fine day an operator places a few shutoff valves in the wrong positions and sends hydrogen gas (specific heat = 3.41 cal/g-K) down the line instead of helium.

Not knowing that the wrong gas is now flowing through this pipe, the operator adjusts a manual flow control valve to stabilize the flow rate at its normal value, looking at the thermal mass flowmeter's indication as the process variable.

First, explain why the two flowmeters no longer agree with each other (assuming they registered in perfect agreement while sensing the flow of helium gas).

Second, identify whether the Coriolis flowmeter registers *more* mass flow than the thermal flowmeter or *less* mass flow than the thermal flowmeter.

Finally, identify which of the two flowmeters (if any!) still registers the true mass flow rate with hydrogen going down the line instead of helium.

Suggestions for Socratic discussion

- Explain what *specific heat* means, and give a practical example from everyday life.
- What does this "thought experiment" tell us about Coriolis versus thermal mass flowmeters in general? Which of these flowmeter types do you think costs less?
- Thermal mass flow measurement is used almost universally for intake air flow measurement on automobile engines with electronic controls. Do you think the same type of problem exists in this application that we saw in our "thought experiment"?
- Suppose the gas composition does not change (i.e. it is still pure helium), but the line pressure increases. How will each of these mass flowmeters respond to this one process condition change?
- Suppose the thermal mass flowmeter were replaced with an orifice plate and DP sensor. Would this solve the problem of discrepancies between flowmeters resulting from fluid composition changes? Explain why or why not.

file i04080

Question 48

Calculate the mass flow rate of a liquid having a density of 59.3 lbm/ft^3 flowing through a pipe at a volumetric rate (Q) of 1100 GPM.

$W =$ _____ lbm/min

$W =$ _____ kg/sec

Suggestions for Socratic discussion

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- Which unit of measurement do you think is best for *custody transfer* applications: GPM or lb/min? Explain your reasoning.
- When expressing mass flow in Imperial measurements, the unit of "lbm" is often used. Why is the letter "m" appended to the symbol for pound? Is there another Imperial unit for mass other than "lbm"??

file i04081

Question 49

Read and outline the "Weirs and Flumes" subsection of the "Variable-Area Flowmeters" section of the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

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file i04082

Question 50

One way to measure the mass flow rate of a fluid stream is to use an impeller spun by a constant-speed motor (usually an AC synchronous motor) and a turbine downstream of the impeller to measure the angular momentum of the fluid. This arrangement is commonly called an *impeller-turbine flowmeter*.

Explain how the synchronous motor maintains a constant speed regardless of mechanical load, and also explain how the angular momentum of the fluid directly relates to flow.
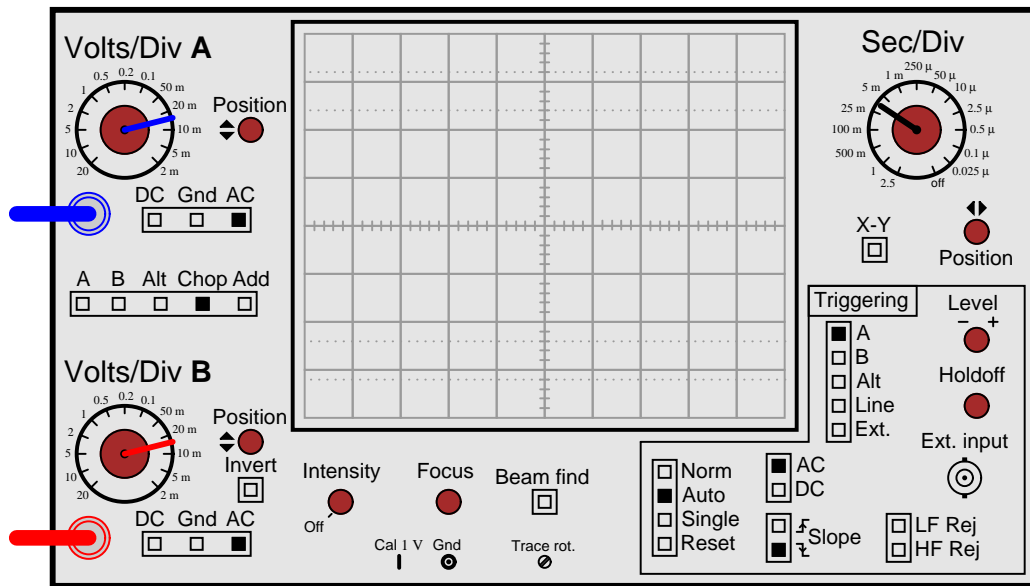
file i00532

A flow measurement technique known as *twin-turbine* is able to measure the true mass flow rate of a fluid stream, by measuring the angular displacement between two turbines connected together by a torsional spring coupling. The two turbines have different blade pitches, which means they "want" to rotate at different speeds for any given flow rate.

Turbine rotation is detected by a "pick-up" coils, one at each turbine. If spun by hand while the flowmeter was placed on a workbench, the two turbines would of course spin at the same speed with no torque generated between them. Their respective pulse output waveforms, when viewed with an oscilloscope, should look something like this:
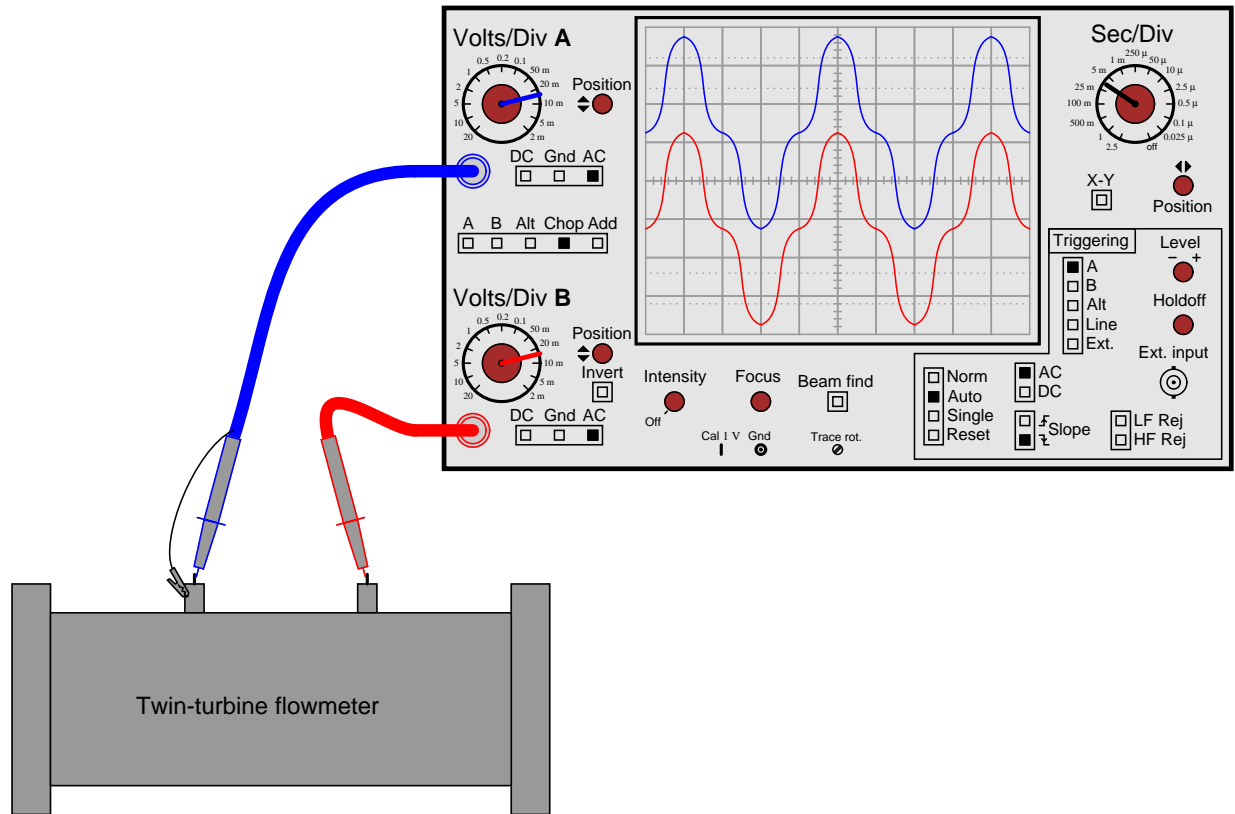
Explain and sketch what the two waveforms would look like if an actual fluid was flowing through the flowmeter body:
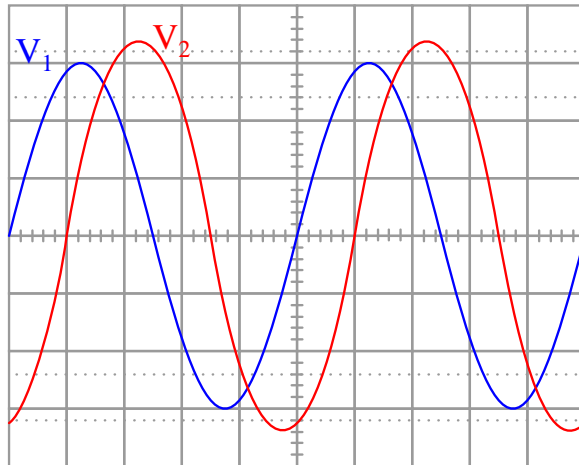
? ? ? ?

file i00533

Question 52

Determine the following parameters of these AC voltage waveforms, assuming a vertical sensitivity of 1 volt per division and a timebase of 2 milliseconds per division:

V_1 (peak) =

V_2 (peak) =

Frequency (f) =

Phase shift (θ) =

Also, determine which waveform is *leading* and which waveform is *lagging*.
file i00538

Question 53

Coriolis-effect mass flowmeters have several advantages over other mass-flow technologies, which make them worth their high price in some applications. Identify what some of these advantages are. Also, identify some of their outstanding disadvantages (besides relatively high cost).

file i00539

Question 54

Calculate the electrical resistance of a 100 ohm RTD (α = 0.00385) at the following temperatures:

- T = 120 ^{o}C ; R = _____

- T = 390 ^{o}F ; R = _____

Calculate the temperature of a 100 ohm RTD ($\alpha = 0.00392$) at the following resistances:

- R = 115 Ω ; T = _____

- R = 180 Ω ; T = _____

Suggestions for Socratic discussion

- Identify some advantages RTDs hold over thermocouples.
- Identify some advantages thermocouples hold over RTDs.

file i04079

Question 55

The "flare" at an oil refinery functions as a safe way to quickly dispose of pressurized hydrocarbon compounds, by burning them far away from anything else that might be flammable. In this system, as with most flare systems, a "knockout drum" exists to separate vapors from liquid, so that only vapors are sent to the flare tip to be burned. Any captured liquid is drained to the Oily Water Sewer (OWS) system:
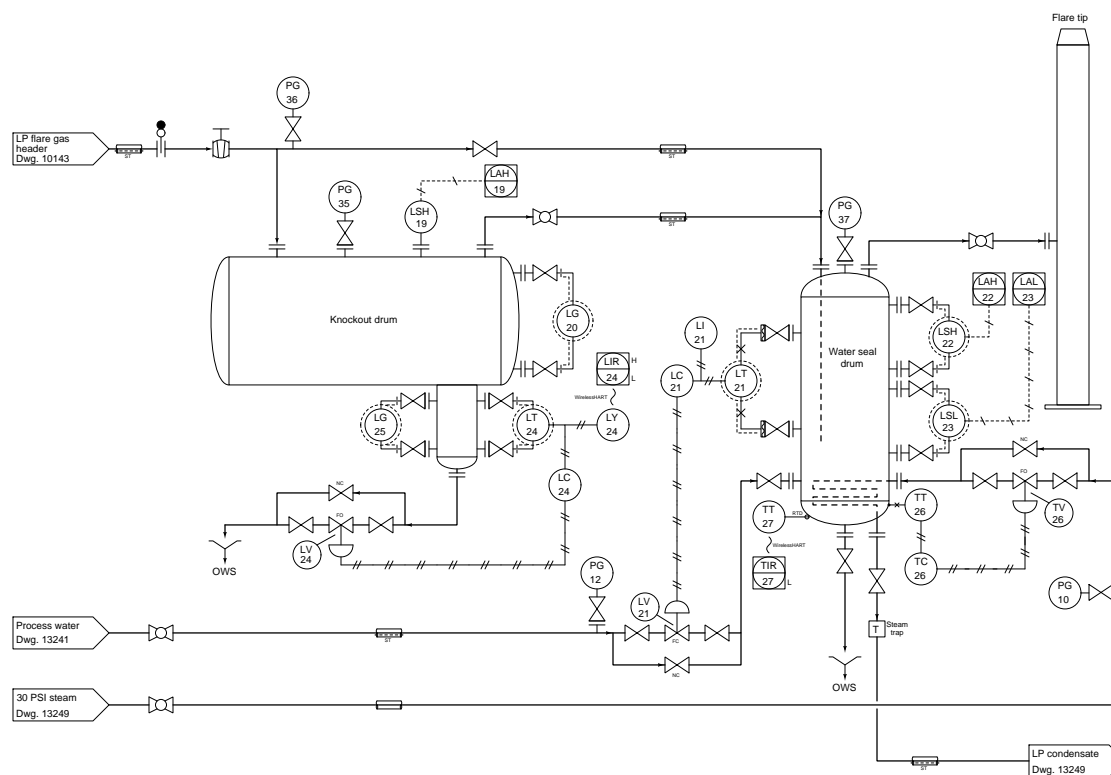
As with most flare systems, the exact composition of material sent to the flare to be burned is both highly variable and unknown from moment to moment. In a typical refinery, anything from hydrogen gas to diesel fuel might get sent to the flare during a "depressurization" event.

Suppose operations personnel at this refinery wish to monitor the total flow rate of hydrocarbon material burned at the flare. Engineers are debating what type(s) of flowmeter might be used for this task, and where exactly it should be placed in the piping system.

Brainstorm some different flow-sensing technologies, and then determine whether or not each one of them could be applied to this problem.

file i00977

A large natural gas compressor takes in gas from three different sources, "knocks out" any liquid that might be entrained in the gas, and then boosts the pressure of that gas for transport through miles of piping:
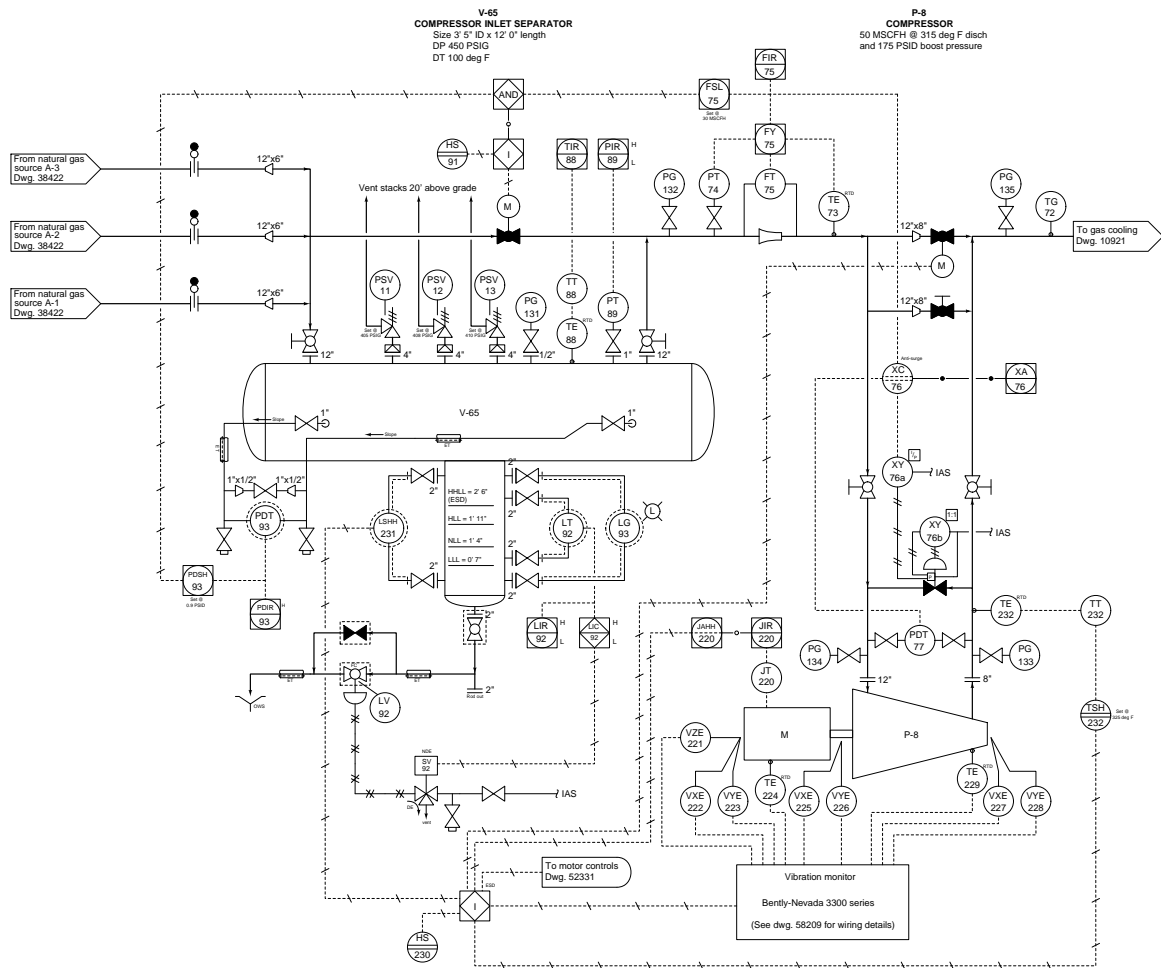
Flowmeter FT-75 has been in service for many years, but unfortunately does not provide good enough turndown for operations' needs when the compressor is operated at a fraction of its rated capacity. Engineers are debating what type(s) of flowmeter might be used to replace FT-75.

First, explain what "turndown" means in the context of this flowmeter, and explain why this particular type of flowmeter might not provide good enough turndown.

Brainstorm some different flow-sensing technologies, and then determine whether or not each one of them could be applied here.

file i00978

Question 57

In this process, liquefied manure from a dairy farm is mixed with pre-consumer food waste for anaerobic digestion, the purpose of which being to produce "biogas" which is largely methane and burns similarly to natural gas. This biogas is used as fuel for a large engine, which turns a generator to make electricity. The heated coolant from this engine is piped back to the digester vessel to maintain the organic matter at a temperature similar to the internal temperature of a cow's digestive tract. Some of the biogas is recycled back into the digester as a means of stirring the liquefied mixture to prevent solids from settling at the bottom and clogging the system:
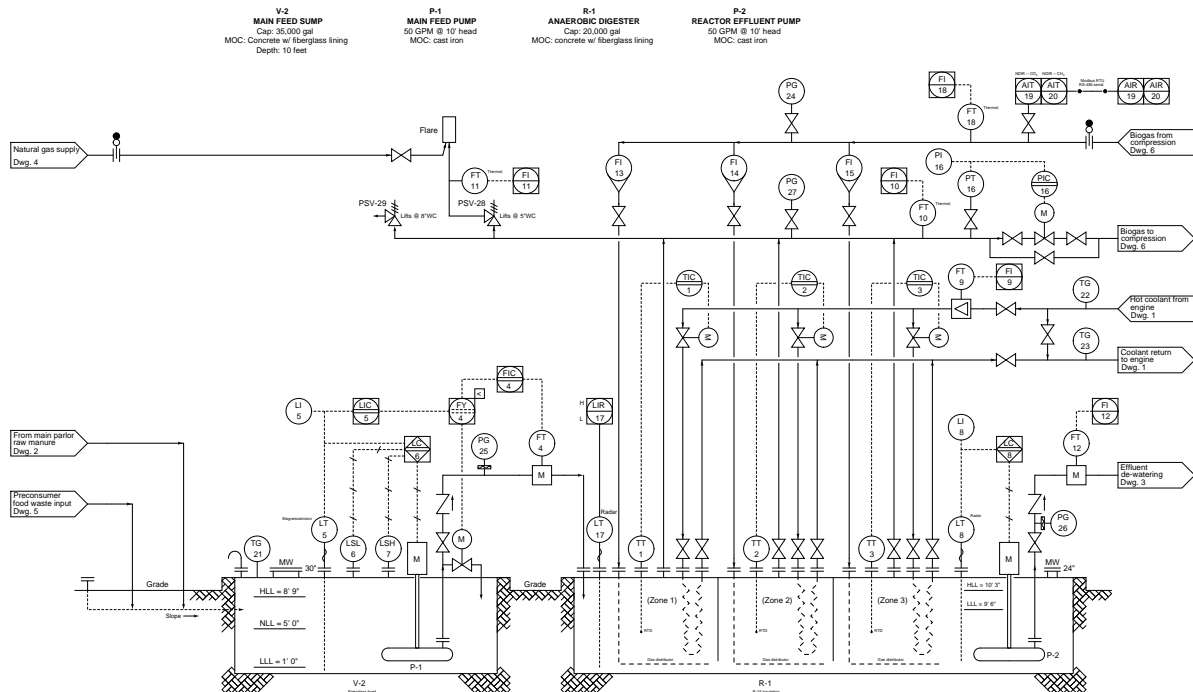
Identify the following flowmeter types and comment on why those types are particularly well-suited to the fluid stream they're measuring:

- FT-4 (influent to digester)
- FT-9 (coolant flow from engine)
- FT-10 and FT-18 (biogas flow)
- FT-12 (effluent flow to de-watering)

file i02146

Question 58

Question 59

Question 60

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Question 61

Describe your recent learning experiences succinctly enough to be included as a line-item in your résumé. Identify how this learning has made you more marketable in this career field. Be as specific as you can, and feel free to include non-technical as well as technical learning in your description (e.g. project management, organization, independent research, troubleshooting, design, software applications, electric circuit analysis, control theory, etc.)!

Identify any knowledge and/or skill areas in which you would like to become stronger, and describe practical steps you can take to achieve that goal. Don't limit yourself to just technical knowledge and skills, but consider behavioral habits (e.g. patience, attention to detail, time management) and general academic abilities (e.g. reading, writing, mathematics) as well. If you find yourself struggling to achieve a goal, don't just say "I'll work harder" as your plan of action – identify something *different* you can do to achieve that goal.

Note: your responses to these questions will not be shared in Socratic discussion with classmates without your consent. Feel free to maintain these as private notes between yourself and your instructor.

A helpful guide to traits and skills valued by employers are the "General Values, Expectations, and Standards" pages near the beginning of this worksheet. Another is the "So You Want To Be An Instrument Technician?" career guide.

file i00999

Question 62

Identify each of the following flowmeters from their photographs, describing as much about each one as possible (e.g. principle of operation, fluid type, advantages and disadvantages):
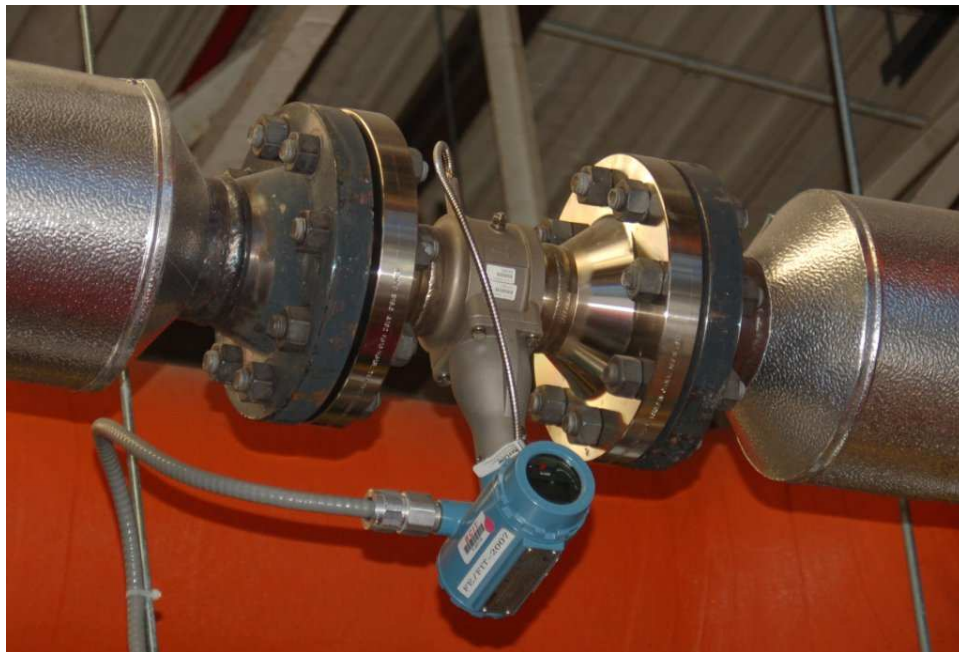
Example #1

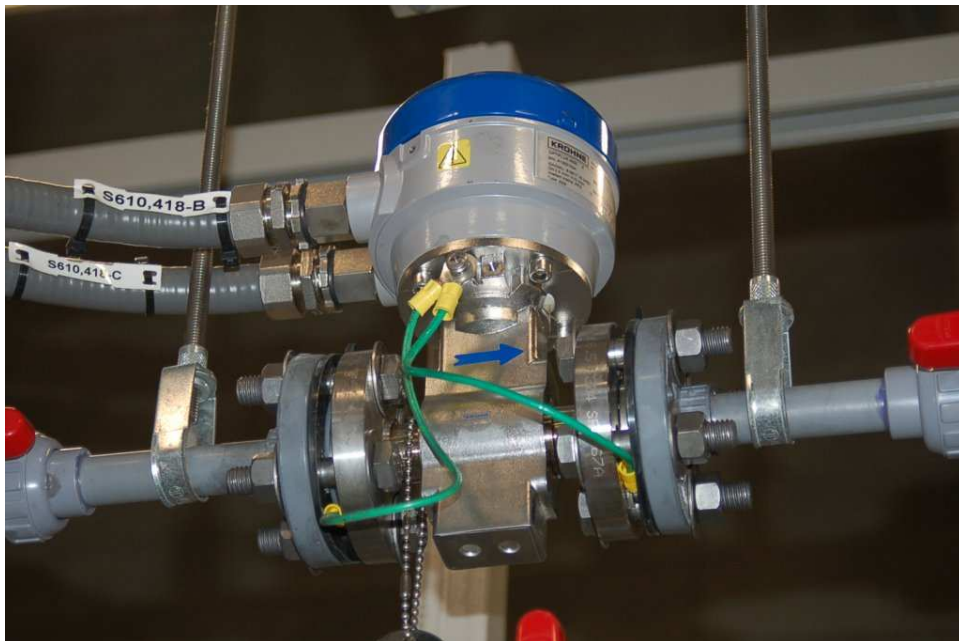**Example #2**

Example #3

Example #4

Example #5

Example #6

Example #7

Example #8

Example #9

Example #10

Example #11

Example #12

Example #13

- Which of these flowmeters is *linear*?
- Which of these flowmeters requires *square root* characterization?
- Which of these flowmeters inherently provides *mass flow* measurement?
- Which of these flowmeters is able to accurately measure flow in *either direction*?
- Which of these flowmeters is suitable for either *liquid or gas* flow measurement?
- Explain why some of these flowmeters are located between a pair of pipe reducers, such that the flowmeter body is substantially smaller in diameter than the rest of the pipe.
- Some of these flowmeters are self-contained, while others are split into two components: a flow *transmitter* (FT) and a *flow element* (FE). Identify at least one of these "split" flowmeter assemblies and identify both the transmitter and the element.
- Identify any *other* instrumentation you happen to see in each photograph, and describe as much about each of those instruments as you can.

file i00724

Question 63

Site visit!

