The University of Melbourne

School of Engineering

Semester 2 Assessment 2012

ENGR30001 – Fluid Mechanics & Thermodynamics

Exam Duration: 3 hours

This paper has THIRTEEN (13) pages consisting of NINE (9) questions.

Authorized material:
Electronic calculators approved by the School of Engineering may be used.
Two Tables, one Chart and a Table of Formulae are attached.

Instructions to Invigilators:
Script books to be provided.

Instructions to Students:
All questions are to be attempted.
Full marks will be awarded for obtaining 100 marks of a potential 110 marks

THIS PAPER MUST NOT BE REMOVED FROM THE EXAMINATION ROOM

This paper is to be held by the Baillieu Library

Question 1

i) Sketch a T - v diagram for H_20 showing the liquid, saturation and superheated regions and at least one isobar passing through each of these regions. Indicate the region on the diagram where H_20 behaves as a perfect gas. **(3 marks)**

ii) What is the boiling point (saturation temperature) of water at an altitude of 11,000 ft where the atmospheric pressure is 94.3 kPa? **(1 mark)**

iii) Calculate the dryness fraction of a saturated mixture of H_20 at a temperature of 40°C and with a density of 800 kg/m^3. **(1 mark)**

iv) What is the pressure of the H_20 in part (iii) above? **(1 mark)**

v) Would H_20 in this state appear more like liquid or more like gas? **(1 mark)**

Find the density of water and/or steam at the following conditions using the Tables provided:

vi) $T = 75$ °C (dry saturated) **(2 marks)**

vii) $p = 2$ MPa, $T = 215$ °C **(2 marks)**

(Total for Question 1 = 11 marks)

QUESTION 2 IS ON THE NEXT PAGE

Question 2

i) The four types of systems considered in thermodynamics are open, closed, isolated and adiabatic. Explain the meaning of each of these systems. **(2 marks)**

ii) Calculate the specific volume of air at a gauge pressure of 101.3 kPa and temperature of 25°C. $\overline{R}$ = 287 J/(kg K) for air. Assume p_{atm} = 101.3 kPa.

(2 marks)

iii) Write down the Clausius statement and the Kelvin-Planck statement (two consequences of the second law). **(2 marks)**

iv) The Carnot engine is the most efficient engine possible. The efficiency of such an engine operating between a hot reservoir temperature, T_H, and a cold reservoir at temperature, T_C, is given by the equation:

$$\eta = 1 - \frac{T_C}{T_H}$$

An engine takes heat from a source at T_H = 400°C and dumps waste heat to a cold source at T_C = 25°C. The specific heat transfer from the hot source, q_H = 500 kJ/kg. Determine:

a. The magnitude of the specific work that can be output by the engine.
b. The specific heat transfer, q_C, to the cold reservoir.

(4 marks)

v) Consider a reversible heat exchanger transferring Q = 1000 J of energy from hot air passing over the heat exchanger to cold water flowing through the heat exchanger.

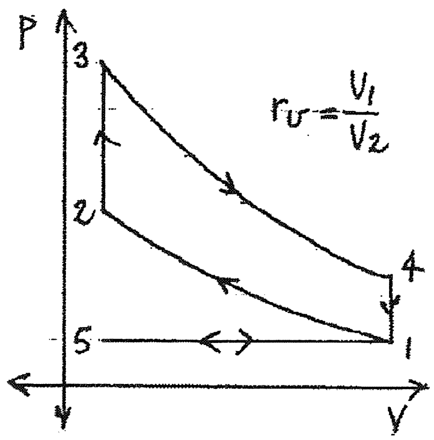
The hot air is initially at a temperature of T = 100°C and the cold water has a controlled temperature of T = 12°C. Calculate the entropy change of the hot air AND the entropy change of the cold water.

(2 marks)

(Total for Question 2 = 12 marks)

Question 3

The figure below shows a thermodynamic cycle.



i) Which of the cycles does this represent (Otto, Diesel, Joule/Barton, Rankine)?

(1 mark)

ii) Describe the processes 1-2, 2-3 and 3-4 (one sentence each). **(3 marks)**

iii) Derive the following equation for the thermal efficiency, η, of the above cycle from first principles:

$$\eta = \frac{W_{out}}{Q_{in}} = 1 - \frac{1}{r_v^{\gamma-1}}$$

(5 marks)

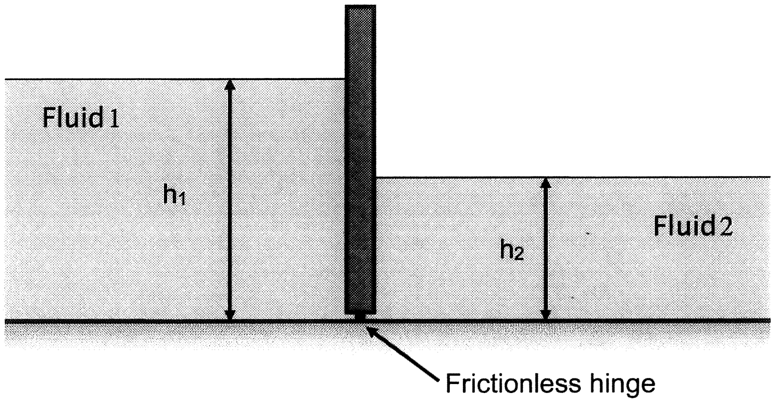
iv) Consider an engine running on the Otto cycle with a compression ratio of 25:1. If the volume at bottom dead centre, $V_1 = 7.9\times10^{-4}$ m^3, determine the volume in the cylinder at top dead centre (V_2).

