First period of examinations
Summer semester 2019 / July

NEW CURRICULUM (PO 2017)

Study Course: ______________________

Module Title: **27101 Fluid Mechanics B.Sc. (Prof. Gebel)**

Written exam: 84 points

Duration: 120 min

Date: 08.07.2019

Family Name: ______________ ______________________

First Name: ______________ Signature (Student)

Register No.: ______________

The exam consists of **21 p**ages. First, check that your copy contains all pages.

All calculations and sketches should be done on the sheets provided for that purpose. If more than one solution is given, mark clearly which one should be rated.

Please write legibly! Good luck!

FOR INTERNAL USE ONLY:

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Written exam	Practical Training	Total
Max. Points	12	10	14	14	12	12	10	84	16	100
Achieved										
								$\geq$ 42 Yes | No	Grade	

Graded by		Checked by

Final Grade

Regular grading key.	
Adjusted grading key. (Please add the adjusted grading key to the exam-results)	X

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Question 1 … Question/Answer Session **Points: 12**

<u>There is only one correct answer for each question.</u>

1. What happens if the flow of water within a horizontal tube changes from laminar to turbulent?

   ☐ The pressure losses remain constant.
   ☒ The pressure losses will increase.
   ☐ The pressure losses will decrease.

2. Consider laminar flow of water under steady-state conditions. What happens if the diameter of a horizontal tube smoothly increases?

   $\lambda = \frac{64}{Re} = \frac{64\eta}{v\rho d}$ $d\uparrow \Rightarrow \lambda\downarrow$

   $\Delta p\downarrow$

   $p\uparrow$

   ☐ The pressure will decrease and the velocity will increase.
   ☐ Pressure and velocity remain constant.
   ☐ Pressure and velocity will decrease.
   ☒ The pressure will increase and the velocity will decrease.

3. Consider laminar flow of air under steady-state conditions through a horizontal tube. What happens if the temperature of the air decreases due to cooling of the tube?

   $T\downarrow \Rightarrow \eta\downarrow$

   $\lambda = \frac{64}{Re} = \frac{\eta * 64}{d * \rho * v} \Rightarrow \lambda\downarrow \Rightarrow \Delta p\downarrow$

   ☐ The pressure losses will increase.
   ☒ The pressure losses will decrease.
   ☐ The pressure remains constant.

4. Plaice are bottom-living flatfish similar to flounder. At rest they constitute low, rounded humps on smooth, sandy bottoms. What happens if the current passing over the fish becomes stronger, i.e. higher flow velocity?

   ☐ The flatfish is pressed on the ground.
   ☒ The flatfish is lifted up into the current.
   ☐ The flatfish remains quiescent.

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5. A streamline is a line in the flow possessing the following property:

   ☐ The velocity vector of each particle occupying a point on the streamline is normal to the streamline.

   ☒ The velocity vector of each particle occupying a point on the streamline is tangent to the streamline.

   ☐ The velocity vector of each particle occupying a point on the streamline is shifted by 45° with respect to the streamline.

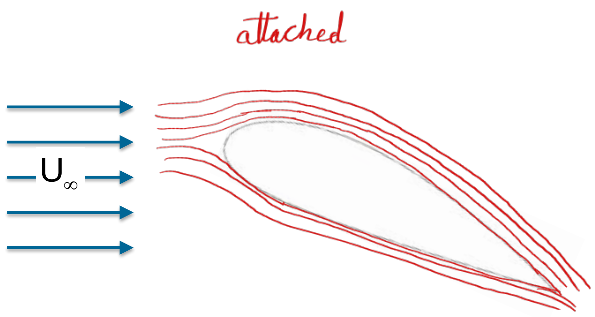
6. Consider a Newtonian fluid contained between two large parallel plates of area A, which are everywhere separated by a very small distance Y. The system is at rest. Then the lower plate is set in motion at a constant velocity v. What velocity profile will appear at steady state, i.e. after acceleration?