As part of today's inverted theory session, you will meet your instructor at a site containing real process equipment, where you will apply your knowledge of fluid flow measurement to various processes there. Prepare yourself to do the following while on site:

- Measure approximate diameters and straight-lengths of pipe
- Calculate Reynolds number values given pipe size and flow rates
- Calculate DP values versus flow rates for an orifice plate given base flow/pressure parameters
- Research installation requirements of specific flowmeter types
- Wear safety glasses and sturdy (closed-toed) shoes

file i00727

Question 64

An ecological survey team installs a Cippoletti weir in a small stream to measure water flow through it. Calculate the amount of water flow (in units of ft^3/sec) represented by a crest height ("head") of 5 inches. Assume the weir has a crest width of 4 feet and that the crest height is being measured by a level sensor located 3 feet upstream of the weir.

Also, convert this flow value into units of gallons per minute.

Suggestions for Socratic discussion

- Why do you think a weir would be a good candidate technology for measuring the flow rate of water down a small stream?
- Do you see any ways that a Cippoletti weir could experience problems measuring water flow down a natural stream? If so, can you think of a better flowmeter technology for this application?

file i04084

Question 65

A municipal wastewater treatment plant uses a 6-foot-wide Parshall flume to measure the flow of effluent (treated water leaving the facility, also called "outfall"). Calculate the head (height of water) immediately upstream of this flume at an effluent flow rate of 5,460 GPM.
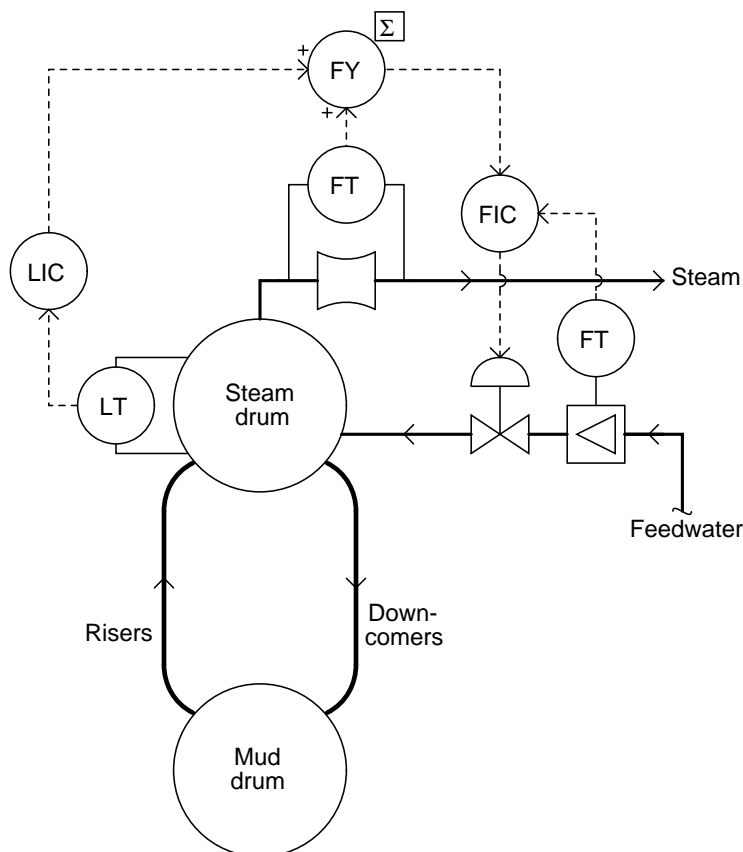
Suggestions for Socratic discussion

- Why do you think a flume is a good candidate technology for measuring the flow rate of wastewater?
- How did you need to apply *algebra* to solve for the height of water in this flume?

file i04085

Question 66

A venturi tube is used to measure the flow rate of steam exiting a power boiler:

Supposing this venturi tube normally develops a differential pressure of 100 inches water column at a flow rate of 970 pounds per minute with a steam density of $\rho = 1.33$ lbm/ft^3, calculate the following:

- Differential pressure at 700 lbm/min mass flow = _____
- Differential pressure at 550 lbm/min mass flow and $\rho = 1.30$ lbm/ft^3 = _____
- Mass flow rate at 90 "W.C. = _____
- Mass flow rate at 43 "W.C. and $\rho = 1.35$ lbm/ft^3 = _____

Explain how it is possible to calculate both the temperature and the pressure of the steam inside the boiler's steam drum by the given information.

Calculate the rate of heat (BTU/minute) delivered by this boiler to a heat exchanger at 25 lb/min steam flow rate and 1.32 lb/ft^3 steam density, if this steam leaves the heat exchanger as water at 160 deg F.

| Suggestions for Socratic discussion |

- Explain why both steam flow and water flow are best measured in *mass* units rather than volumetric in this process application.
- Identify some factors that could realistically cause the steam's density to change.

  file i04087

Question 67

An orifice plate is used to measure the flow rate of diesel fuel exiting the processing unit at an oil refinery where the customary unit for liquid flow measurement within refineries is "barrels per hour" (bbl/hr). Calculate the following parameters in this flow measurement loop, at two different flow rates (10 bbl/hr and 31 bbl/hr):
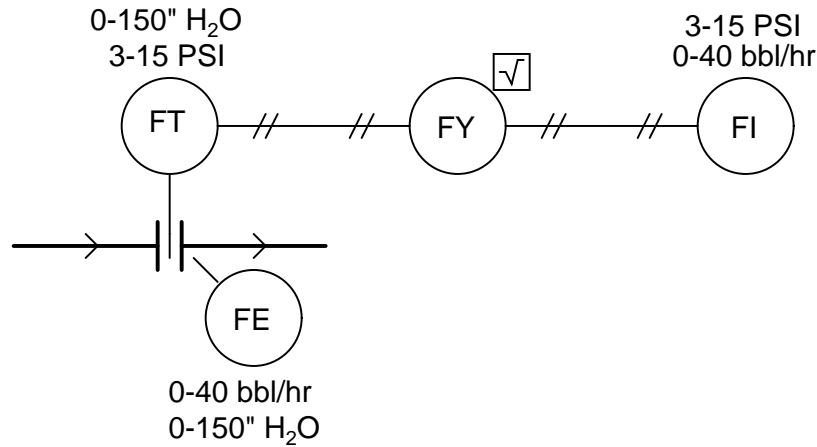
0-150" H_2O
3-15 PSI

3-15 PSI
0-40 bbl/hr

FT   // //   FY   // //   FI

√

FE

0-40 bbl/hr
0-150" H_2O

At a flow rate of 10 bbl/hr:

- Orifice plate ΔP = _____ " H_2O

- Differential pressure transmitter output signal = _____ PSI

- Square root extractor output signal = _____ PSI

- Flow indicator reading = _____ bbl/hr

At a flow rate of 31 bbl/hr:

- Orifice plate ΔP = _____ " H_2O

- Differential pressure transmitter output signal = _____ PSI

- Square root extractor output signal = _____ PSI

- Flow indicator reading = _____ bbl/hr

file i00725

61

Question 68

Suppose we need to measure the volumetric flow rate of deionized water (purified by triple-distillation) used as "make-up" water for a chemical experiment in a laboratory, from a maximum flow rate of 20 GPM down to a minimum flow rate of 1 GPM. Identify the most appropriate technologies from this list, and explain why they others will not work:

- Magnetic
- Coriolis
- Pitot tube
- Ultrasonic
- Orifice plate
- Thermal
- Vortex
- Positive displacement
- Pipe elbow

Suggestions for Socratic discussion

- If we needed to measure mass flow rather than volumetric flow, would this change our selection of flowmeter? Explain why or why not.
- Identify which of these flowmeters are bidirectional, and explain why based on their principles of operation.

file i04088

Question 69

Suppose we need to install a flowmeter in a location where there is plenty of upstream straight-length pipe, but no downstream straight-length pipe (i.e. the flowmeter immediately discharges into an elbow). Identify the most appropriate technologies from this list, and explain why they others will not work:

- Magnetic
- Coriolis
- Ultrasonic
- Vortex
- Positive displacement
- Venturi tube

file i04089

Question 70

Suppose we are measuring the flow rate of a gas using a turbine flowmeter. This is a simple turbine flowmeter, with one turbine spinning freely, generating electronic pulses via a "pick-up" coil sensing the passing of turbine blades.

If the density of this gas suddenly increases with no change in volumetric flow, will the turbine speed increase, decrease, or stay the same?

file i00730

Question 71

A thermal mass flowmeter uses two RTD sensing elements (one heated, one unheated) to infer mass flow rate through a pipe. The following circuit converts the difference in RTD temperatures into a voltage signal for a microprocessor to interpret:
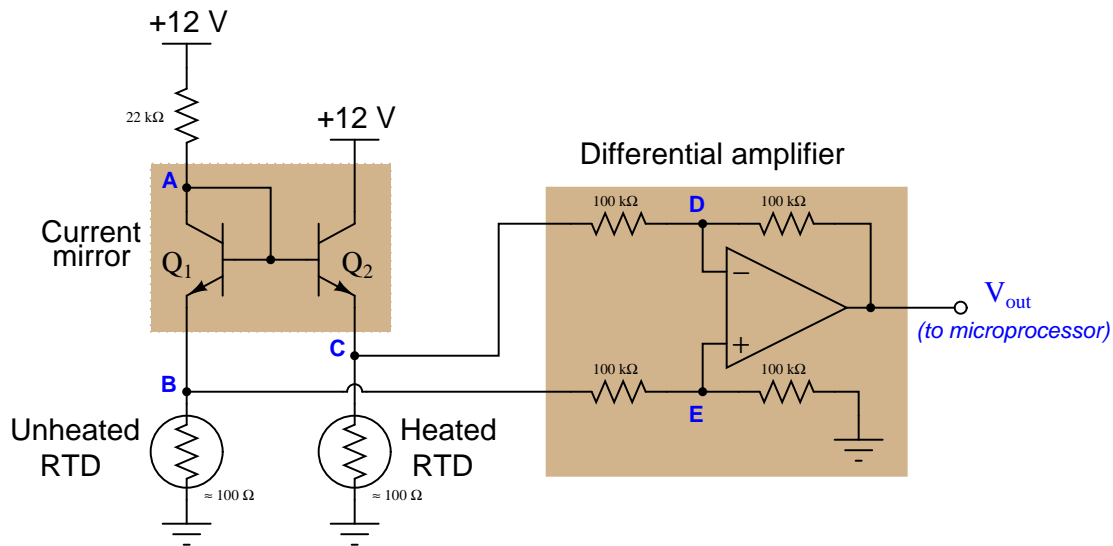
A *current mirror* works to keep current through both RTDs equal, while a differential amplifier measures the difference in voltage drops across the two RTDs.

Unfortunately, this flowmeter is not functioning as it should. The microprocessor reports an over-ranged flow measurement even when the flowmeter has been "blocked in" by closing block valves both upstream and downstream in the pipe. You are summoned to troubleshoot this circuit, and you begin by measuring the output voltage from the amplifier – you read 0 volts DC with your voltmeter. Next, you measure voltage between test points **C** and **B**, again measuring 0 volts DC.

Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
22 kΩ resistor failed open		
Unheated RTD failed open		
Heated RTD failed open		
Unheated RTD failed shorted		
Heated RTD failed shorted		
Transistor Q_1 failed shorted C-E		
Transistor Q_2 failed shorted C-E		
12 VDC source dead		

Also, explain why these initial voltage measurements made sense to take. In other words, explain what each measurement told you about the nature of the fault.

Finally, identify the *next* diagnostic test or measurement you would make on this system. Explain how the result(s) of this next test or measurement help further identify the location and/or nature of the fault.

file i02946

Question 72

In this question, you will be asked to research several different types of flowmeters and determine their specifications with regard to piping geometry (minimum upstream and downstream straight-pipe lengths), minimum or maximum Reynolds number, fluid types, and any other special advantages or disadvantages. This will require a significant amount of research on your part, but the exercise is well worth the effort, because it will educate you on the proper applications of each flowmeter type. This will enable you to make educated decisions on the type of flowmeter to choose for a wide range of fluid flow measurement applications.

Shown here is the standard "form" you should use in researching each flowmeter type:

- **Principle of operation:** *A one-sentence description of what physical phenomenon is used to detect or infer flow rate.*
- **Fluid type(s):** *Gas, liquid, or either.*
- **Minimum straight-run piping lengths (in units of "pipe diameters"):**
- **Reynolds number range:** *Minimum or maximum Reynolds number for pipe flow (not flow through the throat of the device).*
- **Typical accuracy (in percent of full-flow value):**
- **Bidirectional flow measurement:** *Yes or no.*
- **Inherently measures true mass flow:** *Yes or no.*
- **Special advantages:** *Brief description of any peculiar advantages of this device over other flowmeter devices.*
- **Special disadvantages:** *Brief description of any peculiar disadvantages of this device as compared to other flowmeter devices.*

Research these aspects for the following flowmeter types:

- **<u>Orifice plate</u>**

  - Principle of operation:

  - Fluid type(s):

  - Minimum straight-run piping lengths (in units of "pipe diameters"):

  - Reynolds number range:

  - Typical accuracy (in percent of full-flow value):

  - Bidirectional flow measurement:

  - Inherently measures true mass flow:

  - Special advantages:

  - Special disadvantages:

- **<u>Venturi tube</u>**

  - Principle of operation:

  - Fluid type(s):

  - Minimum straight-run piping lengths (in units of "pipe diameters"):

  - Reynolds number range:

  - Typical accuracy (in percent of full-flow value):

  - Bidirectional flow measurement:

  - Inherently measures true mass flow:

  - Special advantages:

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- Special disadvantages:

- **<u>Pitot tube or Annubar</u>**
  - Principle of operation:
  - Fluid type(s):
  - Minimum straight-run piping lengths (in units of "pipe diameters"):
  - Reynolds number range:
  - Typical accuracy (in percent of full-flow value):
  - Bidirectional flow measurement:
  - Inherently measures true mass flow:
  - Special advantages:
  - Special disadvantages:

- **<u>Vortex</u>**
  - Principle of operation:
  - Fluid type(s):
  - Minimum straight-run piping lengths (in units of "pipe diameters"):
  - Reynolds number range:
  - Typical accuracy (in percent of full-flow value):
  - Bidirectional flow measurement:
  - Inherently measures true mass flow:
  - Special advantages:
  - Special disadvantages:

- **<u>V-cone</u>**
  - Principle of operation:
  - Fluid type(s):
  - Minimum straight-run piping lengths (in units of "pipe diameters"):
  - Reynolds number range:
  - Typical accuracy (in percent of full-flow value):
  - Bidirectional flow measurement:
  - Inherently measures true mass flow:
  - Special advantages:
  - Special disadvantages:

- **<u>Segmental wedge</u>**
  - Principle of operation:
  - Fluid type(s):
  - Minimum straight-run piping lengths (in units of "pipe diameters"):
  - Reynolds number range:

- Typical accuracy (in percent of full-flow value):

- Bidirectional flow measurement:

- Inherently measures true mass flow:

- Special advantages:

- Special disadvantages:

- **<u>Magnetic</u>**

  - Principle of operation:

  - Fluid type(s):

  - Minimum straight-run piping lengths (in units of "pipe diameters"):

  - Reynolds number range:

  - Typical accuracy (in percent of full-flow value):

  - Bidirectional flow measurement:

  - Inherently measures true mass flow:

  - Special advantages:

  - Special disadvantages:

- **<u>Coriolis</u>**

  - Principle of operation:

  - Fluid type(s):

  - Minimum straight-run piping lengths (in units of "pipe diameters"):

  - Reynolds number range:

  - Typical accuracy (in percent of full-flow value):

  - Bidirectional flow measurement:

  - Inherently measures true mass flow:

  - Special advantages:

  - Special disadvantages:

- **<u>Weir</u>**

  - Principle of operation:

  - Fluid type(s):

  - Minimum straight-run piping lengths (in units of "pipe diameters"):

  - Reynolds number range:

  - Typical accuracy (in percent of full-flow value):

  - Bidirectional flow measurement:

  - Inherently measures true mass flow:

  - Special advantages:

  - Special disadvantages:

- **Thermal**
  - Principle of operation:
  - Fluid type(s):
  - Minimum straight-run piping lengths (in units of "pipe diameters"):
  - Reynolds number range:
  - Typical accuracy (in percent of full-flow value):
  - Bidirectional flow measurement:
  - Inherently measures true mass flow:
  - Special advantages:
  - Special disadvantages:

- **Ultrasonic**
  - Principle of operation:
  - Fluid type(s):
  - Minimum straight-run piping lengths (in units of "pipe diameters"):
  - Reynolds number range:
  - Typical accuracy (in percent of full-flow value):
  - Bidirectional flow measurement:
  - Inherently measures true mass flow:
  - Special advantages:
  - Special disadvantages:

- **Turbine**
  - Principle of operation:
  - Fluid type(s):
  - Minimum straight-run piping lengths (in units of "pipe diameters"):
  - Reynolds number range:
  - Typical accuracy (in percent of full-flow value):
  - Bidirectional flow measurement:
  - Inherently measures true mass flow:
  - Special advantages:
  - Special disadvantages:

- **Positive displacement**
  - Principle of operation:
  - Fluid type(s):
  - Minimum straight-run piping lengths (in units of "pipe diameters"):
  - Reynolds number range:
  - Typical accuracy (in percent of full-flow value):
  - Bidirectional flow measurement:

- Inherently measures true mass flow:

- Special advantages:

- Special disadvantages:

- **<u>Rotameter</u>**

  - Principle of operation:

  - Fluid type(s):

  - Minimum straight-run piping lengths (in units of "pipe diameters"):

  - Reynolds number range:

  - Typical accuracy (in percent of full-flow value):

  - Bidirectional flow measurement:

  - Inherently measures true mass flow:

  - Special advantages:

  - Special disadvantages:

- **<u>Pipe elbow</u>**

  - Principle of operation:

  - Fluid type(s):

  - Minimum straight-run piping lengths (in units of "pipe diameters"):

  - Reynolds number range:

  - Typical accuracy (in percent of full-flow value):

  - Bidirectional flow measurement:

  - Inherently measures true mass flow:

  - Special advantages:

  - Special disadvantages:

- **<u>Target</u>**

  - Principle of operation:

  - Fluid type(s):

  - Minimum straight-run piping lengths (in units of "pipe diameters"):

  - Reynolds number range:

  - Typical accuracy (in percent of full-flow value):

  - Bidirectional flow measurement:

  - Inherently measures true mass flow:

  - Special advantages:

  - Special disadvantages:

- **Flume**
  - Principle of operation:
  - Fluid type(s):
  - Minimum straight-run piping lengths (in units of "pipe diameters"):
  - Reynolds number range:
  - Typical accuracy (in percent of full-flow value):
  - Bidirectional flow measurement:
  - Inherently measures true mass flow:
 - Special advantages:
  - Special disadvantages:

file i00541

Question 73

Calculate values for the following calibration table, for a displacer-style transmitter measuring water flow through a V-notch weir. The displacer is cylindrical in shape, has a length of 12 inches (matching the weir's V-notch depth), and a diameter of 2 inches. The percentage in the calibration table refers to percent of the weir's flow range, not the percentage of displacer submergence:
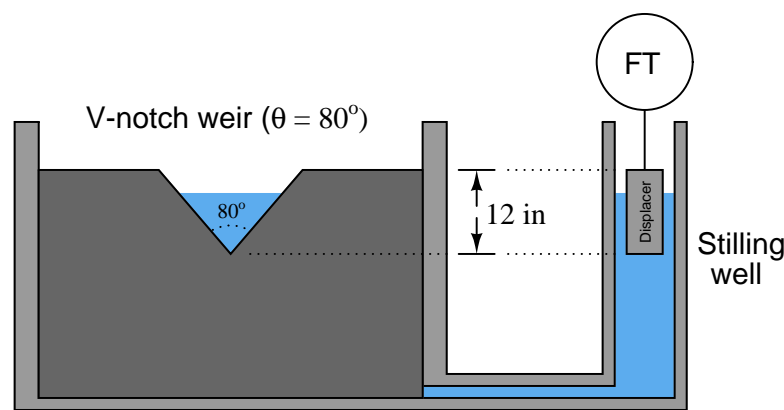
Be sure to show your work!

Water flow rate (ft^3/s)	Percent of flow span (%)	Depth that displacer is submerged (in)	Buoyant force (lb)
	0		
	10		
	25		
	50		
	75		
	90		
	100		

file i00684

Question 74

A turbine flowmeter with a k factor of 53 pulses per gallon generates a pulse signal with a frequency of 381 Hz. Calculate the volumetric flow rate.

file i03050

Question 75

Suppose we are measuring the flow rate of a weak acid solution using a magnetic flowmeter. The conductivity of the acid is well within the acceptable range for this meter, and so it works just fine.

Now suppose the acid solution grows in strength (greater acid concentration). This will increase the conductivity of the solution, because there are now more ions available to carry an electric current. What effect will this have on the magnetic flowmeter's calibration? Will someone have to re-calibrate the flowmeter in order for it to properly measure the acid flow again? If so, will this be a zero or a span shift? Which way will the zero and/or span shift, higher or lower? Explain your answer(s)!

file i00729

Question 76

The fundamental equation for an orifice plate is based on Bernoulli's Law:

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$
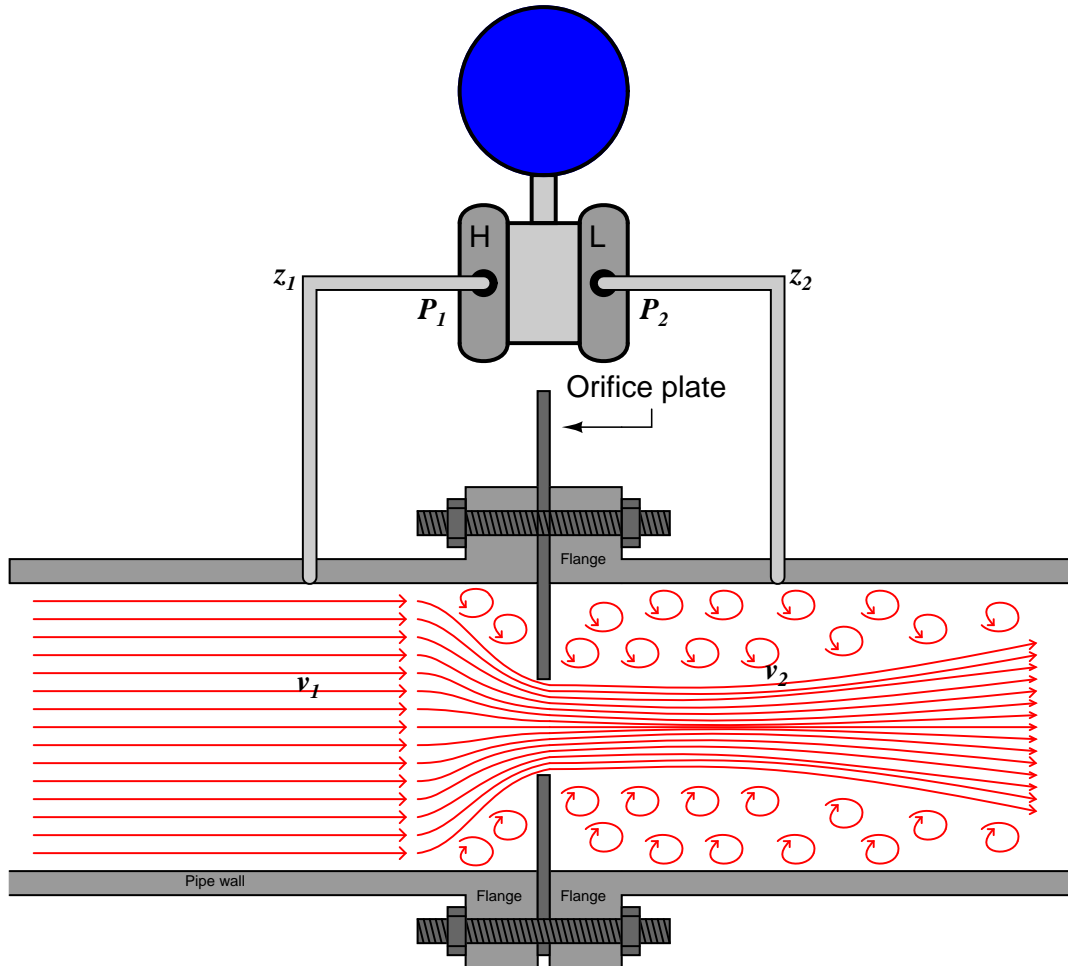
Assuming the same height at both measuring points z_1 and z_2, Bernoulli's equation simplifies to this:

$$\frac{v_1^2 \rho}{2} + P_1 = \frac{v_2^2 \rho}{2} + P_2$$

Collecting like terms to either side of the equation:

$$P_1 - P_2 = \frac{v_2^2 \rho}{2} - \frac{v_1^2 \rho}{2}$$

$$\Delta P = \frac{\rho}{2}(v_2^2 - v_1^2)$$

$$\frac{2\Delta P}{\rho} = v_2^2 - v_1^2$$

If we know that the vena contracta velocity is substantially greater than the full-diameter pipe velocity, we may express the equation as an approximation:

$$\frac{2\Delta P}{\rho} \approx v_2^2$$

$$v_2 \approx \sqrt{\frac{2\Delta P}{\rho}}$$

We know that v_2, in turn, directly relates to flow (Q), and so we may write this as an equation once more using a proportionality constant k to incorporate all sizing variables and coefficients:

$$Q = k\sqrt{\frac{\Delta P}{\rho}}$$

Based on this equation, determine what a differential pressure transmitter will do if the fluid going through an orifice plate suddenly becomes *denser* without changing volumetric flowrate (i.e. the velocity v through the pipe remains the same while ρ increases).

file i00731

Question 77

An orifice plate is used to measure the flow rate of ultra-pure water at a pharmaceuticals processing facility where the customary unit for liquid flow measurement is "liters per minute" (LPM). Calculate the following parameters in this flow measurement loop, at two different flow rates (78 LPM and 120 LPM):

0-100" WC
4-20 mA   √

4-20 mA
0-200 LPM

FT - - - - - - - - - - FI

FE

0-200 LPM
0-100" WC
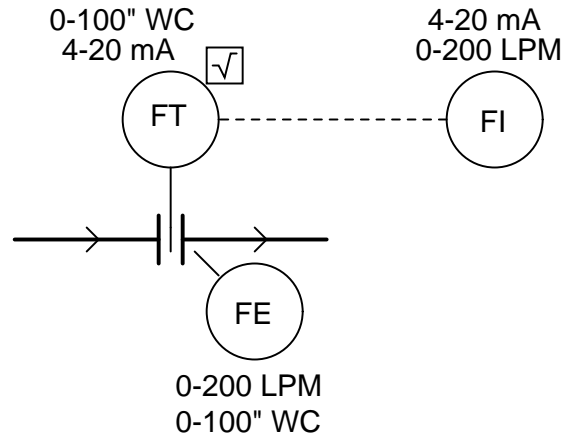
Note that the transmitter is equipped with internal square root characterization, so that no external square root computer is required.