The temperature of exhaust gas is measured as soon as the exhaust valve opens (T_4) and is 180°C. The mass of the gas in the cylinder is known to be 1 gram. Determine the maximum pressure in the cylinder. You may assume that $\gamma = 1.4$ and $\overline{R} = 0.287$ kJ/(kg K) for all gases at all times in the cylinder. **(3 marks)**

(Total for Question 3 = 12 marks)

Question 4

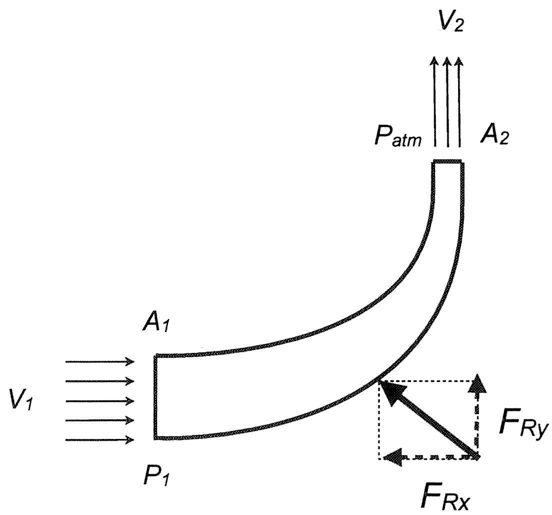
A hinged gate, as shown in the figure below, separates two fluids. Fluid 1 has density ρ_1 and Fluid 2 has density ρ_2. Derive an expression for the ratio h_1/h_2 in order for the gate to remain in the vertical position.



(Total for Question 4 = 10 marks)

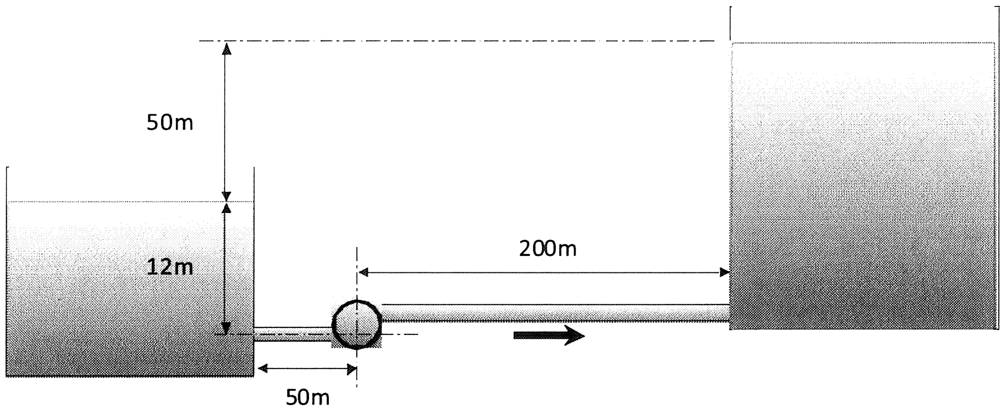
Question 5

Water of density 1000 kg/m^3 moves through a duct that turns through a 90^o bend and exits to atmosphere, as shown in the figure below. For V_1 = 5 m/s, P_1 = 10 kPa above atmospheric pressure, and A_1 = 0.1 m^2, calculate the horizontal component of the restraining force, F_{RX}, as shown in the figure.



(Total for Question 5 = 8 marks)

Question 6



Water of density 1000 kg/m^3 is pumped between two large reservoirs through a pipe that has an internal diameter of 150 mm and a roughness length of 0.6 mm. The tanks are open to the atmosphere where the atmospheric pressure is 101 kPa. Loss coefficients for minor losses are as follows

Minor Loss	Loss coefficient
Inlet loss	0.5
Exit loss	1.0

(a) Given that the pipe flow is in the fully rough regime, write an expression for the system head purely as a function of the volume flow rate Q. **(8 marks)**

(b) The manufacturer of the pump provides details of the performance of the pump, where the pump head (in m) as a function of volume flow rate (in m^3/s) is given by $h_p = 150 - 25Q^2$

Determine the volume flow rate at the operating point of the system. **(4 marks)**