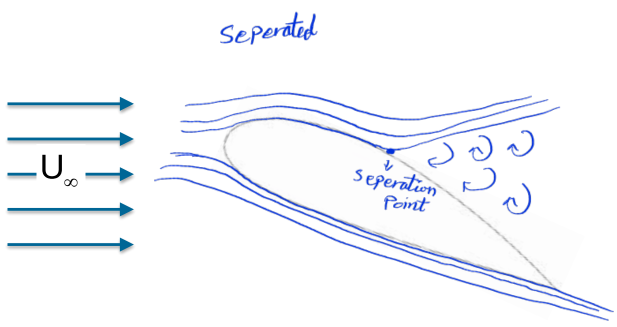
   ☐ A parabolic velocity profile.

   ☒ A linear velocity profile.

   ☐ A hyperbolic velocity profile.

7. Sketch the streamlines over an airfoil at a large angle of attack for both <u>attached</u> flow and <u>separated</u> flow. (2 P)





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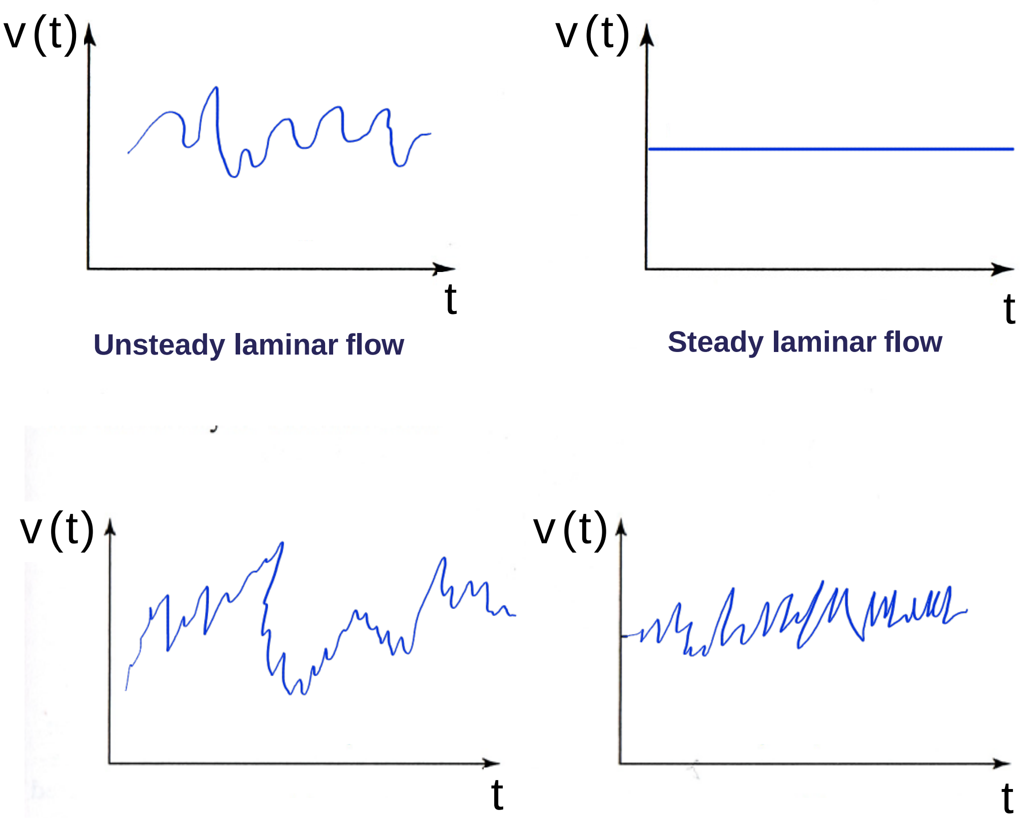
8. Sketch the development of velocity with time, v(t), for the four cases shown in the schematic below. Assume that a high-resolution speed sensor is available. Mark the average velocity for each case



Unsteady laminar flow

Steady laminar flow

Unsteady turbulent flow

Steady turbulent flow

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Question 2 … Equation of continuity **Points: 10**

$\dot m_{in}$

A pipe transports 50 kg/s of water. The pipe tees into a 5-cm-diameter pipe and a 7-cm-diameter pipe.