At a flow rate of 78 LPM:

- Orifice plate ΔP = _____ " H_2O

- Differential pressure transmitter output signal = _____ mA

- Flow indicator reading = _____ LPM

At a flow rate of 120 LPM:

- Orifice plate ΔP = _____ " H_2O

- Differential pressure transmitter output signal = _____ mA

- Flow indicator reading = _____ LPM

| Suggestions for Socratic discussion |

- A poor choice of flowmeters for this particular application would be *magnetic*. Explain why

  file i00726

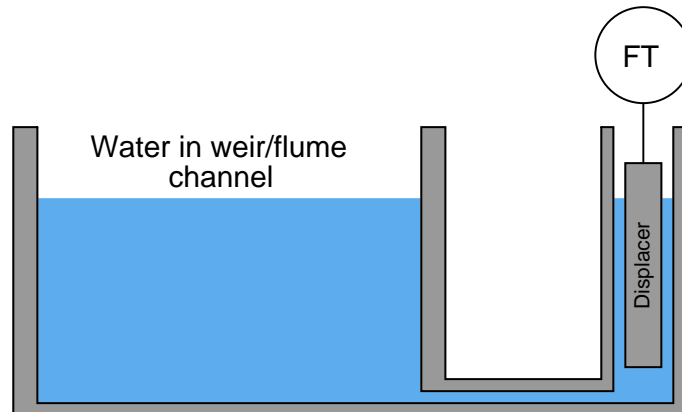Weirs and flumes are frequently equipped with stilling wells to provide a "quiet" liquid height for an instrument to measure, usually an ultrasonic or displacer sensor such as the type used to measure liquid level in a closed vessel:

This level-sensing instrument usually provides the characterization necessary to linearize the weir or flume's nonlinear flow/height response. If the level-sensing instrument is ultrasonic, the flow characterization may be done in the same digital computer that calculates liquid level by timing the sound echoes.

However, there is a low-technology way to do the same thing. If we use a displacer rather than a digital ultrasonic sensor, we may perform this same characterization by carefully choosing the correct non-cylindrical displacer shape, so that liquid height in the stilling well does not linearly translate to buoyant force felt by the transmitter unit.

Suppose we are setting up a transmitter on a Cippoletti weir, whose flow rate varies with the 1.5 power of liquid height in the stilling well ($Q \propto H^{1.5}$). Choose the correct profile of displacer for this application, to properly linearize the liquid height into a flow signal that we may read directly:

Which displacer has the correct profile?
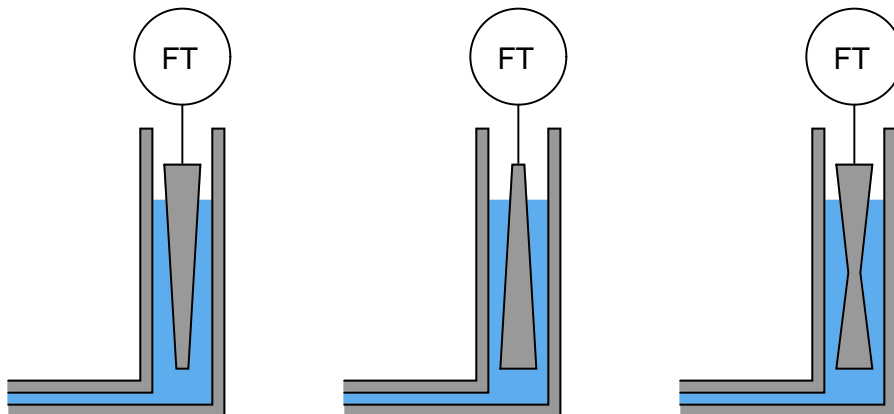
file i00624

Question 79

A "smart" differential pressure transmitter is configured to measure the differential pressure created by an orifice plate, and also to perform the square-root function necessary to linearize the orifice plate's signal:
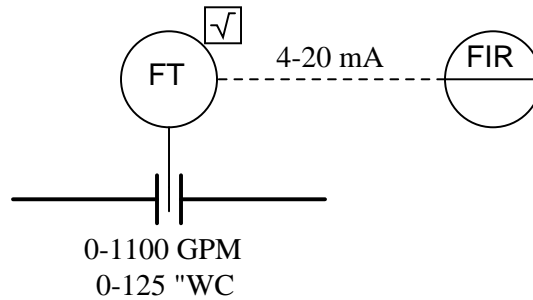
Calculate the following:

- Loop current at 350 GPM = _____ mA
- Differential pressure at 600 GPM = _____ "WC

file i00708

Question 80

An industrial cooling tower uses a vortex flowmeter to measure the flow rate of water through an 8-inch pipe (bore size = 7.981 inches). Calculate the *minimum* water flow rate measurable by this flowmeter, assuming a minimum necessary Reynolds number value of 20,000.

| Suggestions for Socratic discussion |

- Why do vortex flowmeters suffer from *low-flow cutoff*?
- Supposing we needed better low-flow measurement capability in this cooling water flow measurement application than what this flowmeter can deliver, what alternative(s) do you suggest? Keep in mind that we need to minimize cost while making our choices!

file i04086

Question 81

Suppose a venturi tube is installed on a steam line to measure the flow of high-pressure steam coming from a powerhouse boiler and going to a steam turbine (to generate electricity). The contractors who installed the flowmeter left you with this mess:
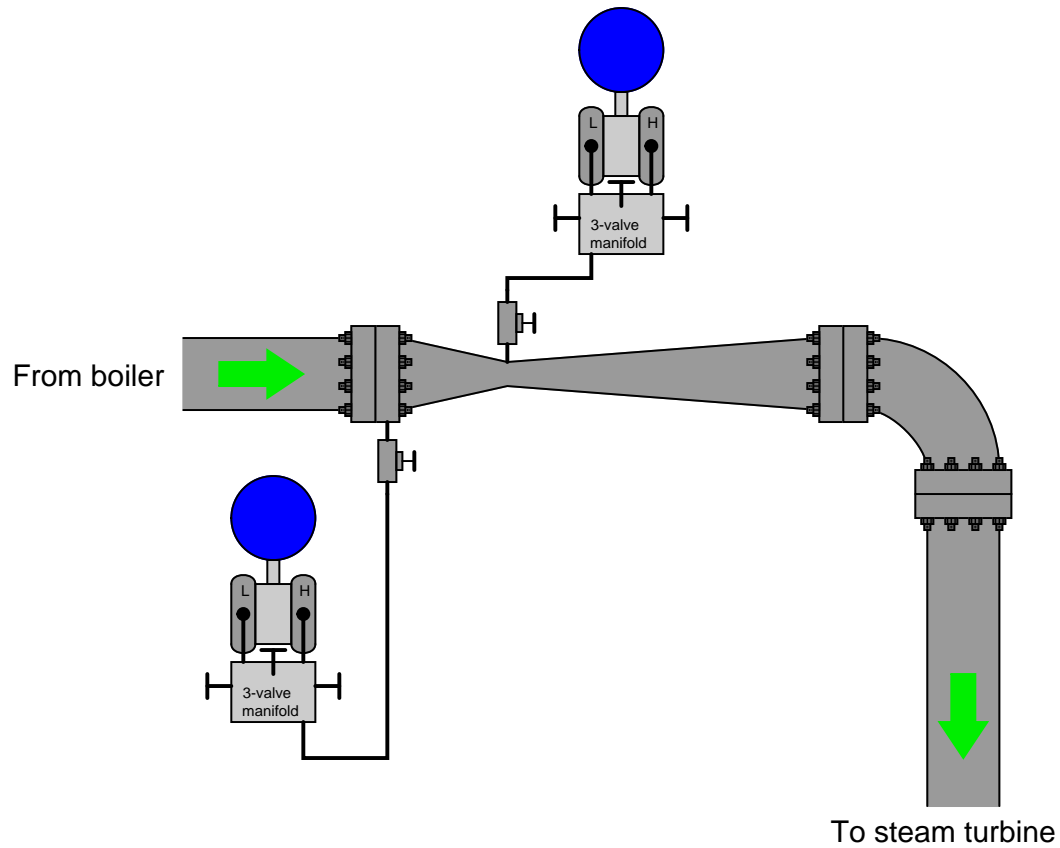
Explain what is wrong with this installation, and what must be done to fix it.

The flow computer connected to this turbine flowmeter (with electronic pick-up) does not register any flow, even though we know there to be fluid flowing through the pipe. A voltmeter connected between terminals TB1-1 and TB1-3 registers approximately 11.0 volts DC, and 10.8 volts AC at a frequency of 86 Hz:
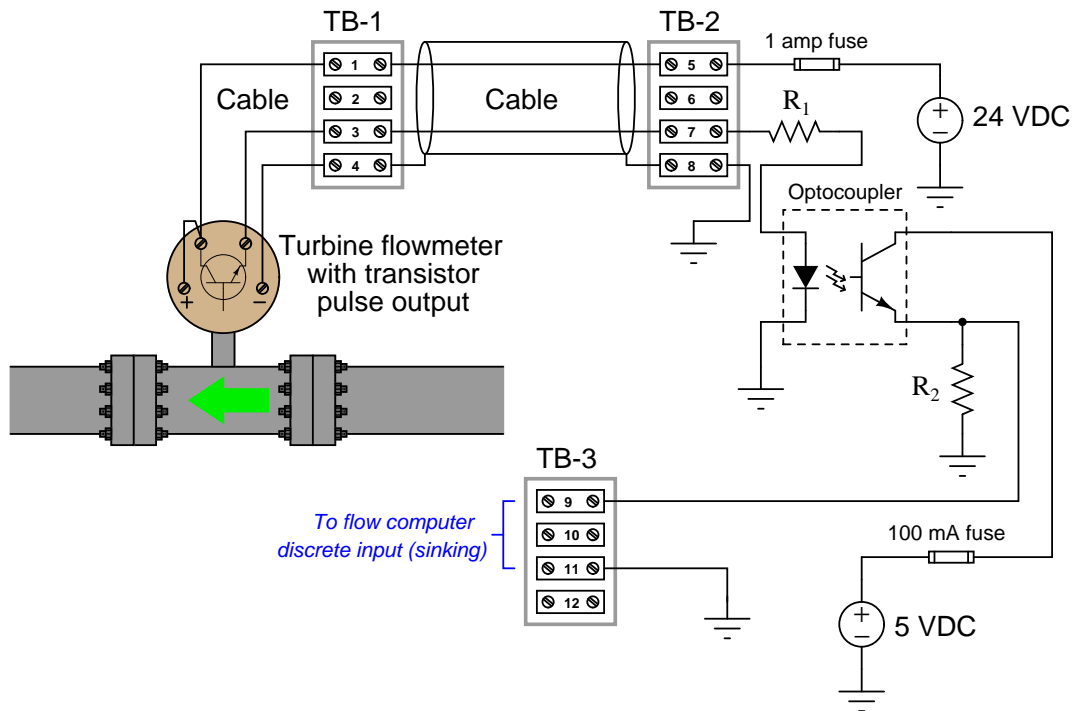
Determine the diagnostic value of each of the following tests. Assume only one fault in the system, including any single component or any single wire/cable/tube connecting components together. If a proposed test could provide new information to help you identify the location and/or nature of the one fault, mark "yes." Otherwise, if a proposed test would not reveal anything relevant to identifying the fault (already discernible from the measurements and symptoms given so far), mark "no."

Diagnostic test	Yes	No
Measure DC voltage between terminals TB2-5 and TB2-8		
Measure resistance between TB2-7 and TB2-8 with the 1 amp fuse pulled		
Measure DC voltage across 100 mA fuse		
Measure DC voltage across 1 amp fuse		
Measure AC voltage between terminals TB3-9 and TB3-11		
Measure continuity of conductor connecting terminals TB1-4 and TB2-8		

<u>file i00500</u>

Calculate the required fluid velocity in order to reduce the pressure at the narrow throat to 0 PSIG, then also calculate the volumetric flow rate corresponding to this velocity in units of GPM:

10 PSI

0 PSI

$v = ???$

$Q = ???$

1" ID

4" ID
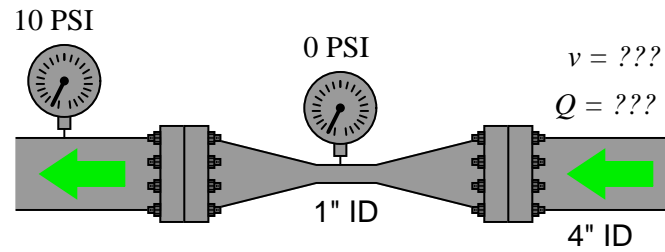
The inside diameter (ID) of the throat is 1 inch, while the inside diameter of the wide pipe is 4 inches. Assume the fluid to be water ($\rho = 1.94$ slugs/ft^3) at a constant downstream pressure of 10 PSIG:

Hint: the trick to solving for velocity (v) is to reduce Bernoulli's equation so that it contains just that one unknown variable. In other words, you need to be able to express the velocity at the 1-inch throat in terms of the velocity at the 4-inch pipe, so you will have just one v in the equation rather than a v_1 and a v_2.

file i00052

Question 84

In this paint mixing system, clear *base* and dark *pigment* are mixed together to form a paint with the desired coloring. A control valve positioned by hand (the human operator) throttles the flow of base, and that amount of flow is matched by pigment automatically throttled by a flow controller, to achieve a set ratio of pigment to base flow:
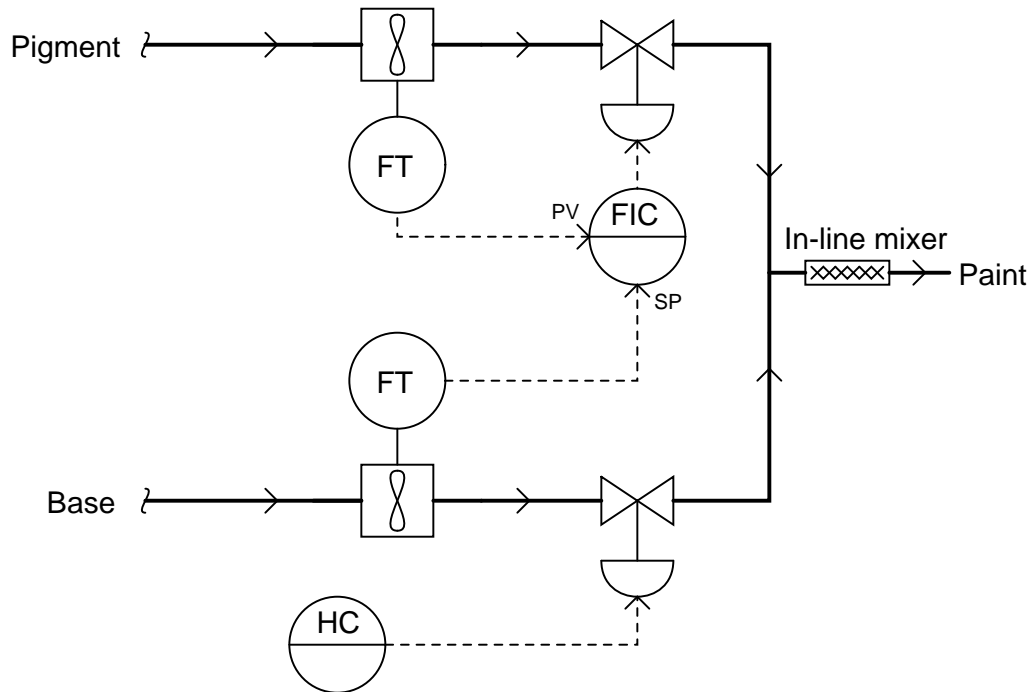
After a couple of years of successful operation, the system begins to output paint that is "paler" in color than it should be. Identify the likelihood of each specified fault for this control system. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for the pale-colored paint.

Fault	Possible	Impossible
Base flowmeter registering reading too low		
Pigment flowmeter registering too low		
Base flowmeter registering reading too high		
Pigment flowmeter registering too high		
Base control valve leaking by		
Pigment control valve leaking by		
Mixer plugged		
Controller in manual mode		

<u>file i00050</u>

Question 85

Two flowmeters are used to simultaneously measure the flow rate of a liquid through a pipe coming from a positive displacement pump:
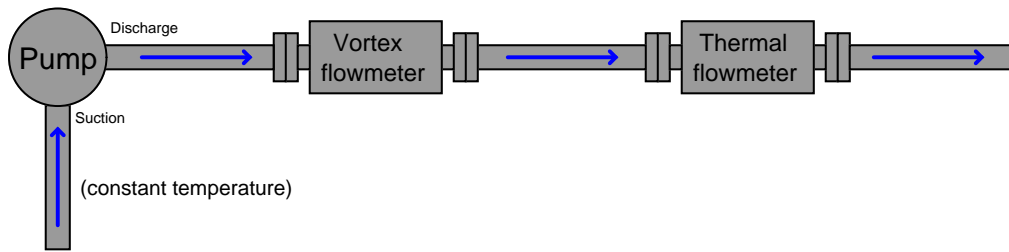
Suppose the positive displacement pump continues to turn at a constant speed, with the temperature of the incoming liquid constant. Suddenly, a steam pipe located near the pump breaks open, directing hot steam at the discharge pipe of the pump, heating the fluid as it exits the pump.

Determine the effect this change in fluid discharge temperature will have on the output signals coming from both flowmeters (vortex and thermal), then explain your answer in detail.

Question 86

The equation for determine volumetric flow rate (Q) of a liquid with a certain specific gravity (G_f) through a control valve given the upstream and downstream liquid pressures (P_1 and P_2, respectively) is as follows:
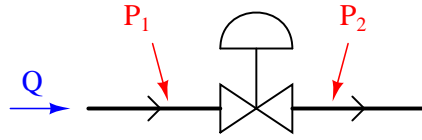
$$Q = C_v \sqrt{\frac{P_1 - P_2}{G_f}}$$

The variable C_v is called the *flow coefficient* of the control valve, and it varies from zero at full-closed to a certain maximum value (depending on valve size and type) at wide-open.

Manipulate this equation to solve for downstream pressure (P_2) in terms of the other variables. Be sure to show all your work!

$P_2 =$

file i03297

Question 87

The flow rate of a fluid measured by a *counterpropagation* ("transit-time") ultrasonic flowmeter is given by the following formula:

$$Q = k \frac{t_{up} - t_{down}}{(t_{up})(t_{down})}$$
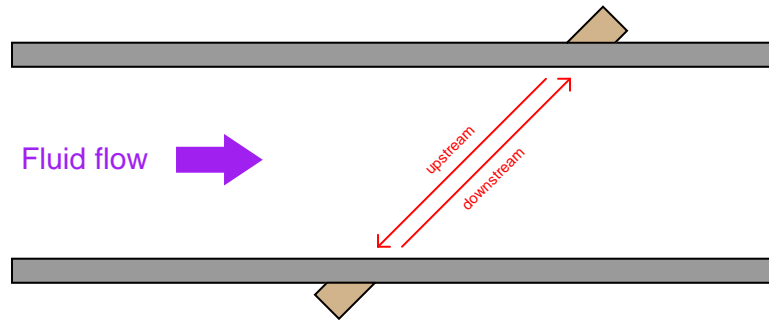
Knowing that the time for a sound wave to propagation upstream is equal to the length of the travel path divided by the difference in sound wave and fluid velocities ($t_{up} = \frac{L}{c-v}$) and that the time for a sound wave to propagation downstream is equal to the length of the travel path divided by the sum of sound wave and fluid velocities ($t_{down} = \frac{L}{c+v}$), prove that the flow rate measurement (Q) does not depend on the speed of sound through the fluid (c). In other words, substitute these mathematical definitions for t_{up} and t_{down} into the flowmeter equation and simplify to show that c is eliminated (canceled out) in the end.

file i03522

82

Question 88

An electronic temperature transmitter has an input range of 100 to 500 degrees Fahrenheit (type J thermocouple) and an output range of 4 to 20 mA. When subjected to a series of simulated temperatures (5-point up/down test), it responds as such:

Simulated temperature (deg F)	Output signal (mA)
100	4.1
200	8.0
300	11.75
400	16.0
500	20.2
400	16.0
300	11.75
200	8.0
100	4.1

Graph this instrument's ideal transfer function on the graph below, along with its *actual* transfer function graph based on the measured values recorded above. Then, determine what kind of calibration error it has (*zero shift*, *span shift*, *linearity*, and/or *hysteresis*).
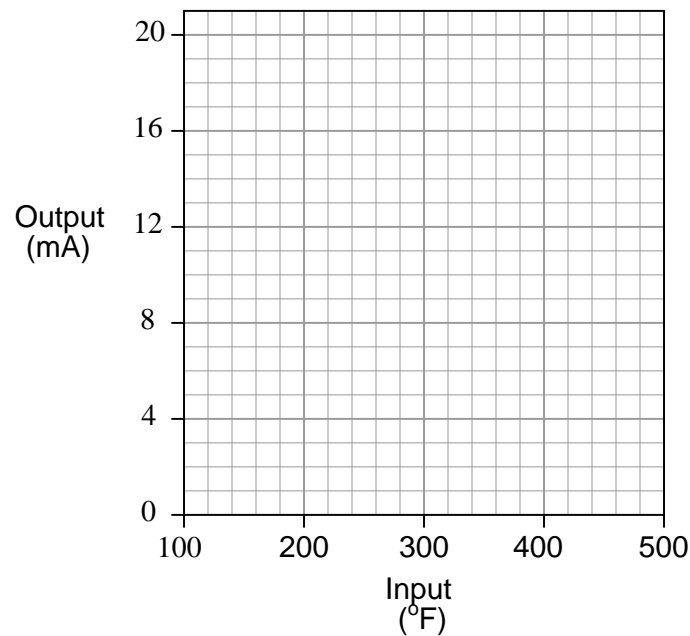
Hint: a computer spreadsheet program might be a useful tool in graphing this instrument's response. Feel free to attach a printed copy of a spreadsheet graph instead of hand-sketching one on this page.
file i03489

Question 89

An antimicrobial agent called *acrolein* used to protect diesel fuel from fungal growth may be manufactured by reacting propylene with steam and air in a reactor vessel:
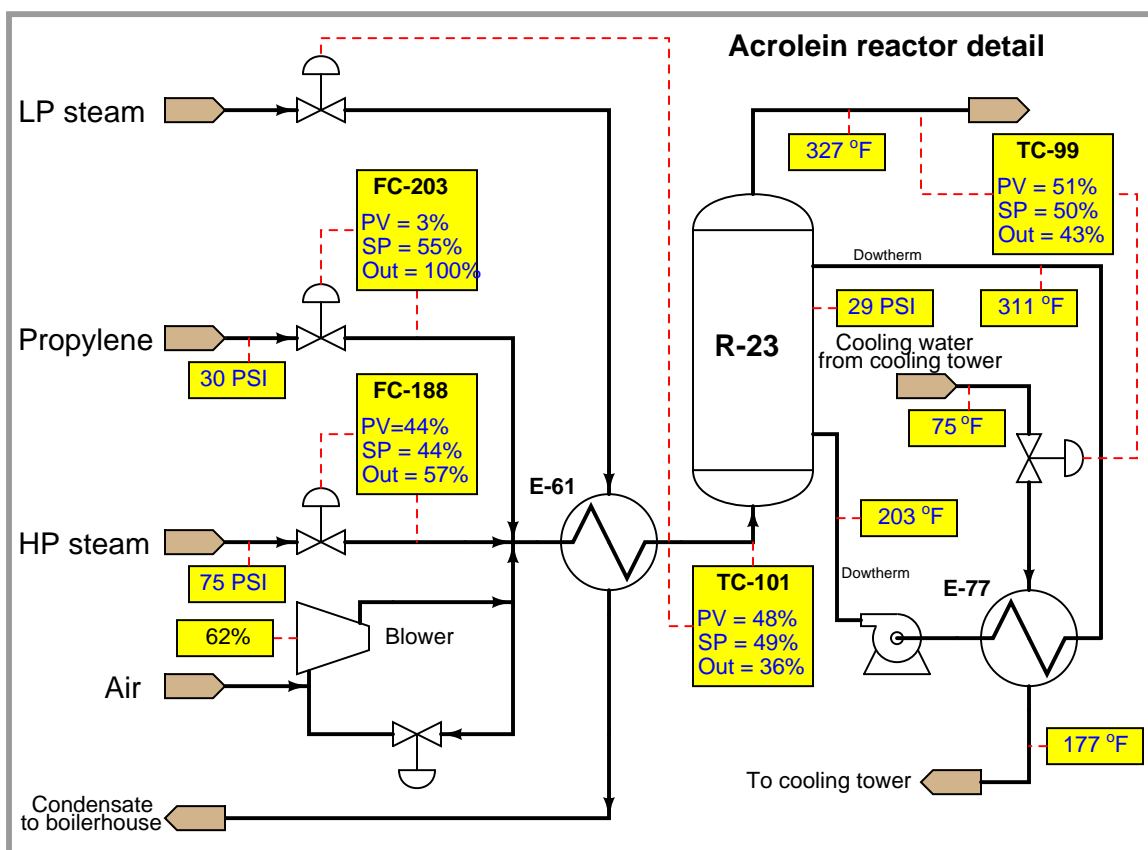
Suppose operators call you to troubleshoot a problem they are having with this process, and to help you start they show you this graphic display on one of their DCS workstations. Identify the problem in this process, suggest at least two possible causes for it, and identify the next diagnostic step you would take to confirm the cause(s).

Also, identify any additional instrumentation which would need to be added to this process to allow automatic calculation of *heat rate* supplied by the HP and LP steam flows. Assume that both steam supplies are saturated rather than superheated.

file i01310

Question 90

The field coil of this AC magnetic flowmeter is energized by 60 Hz line AC power, the coil exhibiting a known quantity of inductance as well as wire resistance:
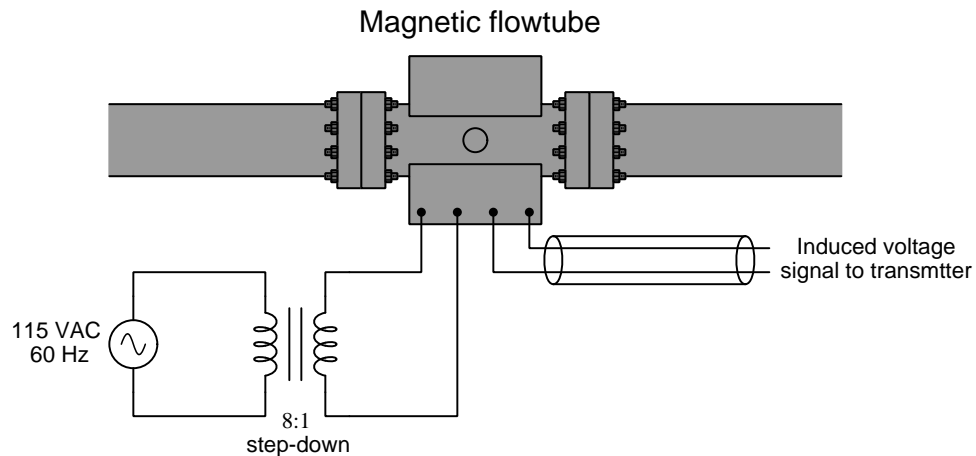
Magnetic flowtube

The *magnitude* of the induced voltage signal is a function of the field coil's magnetic flux density (B), the velocity of the fluid moving through the flowtube (v), and the diameter of the flowtube (d). The *phase angle* of the induced voltage signal will be the same as the phase angle of the current through the field coil, relative to the source voltage.