(c) The required Net Positive Suction Head ($NPSH_R$) supplied by the pump manufacturer is 3 m. Determine whether the pump is within the permissible operating range at the operating point. The vapour pressure of water at the operating conditions is 2000 Pa. **(5 marks)**

(Total for Question 6 = 17 marks)

Question 7

The mechanical energy equation for horizontal, isothermal, ideal gas flow in a pipe of uniform cross-section is

$$\frac{P_2^2 - P_1^2}{2(RT/M)} + \left(\frac{G}{A}\right)^2 \ln\left(\frac{P_1}{P_2}\right) + \frac{2fL}{D}\left(\frac{G}{A}\right)^2 = 0$$

where all symbols have their usual meaning. Use this equation, simplified by ignoring the kinetic energy term, to solve the following problem:

Hydrogen gas flows isothermally at 25 °C from one vessel through a pipe of length 400 m to a second vessel which is at a pressure of 20 bar. The pressure at the pipe inlet is 25 bar. The Fanning friction factor $f = 0.005$

(a) Calculate the diameter of pipe required for a mass flow rate of 0.2 kg s^{-1}

(8 marks)

(b) Calculate the gas velocity at the exit of the pipe **(5 marks)**

(c) Consider the following statement: "For fixed P_1 and P_2, reducing the length of the pipe sufficiently can result in choked flow." Is this statement true or false?

(1 mark)

(d) Calculate the velocity at the pipe exit when the flow is choked. **(2 marks)**

Gram molecular weight of hydrogen	2
1bar	10^5 Pa
Gas constant R	8.314 J mol^{-1} K^{-1}

(Total for Question 7 = 16 marks)

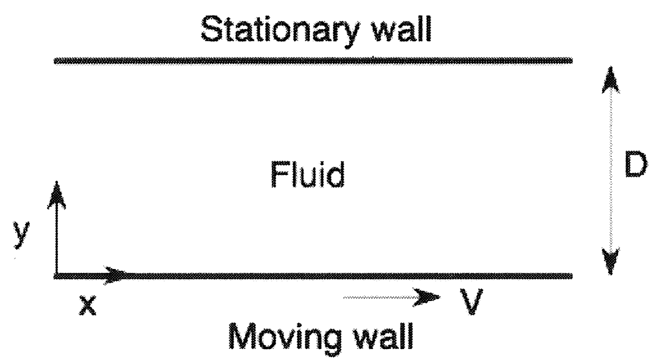
Question 8

Explain what is meant by (i) a Newtonian fluid, (ii) a shear thinning fluid, and (iii) a Bingham fluid. Make a correctly labeled sketch to illustrate. **(7 marks)**

(Total for Question 8 = 7 marks)

Question 9

An incompressible viscous Newtonian fluid fills a uniform channel of width D, as shown in the diagram. The lower wall is moving in the x-direction with velocity V, thus contributing to the motion of the fluid. In addition, a constant pressure gradient $\frac{\partial p}{\partial x}$ is applied, and this also helps drive the motion of the fluid. The resulting fluid flow is steady with velocity components $v_x(y)$, $v_y = 0$, $v_z = 0$. There is no dependence on the z-direction (not shown in the diagram) perpendicular to the page.



a) Find an expression for the fluid velocity $v_x(y)$. **(5 marks)**

b) Find the pressure gradient in terms of V and D for which the volumetric flow rate in the channel is zero **(5 marks)**

(Question 9 continues on next page)

Question 9 (continued)

c) Sketch the curve that relates $\frac{v_x}{V}$ and $\frac{y}{D}$ when the volumetric flow rate is zero. The sketch must show the values of $\frac{y}{D}$ and $\frac{v_x}{V}$ at the turning point and where the curve intersects the axes of the graph. **(7 marks)**

(Total for Question 9 = 17 marks)

(Total for paper = 110 marks)