V_{out}

a) If the average velocity in the smaller-diameter pipe is 5 m/s, calculate the volume flow, in m³/h, in the larger pipe.

b) Determine the average velocity, in m/s, in the larger pipe.

Continuity equation:

$\dot m_{in} = \dot m_{out}$

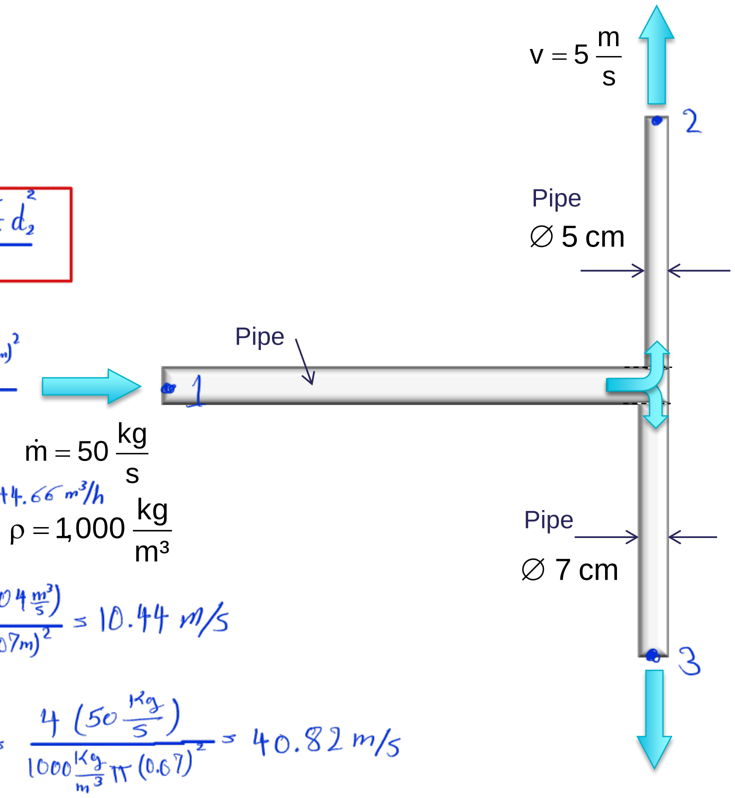
$\dot m_1 = \dot m_2 + \dot m_3$

$V_2 \rho A_2 + \dot V_3 \rho = \dot m_{in}$

$$\boxed{\dot V_3 = \frac{\dot m_{in} - V_2 \rho \frac{\pi}{4} d_2^2}{\rho}}$$

$$\dot V_3 = \frac{50\,kg/s - 5\,\frac{m}{s}(1000\,\frac{kg}{m^3})\frac{\pi}{4}(0.05m)^2}{1000\,\frac{kg}{m^3}}$$

$$\dot V_3 \approx 0.04\,m^3/s \cdot \frac{3600s}{1h} = 144.66\,m^3/h$$



$$\boxed{V_3 = \frac{\dot V_3}{A_3} = \frac{4\dot V_3}{\pi d_3^2}} = \frac{4(0.04\,\frac{m^3}{s})}{\pi(0.07m)^2} = 10.44\,m/s$$

$$\boxed{V_1 = \frac{\dot m_{in}}{\rho A_1} = \frac{4\dot m_{in}}{\rho \pi d_1^2}} = \frac{4(50\,\frac{kg}{s})}{1000\,\frac{kg}{m^3}\pi(0.07)^2} = 40.82\,m/s$$