Calculate the magnitude and phase angle of the induced voltage signal, given the following parameters:

- Flowtube diameter = 14 centimeters
- Magnetic flux density = 1.0 millitesla, RMS
- Field coil resistance = 11 ohms
- Field coil inductance = 4.1 millihenrys
- Fluid velocity = 6.3 meters per second

file i00045

85

Question 91

Lab Exercise – introduction

Your task is to build, calibrate, document, and program a flow measurement system consisting of an electronic differential flow transmitter connected to one of the analog inputs of a data acquisition module (DAQ) for a SCADA RTU (Remote Terminal Unit) node which will serve as a *flow computer*. The particular SCADA system we will be using has been designed specifically for BTC Instrumentation students. It is called *caSCADA* and it is based on a single-board computer running the Linux operating system. In this lab exercise you will be configuring the RTU node to receive the flow transmitter's analog signal and compute the flow rate of that fluid. This will involve editing some of the programming code written in the "C" language. Your instructor will assign the flow to be measured, as well as the specific channel(s) to use on the caSCADA system for your loop.

The following table of objectives show what you and your team must complete within the scheduled time for this lab exercise. Note how some of these objectives are individual, while others are for the team as a whole:

Objective completion table:

Performance objective	Grading	1	2	3	4	Team
Team meeting and prototype sketch (do *first!*)	mastery	–	–	–	–	
Circuit design challenge	mastery					– – – –
Transmitter calibration (with As-Found/As-Left)	mastery	–	–	–	–	
Spreadsheet characterizing flow element	mastery	–	–	–	–	
Flow/DP prediction ($\pm$ 5% of span)	mastery					– – – –
Final loop diagram and system inspection	mastery					– – – –
Simulated troubleshooting of 4-20 mA circuit	mastery					– – – –
Editing code for transmitter channel	mastery					– – – –
Editing code for flow computation channel	mastery	–	–	–	–	
Safety and professionalism	deduction					
Lab percentage score	proportional					– – – –
Decommission and lab clean-up	(ungraded)	–	–	–	–	

The "proportional" score for this activity is based on the number of attempts require to master each objective. Every failed attempt is marked by a 0, and every pass by a 1. The total number of 1 marks divided by the total number of marks (both 1's and 0's) yields a percentage value. Team objectives count as part of every team member's individual score. The *Safety and professionalism* deduction is a flat -10% per instance, levied on occasions of unprofessional or unsafe conduct.

It is essential that your team plans ahead what to accomplish each day. A short (10 minute) team meeting at the beginning of each lab session is a good way to do this, reviewing what's already been done, what's left to do, and what assessments you should be ready for. There is a lot of work involved with building, documenting, and troubleshooting these working instrument systems!

As you and your team work on this system, you will invariably encounter problems. You should always attempt to solve these problems as a team before requesting instructor assistance. If you still require instructor assistance, write your team's color on the lab whiteboard with a brief description of what you need help on. The instructor will meet with each team in order they appear on the whiteboard to address these problems.

Lab Exercise – objectives and expectations

Each objective is assessed at the *mastery* level, which means it is not complete until it meets *all* expectations. Re-tries are allowed, but failed attempts will be recorded and factored into your score for this lab exercise.

Team meeting and prototype sketch

Read the lab exercise documentation and discuss with your teammates the objectives to be achieved and the time allotted to do so. Formulate a plan to achieve these objectives and draft a prototype design for the system you intend to build. Then, meet with your instructor to present your goals, plans, and prototype design. *This prototype sketch should be annotated with all expected physical parameters (e.g. voltage polarities, current directions, fluid pressures, etc.).* Be prepared to answer all manner of questions about your team's goals, plans, and prototype design, including analysis of the design for specific faults and condition changes. <u>Do not begin construction until your design has been analyzed and approved!</u> Note that multiple meetings may be required if the instructor's assistance is needed to select components influencing your design.

Circuit design challenge

Sketch a correct circuit for a 4-20 mA instrument "loop" based on random instrument selections by the instructor and reference manuals for each instrument.

Transmitter calibration

Trim both the pressure sensor and the output (4-20 mA) of the differential pressure transmitter, using trusted test instruments for verifying applied pressure and signal current values. Complete both As-Found and As-Left calibration tables, and tag when complete.

Spreadsheet characterizing flow element

Test your team's flow element based on known flow rate and measured differential pressure values, documenting and plotting these values using an electronic spreadsheet. Use the spreadsheet's *trendline* feature to fit a mathematical function to the data, with that mathematical function eventually being programmed into the caSCADA system.

Flow / DP prediction

Calculate flow rate given differential pressure, or vice-versa, on an actual flow element where the instructor randomizes the actual flow rate. Known values of flow rate and differential pressure for this element will be provided to you as a reference.

Final loop diagram and system inspection

Create a complete loop diagram of your team's completed system according to the ISA 5.1 standard, then show that the constructed system meets or exceed all standards described in the lab exercise documentation.

Troubleshooting simulation

Logically diagnose the nature and location of a fault simulated by computer in a 4-20 mA transmitter circuit (either loop-powered or externally-powered), using the `TROUBLESHOOT` simulation program. Successful completion of this objective consists of identifying the simulated fault at or below "par" in all measures and logically defending each and every step taken.

Editing code for transmitter channel

Individually edit your team's caSCADA code to express the transmitter's output in inches of water column for a range specified by your instructor. Add a conditional statement to the channel's source code causing the status value to change based on pressure.

Editing code for flow computation channel

Edit your team's caSCADA code (as a team) to express flow rate based on one or more transmitter channel output values as specified by the instructor.

Lab Exercise – objectives and expectations (continued)

Lab percentage score

Successful completion of the lab exercise requires demonstrated mastery of all objectives. A percentage value is based on the number of attempts required to achieve mastery on these objectives: the number of objectives divided by the number of total attempts equals the percentage. Thus, a perfect lab percentage score is possible only by completing all objectives on the first attempt. Marks given for team objectives factor into each individual's score. If one or more members of a team repeatedly compromise team performance, they may be removed from the team and required to complete remaining lab exercises alone.

Deductions from this percentage value will be levied for instances of unsafe or unprofessional conduct (see below), the final result being the lab percentage score.

Safety and professionalism (deduction)

In addition to completing the specified learning objectives in each lab exercise, each student is responsible for abiding by all lab safety standards and generally conducting themselves as working professionals (see the *General Values, Expectations, and Standards* page near the beginning of every worksheet for more detail). Expectations include maintaining an orderly work environment and returning all tools and test equipment by the end of every school day (team), as well as following clear instructions (e.g. instructions given in equipment manuals, lab documentation, verbally by the instructor), communicating with teammates, formulating a plan to complete the lab project in the allotted time, and productively managing time. As with the other objectives, chronic patterns of poor performance in this domain may result in the offending student being removed from the team. Deductions to the lab percentage score will *not* be made for performance already graded such as tardiness and attendance.

General format and philosophy

This lab exercise is *project-based:* the instructor serves as the project engineer, while each student's role is to implement the standards set for the project while budgeting time and resources to complete it by the deadline date. Students perform real work as part of the lab exercise, managing their work day and functioning much the same as they will on the job. The tools and equipment and materials used are all industry-standard, and the problems encountered are realistic. This instructional design is intentional, as it is proven effective in teaching project management skills and independent working habits.

When you require the instructor's assistance to answer a question or to check off an objective, write your name (or your team's name) on the lab room whiteboard. Questions take priority over checkoffs, so please distinguish questions from other requests (e.g. writing a question-mark symbol "?" after your name makes this clear). **There will be times when you must wait for extended periods** while the instructor is busy elsewhere – instant service is an impossibility. Adequate time *does* exist to complete the lab exercise if you follow all instructions, communicate well, and work productively. Use all "down time" wisely: filling it with tasks not requiring the instructor's assistance such as other lab objectives, homework, feedback questions, and job searches.

Remember that the lab facility is available to you at all hours of the school day. Students may perform non-hazardous work (e.g. circuit work at less than 30 volts, documentation, low air pressures, general construction not requiring power tools) at *any time during the school day* without the instructor's presence so long as that work does not disturb the learning environment for other students.

DO NOT TAKE SHORTCUTS when completing tasks! Learning requires focused attention and time on task, which means that most 'shortcuts" actually circumvent the learning process. Read the lab exercise instructions, follow all instructions documented in equipment manuals, and follow all advice given to you by your instructor. Make a good-faith effort to solve all problems on your own *before* seeking the help of others. Always remember that this lab exercise is just a means to an end: no one *needs* you to build this project; it is an activity designed to develop marketable knowledge, skills, and self-discipline. In the end it is your *professional development* that matters most, not the finished project!

Lab Exercise – team meeting, prototype sketch, and instrument selection

An important first step in completing this lab project is to **meet with your instructor** as a team to discuss safety concerns, team performance, and specific roles for team members. If you would like to emphasize exposure to certain equipment (e.g. use a particular type of control system, certain power tools), techniques (e.g. fabrication), or tasks to improve your skill set, this is the time to make requests of your team so that your learning during this project will be maximized.

An absolutely essential step in completing this lab project is to work together as a team to **sketch a prototype diagram** showing what you intend to build. This usually takes the form of a simple electrical schematic and/or loop diagram showing all electrical connections between components, as well as any tubing or piping for fluids. This prototype sketch need not be exhaustive in detail, but it does need to show enough detail for the instructor to determine if all components will be correctly connected for their safe function.

You should practice good problem-solving techniques when creating your prototype sketch, such as consulting equipment manuals for information on component functions and marking directions of electric current, voltage polarities, and identifying electrical sources/loads. Use this task as an opportunity to strengthen your analytical skills! Remember that you will be challenged in this program to do all of this on your own (during "capstone" assessments), so do not make the mistake of relying on your teammates to figure this out for you – instead, treat this as a problem *you* must solve and compare your results with those of your teammates.

Your team's prototype sketch is so important that the instructor will demand you provide this plan before any construction on your team's working system begins. *Any team found constructing their system without a verified plan will be ordered to cease construction and not resume until a prototype plan has been drafted and approved!* Similarly, you should not deviate from the prototype design without instructor approval, to ensure nothing will be done to harm equipment by way of incorrect connections. Each member on the team should have ready access to this plan (ideally possessing their own copy of the plan) throughout the construction process. Prototype design sketching is a skill and a habit you should cultivate in school and take with you in your new career.

In this particular lab, you will most likely use a low-range "draft" pressure transmitter to sense the differential pressure created by a primary flow element such as a pitot tube. DP transmitters designed to sense low pressures in HVAC systems work well for this task if the process fluid is air. For liquid flow processes, an industrial DP transmitter such as the Rosemount model 3051 should be used instead. In either case, the transmitter should have a range that can turn down to less than 10 inches water column.

Consult documentation from the manufacturer's website to identify how to properly wire, power, and calibrate the transmitter. Your instructor will check to see you have located and are familiar with the equipment manual(s).

After locating a suitable instrument and its associated documentation, you should qualitatively test it prior to installing it in your system. For a pressure transmitter, this entails applying an air pressure to the "high" pressure port and measuring the transmitter's milliamp output signal to see if it responds to the application of pressure. Since the range of this transmitter is so small, the source of air pressure you use must be very low, and could even be your own breath applied to a tube connected to the transmitter's "H" port. If the transmitter fails to respond properly, tag it with a label explaining what it does (or what it fails to do).

Planning a functioning system should take no more than an hour if the team is working efficiently, and will save you hours of frustration (and possible component destruction!).

Lab Exercise – building the system

The major purpose of this lab exercise is to configure the caSCADA system as a *flow computer*. To this end, you may connect any suitable set of transmitters to the caSCADA system for monitoring flow variables, and measure any available fluid flow. An easy option for flow measurement is the volumetric rate of air flow through a tube, driven by a motor-controlled fan. Another option for flow measurement is *wind speed*, treating air as the process fluid and the speed of the wind as the flow to be measured, and using a Pitot tube as the sensing element.

It is relatively easy to construct a crude venturi tube using PVC plastic piping, and to control air flow through that tube using a type of blower called a *regenerative* or *ring* blower. Volumetric air flow rate is very nearly linear with shaft speed on this type of blower, which means one may drive such a blower using a VFD-powered AC motor and read the VFD's frequency output value as a proportion of flow rate.

One venturi tube may provide differential pressure to multiple DP transmitters, allowing for either redundant measurement (each DP transmitter having the same range) or multi-range measurement (each DP transmitter having a progressively larger range) of fluid flow. The computational power of the caSCADA system may be put to good use by taking the differential pressure measurement and computing flow rate using a nonlinear formula. In other words, the DP transmitter may be configured for linear operation, with the caSCADA RTU computer doing all the necessary calculations to translate this sensed differential pressure into a wind speed. If multiple DP transmitters are plumbed to the same flow sensing element, the caSCADA system may be programmed to average those transmitters readings, or perform a selection function on the redundant signals (e.g. low-select, high-select, median-select) to yield a more reliable wind speed measurement. It is even possible to connect temperature, differential pressure, and absolute pressure transmitters to the caSCADA system's analog inputs and have the RTU computer calculate *mass flow rate* based on the AGA 3 formula (or something similar to it).

Whatever the configuration, the purpose of this system is to showcase the calculation of fluid flow using the computational powers of the caSCADA system, above and beyond a single transmitter registering a single variable.

The caSCADA RTU nodes are built to operate in outdoor locations, each with its own battery backup power system to continue operation when AC line power fails. This lends itself to the measurement of real-world flows such as wind speed, water flow in pipes and streams, tidal motion, etc.

Sample diagrams of the caSCADA system wiring, including loop diagram examples, are given in the next question of this worksheet. The loop diagrams are fairly self-explanatory, and follow a prescribed convention of terminal numbering (versus analog inputs).

Lab Exercise – circuit design challenge

Your instructor will choose one 4-20 mA field instrument and one control system from the lists shown below, for which you must sketch and annotate an accurate circuit diagram showing how the two instruments would connect to each other. If this interconnection between controller and field instrument requires additional electrical components to function (e.g. DC or AC power source, precision 250 Ω resistor, diode, relay, etc.), those must be incorporated into your diagram as well. The required annotation will consist of denoting all expected directions of current (marked by arrows pointing in the direction of conventional flow) and all expected voltage polarities (marked by + and − symbols), as well as identifying all electrical sources and loads as such. Instruction manuals for all instrument listed are available on the electronic Instrumentation Reference for your convenience. When your sketch is complete, you must show the relevant manual pages to your instructor for verification of correct connections.

This exercise tests your ability to locate appropriate information in technical manuals, to sketch a correct 4-20 mA loop circuit for a given pair of instruments, and to correctly annotate all voltages and currents. The electronic Instrumentation Reference will be available to you in order to answer this question.

Since all 4-20 mA "loops" are basically series DC circuits, it is highly recommended that you approach their design the same as for any other DC circuit: carefully identify all *sources* and *loads* in the circuit, trace directions of all currents, and mark the polarities of all voltages. Most of the mistakes made in this type of circuit design challenge may be remedied by careful consideration of these specific circuit-analysis details.

4-20 mA transmitter options

- Pressure
    - → Rosemount 1151 Alphaline (analog), 1151 HART, or 3051 HART
    - → Yokogawa DPharp EJX110A or EJX910
    - → Honeywell ST3000
- Level
    - → Rosemount APEX non-contact radar, 3300 GWR, or 5300 GWR
- Temperature
    - → Rosemount 444, 644, 3044, or 3144
    - → Foxboro RTT15 or RTT30
    - → Moore Industries SPT with sourcing (4-wire) 4-20 mA output
    - → Moore Industries SPT with sinking (2-wire) 4-20 mA output
    - → Moore Industries TRX or TDY
- Flow
    - → Foxboro CFT50 coriolis
- Analytical
    - → Rosemount 5081-P (pH)
    - → Daniel 700 gas chromatograph (4 analog output channels)
    - → Foxboro 876PH (pH/ORP/ISE)

Controller options

- Monolithic
  - → Siemens 352P
  - → Siemens 353
  - → Foxboro 716C
  - → Foxboro 718TC
  - → Foxboro 762CNA
  - → Moore Industries 535
  - → Honeywell UDC2300
  - → Honeywell UDC3500
- Modular – *you choose the appropriate I/O module*
  - → Siemens 353R
  - → Emerson ROC800 SCADA/RTU
- Distributed Control System (DCS) – *you choose the appropriate I/O module*
  - → Emerson DeltaV with M-series I/O
  - → Emerson DeltaV with S-series I/O
  - → Honeywell Experion with 2MLF series I/O
- Programmable Logic Controller (PLC) – *you choose the appropriate I/O module*
  - → Automation Direct "CLICK"
  - → Siemens S7-300
  - → Rockwell ControlLogix (catalog number 1756)
  - → Rockwell CompactLogix (catalog number 1769)

4-20 mA Final Control Element options

- Pneumatic control valve positioners
  - → Fisher 3582i positioner
  - → Fisher DVC6000 positioner
- Electrically actuated valves (MOV)
  - → Limitorque actuator with Modutronic-20 II controller
  - → Rotork AQ with Folomatic controller
- AC motor drives (VFD)
  - → Rockwell PowerFlex 4
  - → Automation Direct GS1

Correct circuit sketch (instructor verifies): _____

Correct voltage annotations (instructor verifies): _____ (+ and − symbols)

Correct current annotations (instructor verifies): _____ (arrows showing conventional flow)

Correct source/load identifications (instructor verifies): _____

Study reference: the "Analog Electronic Instrumentation" chapter of *Lessons In Industrial Instrumentation*, particularly the section on HART.

Lab Exercise – transmitter calibration

If your team's flow transmitter is based on pressure, you must calibrate the differential pressure transmitter ("trim" both the sensor and the output) to ensure it interprets pressure accurately and outputs an accurate current.

As in all cases where an instrument must be calibrated, you will need to check the instrument's response against one or more *standards*. In this case, the ideal standard to use for setting the input pressure to the transmitter is a *manometer*, and the ideal standard to use for measuring the transmitter's electronic output signal is a *multimeter* configured to measure DC milliamps:
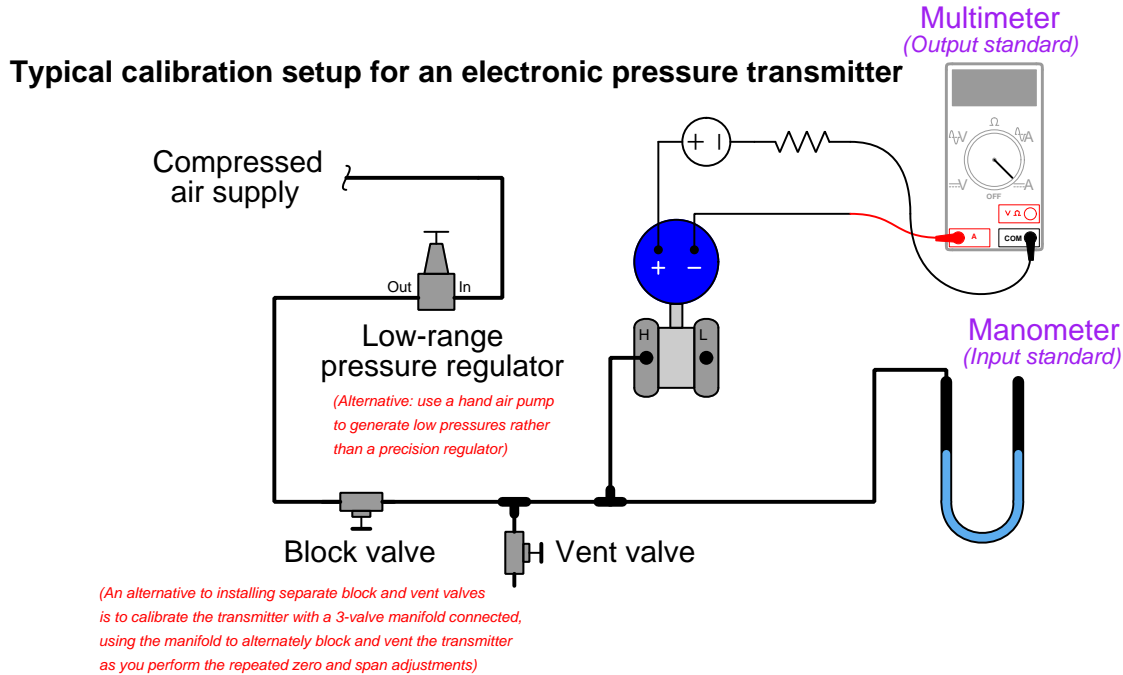
If the low-range pressure regulator does not reliably generate low enough pressures, you may throttle both the block and vent valves, using them as a sort of "pressure divider" (analogous to two resistors throttling current to make a voltage divider) to apply a lower pressure to the manometer and DP transmitter than the regulator outputs:
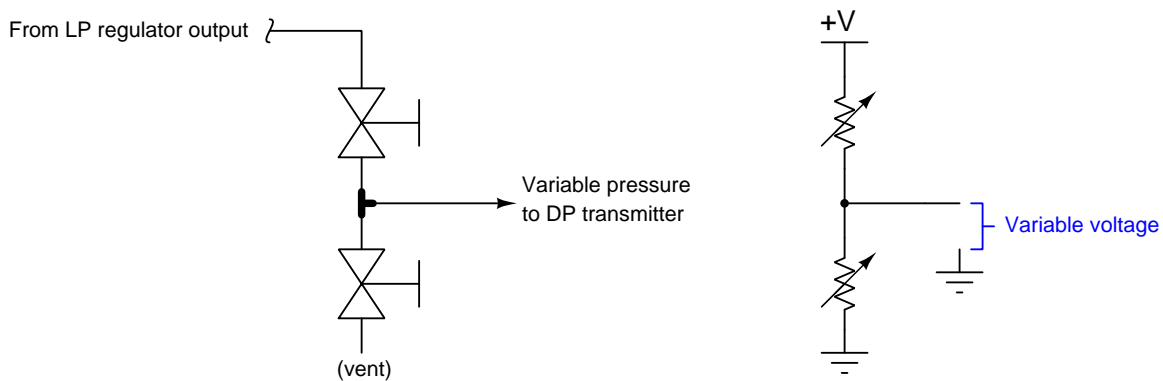
An alternative method for generating very low air pressures is to use a small-volume air pump (e.g. a bicycle tire pump works well for this purpose) connected to a chamber of large volume, such that each stroke of the pump results in a tiny increment of pressure increase applied to the manometer and DP transmitter:

Alternative calibration setup for a pneumatic pressure transmitter
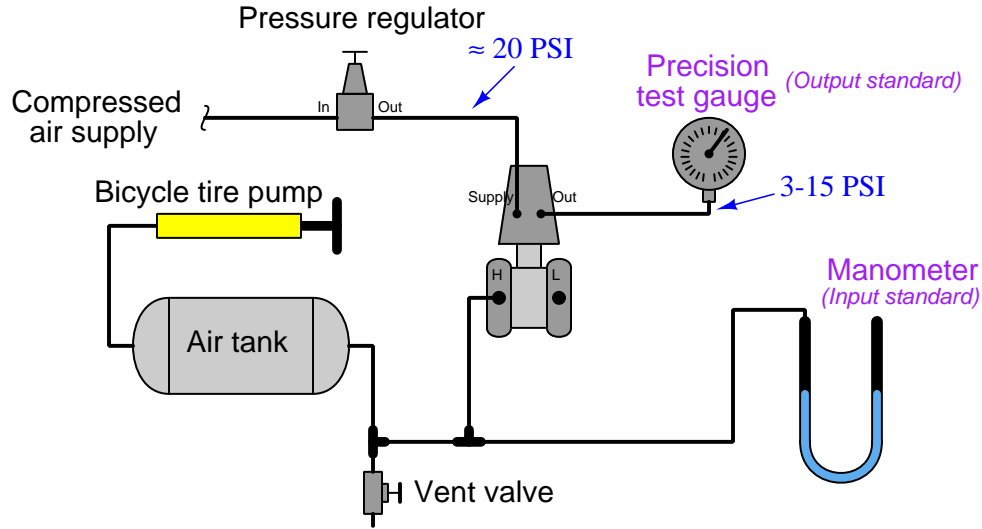
It is entirely permissible for teams to share one transmitter. No matter how well-calibrated one team might have left a transmitter, there is always room for another team to re-calibrate that same transmitter and at least attempt to calibrate it better. A comparison of your team's As-Found versus As-Left values will demonstrate the improvement(s) you were able to make.

It should be noted that when calibrating pressure transmitters with very low ranges, as is often the case when measuring flow in a lab environment, the physical mounting position of the transmitter may make a significant difference in its calibration. If the transmitter is re-oriented, gravity will tug at the pressure-sensing element in a different direction and thereby cause its calibration to shift. This shift is typically just a "zero" error, and is therefore fairly easy to correct, but it will necessitate another calibration check in the field. A good field test, therefore, is to mount the transmitter in its final position and then check its analog output signal with zero differential pressure applied (i.e. with the equalizing valve of a three-valve manifold opened, or by connecting the "H" and "L" ports of the transmitter together with a tube to absolutely ensure no differential pressure exists.

Document the accuracy of your transmitter's sensor trim before and after adjustment in this table, at five different points throughout its sensing range using these two tables:

As-Found calibration table

Applied pressure	Output signal (actual)	Output signal (ideal)	Error (% of span)

As-Left calibration table

Applied pressure	Output signal (actual)	Output signal (ideal)	Error (% of span)

$$\text{Error as \% of span} = \left(\frac{\text{Actual} - \text{Ideal}}{\text{Span}} \right) (100\%)$$

When finished calibrating your team's transmitter, be sure to place a calibration tag on it showing the range and the date it was calibrated. A set of calibration tags are shown here which you may cut out and tape to the transmitter after completing your calibration:

Cut out tag(s) with scissors, then affix to instrument(s) using transparent tape to show calibration:

CALIBRATED	CALIBRATED	CALIBRATED	CALIBRATED
By: _____ Date: _____	By: _____ Date: _____	By: _____ Date: _____	By: _____ Date: _____
Range:_____	Range:_____	Range:_____	Range:_____
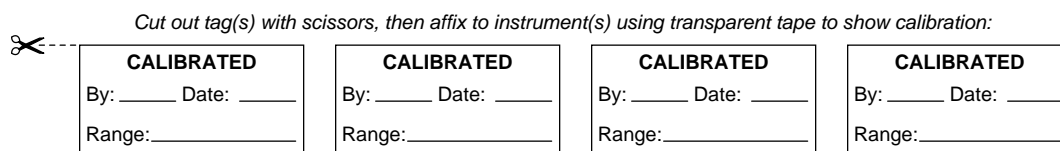
If your team's flow transmitter is not pressure-based (e.g. vortex, magnetic, turbine, Coriolis, etc.) then the input standard you must provide for calibration will not be pressure. In some cases the input standard may be electrically simulated (e.g. simulating the voltage induced by the flowtube in a magnetic flowmeter), but in other cases you may have to do a "bucket test" which involves timing how long it takes to fill a bucket of known volume with the liquid passing through the flowmeter.