Table 2, Temperature Saturation

Saturated Water & Steam

Temperatures from 1 to 120 °C

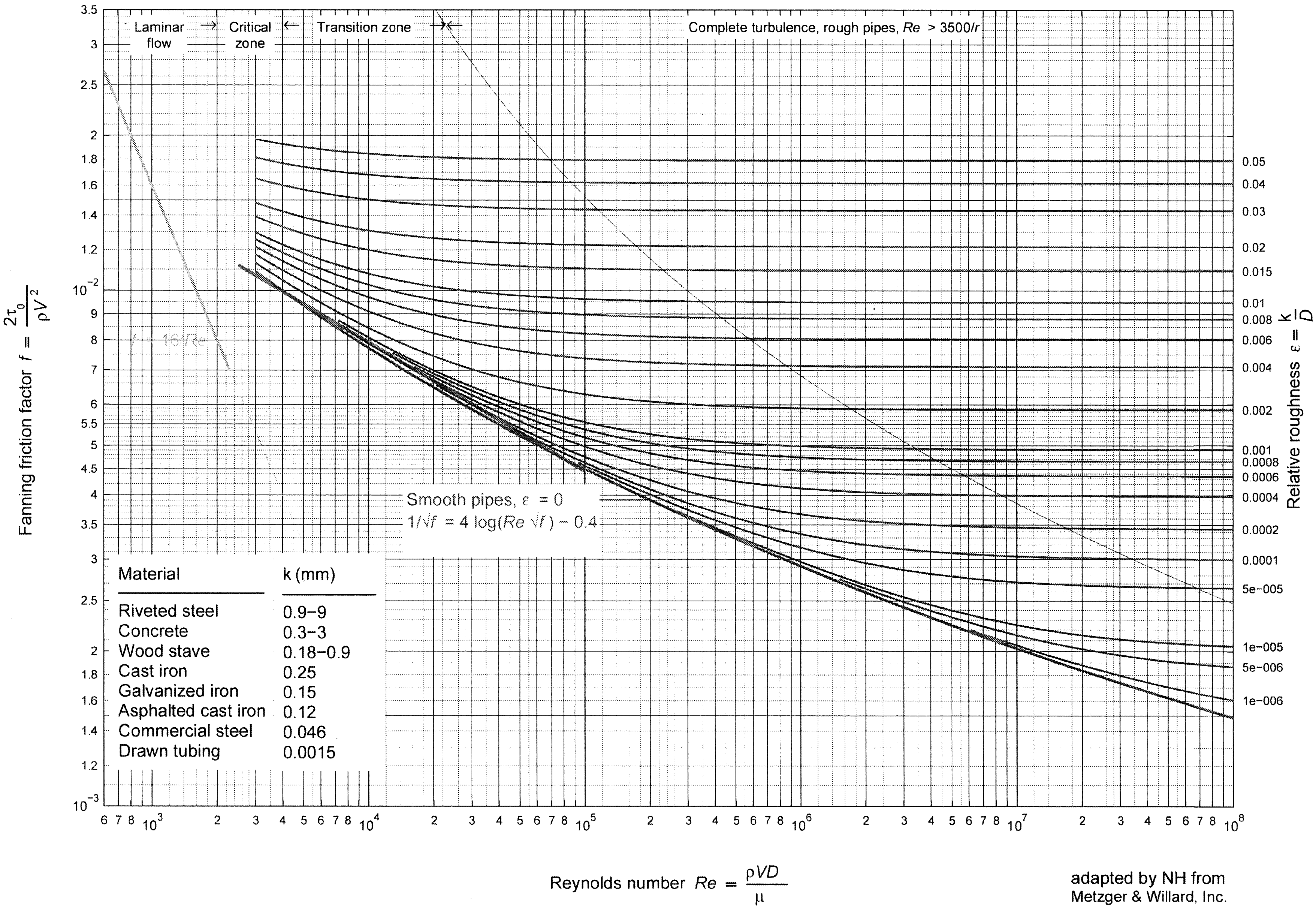
°C	kN/m^2	m^3/kg	m^3/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg K	kJ/kg K	kJ/kg K	°C
T	p	v_f	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	T
1	0.657	0.001000	192.6	4.174	2376.9	4.174	2499.2	2503.4	0.0153	9.116	9.131	1
2	0.705	0.001000	179.9	8.386	2378.3	8.387	2496.8	2505.2	0.0306	9.074	9.105	2
4	0.813	0.001000	157.3	16.80	2381.1	16.80	2492.1	2508.9	0.0611	8.992	9.053	4
6	0.935	0.001000	137.8	25.21	2383.8	25.21	2487.4	2512.6	0.0913	8.910	9.001	6
8	1.072	0.001000	121.0	33.60	2386.6	33.60	2482.6	2516.2	0.1213	8.830	8.951	8
10	1.227	0.001000	106.4	41.99	2389.3	41.99	2477.9	2519.9	0.1510	8.751	8.902	10
12	1.401	0.001000	93.84	50.38	2392.1	50.38	2473.2	2523.6	0.1805	8.673	8.854	12
14	1.597	0.001001	82.90	58.75	2394.8	58.75	2468.5	2527.2	0.2098	8.596	8.806	14
16	1.817	0.001001	73.38	67.12	2397.6	67.13	2463.8	2530.9	0.2388	8.521	8.759	16
18	2.062	0.001001	65.09	75.49	2400.3	75.50	2459.0	2534.5	0.2677	8.446	8.713	18
20	2.337	0.001002	57.84	83.86	2403.0	83.86	2454.3	2538.2	0.2963	8.372	8.668	20
22	2.642	0.001002	51.49	92.22	2405.8	92.23	2449.6	2541.8	0.3247	8.299	8.624	22
24	2.982	0.001003	45.93	100.6	2408.5	100.6	2444.9	2545.5	0.3530	8.228	8.581	24
26	3.360	0.001003	41.03	108.9	2411.2	108.9	2440.2	2549.1	0.3810	8.157	8.538	26
28	3.778	0.001004	36.73	117.3	2414.0	117.3	2435.4	2552.7	0.4088	8.087	8.496	28
30	4.241	0.001004	32.93	125.7	2416.7	125.7	2430.7	2556.4	0.4365	8.018	8.455	30
32	4.753	0.001005	29.57	134.0	2419.4	134.0	2425.9	2560.0	0.4640	7.950	8.414	32
34	5.318	0.001006	26.60	142.4	2422.1	142.4	2421.2	2563.6	0.4913	7.883	8.374	34
36	5.940	0.001006	23.97	150.7	2424.8	150.7	2416.4	2567.2	0.5184	7.816	8.335	36
38	6.624	0.001007	21.63	159.1	2427.5	159.1	2411.7	2570.8	0.5453	7.751	8.296	38
40	7.375	0.001008	19.55	167.4	2430.2	167.5	2406.9	2574.4	0.5721	7.686	8.258	40
42	8.198	0.001009	17.69	175.8	2432.9	175.8	2402.1	2577.9	0.5987	7.622	8.221	42
44	9.100	0.001009	16.04	184.2	2435.6	184.2	2397.3	2581.5	0.6252	7.559	8.184	44
46	10.09	0.001010	14.56	192.5	2438.3	192.5	2392.5	2585.1	0.6514	7.497	8.148	46
48	11.16	0.001011	13.23	200.9	2440.9	200.9	2387.7	2588.6	0.6776	7.435	8.113	48
50	12.34	0.001012	12.05	209.2	2443.6	209.3	2382.9	2592.2	0.7035	7.374	8.078	50