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Answer sheet

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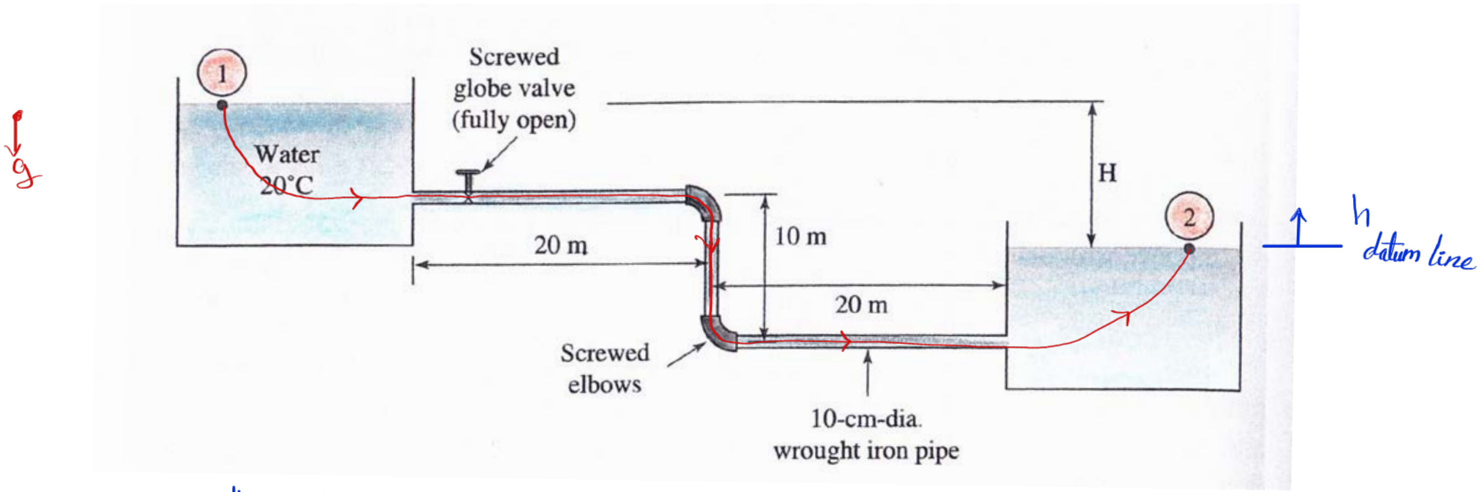
Question 3 … Flow between two reservoirs **Points: 14**

If the flow rate of water through a 10-cm-diameter (d) wrought iron pipe (→ commercial steel) is 0.04 m³/s ($\dot{V}$), find the difference in elevation H of the two reservoirs.

Given:

Density of water:	$\rho = 1{,}000 \dfrac{kg}{m^3}$
Kinematic viscosity	$\nu = 1.002 \cdot 10^{-6} \dfrac{m^2}{s}$ $\quad \dfrac{\eta}{\rho}$
Roughness	$e = 0.046\ mm$
Loss coefficient for minor losses	see attached table
Friction factor	see attached Moody diagram

Assumptions:
- Both reservoirs are large and open to the atmosphere
- Squared-edged entrance
- Standard elbow



Bernoulli equation:
* Steady-state * ρ = Cons.
* Along streamline * No viscous forces

$$\cancel{P_1} + \cancel{\frac{\rho}{2} V_1^2} + \rho g h_1 = \cancel{P_2} + \cancel{\frac{\rho}{2} V_2^2} + \rho g h_2 + \Delta P_{Losses} \Rightarrow \Delta P_{Losses} = \rho g (\overbrace{h_1 - h_2}^{H})$$

$P_1 = P_2 = P_{atm}$

Continuity equation ⇒ $d = cons. \Rightarrow V = cons.$

$$\boxed{H = \frac{\Delta P_{Losses}}{\rho g}}$$

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$$\Delta p_{Losses} = \Delta p_{\lambda} + \Delta p_{\zeta}$$

$$\Delta p_{\zeta} = \sum \zeta \rho \frac{V^2}{2} = (\zeta_{entrance} + \zeta_{valve} + 2\zeta_{elbow} + \zeta_{exit}) \rho \frac{V^2}{2}$$

$$V = \frac{\dot{V}}{A} = \frac{\dot{V}}{\frac{\pi}{4}d^2} = \frac{4\dot{V}}{\pi d^2}$$