Common mistakes:

- Choosing a calibration ("trim") range that is substantially less than the final range of measurement when installed. As a general rule, you should trim the sensor of the transmitter to cover the broadest range of measurement possible with your calibration equipment.
- Changing the physical orientation of the differential pressure transmitter between calibration and field mounting, without re-trimming the sensor's zero point.
- Ignoring the mathematical signs (+ or −) of error calculations.
- Neglecting to place a calibration tag on the transmitter after calibrating it.

Characterizing your team's flow element and calibrating your team's transmitter to match should take no more than one full lab session (3 hours) if the team is working efficiently!

Lab Exercise – flow element characterization

Flowmeters based on the generation of a differential pressure (DP) by acceleration or deceleration of the fluid are inherently non-linear in nature: doubling the flow rate results in approximately quadrupling the DP generated. In order to be able to program the caSCADA system to accurately compute flow rate from differential pressure measurements, you must *characterize* the flow element. This means testing the flow element against known flow rates to see how much pressure it generates at those rates, and then deriving a formula relating pressure to flow rate. You may think of this as analogous to developing a *strapping table* for tank liquid level measurement: exposing the sensor to a set of known values to see how it responds across a wide range of values, and then recording those values for later use in interpreting the process variable.

An important tool for this task is an *electronic spreadsheet program* such as Microsoft Excel. You will take the flow/DP data measured for your flow element, enter those data points in a spreadsheet, and have the spreadsheet plot a graph of the data with DP as the independent variable (horizontal axis) and flow rate as the dependent variable (vertical axis). Most spreadsheets permit both linear and logarithmic plotting. Examples of each type of plot are shown here, with flow rate as the independent (horizontal axis) variable and pressure as the dependent (vertical axis) variable:
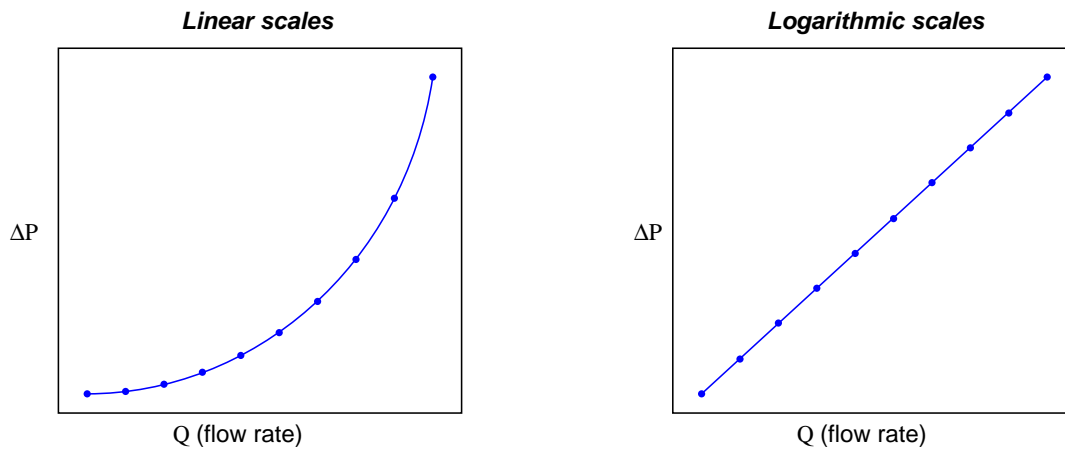
Flow elements such as orifice plates, venturi tubes, Pitot tubes, and flow nozzles should exhibit a simple quadratic characteristic, represented by the formula $Q = k\sqrt{\Delta P}$. Logarithmic scales are very helpful when graphing inherently nonlinear functions such as this. Note what happens to this quadratic function when the logarithm is taken of both sides:

$$Q = \sqrt{\Delta P} = \Delta P^{1/2}$$

$$\log Q = \log \Delta P^{1/2}$$

$$\log Q = \frac{1}{2} \log \Delta P$$

$$\frac{\log Q}{\log \Delta P} = \frac{1}{2}$$

Thus, a graph of the *logarithm* of Q plotted with respect to the *logarithm* of ΔP yields a line with constant slope of one-half ($\frac{1}{2}$). Deviations from the ideal quadratic function are more readily seen in such a log/log plot because they appear as deviations from a straight line. It is more difficult for a person to detect the same deviations on a graph when the ideal plot is a curve instead of a line.

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Another powerful feature of electronic spreadsheets is their ability to *fit a mathematical function* to your data. Once you have plots of your flow/DP data, you will instruct the spreadsheet to trace a function over that same data to mathematically approximate it. In Microsoft Excel, this feature is called a *trendline*, which may be enabled and configured by right-clicking on any of the points on the plotted function. This function in the form of $y = f(x)$ will be something you may then program into the caSCADA system to convert x (differential pressure) into y (flow rate or flow velocity). The formula fit by the spreadsheet will likely be more accurate to your flow element than $Q = k\sqrt{\Delta P}$ because the latter is based on theory while the former is based on empirical data.

It is highly recommended that you plot differential pressure as the independent variable (x) and flow rate (Q) as the dependent variable (y), so that the mathematical function fit to the data will be ready to accept values of DP in inches water column and output values for flow rate when programmed into the caSCADA system. A good rule of thumb here is that your mathematical function should fit all data points to within $\pm 1\%$ of range.

This is the end-goal of your spreadsheet use in this lab exercise: to generate a formula relating differential pressure (in inches water column) to flow rate (e.g. volumetric units, or mass units, or flowing velocity, or blower speed). Your team must show your spreadsheet to the instructor, explain how you plotted the data and displayed the trendline formula, and explain what the data and formula mean.

You may find it challenging to find one mathematical function that fits *all* data points precisely, especially when you include the data point (0,0) (i.e. zero differential pressure at zero flow). It may be more practical to fit one mathematical function to part of the data, and a different mathematical function to the rest of the data. One option you have when programming your caSCADA RTU to calculate flow from measured pressure is to use this multi-function approach (called a *piecewise function*): program the flow computation channel function using "if" conditional statements telling the computer to use one mathematical function for part of the flow range and a different mathematical function for the rest of the flow range. You may set up your spreadsheet to generate multiple functions, each one fitting a portion of the data range:
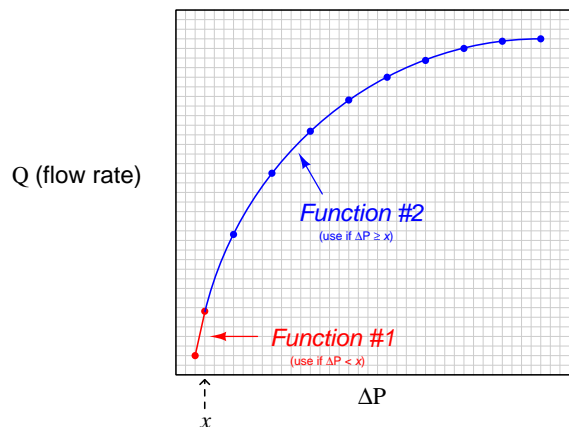
Common mistakes:

- Not recording enough data points. There really is no maximum number of data points to collect during your characterization test. The more data points, the better, because it means the spreadsheet will have more data to analyze in deriving its mathematical function, and that function will likely be a better fit to the true measurement!
- Not including zero (no flow) as part of the collected data set.
- Not recognizing poor data. The data you collect during the characterization process should closely resemble the function predicted by theory. If you see one or more data points that deviate substantially from the smooth curve connecting the other data points together (i.e. "outliers"), something likely went wrong during the testing process and it should be repeated.

- Reversing the axes on the plots. Remember, in order for the spreadsheet-generated formula to be useful to you in programming the caSCADA system, differential pressure must be the independent variable (x) and flow must be the dependent variable (y).

Lab Exercise – flow/DP prediction

Regardless of the type of flowmeter used by your team to measure process flow rate, everyone must also demonstrate competence calculating differential pressure generated by a DP-based flow element given a known flow rate, or vice-versa. A system called the *turbocompressor* already exists in the main lab room with a variable-frequency-driven air fan blowing air through a venturi tube, and an indicating differential pressure transmitter sensing the DP generated by that venturi tube. Air flow rate is a direct (linear) function of the fan's speed, which is a direct (linear) function of the motor's drive frequency.

The mathematical relationship between flow rate and DP for any given flow element and fluid type, of course, is given by the following formula:

$$Q = k\sqrt{\Delta P}$$

Where,
Q = Flow rate
k = Proportionality constant
ΔP = Differential pressure

The "k factor" of this venturi tube assembly may be derived by manipulating that formula to solve for k and plugging in known values of Q (i.e. fan drive frequency) and ΔP. Known values for one particular fan speed will be provided by the instructor prior to each student's challenge. After providing these Q and ΔP values, the instructor will then randomly change the fan's speed and either hide that new fan speed or hide the new ΔP value, and have each student calculate the hidden value based on the *other* value which will be evident for all to see.

Each student passes this challenge when they are able to correctly calculate the hidden variable from the revealed variable.

Lab Exercise – Linux command-line usage

The caSCADA telemetry system is built on the foundation of a single-board computer running the Linux operating system. Linux is a free and open-source version of the venerable Unix operating system which was developed for large mainframe computers in the early 1970's. In this lab exercise you will find the following Linux commands useful in addition to the commands you have already learned in the last lab exercise.

<div style="border:1px solid; display:inline-block; padding:2px 6px;">man</div>

A standard feature of all Unix systems is the *manual* library with documentation on virtually all commands and installed software. This documentation is available at the command line simply by typing `man` followed by the name of the command or program you wish to learn about. For example, if you wished to learn how to properly use the `ifconfig` command to view network parameters, you would type `man ifconfig`. The screen then switches to a display of the "manual" page for that command, where you may scroll up and down using arrow keys and page up/down keys, and search for terms by pressing the `/` key. You may exit the manual page at any time by pressing the `q` key.

<div style="border:1px solid; display:inline-block; padding:2px 6px;">cp</div>

The `cp` command makes a *copy* of a file. Both the original file name and the new (copied) file name are specified, in that order, as arguments to the `cp` command. For example, entering the command `cp data.txt mydata` copies the contents of the text file `data.txt` into a new file within that same directory named `mydata`.

Without any options specified, the `cp` command acts silently, not prompting for confirmation of a file's duplication or even giving any indication that the job is done. For this reason, I prefer to get into the habit of including the `v` ("verbose") and `i` ("interactive") options when invoking the `cp` command. If you were to type `cp -vi data.txt mydata` and press Enter, it would prompt you with a question to confirm whether you really wanted to copy this file if indeed a file named `mydata` already existed (press `y` to confirm and `n` to escape) which is the "interactive" option at work. It would also tell you the file had been copied when complete – that's the "verbose" option at work.

Here are some example uses of the `cp` command:

`cp -i mydata yourdata`   *copies the contents of the file "mydata" into a new file named "yourdata". If the file "yourdata" already exists, the command will prompt you to confirm whether or not to over-write the existing file (this is the "interactive" option at work).*

`cp data.txt newdir/`   *copies the file "data.txt" into a directory named "newdir" where a new file named "data.txt" will be created. If the file "data.txt" already exists within the "newdir" directory, its contents will be over-written without asking.*

`cp -v source/input.dat .`   *copies the file "input.dat" located in a directory named "source" to the present directory (.) where a new file named "input.dat" will be created. If the file "input.dat" already exists within the present directory, its contents will be over-written. The -v option instructs the copy command to print a short message confirming completion of the copying task.*

`cp -vi data.txt ../`   *copies the file "data.txt" into the next higher-level directory (../) where a new file named "data.txt" will be created. The interactive option prompts you confirm over-writing is the file "data.txt" already exists in that directory, and the verbose option instructs the copy command to print a short message of confirmation when complete.*

mv

The `mv` command does the same thing as the `cp` command, but deletes the original file after the copying process is complete. In other words, the `mv` command *moves* the file rather than duplicating it. Like the `cp` command, the `mv` command also obeys the `-vi` options. This is highly recommended as a habit to build, as it will save you someday from accidently relocating a file.

rm

Okay, here is where we could potentially do some damage to the system! The `rm` command removes, or deletes, any file specified. If you were to type `rm data.txt` it would delete any file named `data.txt`. Like the copy (`cp`) command, `rm` supports both the "verbose" and "interactive" options which are highly recommended to avoid accidental deletions.

To get some practice using this command, you will need to have some files available that are safe to delete. Two such files are the `data.txt` and `data.html` files which are refreshed and re-written periodically any time the `poll` or `simulate` caSCADA processes are running. Another way to practice using the `rm` command is to first use the `touch` command to create a new file of zero byte size which you may then delete (e.g. typing `touch junk` creates a new file named "junk" which of course is safe for anyone to remove because it contains no data whatsoever).

*

The asterisk symbol isn't really a command, but rather a "wildcard" character useful for representing portions of file names or directory names. Specifically, the asterisk character represents *any* one or multiple characters that might be part of a file name or directory name. For example, if you were to issue the command `ls -l *.txt` it would display a listing of all files ending with the `.txt` extension (i.e. all text files).

The asterisk wildcard may be used at the beginning, middle, or even end of a specified file or directory name. Note the following examples:

`cd engineer*` *Relocates you to the directory beginning with the letters "engineer". If more than one directory is so named, this will return an error message.*

`rm -vi junk*txt` *Removes all files having names beginning with the letters "junk" and ending with the letters "txt".*

`cp -vi *poll* ../../` *Copies all files containing the letters "poll" in their names two directory levels above where we are right now. If multiple files exist fitting this name pattern, all of them will be copied to that location under their original names.*

`cp -vi ../* .` *Copies all files residing one directory level above where we are right now, to where we are right now (the present directory).*

Another wildcard character that is sometimes useful is the `?` which is a wildcard *only for a single character* in a file name or directory name, versus `*` which is a wildcard for any number of consecutive characters in a name.

mkdir

This command creates ("makes") a new subdirectory under the directory you happen to presently reside. The name of the new subdirectory must be specified as an argument to the `mkdir` command. For example, if you were to type `mkdir Elvis` it would create a new subdirectory named `Elvis`.

This command deletes ("removes") a specified subdirectory. For example, `rmdir Elvis` will delete the `Elvis` subdirectory, but only if that directory is empty. The `rmdir` command does nothing if there are files located within the specified subdirectory, acting out of precaution.

grep

This highly useful command scans a text file and prints to the screen only those lines within the file containing a specified string of text you specify as an argument to the command. The `grep` command requires you to provide at least two arguments: the first specifying the text string to search for, and the second specifying the file to search within. Multiple files may be specified. For example, if you were to type the command `grep PT-45 data.txt` it would scan the file `data.txt` and only print out those lines of the file containing the text `PT-45`.

The text string `grep` searches for is case-sensitive, and must be spelled perfectly. If space characters are part of the desired search string, you will need to enclose the text string in quotation marks (e.g. `grep "Is anyone there" letter.txt`) in order to not interpret the space characters between `Is` and `anyone` and `there` as delimiters between additional arguments to the `grep` command. If we were to have omitted the quotation marks, `grep` would only have searched for the text string `Is`, but it would have looked for that string within three different files: `anyone`, `there`, and `letter.txt`!

Note the following example uses of `grep`:

`grep AIN3 f_channel_03.c`   *returns any line(s) within the file f_channel_03.c containing the text string "AIN3".*

`grep data README.txt LICENSE.txt`   *returns any line(s) within the files README.txt or INSTALL.txt containing the text string "data".*

`grep "float x" *.c`   *searches any file whose filename ends in ".c" for the text string "float x".*

As you can probably guess, the `grep` command is very useful when using the caSCADA system, as it allows you to scan any of the live data files updated by the `poll` or `simulate` processes for just the channel you are interested in.

grep -v

The `-v` option for the `grep` command instructs it to obey an *inverse match* rule. That is to say, the `-v` option tells `grep` to search for lines in a file that *do not* contain the text string you specify.

Note that the `-v` option in `grep` does something entirely different from the `-v` option in either the `cp` or `mv` commands. As it happens, each person who developed these Unix commands was free to assign any meaning they wished to the various options, and there appears to be little standardization between different commands. As always, the `man` utility is helpful here, showing you which options exist for each command and what each of them mean.

$\boxed{|}$

Like the asterisk character (*), the "pipe" character (|, which is located on most keyboards as the shift-character on the backslash key) isn't really a command at all, but rather a different kind of function in the Unix command-line environment. The "pipe" character links two or more commands together, so that the text output of the first command gets sent as input into the next command, as though those two commands were linked together with a section of virtual pipe.

One of the most common uses of such "plumbing" in Unix systems is the pipe a command to the `grep` command to filter for a particular string of text. Consider, for example, the `ps -e` command, which displays to the terminal a list of all "processes" currently running on the computer. If you wished to scan that list of running processes to look for a particular process name, or process ID number, or terminal ID, it could be very tedious and error-prone to do it manually by visually scanning the list with your eyes. Instead, we could issue the `ps -e` command followed by the pipe symbol and then use `grep` to display only certain lines. For example, the command `ps -e | grep poll` will display all instances of processes running which contain the string "poll" anywhere in the line output by `ps`.

Note how when using the "pipe" symbol between `ps -e` and `grep`, the `grep` command does not need a filename specified to search in. This is because the text output by the `ps -e` command is what is being searched through by `grep`. Whenever Unix commands are "plumbed" together by the pipe symbol, the following command gets its data from the output of the previous command.

Consider the following example, used by someone to screen all files and directories owned by "root" and edited in the year 2017:

```
ls -l | grep 2017 | grep root
```

This example uses the `ls` command to list all files and subdirectories within the current directory, and so do in "long" format (`-l`) so as to show all dates, sizes, owners, and permissions. The *two* casdaded `grep` commands first select only those lines containing the number 2017 (a calendar year), and then select from that list only those lines containing the word "root". Of course, this will screen for *any* lines of text in the listing containing the number 2017 and the word root, so if there is a file that happens to be named `groot.txt` and is 2017 bytes in size, that file will be listed as well. The `grep` command merely searches for matching text, not appropriate context. However, even with this limitation it should be clear how piping multiple `grep` commands can make fast work of an otherwise tedious searching operation.

Common mistakes:

- Not practicing the use of these commands!
- Not practicing the use of these commands!!
- *Not practicing the use of these commands!!!*

Lab Exercise – troubleshooting

An important aspect of this lab exercise is *troubleshooting*, where you demonstrate your ability to logically isolate a fault in a simulated circuit. You will use the open-source software called TROUBLESHOOT for this objective, which natively runs on the Linux operating system and is already installed on the caSCADA nodes in the main lab room (under the /tshoot directory). You may also compile and run this free software natively on an Apple personal computer, or if running Windows you may install the free Cygwin emulator complete with development tools and use that to compile and run TROUBLESHOOT.

The TROUBLESHOOT software offers multiple simulated circuits to select, *the particular circuit for this lab exercise being specified earlier in this outline.* The software tracks every step you take, and the amount of time taken for each step. Scores are given at the end for such metrics as number of steps taken, total "cost" incurred (with different cost values associated with different actions), and total time taken. The software also provides reasonable "par" scores for each of the randomly-selected faults.

Included with every installation of TROUBLESHOOT is a set of PDF files, each one depicting the schematic diagram for a simulated circuit. It is advisable for you to print a paper copy of this schematic so that you can easily annotate measurements you take during the simulation.

In order to successfully pass this objective, you must start up the simulation in the instructor's presence, document the randomly-selected circuit values on paper (in order to later verify it is the exact same simulation scenario), complete the simulation on your own, and then logically defend each of your steps (recounted by the software after your declaration of the fault). You must meet or improve upon *all* of the "par" values given by the software. Like all mastery objectives, multiple re-tries will be permitted. You are also welcome to practice using this software on your own before committing to a graded demonstration.

Failure to achieve all par scores, or failure to apply logical reasoning to the defense of every step take, or simple failure to identify the random fault will disqualify the effort, in which case you must re-try with a different (random) fault.

The instructor will review each troubleshooting effort after completion, highlighting good and bad points for the purpose of learning. Troubleshooting is a skill born of practice and failure, so do not be disappointed in yourself if you must make multiple attempts to pass! One of the important life-lessons embedded in this activity is how to deal with failure, because it *will* eventually happen to you on the job! There is no dishonor in failing to properly diagnose a fault after doing your level best. The only dishonor is in taking shortcuts or in giving up.

Common mistakes:

- Not practicing the use of the TROUBLESHOOT software.

The purpose of every troubleshooting exercise is to foster and assess your ability to intelligently diagnose a complex system. Finding the fault by luck, or by trial-and-error inspection, is no demonstration of skill. Competence is only revealed by your demonstrated ability to logically analyze and isolate the problem, correctly explaining all your steps!

Lab Exercise – editing and running caSCADA code

For each transmitter connected to the DAQ unit in the RTU, there will be one designated caSCADA channel. For a flow measurement system with three redundant pressure transmitters sensing DP generated by a common flow element, this means three channels: one for each of the redundant transmitters.

Each of these transmitter channels will be scaled linearly, representing the variable directly sensed by the transmitter. If the transmitters in question sense differential pressure, then the scaled value will be in units appropriate to differential pressure rather than units appropriate to flow. A new requirement for this lab exercise is that the transmitter channel must employ conditional ("if") statements to set the channel's status value to something other than 1 if the reading falls outside of the proper or usable range.

Additional channel(s) will be designated on the caSCADA system for the computation of flow rate. These channels will take value and status data from the transmitter channels and perform appropriate mathematical calculations on that data to convert it into a flow rate. It is each *team's* responsibility to edit the C code for a flow-computation channel.

For example, suppose the system you're assigned will have three redundant DP transmitters wired to analog inputs 1, 2, and 3 on the LabJack DAQ. Each of the channel functions will be written to scale the 4-20 mA signal into appropriate pressure readings, as shown in this example code for the file **f_channel_02.c** which takes in the 1-5 VDC analog signal and scales it into 0-5 inches WC differential pressure. Here, the status is set to 0 if the transmitter becomes under-ranged (less than 0.0) or over-ranged (more than 5.0):

```
/********************************************************
Consult the "README.txt" file for help editing this function!
********************************************************/

#include <stdio.h>
#include <math.h> // Necessary for any advanced math functions
#include "cascada.h" // Contains all the declarations specific to caSCADA

int
f_channel_02 (void)
{

  f_channel[2].value = ain[2] * 1.25 - 1.25;
  f_channel[2].tag = "PDT-102";
  f_channel[2].unit = "Inches WC";

  if (f_channel[2].value < 0.0 || f_channel[2].value > 5.0)
    f_channel[2].status = 0;

  else
    f_channel[2].status = 1;

  f_channel[2].comment = "Redundant DP transmitter number 2";

  return 1;
}
```

Since each student will be responsible for editing the transmitter channel code, the instructor will assign different "if" conditions to every student to ensure a genuine learning experience. For example, the instructor may assign a different threshold for a "bad" (0) status value on a DP transmitter: perhaps any signal less than 10% of the scaled range rather than only for values less than zero. Alternatively, the instructor may request that the comment change dynamically with the status as well.

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Using conditional ("if") expressions in C language programming is a new objective and requires new knowledge. First, a list of the relational (comparative) and logical (AND/OR) operators used by the `if` conditional:

Relational operator	Meaning
==	Equal to
!=	Not equal to
<	Less than
<=	Less than or equal to
>	Greater than
>=	Greater than or equal to

Logical operator	Meaning
&&	AND
||	OR

Next, some examples of `if` conditionals shown in code snippets (with explanatory comments). This first example sets the status to different values depending on if the measurement is under-ranged, over-ranged, or within range:

```c
    if (f_channel[2].value < 0.0)
      f_channel[2].status = 0;          // Sets status = 0 if negative

    else if (f_channel[2].value > 5.0)
      f_channel[2].status = 2;          // Sets status = 2 if over 5.0 inches WC

    else
      f_channel[2].status = 1;          // Sets status = 1 if neither
```

Pay close attention to which lines are terminated with semicolon characters (;) and which are not. Every "action" statement ends with one, but the `if` conditional lines do not.

This next example takes multiple actions with each condition of the measurement. Note the use of curly-brace characters to encompass all the statements executed for a given condition, which were not needed when there was only one statement executed per "if" condition:

```c
    if (f_channel[2].value < 0.0 || f_channel[2].value > 5.0)
    {
      f_channel[2].status = 0;                  // Sets status = 0 if out of range
      f_channel[2].comment = "Out of range";   // Sets comment too
    }

    else
    {
      f_channel[2].status = 1;                  // Sets status = 1 if range is good
      f_channel[2].comment = "Range okay";     // Sets comment too
    }
```

Again, it will be the instructor who decides what conditions shall trigger a different status value, and each student's task will be to implement that functionality in code.

As mentioned previously, additional channels will be assigned in the caSCADA system for the computation of flow rates from the scaled transmitter signals. The coding for these channels will be done by *team* effort rather than by *individual* students. Your instructor will assign each team a programming challenge for this flow computation channel, such as averaging multiple transmitter pressures, selecting one pressure from multiple pressures, or capturing high or low values of flow.

These other channels will have no direct association with the analog inputs on the LabJack, but instead will get their data from the transmitter channels. Take for example this code for channel 5, which reads the scaled differential pressures from channels 1, 2, and 3 and averages them together before calculating flow using the formula $Q = k\sqrt{\Delta P}$:

```
/***********************************************************
Consult the "README.txt" file for help editing this function!
***********************************************************/

#include <stdio.h>
#include <math.h> // Necessary for any advanced math functions
#include "cascada.h" // Contains all the declarations specific to caSCADA

int
f_channel_05 (void)
{

  float average;
  float k = 34.6;

  average = (f_channel[1].value + f_channel[2].value + f_channel[3].value) / 3.0;
  f_channel[5].value = k * sqrt(average);
  f_channel[5].tag = "FY-101";
  f_channel[5].unit = "SCFM";
  f_channel[5].status = 1;
  f_channel[5].comment = "Air flow rate";

  return 1;
}
```

Note the introduction of two new floating-point variables: `average` which gets computed as the mathematical mean of the three transmitter channel values, and `k` which is set as the k factor in the $Q = k\sqrt{\Delta P}$ flow formula. These are not strictly necessary, for it is possible to consolidate all the arithmetic in a single statement where we compute `f_channel[5].value`. The result would function just the same:

```
f_channel[5].value = 34.6 * sqrt((f_channel[1].value + f_channel[2].value +
f_channel[3].value) / 3.0);
```

However, inserting these "local" variables into the channel function makes it easier for any human being reading the code to understand, in the same way that writing intermediate calculations on paper makes any long-winded computation easier to comprehend and therefore less liable to misinterpret.