52	13.61	0.001013	10.98	217.6	2446.2	217.6	2378.1	2595.7	0.7293	7.314	8.043	52
54	15.00	0.001014	10.02	226.0	2448.9	226.0	2373.2	2599.2	0.7550	7.254	8.009	54
56	16.51	0.001015	9.159	234.3	2451.5	234.4	2368.4	2602.7	0.7804	7.195	7.976	56
58	18.15	0.001016	8.381	242.7	2454.1	242.7	2363.5	2606.2	0.8058	7.137	7.943	58
60	19.92	0.001017	7.679	251.1	2456.8	251.1	2358.6	2609.7	0.8310	7.080	7.911	60
62	21.84	0.001018	7.044	259.4	2459.4	259.5	2353.7	2613.2	0.8560	7.023	7.879	62
64	23.91	0.001019	6.469	267.8	2462.0	267.8	2348.8	2616.6	0.8809	6.967	7.848	64
66	26.15	0.001020	5.948	276.2	2464.5	276.2	2343.9	2620.1	0.9057	6.911	7.817	66
68	28.56	0.001022	5.476	284.6	2467.1	284.6	2338.9	2623.5	0.9303	6.856	7.786	68
70	31.16	0.001023	5.046	292.9	2469.7	293.0	2334.0	2626.9	0.9548	6.802	7.756	70
72	33.96	0.001024	4.656	301.3	2472.2	301.4	2329.0	2630.3	0.9792	6.748	7.727	72
74	36.96	0.001025	4.300	309.7	2474.8	309.7	2324.0	2633.7	1.003	6.695	7.698	74
76	40.19	0.001027	3.976	318.1	2477.3	318.1	2318.9	2637.1	1.027	6.642	7.669	76
78	43.65	0.001028	3.680	326.5	2479.8	326.5	2313.9	2640.4	1.051	6.590	7.641	78
80	47.36	0.001029	3.409	334.9	2482.3	334.9	2308.8	2643.8	1.075	6.538	7.613	80
82	51.33	0.001031	3.162	343.3	2484.8	343.3	2303.8	2647.1	1.099	6.487	7.586	82
84	55.57	0.001032	2.935	351.7	2487.3	351.7	2298.6	2650.4	1.123	6.436	7.559	84
86	60.11	0.001033	2.727	360.1	2489.7	360.1	2293.5	2653.6	1.146	6.386	7.532	86
88	64.95	0.001035	2.536	368.5	2492.2	368.5	2288.4	2656.9	1.169	6.336	7.506	88
90	70.11	0.001036	2.361	376.9	2494.6	376.9	2283.2	2660.1	1.193	6.287	7.480	90
92	75.61	0.001038	2.200	385.3	2497.0	385.4	2278.0	2663.4	1.216	6.239	7.454	92
94	81.46	0.001039	2.052	393.7	2499.4	393.8	2272.8	2666.6	1.239	6.190	7.429	94
96	87.69	0.001041	1.915	402.1	2501.8	402.2	2267.5	2669.7	1.261	6.143	7.404	96
98	94.30	0.001042	1.789	410.5	2504.1	410.6	2262.2	2672.9	1.284	6.095	7.380	98
100	101.3	0.001044	1.673	419.0	2506.5	419.1	2256.9	2676.0	1.307	6.049	7.355	100
105	120.8	0.001048	1.419	440.0	2512.3	440.2	2243.6	2683.7	1.363	5.933	7.296	105
110	143.3	0.001052	1.210	461.2	2518.0	461.3	2230.0	2691.3	1.418	5.820	7.239	110
115	169.1	0.001056	1.036	482.3	2523.5	482.5	2216.2	2698.7	1.473	5.710	7.183	115
120	198.5	0.001061	0.892	503.5	2529.0	503.7	2202.2	2706.0	1.528	5.602	7.129	120