$$\Delta p_{\zeta} = (\zeta_{entrance} + \zeta_{valve} + 2\zeta_{elbow} + \zeta_{exit}) \rho \frac{8\dot{V}^2}{\pi^2 d^4}$$

$$\Delta p_{\zeta} = (0.5 + 5.7 + 2(0.64) + 1)\, 1000 \frac{Kg}{m^3} \frac{8(0.04\frac{m^3}{s})^2}{\pi^2 (0.1m)^4} = 109978.0656\ Pa$$

$$\Delta p_{\lambda} = \lambda \frac{L}{d} \frac{\rho}{2} V^2$$

$$Re = \frac{\rho V d}{\eta} = \frac{Vd}{\nu} = \frac{4\dot{V}}{\pi d \nu} = \frac{4(0.04\frac{m^3}{s})}{\pi(0.1m)(1.002\times10^{-6}\frac{m^2}{s})} = 5.08\times10^5 >> 2300$$

Turbulent flow

$$e = 0.046 \Rightarrow \frac{e}{d} = 4.6\times10^{-4}$$

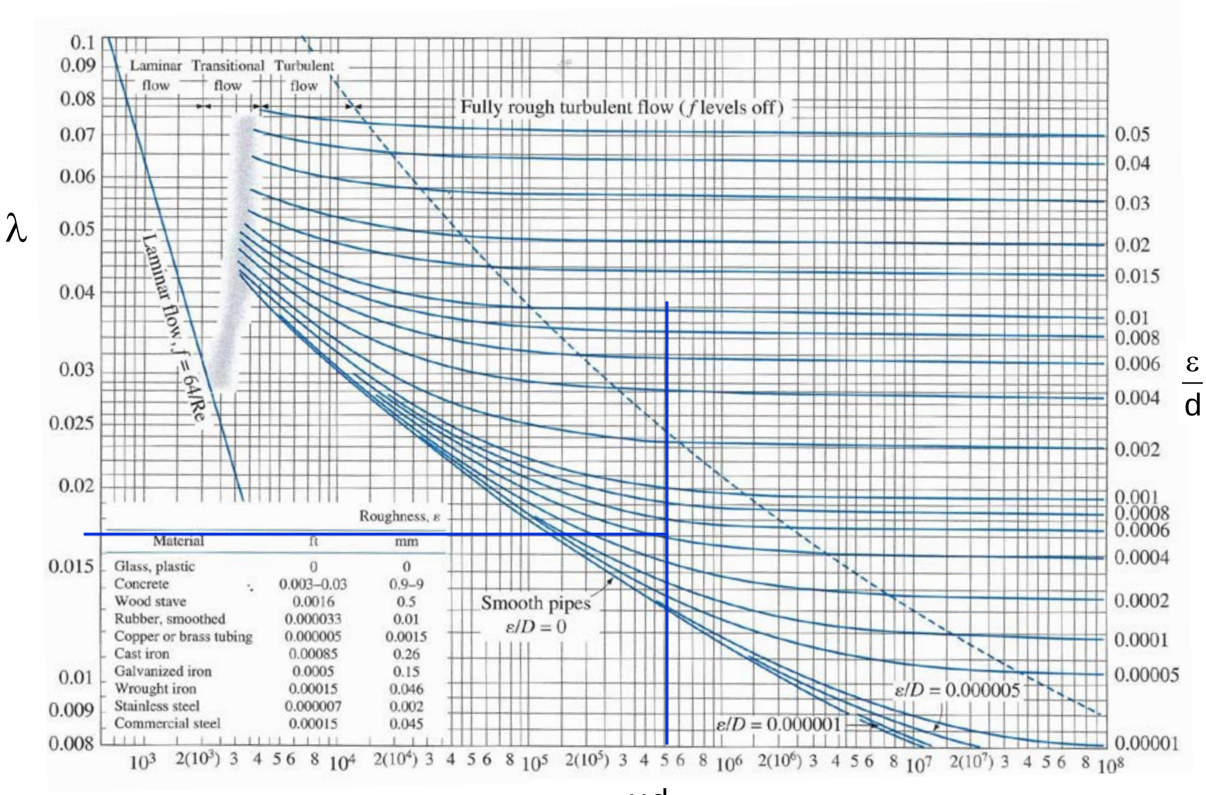
Moody diagram $\boxed{\lambda = 0.0175}$