It should be mentioned that variables declared inside a function (such as `average` and `k` shown in this example) are called *automatic* variables in the C programming language, which means they are usable to that function only: their values are discarded and forgotten after the function finishes executing. The next time that function is "called" by the main portion of the program, the variables `average` and `k` will no longer contain their previous values. This stands in contrast to *external* (also called *global*) variables which are defined outside of the function and retain their values whether the function is called or not. All `f_channel[]` variables in caSCADA, for example, are external which means they are accessible globally to functions within the caSCADA program.

If we have need for a variable within a function to retain its last value each time the function is called again, we may do so by making that function's variable *static*. Consider this example, where channel 5's function displays the *maximum* float rate seen:

```
/*********************************************************
Consult the "README.txt" file for help editing this function!
*********************************************************/

#include <stdio.h>
#include <math.h> // Necessary for any advanced math functions
#include "cascada.h" // Contains all the declarations specific to caSCADA

int
f_channel_05 (void)
{

  float average, flow;
  float k = 34.6;
  static float maxflow;

  average = (f_channel[1].value + f_channel[2].value + f_channel[3].value) / 3.0;

  flow = k * sqrt(average);

  if (flow > maxflow)          // Checks for a new (high) value for flow
    maxflow = flow;            // and updates maxflow if necessary

  f_channel[5].value = maxflow;
  f_channel[5].tag = "FY-101";
  f_channel[5].unit = "SCFM";
  f_channel[5].status = 1;
  f_channel[5].comment = "Maximum air flow rate";

  return 1;
}
```

Here we declare two new variables: another floating-point called `flow` and a *static* floating-point called `maxflow`. Both are accessible only to this function, but while `average` and `flow` are regular "automatic" variables, `maxflow` retains its previous value every time the function is called. Therefore it remembers its value from the last time that function executes. The "if" conditional updates `maxflow` any time the newly computed `flow` is seen to be greater in value.

The capabilities of caSCADA are limited only by the features available within the C programming language, which is to say *essentially limitless* given the requisite programming knowledge. Some of the mathematical functions available for your use in coding this flow-computation channel are listed here, some of which may become extremely useful when implementing the formula given to you by the electronic spreadsheet for your flow element:

Mathematical function	Explanation
pow(x,y)	calculates x^y
sqrt(x)	calculates $\sqrt{x}$
exp(x)	calculates e^y
log(x)	calculates $\ln x$
log10(x)	calculates $\log x$

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Consider an example where we need the value of caSCADA channel #5 to be set by the following formula, where x is the measured differential pressure from the median (i.e. *middle* value) of three redundant transmitter measurements and y is the computed flow rate:

$$y = 2.4x^2 - 0.83x^3$$

Comments (text preceded by double-slash symbols //) are included in this example to help explain what the code is doing:

```c
/***********************************************************
Consult the "README.txt" file for help editing this function!
***********************************************************/

#include <stdio.h>
#include <math.h> // Necessary for any advanced math functions
#include "cascada.h" // Contains all the declarations specific to caSCADA

int
f_channel_05 (void)
{

  float p1, p2, p3, median;     // Declares four floating-point variables

  p1 = f_channel[1].value;     // Assigns channel 1's value to variable p1
  p2 = f_channel[2].value;     // etc.
  p3 = f_channel[3].value;     // etc.

  if ((p1 >= p2 && p1 <= p3) || (p1 >= p3 && p1 <= p2) )   // Selects p1 as middle
    median = p1;

  if ((p2 >= p1 && p2 <= p3) || (p2 >= p3 && p2 <= p1) )   // Selects p2 as middle
    median = p2;

  if ((p3 >= p1 && p3 <= p2) || (p3 >= p2 && p3 <= p1) )   // Selects p3 as middle
    median = p3;

  f_channel[5].value = (2.4 * pow(median,2)) - (0.83 * pow(median,3));
  f_channel[5].tag = "FY-114";
  f_channel[5].unit = "GPM";
  f_channel[5].status = 1;
  f_channel[5].comment = "Water flow rate";

  return 1;
}
```

Note once again the use of "local" variables p1, p2, p3, and median to simplify the reading of this code. The "p" variables serve as aliases for the three pressure-measurement channel values, so that the "if" conditional expressions don't become cumbersome and hard to read (and therefore hard to identify problems within).

Note also that the else conditional is not strictly necessary in C programming. Three if conditionals in sequence work just fine for this purpose.

Common mistakes:

- Syntax errors resulting from incorrect characters added to the code, or necessary characters deleted from it. *Pay close attention to the color highlighting presented by the text editor (*`nano`*), as this often reveals such errors.*
- Failing to follow all steps of the programming development cycle (e.g. neglecting to recompile edited source code using the `make` command, failing to kill the old (running) version and re-start the new version).
- Running multiple instances of `poll` and/or `simulate` on the same RTU. This will cause conflicting data to be written and re-written to the `data.txt` file. The most common cause of this problem is when multiple students log in to the same caSCADA RTU and attempt to test their code simultaneously.
- Leaving a HART communicator connected to the transmitter's 4-20 mA circuit, which will result in the caSCADA system picking up on bursts of FSK data. This will make the signal appear to "jump" around.
- Not using ISA-standard tag names for each channel.

file i00490

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RTU component layout

An "RTU" is a *Remote Terminal Unit* in a SCADA system serving as the interface between field instruments and a central control/display unit called the "MTU" (*Master Terminal Unit*). In our caSCADA system, the MTU is just a laptop computer viewing data generated by the single-board Linux computer in each RTU. Each RTU uses a LabJack data acquisition unit to sense analog signals sent by field transmitters and a single-board computer to condition and present that data in the form of digital data files readable by the MTU. Communication takes place via a wireless access point (WAP) router:
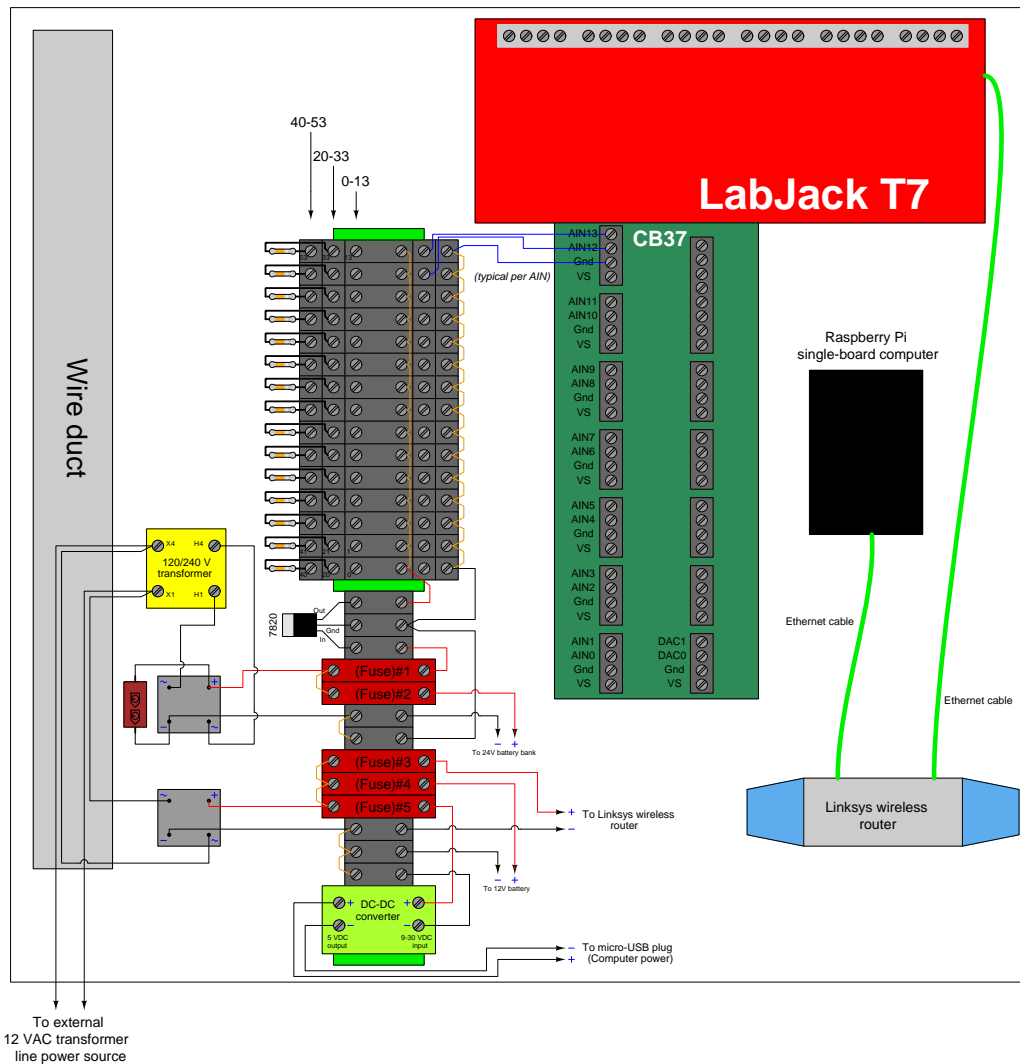
Each RTU enclosure is weatherproof, and equipped with a set of batteries to maintain DC power to all the system components in the event of an external AC power failure.

The upper level of terminals on the triple-level blocks should all be jumpered together because this is the 20 VDC "bus" used to power all field instruments. The lower level of terminals should also be jumpered together because they comprise the negative side ("Common" or "GND") of that same 20 VDC loop power supply.

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Sample loop diagrams

Generic loop diagram for LabJack T7 based caSCADA RTU
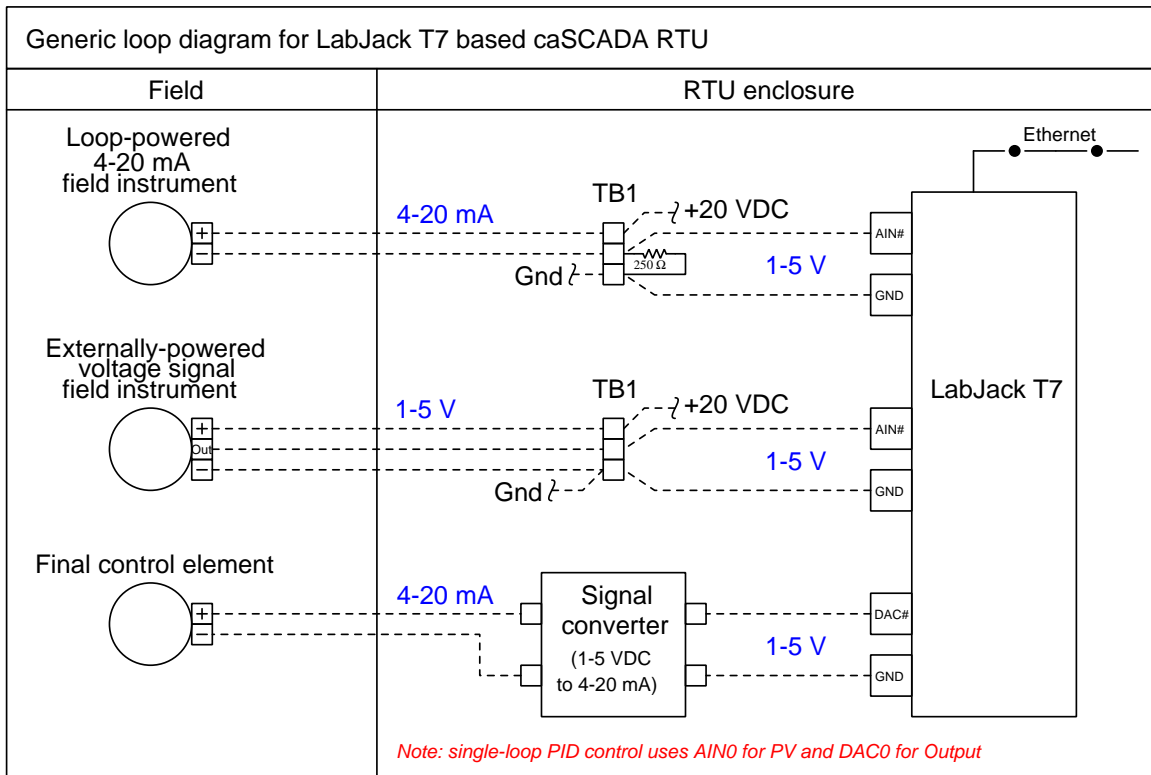
A set of triple-height terminal blocks marshall field instrument signals to the DAQ input terminals, with the three terminals of each block represented in the above diagram. The top-most terminal is the + DC power supply bus, the middle terminal connects to the LabJack DAQ input channel, and the bottom terminal is the − DC power (GND) supply bus. Both current-based and voltage-based instrument signals may be accepted by the DAQ. In the case of 4-20 mA loop instruments, a precision 250 Ω resistor is connected in such a way to provide a 1-5 VDC signal for the DAQ to sense. If the field instrument outputs a voltage signal instead (which is actually quite common for RTU loops in remote installations relying on solar power) then the resistor is omitted and the LabJack AIN directly reads that instrument's output voltage.

The LabJack DAQ also provides two analog *output* channels (DAC0 and DAC1) for analog control of a final control element. In a caSCADA system these output channels are connected to an external signal converter, and the resulting 4-20 mA output signal may be used to drive an I/P transducer, electronic valve positioner, or VFD.

When using a caSCADA system for PID loop control, the Process Variable (PV) input is input channel AIN0 and the Manipulated Variable output is output channel DAC0. The PID control application may be invoked by entering `./pid` at the command line.

Electrical power diagram
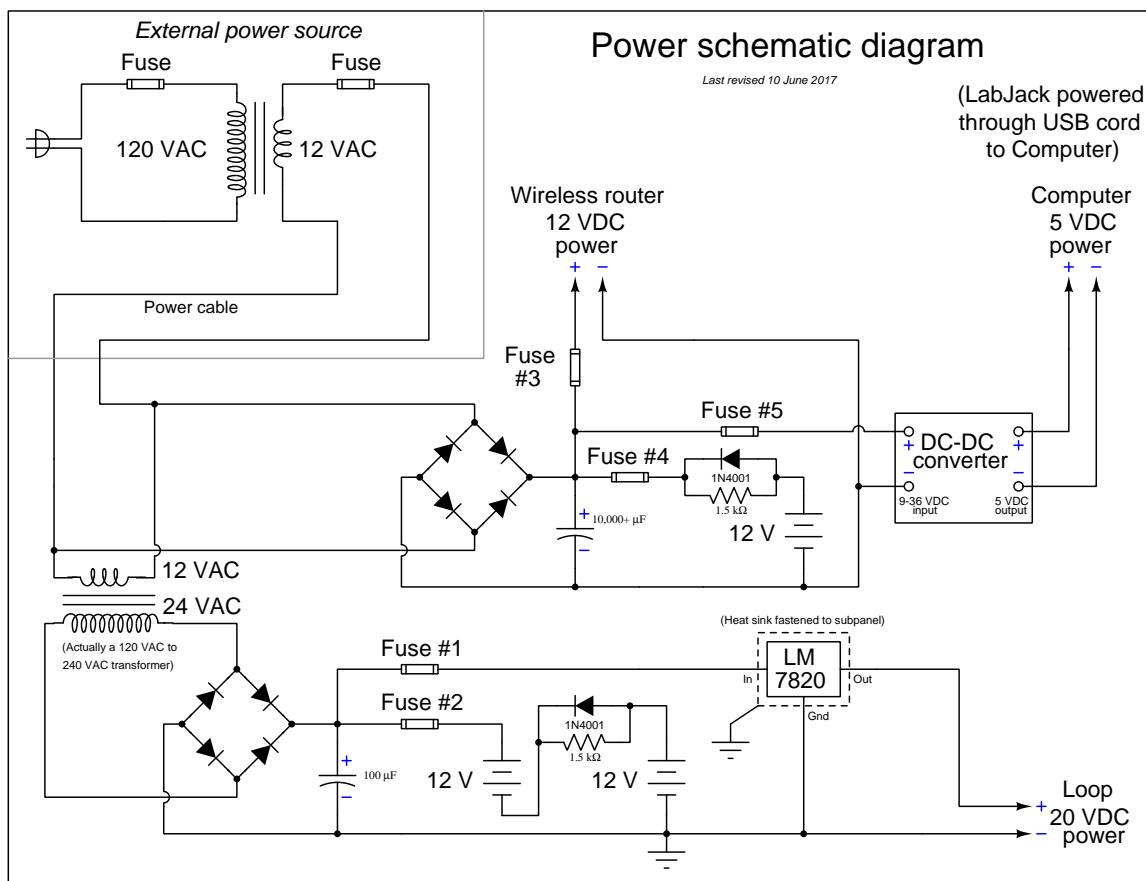
Power is sent to each RTU box at 12 volts AC, from a transformer located near a 120 VAC power source. This keeps the field power cable at a safe, low voltage (similar to outside sprinkler control systems and walkway lighting).

Internal to each RTU is a dual-voltage DC system: 12 volts (regulated down to 5 VDC) for running the Linux-based computer, LabJack DAQ, and Linksys WRT54GL wireless router; and 20 volts for powering the field instruments. Lead-acid batteries provide back-up power for the RTU to continue running in the event of a power outage. The resistor-diode network limits battery charging current to a bare minimum, while providing full current capacity in the discharge direction (in the event of an AC line power outage).

24 volts is a more customary DC supply voltage for loop-powered field instruments, but the LabJack model T7 DAQ has an absolute maximum input voltage of 20 VDC. Thus, the loop supply voltage is limited to this value to avoid the potential for damage to the LabJack in the event of a shorted instrument cable which would apply full power supply voltage to the DAQ input.

RTU power system testing procedure

You must follow this procedure when first commissioning a new RTU. When working with an existing RTU, you may follow the same procedure to test the continuing health of the DC power system.

(1) Test the external 12 VAC transformer by itself: when plugged into a 120 volt AC source, does it output at least 12 volts AC?

(2) Open up all fuses (#1 through #5) to ensure no device will become powered until you intend so.

(3) Connect this external 12 VAC transformer's output to the RTU as shown in the diagrams and apply power. Check the output of both bridge rectifiers for proper DC voltage magnitude and polarity. Due to the filter capacitors the DC voltage magnitudes will register greater than the AC voltage magnitudes feeding each of the bridge rectifiers.

(4) Ensure the batteries are wired to the proper terminal blocks and fuse holders, and measure DC voltage magnitudes and polarities at the battery-side of each open fuse. This ensures the batteries are properly connected.

(5) Close fuses #2 and #4. This connects the two battery banks to their respective charging sources. Re-measure the voltage magnitudes at the battery-side of each closed fuse. You should read slightly higher voltage now than in the previous step, because the batteries are charging.

(6) Ensure all power plugs are removed from the caSCADA electronic devices: the LabJack DAQ unit, the RTU computer, and the Linksys wireless router. Prepare to measure DC voltage at the ends of those power plugs.

(7) Close fuse #3 and measure DC voltage magnitude and polarity at the Linksys router's power plug. Check the router's documentation for the proper DC polarity of the plug's shell and tip to see that the polarity is correct. If all is well, plug the power cable into the router and check to see that it powers up. Re-measure voltage magnitude at fuse #3 to see that the router is receiving adequate voltage while powered (i.e. under load).

(8) Close fuse #5 and measure DC voltage magnitude and polarity at the RTU computer's micro-USB power plug. Check online for the "pinout" specification of a micro-USB power plug to see that the polarity is correct. If the pins on the micro-USB plug are too small to safely probe using your multimeter, you may check DC voltage at the stripped end of that cable where it lands at the terminal block, and verify correct voltage and polarity according to the colors of that cable's wires. If all is well, plug the power cable into the RTU computer and check to see that it powers up.

(9) Plug the B-style USB cable into the LabJack. It receives power through the RTU computer and should power up immediately. Re-measure voltage magnitude at fuse #5 to see that both the RTU computer and LabJack units are receiving adequate voltage while powered (i.e. under load).

(10) Close fuse #1 to apply 20 VDC power to the field instrument terminal blocks. Measure DC voltage magnitude and polarity between terminals 13 and 53 to ensure 20 VDC is supplied all the way to the end of the terminal block section.

(11) At this point in time you may initialize the caSCADA system MTU (a laptop PC) and test the system for proper data. A procedure for this is given on the following page.

(12) Unplug the external 12 VAC transformer from its line power source, and re-measure all DC supply voltages to ensure all devices are receiving adequate voltage under battery power alone.

(13) Repeat these DC voltage measurements at one-hour intervals to check the health of the batteries.

RTU data system testing

You must follow this procedure when first commissioning new devices for an RTU.

(1) Ensure that the proper IP addresses are all written on labels affixed to each of the networked devices in the RTU: the LabJack DAQ unit, the Linksys wireless router, and the single-board computer.

(2) Set the IP address and subnet mask of your personal computer to appropriate values for the Ethernet device you wish to connect to. For each octet of the subnet mask with the value "255" the octet of your PC's IP address must match the IP addresses of all devices in the RTU. For each octet of the subnet mask with the value of "0" the octet of your PC's IP address must be different from any device in the RTU. This will prepare your PC for direct Ethernet cable connection to the device you intend to configure.

(3) Plug your computer into the Linksys router using an Ethernet cable, and set the router's IP address and subnet mask and name using a web browser. Follow the instructions given in the manual for the router. The router's name should make sense to any user of the system. In an area with multiple RTUs, the name should be specific enough to clearly identify which RTU it is.

(4) Plug your computer into the LabJack DAQ using an Ethernet cable, and set the DAQ's IP address and subnet mask using the software provided by LabJack for this task. Follow the instructions given in the LabJack manual.

(5) Plug an HDMI monitor and USB keyboard into the single-board computer, and log in directly to set its IP address and subnet mask. To check its current settings, use the `ifconfig` command (similar to the `ipconfig` command in Microsoft Windows). If the settings are not correct, you may change them by editing the file `/etc/network/interfaces`. This requires "root" privileges. Lines of text in this `interfaces` file follow this pattern:
   - The line specifying the `eth0` interface must read `iface eth0 inet static`
   - Prior to the `eth0` line must be a line that reads `auto eth0`
   - The "address" line contains the IP address (e.g. `address 169.254.8.3`)
   - The "netmask" line contains the subnet mask (e.g. `netmask 255.255.0.0`)

(6) Unplug the Ethernet cable from your personal computer and wirelessly connect to the Linksys router. The router will automatically assign an appropriate IP address to your computer's wireless card, as routers are designed to do.

(7) Use the `ping` command in your computer to test network connectivity with each device in the RTU. This command is simply the word "ping" followed by the IP address of the device you wish to ping. For example, `ping 169.254.8.1` will test to see whether your computer has connectivity with the device bearing the IP address 169.254.8.1.

(8) Once all devices have been proven to ping successfully, you may use an SSH client program in your personal computer (e.g. `Bitvise`) to log into the RTU computer. The login account is simply `btc` with the password `btc`.

(9) Once you are logged in to the Linux operating system, you may try compiling the caSCADA code and then running it (either `poll` process or the `pid` process) to test its ability to communicate with the DAQ unit.

Preparing the "Raspberry Pi" single-board computer for use in the caSCADA system

To initially configuring a Raspberry Pi to be used in the caSCADA system, there are several things which must be done:

- Log in as the default user (name = `pi` and password = `raspberry`)

- Use the `sudo` and `passwd` commands to reset the root account's password to your liking (e.g. `sudo passwd root`). There are several tasks for which root privileges are necessary, so it's convenient to be able to log into the root account and do that work there, rather than have to preface all those commands typed under the `pi` login user with the "`sudo`" qualifier.

- Use the `raspi-config` utility to set the system's hostname, configure the keyboard for US mapping (as British "UK" mapping is the default!), and also enable the `ssh` server which will be essential for remote login and system administration.

- Add a new user account called `btc`.

- Feel free to edit the hidden file named `.profile` in the `/home/btc` directory with any special instructions to be executed at login. For example, you may add lines containing the `echo` shell command to print messages to the screen for the user once they log in (e.g. `echo "Welcome to the fish hatchery RTU"`).

- Set the current time and date using the `date` command. The format is MMDDhhmmCCYY. For example, 3:21 PM on November 5, 2016 would be set by issuing the command `date 110515212016`.

- Navigate to the `/etc/network` directory and edit the file named `interfaces` to set all the required IP address and netmask information to give the Raspberry Pi a static IP address for use in the caSCADA system. Lines of text in this `interfaces` file follow this pattern:
  - The line specifying the `eth0` interface must read `iface eth0 inet static`
  - Prior to the `eth0` line must be a line that reads `auto eth0`
  - The "address" line contains the IP address (e.g. `address 169.254.8.3`)
  - The "netmask" line contains the subnet mask (e.g. `netmask 255.255.255.0`)

- Install the `cascada.tar` archive file in the `/home/btc` directory, and then use the command `tar xvf cascada.tar` to unpack that archive file.

- Install the latest `libmodbus` library archive file in the `root` directory, then uncompress it (`gunzip libmodbus*.gz`) and unpack the archive (`tar xvf libmodbus*tar`) and then descend into the new `libmodbus` directory to build it. This library is absolutely necessary for caSCADA to run, as it contains all the code necessary to read and write Modbus device registers over a TCP/IP network. Build and install the new software using the commands `./configure ; make ; make install ; ldconfig`. Check the general header file repository (located in the directory `/usr/include/`) to see if the installation script successfully copied the file named `modbus.h` there. In the versions of `libmodbus` I've installed, I have had to copy the `modbus.h` file to the `/usr/include` directory manually.

- Install the latest `ncurses` library archive file in the `root` directory, then uncompress it (`gunzip ncurses*.gz`) and unpack the archive (`tar xvf ncurses*tar`) and then descend into the new `ncurses` directory to build it. This library is necessary to run the `lynx` web browser, as well as the graphic interface for the caSCADA `pid` controller process. Build and install the new software using the commands `./configure ; make ; make install ; ldconfig`.

- Install the latest `lynx` text-based web browser software archive file in the `root` directory, then uncompress it (`gunzip lynx*.gz`) and unpack the archive (`tar xvf lynx*tar`) and then descend into the new `lynx` directory to build it. Build and install the new software using the commands `./configure ; make ; make install ; ldconfig`.

- Navigate to the `/home/btc` directory and edit the file `cascada_poll.c` with the correct IP address to establish a Modbus/TCP connection with the LabJack DAQ unit in your RTU. The function establishing the address will be easy to find in this file, as it calls out the IP address in standard four-octet format. Just edit the IP address that's shown, and the caSCADA `poll` software will be able to communicate with that LabJack DAQ.