MN/m^2

°C T \ p	0.001	0.01	0.02	0.05	0.1	0.5	1	2	4	6	8	10	15	20	25	30	35	40	45	50	60	80	100	T
0	999.8	999.8	999.8	999.8	999.8	1000	1000	1001	1002	1003	1004	1005	1007	1010	1012	1014	1017	1019	1022	1024	1028	1037	1046	0
5	999.9	999.8	999.8	999.8	999.8	1000	1000	1001	1002	1003	1004	1005	1007	1009	1012	1014	1016	1019	1021	1023	1028	1036	1044	5
10	0.00766	999.8	999.8	999.8	999.8	1000	1000	1001	1002	1003	1004	1004	1007	1009	1011	1014	1016	1018	1020	1022	1027	1035	1043	10
20	0.00739	998.3	998.3	998.3	998.3	998.5	998.7	999.2	1000	1001	1002	1003	1005	1007	1009	1012	1014	1016	1018	1020	1024	1032	1040	20
25	0.00727	997.0	997.0	997.0	997.0	997.2	997.4	997.9	998.8	999.7	1001	1001	1004	1006	1008	1010	1012	1014	1016	1018	1022	1030	1038	25
30	0.00715	995.7	995.7	995.7	995.8	995.9	996.2	996.6	997.5	998.4	999.2	1000	1002	1004	1007	1009	1011	1013	1015	1017	1021	1029	1036	30
40	0.00692	992.3	992.3	992.3	992.3	992.5	992.7	993.1	994.0	994.9	995.7	996.6	998.7	1001	1003	1005	1007	1009	1011	1013	1017	1025	1032	40
50	0.00671	0.0673	988.0	988.0	988.1	988.2	988.5	988.9	989.8	990.6	991.5	992.4	994.5	996.6	998.7	1001	1003	1005	1007	1009	1013	1020	1027	50
60	0.00651	0.0652	981.9	983.2	983.2	983.4	983.6	984.0	984.9	985.8	986.6	987.5	989.6	991.8	993.8	995.9	997.9	999.9	1002	1004	1008	1015	1023	60
70	0.00632	0.0633	0.1269	977.7	977.7	977.9	978.1	978.5	979.4	980.3	981.2	982.1	984.2	986.4	988.5	990.6	992.6	994.7	996.7	998.6	1003	1010	1017	70
80	0.00614	0.0615	0.1232	971.6	971.7	971.8	972.1	972.5	973.4	974.3	975.2	976.1	978.3	980.5	982.7	984.8	986.9	988.9	990.9	993.0	996.9	1005	1012	80
90	0.00597	0.0598	0.1197	0.301	965.1	965.3	965.5	966.0	966.9	967.9	968.8	969.7	972.0	974.2	976.4	978.5	980.7	982.8	984.8	986.9	990.9	998.7	1006	90
100	0.00581	0.0582	0.1165	0.293	0.590	958.3	958.6	959.0	960.0	960.9	961.9	962.8	965.1	967.4	969.7	971.9	974.1	976.2	978.3	980.4	984.5	992.5	1000	100
125	0.00544	0.0545	0.1091	0.274	0.550	938.8	939.1	939.6	940.6	941.7	942.7	943.7	946.2	948.7	951.1	953.5	955.9	958.2	960.4	962.7	967.0	975.5	983.5	125
150	0.00512	0.0512	0.1026	0.257	0.516	916.8	917.1	917.7	918.8	920.0	921.1	922.2	925.0	927.7	930.4	933.0	935.6	938.1	940.5	943.0	947.7	956.7	965.3	150
175	0.00484	0.0484	0.0968	0.243	0.487	2.504	892.1	892.8	894.1	895.4	896.7	898.0	901.1	904.2	907.2	910.1	912.9	915.7	918.4	921.1	926.3	936.2	945.5	175
200	0.00458	0.0458	0.0917	0.230	0.460	2.353	4.856	865.0	866.6	868.1	869.6	871.1	874.7	878.2	881.6	884.9	888.1	891.3	894.3	897.3	903.1	914.0	924.1	200
225	0.00435	0.0435	0.0871	0.218	0.437	2.223	4.554	9.643	835.1	837.0	838.8	840.6	844.9	849.0	853.0	856.9	860.6	864.3	867.8	871.2	877.7	889.9	901.1	225
250	0.00414	0.0414	0.0829	0.207	0.416	2.108	4.296	8.973	799.2	801.5	803.8	806.1	811.4	816.5	821.3	826.0	830.4	834.7	838.8	842.7	850.3	864.1	876.6	250