$$\Delta p_{\lambda} = \lambda \frac{L}{\pi^2} \frac{8\rho\dot{V}^2}{d^5} = 0.0175 \frac{8(20\times2+10)m(10^3\frac{Kg}{m^3})(0.04\frac{m^3}{s})^2}{\pi^2(0.1m)^5} = 110237.4478\ Pa$$

$$H = \frac{\Delta p_{\zeta}}{\rho g} + \frac{\Delta p_{\lambda}}{\rho g} = \frac{109978.0656\ Pa}{10^3\frac{Kg}{m^3}(9.81\ m/s^2)} + \frac{113479.7257\ Pa}{10^3\frac{Kg}{m^3}(9.81\frac{m}{s^2})} = 11.211\ m + 11.57m = 22.78m$$

TABLE 7.2 Nominal Loss Coefficients K (Turbulent Flow)[a]

Type of fitting	*Screwed*		*Flanged*		
Diameter	2.5 cm	10 cm	5 cm	10 cm	20 cm
Globe valve (fully open)	8.2	5.7	8.5	6.0	5.8
(half open)	20	14	21	15	14
(one-quarter open)	57	40	60	42	41
Angle valve (fully open)	4.7	1.0	2.4	2.0	2.0
Swing check valve (fully open)	2.9	2.0	2.0	2.0	2.0
Gate valve (fully open)	0.24	0.11	0.35	0.16	0.07
Return bend	1.5	0.64	0.35	0.30	0.25
Tee (branch)	1.8	1.1	0.80	0.64	0.58
Tee (line)	0.9	0.9	0.19	0.14	0.10
Standard elbow	1.5	$\boxed{0.64}$	0.39	0.30	0.26
Long sweep elbow	0.72	0.23	0.30	0.19	0.15
45° elbow	0.32	0.29			
Square-edged entrance		0.5			
Reentrant entrance		0.8			
Well-rounded entrance		0.03			
Pipe exit		1.0			



$$Re = \frac{\rho v d}{\eta}$$

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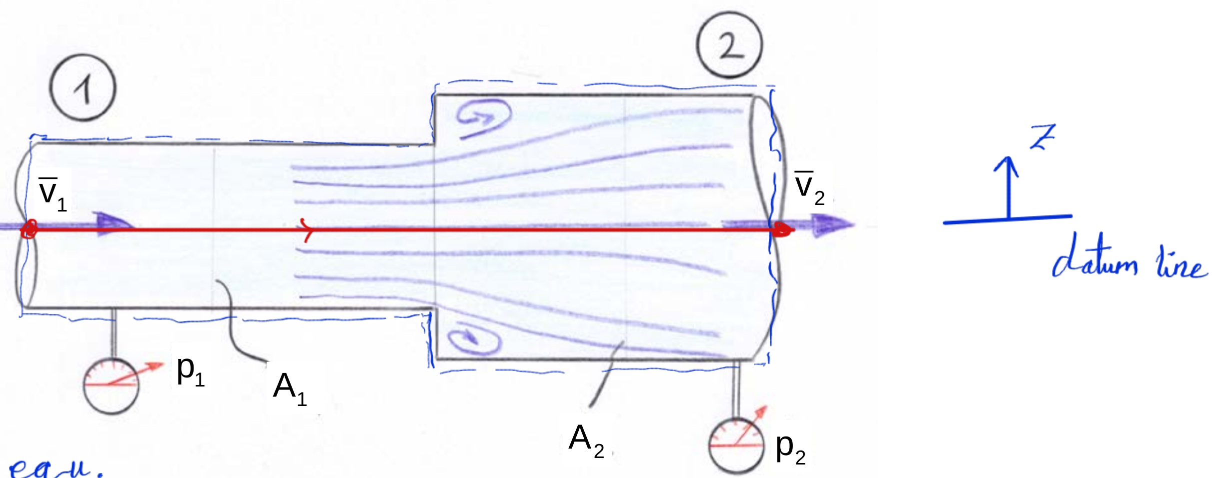
Question 4 … Equation of momentum / Bernoulli equation **Points: 14**