- Try running `make` in the `/home/btc` directory to verify all the caSCADA software components successfully compile.

file i02566

Loop Diagram: Furnace temperature control	Revised by: Mason Neilan	Date: April 1, 2007

Process area	Field panel JB-12	Control room panel CP-1

0-1500°F

TE 205

Yel

1 TT + Red
2 205 − Blk

Red

0-1500°F

TB-15

Red Wht/Blu
3
4
Blk Blu

Cable TT-205

Cable 3, Pr 1

TB-11

Wht/Blu Red
1
2
Blu Blk

Cable TT-205

Red
7
Blk
22 TIC
21 205
Red
19
Blk
18

TY 205a

TB-15

Red Wht/Org
5
6
Blk Org

I/P

Out TY + Red
205b − Blk

S

Tube TV-205

TV 205

Cable TY-205b

Cable 3, Pr 2

TB-11

Wht/Org Red
3
4
Org Blk

Cable TY-205b

Blk
H
Wht
N

AS 20 PSI
Valve #15
Column #8

ES 120 VAC
Breaker #4
Panel L2

Tag #	Description	Manufacturer	Model	Input range	Output range	Notes
TE-205	Thermocouple	Omega			Type K	Ungrounded tip
TT-205	Temperature transmitter	Rosemount	444	0-1500° F	4-20 mA	Upscale burnout
TY-205a	Resistor	Vishay			250 Ω	
TIC-205	Controller	Siemens	PAC 353	1-5 V	0-1500° F	Reverse-acting control
TY-205b	I/P transducer	Fisher	546	4-20 mA	3-15 PSI	
TV-205	Control valve	Fisher	Easy-E	3-15 PSI	0-100%	Fail-closed

Loop Diagram: Blue team pressure loop		Revised by: Duncan D.V.	Date: April 1, 2009

Field process area	Field panel JB-25	DCS cabinet

0-50 PSI

H
L
PT 73
+ Red
− Blk

Cable PT-73

TB-52
Red 1 Red
Blk 2 Blk

Cable 4, Pr 1

TB-80
Red 11 Red
Blk 12 Blk

Cable PT-73

Red 11 Red
Blk 12 Blk

Card 4
Channel 6
Analog input

0-50 PSI

PIC 73

Tube PV-73

PV 73

I/P
O
PY 73
+ Red
−
S
Blk

AS 20 PSI

Cable PV-73

TB-52
Red 15 Red
Blk 16 Blk

Cable 4, Pr 8

TB-80
Red 29 Red
Blk 30 Blk

Cable PV-73

Red 11 Red
Blk 12 Blk

Card 6
Channel 6
Analog output

Tag #	Description	Manufacturer	Model	Input range	Output range	Notes
PT-73	Pressure transmitter	Rosemount	3051CD	0-50 PSI	4-20 mA	
PIC-73	Controller	Emerson	DeltaV	4-20 mA	4-20 mA	HART-enabled input, Direct-acting control
PY-73	I/P transducer	Fisher	846	4-20 mA	3-15 PSI	
PV-73	Control valve	Fisher	Vee-ball	3-15 PSI	0-100%	Fail-open

Loop Diagram: Sludge tank level control	Revised by: I. Leaky		Date: April 1, 2008

Process area	Bulkhead panel B-104	Control panel CP-11

Tube LT-24a   14   Tube LT-24b

H   L   LT 24   Out   In

(vent)

A.S. 21 PSI

LV 24   Tube LV-24

Tube LV-24   Tube LV-24

C   LIC 24   D   Supply

A.S. 21 PSI

Tag #	Description	Manufacturer	Model	Input range	Output range	Notes
LT-24	Level transmitter	Foxboro	13A	25-150 "H_2O	3-15 PSI	
LIC-24	Controller	Foxboro	130	3-15 PSI	3-15 PSI	
LV-24	Control valve	Fisher	Easy-E / 667	3-15 PSI	0-100%	Fail closed

Sample Loop Diagram (using PLC, with electronic positioner installed on valve)

Loop Diagram: Unit feed flow control	Revised by: A. Bradley	Date: April 1, 2013

Process area | **Field panel FP-25**

FT 18 — H / L — + (Red) / − (Blk) — 0-75 GPM

Cable FT-18

21 (Blu) / 22 (Blu) — 10 [800 mA] — Blu

PS-1 — 24 VDC 1 amp — 120 VAC — L1 / N — Blk / Wht / Grn

1762-IF4 analog input card expansion slot 1 — IN0+, IN0-, IN1+, IN1-, IN2+, IN2-, IN3+, IN3-

P — A — Loop + (Red) / Loop − (Blk) — Supply — IAS 20 PSI

Cable FV-18

11 (Blu) / 12 (Blu)

1762-OF4 analog output card expansion slot 2 — I out 0, I out 1, I out 2, I out 3, V out 0, V out 1, V out 2, V out 3, Com, Com

FV 18

FC 18 — L2/N / L1

FIR 18 — (Located in main control room) — Ethernet

ES 120 VAC From field panel disconnect — 1A / 1A — 1, 2, 3, 4 — Blk / Wht / Grn

Tag number	Description	Manufacturer	Model	Calibration	Notes
FT-18	Flow transmitter	Rosemount	3051S	0-100" WC input 4-20 mA output	Square-root characterization
FC-18	PLC	Allen-Bradley	ML1100	1762-IF4 input 4-20 mA 1762-OF4 output 4-20 mA	IP = 169.254.10.9 Mask = 255.255.0.0
FIR-18	HMI touch-panel	AutomationDirect	C-More		
FV-18	Flow valve with positioner	Fisher	ED / 667 DVC6010	4 mA = fully closed 20 mA = fully open	Fail-closed

Lab Exercise – loop diagram and system inspection

Each team's system will undergo an inspection simulaneous with inspection of each team member's loop diagram. Team members will exchange diagrams with each other and then verify from those diagrams what the instructor sees when inspecting each and every panel and connection. *Please note that the "Lessons In Industrial Instrumentation" textbook describes good practices for construction and documentation.*

Construction Standards

- All construction must be *safe* (i.e. must not pose any unnecessary hazard to students or visitors). This includes electrical, chemical, thermal, pressure, and general safety hazards (e.g. trip hazards, cut hazards). *Unsafe construction will be dismantled upon discovery.*
- All electrical sources greater than 30 volts must be overcurrent-protected and all related wire connections must be guarded against accidental contact (e.g. use recessed terminals with no exposed metal).
- Proper use of colors for electrical power source wiring (e.g. red and black for DC + and −, black and white for AC "hot" and "neutral", green for earth ground).
- All metallic electrical enclosures must be bonded to earth ground for safety.
- Proper wire types and attachment to terminals (e.g. appropriate wire gauge for the expected current, use of stranded wire wherever possible, correct terminals crimped to ends of wires, no stray wire strands at any point).
- Attached wires must withstand being lightly pulled with fingers.
- Wire insulation must be intact (i.e. no bare wires anywhere).
- Panel wiring must be neat in appearance (e.g. all cables run directly from terminal block to nearest wire duct, with all excess wire length tucked inside wire duct).
- Wiring outside of panels should be run through conduit wherever possible.
- Correct tools must be used at all times. This includes the use of fixed-size wrenches rather than adjustable wrenches whenever possible, box-end over open-end wrenches whenever possible, and the correct type and size of screwdriver used to turn screw heads.
- All electrical components must be located to avoid exposure to liquids.
- All tube and pipe connections must be properly made (e.g. correct "swaging" of tube ends, no over- or under-tightened fittings, Teflon tape or pipe sealant used on all NPT threads).
- All manual controls (e.g. buttons, handles, knobs) must be accessible and function without undue effort.

Documentation Standards

- Loop diagrams must be drawn in accordance with ISA standard 5.1.
- Each instrument must have an appropriate ISA-standard tag name, and this tag name must be visible on the actual instrument (e.g. written on masking tape and attached to the instrument).
- Each signal cable and each signal tube must have an identifying label documented and attached. Long cables must be labeled at each end, as close to the termination points as practical.
- Each team must have its own unique loop number.
- Each instrument's (final) calibrated range must be shown.
- Each control valve's fail mode (e.g. fail-open, fail-closed) or action must be shown.
- All writing must be legible (i.e. easy for anyone to read). *Hint: large-format paper helps!*
- All instrument symbols must be appropriate to the device, function, and location. The large white-colored control panel and the DCS operator stations constitute the *main control room*. All electrical enclosures in the lab room are *auxiliary* locations, and everything else is considered a *field* location.
- Instrument functions shared within a common device must be represented by the "shared" symbol on the diagram (e.g. a controller that is part of a multi-loop control system such as a DCS). Shared controllers must have their identifying loop noted on the diagram (e.g. DCS South Loop #23).
- Any controller I/O cards must be labeled with slot number and channel number in addition to terminal numbers.

- Each location (e.g. field, junction box, control room) must be clearly delineated with vertical seperation lines on the diagram.
- Each diagram must be sufficiently detailed so that no other student will have difficulty locating components (e.g. *"Where is the controller for this loop?"*) or determining important configuration parameters (e.g. range settings).

Sample diagrams are provided in this worksheet (immediately following the lab exercise documentation), and each student is urged to use these sample diagrams as references when drafting their own. The "Lessons In Industrial Instrumentation" textbook also describes ISA-standard documentation practices.

Common mistakes:

- Incorrect tag name format, using letters that do not conform to the ISA 5.1 standard (e.g. including "PLC" or "DCS" in a controller's tag name).
- Forgetting that every instrument's tag name in a loop must begin with the same letter, and that this first letter represents the process variable being measured/controlled.
- Forgetting to label all field instruments with their own tag names (e.g. AT-83).
- Failing to label termination points (e.g. terminal block screws) *exactly* as they are labeled in real life.
- Poor use of space on the diagram paper, causing some portions of the diagram to become "crowded" rather than all components being evenly spaced. *Hint: begin your diagram by sketching the field instrument at the far left of the paper and the control room instrument at the far right of the paper, then draw all other instruments and connections in between!*
- Forgetting to label all signal wires (see example loop diagrams).
- Forgetting to note all wire colors.
- Forgetting to put your name on the loop diagram!
- Leaving junction box cables outside of wire duct, looking messy.
- Leaving wire duct covers off.
- Basing your diagram off of a team-mate's diagram, rather than closely inspecting the system for yourself.
- Not placing loop sheet instruments in the correct orientation (field instruments on the left, control room instruments on the right).

Creating and inspecting accurate loop diagrams should take no more than one full lab session (3 hours) if the team is working efficiently!

file i00654

Answer 1

Answer 2

Partial answer:

The amount of time required to accumulate 525,000 pulses (on a digital counter circuit) give a steady flow rate of 170 SCFM = **1 hour, 23 minutes**

Answer 3

Answer 4

Answer 5

Partial answer:

The total amount of fuel consumed by the boiler after a digital counter circuit records 800,000 pulses = **77,339.5 gallons**

Answer 6

Answer 7

Answer 8

Partial answer:

The pulse frequency given a flow rate of 310 cubic feet per minute = **1.932 Hz**

Viscosity is of no concern with a positive-displacement flowmeter!

Answer 9

Answer 10

- **Advantages of turbine meters over orifice plates**
- Very high accuracy
- Linear output requires no square-root characterization
- Better rangeability due to linear response to flow

- **Advantages of orifice plates over turbine meters**
- Typically cheaper
- Cleanliness of flow stream not as critical
- Turbine may become bound if viscous or fibrous solids are present in the flow stream
- Less wear over time (no bearings to wear out)

Answer 11

Measured flow (GPM)	Pickup signal frequency (Hz)	Percent of output span (%)	Output signal (mA)
250	412.5	50	12
412	679.8	82.4	17.18
184.8	305	36.97	9.915
472.7	780	94.55	19.13
315	519.8	63	14.08
245	404.3	49	11.84
187.5	309.4	37.5	10
375	618.8	75	16

$$f = kQ$$

Where,
f = Frequency in Hertz (pulses per second)
k = Calibration factor in pulses per gallon
Q = Volumetric flow rate in gallons per second

$$f = \frac{kQ}{60}$$

Where,
f = Frequency in Hertz (pulses per second)
k = Calibration factor in pulses per gallon
Q = Volumetric flow rate in gallons per minute

Answer 12

The large pipe carries a greater volumetric rate of water flow than the small pipe.

Since the vortex shedding frequency is proportional to the fluid *velocity*, we know that the flow velocities in both cases must be the same (given identical bluff body geometries). However, since the larger pipe has a greater cross-sectional area, an identical velocity equates to a greater *volume* rate of water moving past the bluff body and sensor.

Answer 13

- **Advantages of vortex meters over orifice plates**
- Immune to changes in fluid density (and therefore temperature and pressure as well)
- Linear output requires no square-root characterization
- Better rangeability due to linear flow response (at least down to the "cut off" point)

- **Advantages of orifice plates over vortex meters**
- Cheaper for very large pipe sizes
- Orifice plates may be more tolerant of low-frequency pipe vibrations
- Some orifice plates may measure bidirectional flow
- Able to sense flow down to zero (vortex flowmeters will "cut off" at some low flow rate)

Low-flow cutoff is a problem unique to vortex flowmeters. At low flow rates, the Reynolds number drops below the turbulent threshold, at which point fluid viscosity prevents vortices from shedding. The vortex street simply ceases to exist at any flow rate below this critical point, meaning the flowmeter's output goes to zero at any flow rate below the cutoff point.

Answer 14

The Strouhal number (approximately equal to 0.17) is the ratio of a blunt object's width to the distance between successive fluid vortices spilling off of the side of that object.
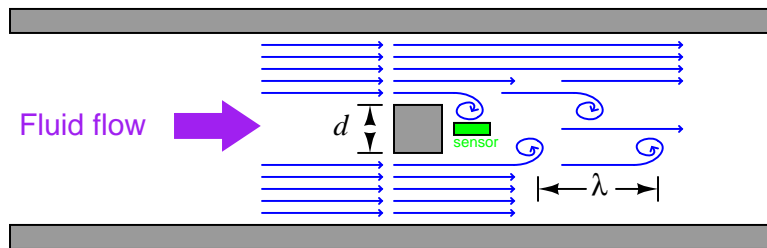
$$\frac{d}{\lambda} = 0.17$$

In essence, the Strouhal number tells us that the *wavelength* (λ) of vortex "waves" is always constant given a bluff body of constant width. Therefore, the frequency of these waves is directly proportional to the velocity of the fluid (and thus the volumetric flow rate in a pipe of constant cross-sectional area).

It should also be noted that wavelength (λ), wave velocity (v), and wave frequency (f) are related to each other by the following equation:

$$v = f\lambda$$

Dimensional analysis helps prove this is true:

$$\left[\frac{\text{meters}}{\text{second}}\right] = \left[\frac{\text{cycles}}{\text{second}}\right]\left[\frac{\text{meters}}{\text{cycle}}\right]$$

My choice to use "meters" here is arbitrary. The relationship is true regardless of length unit (feet, inches, centimeters, miles, cubits, whatever!).

Answer 15

$Q = 500.04$ GPM

We may derive an exact formula by using a *proportionality factor* (k) and the specific set of values used to answer the quantitative question. We know that flow rate will be proportional to the product of frequency, bluff body width, and the square of pipe diameter[1]:

$$Q \propto fwD^2$$

We may express this as an exact equation by adding a factor k:

$$Q = kfwD^2$$

Solving for k:

$$k = \frac{Q}{fwD^2}$$

$$k = \frac{500.04}{(4.167)(1)(10)^2} = 1.2$$

Therefore,

$$Q = 1.2fwD^2$$

Where,
Q = Flow rate, in gallons per minute (GPM)
f = Vortex shedding frequency, in Hertz (Hz)
w = Bluff body width, in inches (in)
D = Diameter of pipe, in inches (in)

One really neat advantage of calculating k in this manner is that it incorporates all the necessary unit conversions performed in the original solution of $Q = 500.04$ GPM. Now, all we do is enter f in Hertz, w in inches, and D in inches, and we automatically get an answer for Q in units of gallons per minute.

Answer 16

Positive displacement flowmeters of all types use mechanisms to move specific volumes of fluid through with each rotation or other mechanism cycle. Many positive displacement meters resemble pump mechanisms in design.

Because positive displacement meters move specified volumes of fluid through them per cycle, they are immune to changes in viscosity, density, and other fluid parameters. However, it must be understood that the quantity being measured is actual volume, not *standardized* volume units. In other words, a positive displacement gas flowmeter inherently measures in units such as cubic feet per minute (CFM), not standard cubic feet per minute (SCFM).

---

[1] Using qualitative analysis, we can tell that Q increases proportionally with increases in f and with increases in w. We can also tell that Q increases proportionally with the *square* of increases in D. Just imagine doubling each of these variables, one at a time (while holding the others constant) and determine the effect on Q.

Answer 17

A "prover" is a precision device used to measure a flow rate for a short period of time. Provers are typically of the piston-and-cylinder design, measuring flow rate by timing how long it takes the piston to travel a certain distance (i.e. displace a certain volume of fluid).

Periodic re-calibration of positive-displacement flowmeters is necessary because they all suffer from internal friction and mechanical wear.

Answer 18

Vortex meter and turbine meter both: 15 to 50 pipe diameters upstream; 5 pipe diameters downstream.

Answer 19

At 0% flow and 100% flow rates, the meter will indicate accurately. It will be very much in error at any point in between. At 50% true flow rate, for example, the meter will only indicate 25%, since the differential pressure drop generated by the orifice plate will only be that much at the half-flow rate.

Follow-up question: identify a way we may correct this system so that all the points along the indicator's scale accurately reflect flow rate through the orifice.

Answer 20

Answer 21

Answer 22

Answer 23

Answer 24

Partial answer:

Voltage = 27.99 millivolts

Answer 25

Answer 26

Answer 27

Answer 28

Answer 29

$$e = N\frac{d\Phi}{dt}$$

Where,

e = Instantaneous voltage induced in a wire coil

N = Number of turns of wire in the coil

$\frac{d\Phi}{dt}$ = Instantaneous rate of change of magnetic flux over time

$$e = Blv$$

Where,

e = Instantaneous voltage induced along a straight wire
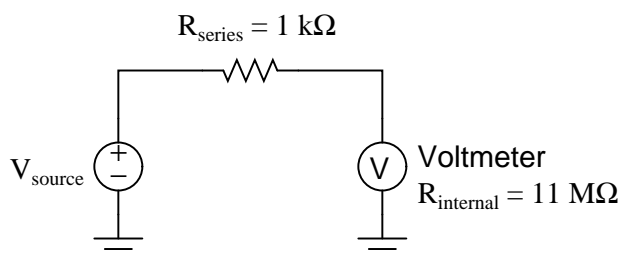
B = Magnetic flux density
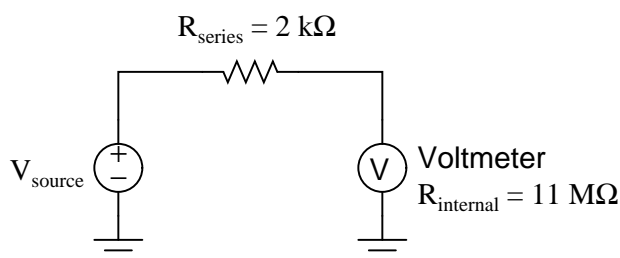
l = Length of wire

v = Velocity of wire

Answer 30

Answer to second question: most oils and concentrated alcohols have very low conductivity and thus cannot be measured by a magnetic flowmeter. Gases and vapors suffer the same problem.

In answer to the third question, I offer the following electrical "thought experiment." Consider the effect of doubling the series resistance in this circuit:

R$_{series}$ = 1 kΩ

V$_{source}$ Voltmeter

V   R$_{internal}$ = 11 MΩ

Does the voltmeter accurately measure V$_{source}$?

R$_{series}$ = 2 kΩ

V$_{source}$ Voltmeter

V   R$_{internal}$ = 11 MΩ

Does the voltmeter accurately measure V$_{source}$?

Answer 31

"AC" flowmeters indeed use alternating current to energize their field windings, but "DC" meters do not use steady direct current. Rather, "DC" flowmeters use *pulsed* magnetic fields, sometimes of consistent polarity and other times with reversing polarity (making them "alternating" after all!).

Dual-frequency magflow meters attempt to capitalize on the best features of both DC and AC techniques, by employing specialized pulse waveforms.

DC magflow meters enjoy good rejection of "noise" voltages, while AC magflow meters typically exhibit faster response times.

Answer 32

Since the output of a magnetic flowmeter is linear with regard to flow, there is no need for square root extraction, as indicated by the first "FY" device in the loop. Square-rooting the flow signal will only cause problems if there is no need to do so!

Answer 33

The time elapsed between the generation of an acoustic pulse and the reception of its echo (reflected off the solid object) is directly proportional to the distance between the pulse source and the object. *Velocity* is simply the first derivative of distance with respect to time ($v = \frac{dx}{dt}$).

Answer 34

Flow stream velocity may be measured via the use of sound waves transmitted and received through the liquid. One sonic technology, called *Doppler*, infers velocity by the change in sound frequency between the transmitted sound wave and the received sound wave.

Another sonic flowmeter technology, called *transit-time*, measures liquid velocity by measuring the difference between upstream and downstream velocities of sound waves transmitted through the fluid.

Doppler flowmeter calibration depends on the speed of sound through the process fluid. Transit-time flowmeter calibration does not. Ultrasonic flowmeters are not suitable for multiphase (vapor/liquid mixed) flows, and thus the pipe must be completely full of liquid (no gas pockets) or completely full of gas (no puddles or streams of liquid) in order to function properly.

Answer 35

Transit-time = clean flow streams ; Doppler = flow streams containing particulate and/or bubbles.

Answer 36

Why has the traditional recommendation for DP flow transmitter on steam lines been to locate the transmitter *below* the line? *Below-line mounting in steam service helps protect the transmitter against damage from high steam temperatures.*

What kind(s) of problem(s) are typically experienced with below-pipe mounting of DP flow transmitters in steam line applications? *Measurement errors at low DP values due to uneven water columns in "wet leg" impulse lines. The water in the wet impulse legs can also freeze in cold weather.*

Can DP flowmeters *always* be top-mounted? If not, what limitations dictate whether or not to top-mount? *Top-mounting is applicable only for certain limited temperature ranges. Otherwise, the pipe is simply too hot and the transmitter will be "cooked" to death.*

Why shouldn't Annubar-style flow elements be mounted *vertically* in a steam pipe, but rather should be canted at least 15 degrees from vertical? *To avoid measurement errors due to water running alongside the bottom of the steam line, impacting the lowest port on the Annubar element.*

Answer 37

Answer 38

Answer 39

Answer 40

Answer 41

Answer 42

Answer 43

Answer 44

Answer 45

Increased volumetric flow rate with constant density: the undulating motion of the tubes will *increase* in amplitude due to the greater inertial forces, but the resonant frequency of the tubes will *remain the same* because the tubes' mass has not changed.

Increased density with constant volumetric flow rate: the undulating motion of the tubes will *increase* in amplitude due to the greater inertial forces resulting from an increased mass flow rate, and the resonant frequency of the tubes will *decrease* due to increased tube mass.

Changes in fluid density at zero flow: there will be no undulating motion, because there will be no Coriolis force with zero flow. The tubes' resonant frequency, however, will vary inversely with fluid density. One practical caveat is that there will need to be *some* flow in order to push a new fluid of different density into the flowmeter's vibrating tubes, in order to sense that new density.

Answer 46

As flow increases, temperature decreases.

As incoming temperature increases, sensor temperature increases as well. This is interpreted to be *less* flow.

In order to compensate for the fluid's temperature entering the flowmeter and thus cancel any effects resulting from temperature change, we must have an unheated sensor that detects the fluid's "ambient" temperature.

Answer 47

Answer 48

Answer 49

Answer 50

Synchronous AC motors spin at a speed dictated by the frequency of the power line voltage (60 Hz in the United States) regardless of loading. The rotor of a synchronous AC motor is magnetically "locked" on to the rotating magnetic field produced by the stator windings.

As for explaining how the fluid's angular momentum relates to mass flow, I'll let you explore that concept by setting up a few "thought experiments" of different fluids and different flow rates.

Answer 51

Answer 52
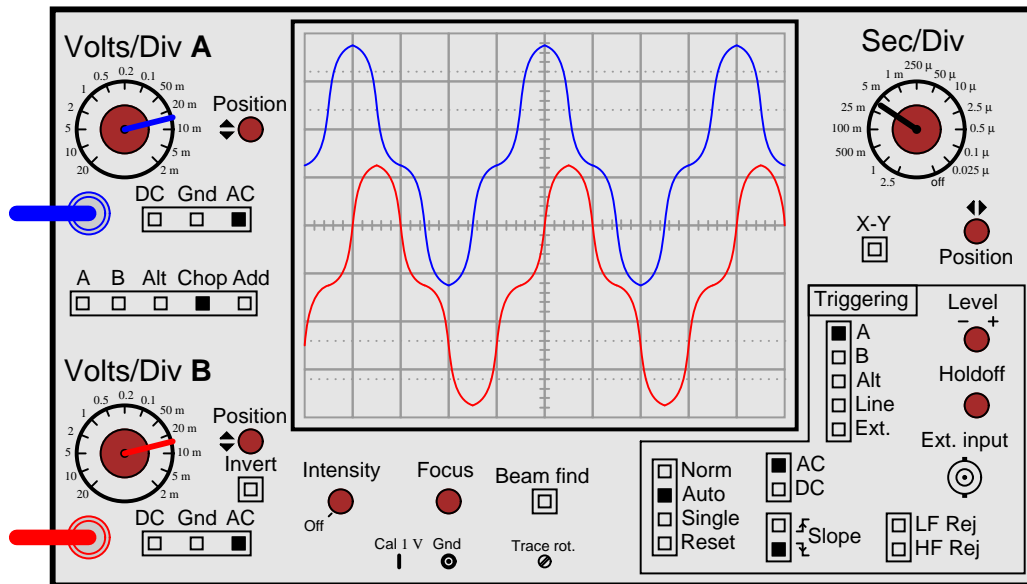
V_1 (peak) = 3 volts V_2 (peak) = 3.4 volts

$f = 100$ Hz $\theta = 72^o$

V_1 leads V_2 by $+72^o$. V_2 lags V_1 by -72°.

Answer 53

Advantages:

- Very high accuracy
- Immunity to upstream/downstream piping disturbances
- Provides real measurement of mass flow, fluid density, and fluid temperature
- Excellent rangeability
- Immunity to changes in density – this makes Coriolis flowmeters particularly well-suited for measuring non-Newtonian fluids
- Bidirectional

Disadvantages:

- Relatively low operating temperature limit ($< 800^o$ F)
- Difficulty measuring multi-phase flows (e.g. gas + liquid)
- Prohibitively expensive for large pipe sizes
- Cannot measure low-pressure gases very well (Coriolis forces too small)
- May suffer errors from external vibrations

Mass flow measurement is obtained by measuring the phase shift of the tube's oscillation between the two ends.

Density measurement is obtained by measuring the resonant frequency of the tubes. The basic equation for a mass-and-spring mechanical system is as follows:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

Where,

f_r = Resonant frequency
k = Spring constant
m = Mass

Given a known tube mass and a known tube volume, knowing the resonant frequency of the tubes makes it quite easy to calculate the mass of the fluid filling the tubes, and thus the fluid density.

Temperature measurement comes from an RTD sensing fluid temperature as it enters the tube assembly.