275	0.00395	0.0395	0.0791	0.198	0.396	2.006	4.073	8.429	18.34	759.3	762.2	765.2	772.3	778.9	785.1	790.9	796.4	801.6	806.6	811.3	820.2	836.2	850.4	275
300	0.00378	0.0378	0.0756	0.189	0.379	1.914	3.876	7.968	17.00	27.67	41.21	715.4	725.7	735.0	743.3	751.0	758.1	764.7	770.9	776.7	787.5	806.4	822.7	300
325	0.00362	0.0362	0.0725	0.181	0.363	1.830	3.700	7.569	15.94	25.42	36.54	50.40	663.6	679.0	691.8	703.0	712.9	721.8	729.9	737.5	751.0	773.9	792.9	325
350	0.00348	0.0348	0.0696	0.174	0.348	1.754	3.541	7.217	15.05	23.68	33.39	44.60	87.24	600.1	625.0	643.5	658.6	671.4	682.6	692.6	710.0	738.1	760.6	350
375	0.00334	0.0334	0.0669	0.167	0.335	1.685	3.396	6.902	14.29	22.29	31.04	40.76	72.04	132.0	488.7	555.4	586.5	608.5	625.9	640.4	664.2	699.7	726.5	375
400	0.00322	0.0322	0.0644	0.161	0.322	1.620	3.263	6.617	13.63	21.11	29.15	37.87	63.85	100.5	166.3	353.3	473.8	523.8	555.1	578.3	612.6	658.8	691.4	400
425	0.00310	0.0310	0.0621	0.155	0.311	1.561	3.141	6.357	13.04	20.09	27.57	35.55	58.37	87.21	127.0	189.3	292.3	390.6	455.0	497.2	551.1	613.6	653.9	425
450	0.00300	0.0300	0.0599	0.150	0.300	1.506	3.028	6.119	12.51	19.19	26.22	33.62	54.20	78.70	109.0	148.5	201.8	272.1	343.2	401.3	479.9	564.3	613.9	450
475	0.00290	0.0290	0.0579	0.145	0.290	1.455	2.923	5.900	12.02	18.39	25.03	31.97	50.87	72.54	97.92	128.3	165.4	210.5	262.9	315.9	403.9	510.8	571.2	475
500	0.00280	0.0280	0.0561	0.140	0.280	1.407	2.825	5.696	11.58	17.67	23.98	30.53	48.09	67.70	89.86	115.2	144.4	178.1	216.2	257.6	338.8	457.0	528.2	500
550	0.00263	0.0263	0.0527	0.132	0.263	1.320	2.649	5.331	10.80	16.41	22.17	28.09	43.65	60.43	78.61	98.37	119.9	143.2	168.5	195.6	253.3	361.8	445.3	550
600	0.00248	0.0248	0.0496	0.124	0.248	1.244	2.494	5.012	10.13	15.34	20.66	26.10	40.19	55.06	70.79	87.44	105.0	123.6	143.2	163.6	206.8	295.9	374.8	600
650	0.00235	0.0235	0.0469	0.117	0.235	1.176	2.356	4.731	9.537	14.42	19.38	24.41	37.36	50.83	64.87	79.48	94.68	110.5	126.8	143.7	178.7	251.6	322.0	650
700	0.00223	0.0223	0.0445	0.111	0.223	1.115	2.233	4.481	9.017	13.61	18.26	22.96	34.98	47.37	60.13	73.28	86.80	100.7	115.0	129.5	159.5	221.3	282.8	700
750	0.00212	0.0212	0.0424	0.106	0.212	1.060	2.123	4.256	8.555	12.89	17.28	21.70	32.94	44.45	56.21	68.24	80.52	93.04	105.8	118.8	145.2	199.3	253.0	750
800	0.00202	0.0202	0.0404	0.101	0.202	1.011	2.023	4.054	8.140	12.26	16.41	20.58	31.17	41.94	52.89	64.03	75.33	86.80	98.42	110.2	134.0	182.5	230.4	800
T_{sat}	6.98	45.83	60.09	81.35	99.63	151.8	179.9	212.4	250.3	275.5	295.0	311.0	342.1	365.7										
ρ_f	999.9	989.9	983.1	970.8	958.4	915.0	887.0	849.9	798.7	758.3	722.4	688.4	603.2	490.9										
ρ_g	0.00774	0.0681	0.1307	0.309	0.590	2.669	5.147	10.05	20.10	30.83	42.51	55.43	96.71	170.2										