Find an expression for the head loss in a sudden expansion in a pipe in terms of v_1 and the area ratio, i.e. $\Delta H_{Losses} = fn(\overline{v}_1, A_1, A_2)$

Assumptions:

- Assume uniform velocity profiles and assume that the pressure at the beginning of the sudden enlargement is p_1.
- Introduce an appropriate control volume for the momentum balance.
- The arrangement is horizontal.
- The fluid is incompressible.
- All pressures are gage pressures.



Momentum equ.

$\sum F = 0 \qquad \dot{M}_2 - \dot{M}_1 = 0 \Rightarrow \rho A_1 V_1^2 = \rho A_2 V_2^2$

Benoulli equ. * Steadystate, * ρ = Cons., * along streamline, * Noviscous Forces

$$P_1 + \frac{\rho}{2} V_1 + \cancel{\rho g z_1} = P_2 + \frac{\rho}{2} V_2 + \cancel{\rho g z_2}$$

horizontal arrangement

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Question 5 … Dimensional analysis **Points: 12**

Long blunt objects, such as circular cylinders, exhibit a particularly interesting phenomenon when placed normal to a fluid flow: vortices or eddies (regions of circulating fluid) are shed from the object, regularly and alternately from opposite sides.

The task is to determine the dimensionless numbers (π –terms), which describe the dependency of the frequency f from the diameter of the cylinder and the relevant fluid mechanical variables. $f = f(d, \rho, \eta, v)$

a) Please explain what the Buckingham π-theorem states.

b) Define the set of variables the frequency depends on.

c) Identify appropriate repeating variables.

d) Determine the π –terms by combining the repeating variables with each of the remaining variables.

e) Which well-known dimensionless numbers have you found? Please express these numbers as ratio of different forces.

a) Buckingham Theorem states: The $(n-m)$ dimentionless groups are called π-terms such that $\Pi_1 = f(\Pi_2, \Pi_3, \ldots, \Pi_{n-m})$, where n is the num. of variable, and m is the num. of basic dimentions.

b) $f = f(d, v, \rho, \eta)$ $n = 5$, $m = 3$

d → diamter, v → velocity, ρ → density of fluid, η → Viscousity

$n - m = 2$

$\Pi_1 = f(\Pi_2)$

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Answer sheet

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remaining variables

→ repeating variables

	f	d	v	ρ	η
M	0	0	0	1	1
L	0	1	1	-3	-1
T	-1	0	-1	0	-1

$$\Pi_1 = \frac{f\,d}{v}$$

$$\Pi_2 = \frac{d\,\rho\,v}{\eta}$$

$$\therefore \frac{f \cdot d}{v} = f\Big(\underbrace{\frac{d\,\rho\,v}{\eta}}_{\text{Renoulds number}}\Big)$$

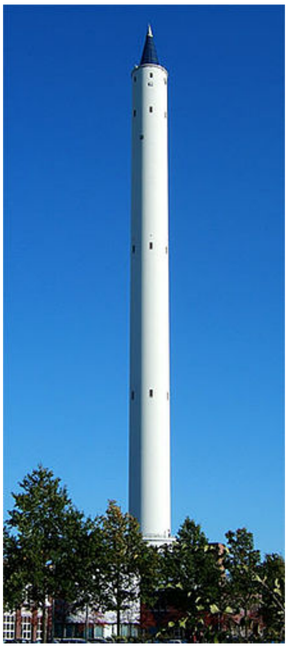
$$\Pi_2 = Re = \frac{\rho\,d\,v}{\eta} = \frac{\text{Inertial force}}{\text{Viscous force}}$$

$$\Pi_1 = \frac{f \cdot d}{v} = \frac{\text{Centirfugal force}}{\text{Inertial force}}$$

Question 6 … Drag and terminal velocity **Points: 12**

Determine the stationary sinking rate, the so-called terminal velocity of a 20-cm-diameter smooth sphere if it is released from rest in air at 20°C.