Answer 54

134

Answer 55

First, the proper location of the vapor flowmeter: between the knockout drum and the water-seal drum, or between the water-seal drum and the flare tip. Proper straight-pipe lengths should be observed in order to achieve best measurement accuracy.

- **Orifice plate/venturi/etc.** – Probably not suitable, due to the unknown density (ρ) of the vapors going through the pipe. If a gas density analyzer were added to the system, and its signal used along with absolute pressure and temperature compensation, accurate measurement of either volumetric or mass flow might be possible.

- **Positive displacement** – Probably not suitable, due to possible particulate matter in the gas stream, and rapid temperature changes. Most importantly, if this flowmeter ever jammed, it would "plug up" the flare and prevent its safe operation!

- **Turbine** – Possibly suitable. Pressure and temperature compensation would both be necessary to calculate true volumetric flow rate, however.

- **Vortex** – Probably not suitable, due to low-flow cutoff interfering with operation at low flare flow rates. Even if minimum flow could be ensured, pressure and temperature compensation would both be necessary to calculate true volumetric flow rate.

- **Magnetic** – Definitely unsuitable, due to non-conductivity of vapors in general.

- **Ultrasonic** (Doppler) – Definitely unsuitable, due to lack of objects in flow stream to reflect sound waves.

- **Ultrasonic** (transit time) – Possibly suitable. Pressure and temperature compensation would both be necessary to calculate true volumetric flow rate, however.

- **Coriolis** – Definitely suitable, but most likely too expensive to consider for this application.

- **Thermal mass** – Definitely unsuitable, due to the unknown and randomly changing specific heat of flare vapors.

Answer 56

Turndown refers to the ratio of minimum to maximum flow rate that may be accurately sensed by a particular flowmeter while remaining within acceptable limits of measurement error. Differential-pressure based flowmeters such as this venturi tube typically exhibit turndown ratios of only 4:1 (or sometimes worse) due to measurement uncertainties caused by uneven impulse line liquid heights, DP sensor calibration error, etc. The nonlinear nature of the flow/pressure relationship is the root of this problem.

- **Positive displacement** – Probably not suitable, due to possible particulate matter in the gas stream, and the high volume of flow expected. High volumes would require either a huge flowmeter, or would induce undue wear and tear in the fast-moving meter mechanism.

- **Turbine** – Possibly suitable. Pressure and temperature compensation would both be necessary to calculate true volumetric flow rate, however.

- **Vortex** – Possibly suitable, so long as the minimum flow rate exceeded the low-flow cutoff point for the flowmeter. If minimum flow could be ensured, pressure and temperature compensation would both be necessary to calculate true volumetric flow rate.

- **Magnetic** – Definitely unsuitable, due to non-conductivity of vapors in general.

- **Ultrasonic** (Doppler) – Definitely unsuitable, due to lack of objects in flow stream to reflect sound waves.

- **Ultrasonic** (transit time) – Possibly suitable. Pressure and temperature compensation would both be necessary to calculate true volumetric flow rate, however.

- **Coriolis** – Definitely suitable, but most likely too expensive to consider for this application.

- **Thermal mass** – Possibly suitable, so long as the specific heat of the natural gas was relatively stable over time. If not, compensation may be possible using a gas chromatograph to analyze the composition of the natural gas stream (gas chromatography is typically done anyway in the gas pipeline industry to determine the chemical heating value of the gas!).

Answer 57

- **FT-4 (influent to digester):** This is a magnetic flowmeter, which is a good choice for this application because it is non-restrictive, linear, and handles entrained solids with ease.

- **FT-9 (coolant flow from engine):** This is a vortex flowmeter, which is a good choice for this application because it is linear-responding and senses a flow rate that is unlikely to drop below the meter's low-flow cutoff point (because engine coolant flow is critically important and therefore will be at or near full flow at all times).

- **FT-10 and FT-18 (biogas flow):** These are thermal flowmeters, which is a good choice for this application because it is a technology yielding true mass flow rate (ideal for regulatory monitoring, for carbon credits), is linear, and is relatively inexpensive. The only potential problem in this application is the potential of the biogas composition to change with changes in biomass chemistry. Thermal mass flowmeters are dependent upon the fluid's specific heat value remaining constant (or at least known), and in this case changes in biogas composition may effect specific heat and therefore introduce errors.

- **FT-12 (effluent flow to de-watering):** This is another magnetic flowmeter, which is a good choice for this application because it is non-restrictive, linear, and handles entrained solids with ease.

Answer 58

Answer 59

Answer 60

Answer 61

Answer 62

Answer 63

Answer 64

$$Q = 3.367LH^{1.5} \qquad \text{Cippoletti weir}$$

Where,
Q = Volumetric flow rate (cubic feet per second – CFS)
L = Width of crest (feet)
H = Head (feet)

$H = 5$ inches $= \frac{5}{12}$ feet $= 0.4167$ feet

$$Q = (3.367)(4)(0.4167)^{1.5}$$

$Q = 3.622$ CFS

Now, converting 3.622 cubic feet per second into gallons per minute:

$$\left(\frac{3.622 \text{ ft}^3}{\text{sec}}\right) \left(\frac{60 \text{ sec}}{1 \text{ min}}\right) \left(\frac{12^3 \text{ in}^3}{1^3 \text{ ft}^3}\right) \left(\frac{1 \text{ gal}}{231 \text{ in}^3}\right)$$

$Q = 1625.8$ GPM

The location of the level-sensing element (3 feet upstream of the weir) is extraneous information, included for the purpose of challenging students to identify whether or not information is relevant to solving a particular problem.

Answer 65

$$Q = 4LH^{1.53} \qquad \text{1-foot to 8-foot wide throat Parshall flume}$$

Where,

Q = Volumetric flow rate (cubic feet per second – CFS)
L = Width of flume throat (feet)
H = Head (feet)

First, converting the given flow rate from units of GPM to units of cubic feet per second:

$$\left(\frac{5460 \text{ gal}}{\text{min}}\right)\left(\frac{1 \text{ min}}{60 \text{ sec}}\right)\left(\frac{231 \text{ in}^3}{1 \text{ gal}}\right)\left(\frac{1 \text{ ft}^3}{1728 \text{ in}^3}\right) = 12.165 \text{ CFS}$$

Now, manipulating the formula to solve for H:

$$Q = 4LH^{1.53}$$

$$\frac{Q}{4L} = H^{1.53}$$

$$H = \left(\frac{Q}{4L}\right)^{\frac{1}{1.53}}$$

$$H = \left(\frac{Q}{4L}\right)^{\frac{1}{1.53}}$$

$$H = \left(\frac{12.165}{(4)(6)}\right)^{\frac{1}{1.53}}$$

$$H = 0.6414 \text{ ft} = 7.697 \text{ in}$$

Answer 66

$$W = k\sqrt{\rho \Delta P}$$

For a mass flow rate of 970 pounds per minute at a differential pressure of 100 "WC and a flowing density of 1.33 pounds per cubic foot, the value of k will be 84.1097.

- Differential pressure at 700 lbm/min mass flow = **52.08 "W.C.**
- Differential pressure at 550 lbm/min mass flow and $\rho = 1.30$ lbm/ft^3 = **32.89 "W.C.**
- Mass flow rate at 90 "W.C. = **920.22 lbm/min**
- Mass flow rate at 43 "W.C. and $\rho = 1.35$ lbm/ft^3 = **640.84 lbm/min**

Since steam inside a boiler's steam drum is in direct contact with the boiling water, it is *saturated* and therefore its properties may be referenced in a saturated steam table. One of the parameters typically specified in a steam table is steam *density*, which is given to us in this problem (first at 1.33 lb/ft^3 and then later as 1.30 lb/ft^3 and 1.35 lb/ft^3. For all three of these density figures, the approximate temperature of the steam is 490 degrees Fahrenheit and the approximate pressure is 620 PSIA (605 PSIG).

A saturated steam table gives the enthalpy of 1.32 lb/ft^3 saturated steam as 1211 BTU/lb. The enthalpy of 160 ^{o}F water is of course 128 BTU/lb (160−32). The difference between the enthalpy of the steam entering the heat exchanger and the enthalpy of the water leaving the heat exchanger is the amount of heat (per pound) delivered to the heat exchanger, so:

$$1211 \text{ BTU/lb (entering)} - 128 \text{ BTU/lb (exiting)} = 1083 \text{ BTU/lb (delivered)}$$

Given the mass flow rate of 25 lb/min, this equates to the following heat rate:

$$\left(\frac{25 \text{ lb}}{\text{min}}\right)\left(\frac{1083 \text{ BTU}}{\text{lb}}\right) = 27075 \text{ BTU/min}$$

Answer 67

$$Q = k\sqrt{\Delta P}$$

At a volumetric flow rate of 40 barrels per hour and a corresponding differential pressure of 150 "WC, the value of k will be 3.266.

At a flow rate of 10 bbl/hr:

- Orifice plate ΔP = **9.375** " H$_2$O

- Differential pressure transmitter output signal = **3.75** PSI

- Square root extractor output signal = **6** PSI

- Flow indicator reading = **10** bbl/hr

At a flow rate of 31 bbl/hr:

- Orifice plate ΔP = **90.09** " H$_2$O

- Differential pressure transmitter output signal = **10.21** PSI

- Square root extractor output signal = **12.3** PSI

- Flow indicator reading = **31** bbl/hr

Answer 68

These flowmeter technologies will work:

- Coriolis *(may be programmed to output volumetric flow signal, inferred from mass flow rate and temperature)*
- Ultrasonic *(if using transit-time method)*
- Positive displacement

These flowmeter technologies will **not** work for this application:

- Magnetic *(liquid needs to conduct electricity)*
- Thermal *yields mass flow, not volumetric*
- Vortex (*depends on how low the low-flow cutoff is*)
- Pitot tube *insufficient rangeability (turndown)*
- Orifice plate *insufficient rangeability (turndown)*
- Pipe elbow *poor accuracy under any conditions, as well as insufficient rangeability*

Answer 69

These flowmeter technologies will work, because they do not require downstream flow conditioning:

- Coriolis
- Venturi tube
- Positive displacement

These flowmeter technologies will **not** work for this application because they require downstream flow conditioning:

- Magnetic
- Ultrasonic
- Vortex

Answer 70

The turbine will keep spinning at the same speed, being a direct function of fluid *velocity* past the turbine, and not fluid density.

The only time fluid density will make a difference for a turbine is if the turbine cannot spin freely. Fluid density directly impacts fluid momentum, which will affect the *impulse* of the fluid striking a resisting turbine blade. For normal turbine meter operation, however, the turbine spins very freely and so it does not "resist" the fluid passing by at all. Thus, density does not come into play.

A notable exception to this rule is the *twin-turbine* mass flowmeter design, which intentionally pits two turbines against one another by giving them different blade pitches, and coupling them through a spring to the same shaft. Here, differential torque is used as an indicator of fluid momentum, which is a direct function of *mass* flow rate.

Fault	Possible	Impossible
22 kΩ resistor failed open	√	
Unheated RTD failed open		√
Heated RTD failed open		√
Unheated RTD failed shorted		√
Heated RTD failed shorted		√
Transistor Q_1 failed shorted C-E		√
Transistor Q_2 failed shorted C-E		√
12 VDC source dead	√	

The 0 VDC measurement at the amplifier's output told you the microprocessor was correctly interpreting the signal, as 0 volts *should* cause it to register over-ranged flow. This is true since only under infinite flow conditions should both the heated and unheated RTDs be at the same temperature!

The next measurement between test points **C** and **B** is to see what signal the amplifier is getting from the RTDs. In other words, we're checking to see whether or not the amplifier has any differential signal to amplify. If so, we know the amplifier has a problem. If not (as is the case here), we know there is a problem somewhere in the current mirror / RTD network because we *do* expect to read a voltage here.

Answer 72

Note: All data obtained from the *Instrument Engineer's Handbook, Process Measurement and Analysis, Fourth Edition*, except where noted. Accuracy figures given here are conservative.

- **<u>Orifice plate</u>**

  - Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

  - Fluid type(s): *Gas or liquid.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *Up to 50 D upstream, 5 D downstream ; 12 D up and 5 D down typical.*

  - Reynolds number range: *10,000 or greater for concentric, square-edge orifice plates ; special orifices may work well at lower Reynolds number values.*

  - Typical accuracy (in percent of full-flow value): *+/- 0.5%*

  - Bidirectional flow measurement: *Yes, with square-edged orifice plate and symmetrical upstream/downstream tap locations such as flange or corner.*

  - Inherently measures true mass flow: *No.*

  - Special advantages: *Relatively inexpensive and applicable to a wide range of fluids.*

  - Special disadvantages: *Square-edged orifice plates are particularly sensitive to wear, making them unsuitable for abrasive flow measurement.*

- **<u>Venturi tube</u>**

  - Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

  - Fluid type(s): *Gas or liquid.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *Up to 26 D upstream, 2 D downstream ; 4 D up and 0 D down typical.*

  - Reynolds number range: *100,000 minimum.*

  - Typical accuracy (in percent of full-flow value): *+/- 0.75%*

  - Bidirectional flow measurement: *No.*

  - Inherently measures true mass flow: *No.*

  - Special advantages: *High pressure recovery.*

  - Special disadvantages: *Requires flowmeter spool – cannot sandwich between flanges or be inserted through a tap.*

- **<u>Pitot tube or Annubar</u>**

  - Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

  - Fluid type(s): *Gas or liquid.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *Up to 30 D upstream, 5 D downstream.*

  - Reynolds number range: *50,000 minimum.*

  - Typical accuracy (in percent of full-flow value): *+/- 5% typical ; +/- 1% possible with custom calibration.*

- Bidirectional flow measurement: *No.*

- Inherently measures true mass flow: *No.*

- Special advantages: *May be inserted into pipe through tap.*

- Special disadvantages: *Most pitot tubes sample flow profile at one point only, possibly leading to inaccurate measurements.*

- **Vortex**

  - Principle of operation: *Von Kármán effect of vortices produced alternately from a blunt object in the flow path.*

  - Fluid type(s): *Gas or liquid.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *Up to 50 D upstream, 5 D downstream ; 20 D up and 5 D down typical.*

  - Reynolds number range: *20,000 to 7,000,000 is where the Strouhal number remains constant at about 0.17.*

  - Typical accuracy (in percent of full-flow value): *+/- 2%*

  - Bidirectional flow measurement: *No.*

  - Inherently measures true mass flow: *No.*

  - Special advantages: *High pressure recovery, easy integration of fluid volume (counting pulses), insertable elements possible.*

  - Special disadvantages: *Pipe vibrations may fool the vortex detector.*

- **V-cone**

  - Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

  - Fluid type(s): *Gas or liquid.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *2 D up (!) and 5 D down typical.*

  - Reynolds number range: *8,000 minimum (according to manufacturer).*

  - Typical accuracy (in percent of full-flow value): *+/- 0.25% if two ΔP transmitters used.*

  - Bidirectional flow measurement: *No.*

  - Inherently measures true mass flow: *No.*

  - Special advantages: *Fewer upstream straight-pipe lengths required to condition flow compared to other head-based flow elements.*

  - Special disadvantages: *Requires flowmeter spool – cannot sandwich between flanges or be inserted through a tap.*

- **Segmental wedge**

  - Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

  - Fluid type(s): *Gas or liquid.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *10 to 30 D upstream (Source:* `http://www.flowmeterdirectory.com/flowmeter_artc/flowmeter_artc_02021404.html`*), and no downstream requirement specified. One manufacturer (ABB) claims that their wedge flow element requires "minimum upstream and downstream piping requirements" (Source:* `http://www.abb.com`*), whatever that means.*

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- Reynolds number range: *As low as 500 (!).*

- Typical accuracy (in percent of full-flow value): *+/- 5% typical ; +/- 0.75% possible with custom calibration.*

- Bidirectional flow measurement: *Yes.*

- Inherently measures true mass flow: *No.*

- Special advantages: *Well suited for viscous and slurry applications.*

- Special disadvantages: *Requires flowmeter spool – cannot sandwich between flanges or be inserted through a tap.*

- **<u>Magnetic</u>**

  - Principle of operation: *Electromagnetic induction, as a conductive fluid flows perpendicular to a magnetic field.*

  - Fluid type(s): *Liquids only, that are electrically conductive (1 μS/cm conductivity minimum).*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *Up to 5 D upstream, 3 D downstream ; 3 D up and 2 D down typical.*

  - Reynolds number range: *No minimum.*

  - Typical accuracy (in percent of full-flow value): *+/- 2% for AC ; +/- 1% for DC.*

  - Bidirectional flow measurement: *Yes.*

  - Inherently measures true mass flow: *No.*

  - Special advantages: *Obstructionless, work well with slurries.*

  - Special disadvantages: *Can be expensive for large pipe sizes, fouling of electrodes by insulating deposits such as minerals from "hard" water or oil residue may cause problems.*

- **<u>Coriolis</u>**

  - Principle of operation: *Inertial force of a fluid flowing in a rotating reference frame (the "Coriolis" force).*

  - Fluid type(s): *Either gas or liquid, although liquid is easier due to greater density.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *No special piping requirements.*

  - Reynolds number range: *No minimum.*

  - Typical accuracy (in percent of full-flow value): *+/- 0.1% (!)*

  - Bidirectional flow measurement: *Yes.*

  - Inherently measures true mass flow: *Yes!*

  - Special advantages: *High accuracy, offers fluid density and temperature measurements independent from mass flow measurement.*

  - Special disadvantages: *Sensitive to certain vibrations, cannot be used on temperatures above about 800° F, transmitter must be factory-matched to flow tube to be accurate.*

- **<u>Weir</u>**

  - Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

  - Fluid type(s): *Liquid in an open channel.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *No special piping requirements.*

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- Reynolds number range: *Liquid must be fairly low in viscosity.*

- Typical accuracy (in percent of full-flow value): *+/- 10%*

- Bidirectional flow measurement: *Theoretically possible, but seldom practiced.*

- Inherently measures true mass flow: *No.*

- Special advantages: *Simple and inexpensive.*

- Special disadvantages: *Suitable only for open-channel flow.*

- **Thermal**

  - Principle of operation: *Cooling of a heated element by fluid convection.*

  - Fluid type(s): *Gas or liquid.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *Up to 10 D upstream.*

  - Reynolds number range: *No minimum.*

  - Typical accuracy (in percent of full-flow value): *+/- 2%*

  - Bidirectional flow measurement: *Yes.*

  - Inherently measures true mass flow: *Yes!*

  - Special advantages: *Function better for low-flow gas streams than most other mass flowmeter technologies.*

  - Special disadvantages: *Usually practical only for low flow rates.*

- **Ultrasonic**

  - Principle of operation: *Time-of-flight for sound waves changing with fluid velocity, Doppler effect on reflected sound waves.*

  - Fluid type(s): *Gas or liquid.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *20 D upstream, 5 D downstream ; possibly more upstream if disturbances are severe.*

  - Reynolds number range: *No minimum, although meter calibration varies with Reynolds number.*

  - Typical accuracy (in percent of full-flow value): *+/- 1% for transit-time, +/- 5% for Doppler.*

  - Bidirectional flow measurement: *Yes.*

  - Inherently measures true mass flow: *No.*

  - Special advantages: *May be bolted to outside of pipe for non-intrusive flow measurement.*

  - Special disadvantages: *Sound waves may "ring around the pipe" without even going through the fluid, causing false readings.*

- **Turbine**

  - Principle of operation: *Windmill operation: fluid turns a bladed turbine at a speed dependent on the fluid's velocity.*

  - Fluid type(s): *Gas or liquid.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *Up to 50 D upstream, 5 D downstream ; 20 D up and 5 D down typical.*

  - Reynolds number range: *Liquid must be fairly low in viscosity, otherwise fluid drag on the turbine blades will affect low-flow accuracy.*

  - Typical accuracy (in percent of full-flow value): *+/- 1%*

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- Bidirectional flow measurement: *Yes.*

- Inherently measures true mass flow: *No.*

- Special advantages: *High accuracy and repeatability, easy integration of fluid volume (counting pulses).*

- Special disadvantages: *Moving parts will wear over time, can be damaged from overspeeding.*

- **Positive displacement**

  - Principle of operation: *Measuring precise volumes of fluid passing through with a positive-displacement mechanism.*

  - Fluid type(s): *Gas or liquid.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *No special piping requirements.*

  - Reynolds number range: *No minimum.*

  - Typical accuracy (in percent of full-flow value): *+/- 1% or better. Flow "provers" may attain extremely high accuracies.*

  - Bidirectional flow measurement: *Yes.*

  - Inherently measures true mass flow: *No.*

  - Special advantages: *Inherently totalizes (integrates) flow rate into a fluid volume quantity.*

  - Special disadvantages: *Greatest friction and mechanical wear of any flowmeter type.*

- **Rotameter**

  - Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

  - Fluid type(s): *Gas or liquid.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *No special piping requirements.*

  - Reynolds number range: *No minimum.*

  - Typical accuracy (in percent of full-flow value): *+/- 5%*

  - Bidirectional flow measurement: *No.*

  - Inherently measures true mass flow: *No.*

  - Special advantages: *Inexpensive, reads out directly for people to see.*

  - Special disadvantages: *Not suitable for very high pressures, due to need for transparent viewing tube; fluid must be fairly clear; limited to relatively low flow rates.*

- **Pipe elbow**

  - Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

  - Fluid type(s): *Gas or liquid.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *25 D upstream, 10 D downstream typical.*

  - Reynolds number range: *10,000 minimum.*

  - Typical accuracy (in percent of full-flow value): *+/- 10%*

  - Bidirectional flow measurement: *Yes, if taps at 45º position.*

  - Inherently measures true mass flow: *No.*

  - Special advantages: *Pipe elbow is already there – cheap!*

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- Special disadvantages: *Poor accuracy.*

- **Target**

  - Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

  - Fluid type(s): *Gas or liquid.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *10 to 30 D upstream (Source:* `http://www.geocities.com/ull_km1980/flowmeterselectionguide.html`*). Downstream = 10 D (Source:* `http://www.hersheymeasurement.com/specsheets/Target_Flow_Manual.pdf`*).*

  - Reynolds number range: *No minimum with proper calibration.*

  - Typical accuracy (in percent of full-flow value): *+/- 0.5% for standard, +/- 5% for insertion.*

  - Bidirectional flow measurement: *Theoretically possible, but seldom practiced.*

  - Inherently measures true mass flow: *No.*

  - Special advantages: *Insertion design is relatively easy to install in large pipes.*

  - Special disadvantages: *Difficult to calibrate.*

- **Flume**

  - Principle of operation: *Differential pressure caused by energy exchange between kinetic and potential forms.*

  - Fluid type(s): *Liquid in an open channel.*

  - Minimum straight-run piping lengths (in units of "pipe diameters"): *No special piping requirements.*

  - Reynolds number range: *Liquid must be fairly low in viscosity.*

  - Typical accuracy (in percent of full-flow value): *+/- 10%*

  - Bidirectional flow measurement: *No.*

  - Inherently measures true mass flow: *No.*

  - Special advantages: *Simple and inexpensive, no pockets for solids to collect in (unlike a weir).*

  - Special disadvantages: *Suitable only for open-channel flow.*

Answer 73

Water flow rate (ft^3/s)	Percent of flow span (%)	Depth that displacer is submerged (in)	Buoyant force (lb)
0	0	0	0
0.208	10	4.777	0.542
0.520	25	6.892	0.782
1.040	50	9.094	1.032
1.561	75	10.70	1.214
1.873	90	11.50	1.306
2.081	100	12	1.362

Answer 74

$Q = 431.3$ GPM (gallons per minute)

Answer 75

There is negligible effect on the flowmeter's calibration with changes in liquid conductivity.

A common misunderstanding with magnetic flowmeters is the relationship between liquid conductivity and magnetic flowmeter calibration. So long as the conductivity stays within the acceptable range for the meter, changes in conductivity have negligible effect on calibration. The flowmeter's voltage-measuring circuitry has such vastly greater impedance than the electrical path through the liquid, that any changes in liquid conductivity are "swamped" by the much greater input impedance of the meter.

Answer 76

If ρ increases without any change in v, the differential pressure ΔP will increase.

If ρ doubles, ΔP will double as well. However, we would actually need the ΔP to increase by a factor of *four (4)* in order to represent a doubling of flowrate, since the ΔP is customarily square-rooted to linearize the nonlinear behavior of the orifice plate. As it is, a doubling of fluid density will only cause the indicated flow rate to increase by a factor of $\sqrt{2}$. "Close, but no cigar," as the saying goes.
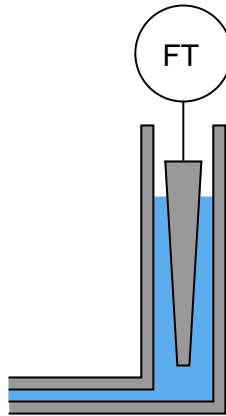
Answer 77

$$Q = k\sqrt{\Delta P}$$

At a volumetric flow rate of 200 liters per minute and a corresponding differential pressure of 100 "WC, the value of k will be 20.

At a flow rate of 78 LPM:

- Orifice plate ΔP = **15.21** " H_2O

- Differential pressure transmitter output signal = **10.24** mA

- Flow indicator reading = **78** LPM

At a flow rate of 120 LPM:

- Orifice plate ΔP = **36** " H_2O

- Differential pressure transmitter output signal = **13.6** mA

- Flow indicator reading = **120** LPM

Now, explain *why* the displacer must have this kind of shape, and not one of the other shapes! Hint: sketch a graph of the weir's flow/height transfer function.

Answer 79

- Loop current at 350 GPM = **9.091** mA
- Differential pressure at 600 GPM = **37.19** "WC

Answer 80

$$\text{Re} = \frac{(3160)G_f Q}{D\mu}$$

Where,
  Re = Reynolds number (unitless)
  G_f = Specific gravity of liquid (unitless)
  Q = Flow rate (gallons per minute)
  D = Diameter of pipe (inches)
  μ = Absolute viscosity of fluid (centipoise)
  3160 = Conversion factor for British units

Since the process fluid in question here is *water*, we know that both G_f and μ are equal to 1:

Solving for Q:

$$\text{Re} = \frac{(3160)G_f Q}{D\mu}$$

$$Q = \frac{(\text{Re})D\mu}{3160 G_f}$$

$$Q = \frac{(20000)(7.981)(1)}{(3160)(1)}$$

$$Q = \frac{(20000)(7.981)(1)}{(3160)(1)}$$

$$Q = 50.51 \text{ GPM}$$

Answer 81
  This is a graded question – no answers or hints given!

Answer 82
  This is a graded question – no answers or hints given!

Answer 83
  This is a graded question – no answers or hints given!

Answer 84
  This is a graded question – no answers or hints given!

Answer 85
  This is a graded question – no answers or hints given!

Answer 86
  This is a graded question – no answers or hints given!

Answer 87
  This is a graded question – no answers or hints given!

Answer 88

This is a graded question – no answers or hints given!

Answer 89

This is a graded question – no answers or hints given!

Answer 90

This is a graded question – no answers or hints given!

Answer 91

Answer 92

Answer 93

Your loop diagram will be validated when the instructor inspects the loop with you and the rest of your team.