Density of Water & Steam kg/m^3

Moody Diagram



Material	k (mm)
Riveted steel	0.9–9
Concrete	0.3–3
Wood stave	0.18–0.9
Cast iron	0.25
Galvanized iron	0.15
Asphalted cast iron	0.12
Commercial steel	0.046
Drawn tubing	0.0015

adapted by NH from Metzger & Willard, Inc.

Continuity and Navier-Stokes equations for incompressible homogeneous fluids in Cartesian, cylindrical, and spherical coordinates

Cartesian	Cylindrical	Spherical

Continuity equation

$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0$	$\frac{1}{r}\frac{\partial (rv_r)}{\partial r}+\frac{1}{r}\left(\frac{\partial v_\theta}{\partial \theta}\right)+\frac{\partial v_z}{\partial z}=0$	$\frac{1}{r^2}\frac{\partial (r^2 v_r)}{\partial r}+\frac{1}{r\sin\theta}\frac{\partial (v_\theta \sin\theta)}{\partial \theta}+\frac{1}{r\sin\theta}\frac{\partial v_\phi}{\partial \phi}=0$

Navier-Stokes equation

$\rho\left(\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}+v_y\frac{\partial v_x}{\partial y}+v_z\frac{\partial v_x}{\partial z}\right)$ $=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 v_x}{\partial x^2}+\frac{\partial^2 v_x}{\partial y^2}+\frac{\partial^2 v_x}{\partial z^2}\right)$	$\rho\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta}-\frac{v_\theta^2}{r}+v_z\frac{\partial v_r}{\partial z}\right)$ $=-\frac{\partial p}{\partial r}+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(rv_r)\right)+\frac{1}{r^2}\frac{\partial^2 v_r}{\partial \theta^2}-\frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta}+\frac{\partial^2 v_r}{\partial z^2}\right]$	$\rho\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial v_r}{\partial \phi}-\frac{v_\theta^2+v_\phi^2}{r}\right)$ $=-\frac{\partial p}{\partial r}+\mu\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial v_r}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta\frac{\partial v_r}{\partial \theta}\right)\right.$ $\left.+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 v_r}{\partial \phi^2}-\frac{2v_r}{r^2}-\frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta}-\frac{2v_\theta\cot\theta}{r^2}-\frac{2}{r^2\sin\theta}\frac{\partial v_\phi}{\partial \phi}\right]$
$\rho\left(\frac{\partial v_y}{\partial t}+v_x\frac{\partial v_y}{\partial x}+v_y\frac{\partial v_y}{\partial y}+v_z\frac{\partial v_y}{\partial z}\right)$ $=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v_y}{\partial x^2}+\frac{\partial^2 v_y}{\partial y^2}+\frac{\partial^2 v_y}{\partial z^2}\right)$	$\rho\left(\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta}+\frac{v_r v_\theta}{r}+v_z\frac{\partial v_\theta}{\partial z}\right)$ $=-\frac{1}{r}\frac{\partial p}{\partial \theta}+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(rv_\theta)\right)+\frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial \theta^2}+\frac{2}{r^2}\frac{\partial v_r}{\partial \theta}+\frac{\partial^2 v_\theta}{\partial z^2}\right]$	$\rho\left(\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial v_\theta}{\partial \phi}+\frac{v_r v_\theta}{r}-\frac{v_\phi^2\cot\theta}{r}\right)$ $=-\frac{1}{r}\frac{\partial p}{\partial \theta}+\mu\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial v_\theta}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta\frac{\partial v_\theta}{\partial \theta}\right)\right.$ $\left.+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 v_\theta}{\partial \phi^2}+\frac{2}{r^2}\frac{\partial v_r}{\partial \theta}-\frac{v_\theta}{r^2\sin^2\theta}-\frac{2\cos\theta}{r^2\sin^2\theta}\frac{\partial v_\phi}{\partial \phi}\right]$
$\rho\left(\frac{\partial v_z}{\partial t}+v_x\frac{\partial v_z}{\partial x}+v_y\frac{\partial v_z}{\partial y}+v_z\frac{\partial v_z}{\partial z}\right)$ $=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 v_z}{\partial x^2}+\frac{\partial^2 v_z}{\partial y^2}+\frac{\partial^2 v_z}{\partial z^2}\right)$	$\rho\left(\frac{\partial v_z}{\partial t}+v_r\frac{\partial v_z}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta}+v_z\frac{\partial v_z}{\partial z}\right)$ $=-\frac{\partial p}{\partial z}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_z}{\partial \theta^2}+\frac{\partial^2 v_z}{\partial z^2}\right]$	$\rho\left(\frac{\partial v_\phi}{\partial t}+v_r\frac{\partial v_\phi}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\phi}{\partial \theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial v_\phi}{\partial \phi}+\frac{v_r v_\phi}{r}+\frac{v_\theta v_\phi\cot\theta}{r}\right)$ $=-\frac{1}{r\sin\theta}\frac{\partial p}{\partial \phi}+\mu\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial v_\phi}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta\frac{\partial v_\phi}{\partial \theta}\right)\right.$ $\left.+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 v_\phi}{\partial \phi^2}-\frac{v_\phi}{r^2\sin^2\theta}+\frac{2}{r^2\sin\theta}\frac{\partial v_r}{\partial \phi}+\frac{2\cos\theta}{r^2\sin^2\theta}\frac{\partial v_\theta}{\partial \phi}\right]$