Hint: Start with a force balance for the falling sphere.



Given:

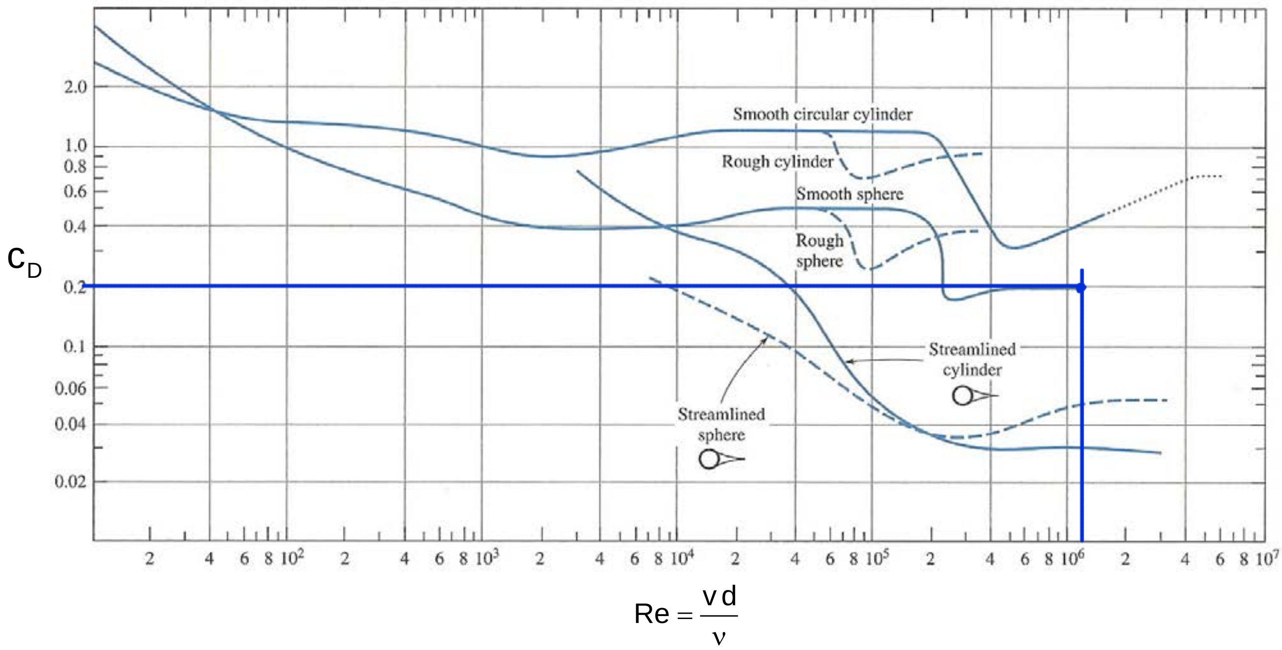
Density of sphere: $\rho_{Sphere} = 1{,}050 \dfrac{kg}{m^3}$

Density of air: $\rho_{Air} = 1.28 \dfrac{kg}{m^3}$

Kinematic viscosity of air: $\nu_{Air} = 1.6 \times 10^{-5} \dfrac{m^2}{s}$

Volume of sphere: $V_{Sphere} = \dfrac{\pi}{6} d^3$

Give rationale for your assumptions!



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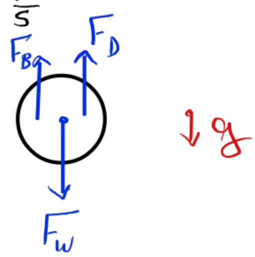
Data: $d = 0.2m$, $\rho_s = 1050 \frac{Kg}{m^3}$, $\rho_{air} = 1.28 \frac{Kg}{m^3}$, $\nu_{air} = \frac{\eta_{air}}{\rho_{air}} = 1.6\times10^{-5} \frac{m^2}{s}$



$$\Sigma F_y = 0$$

$$F_D = F_W - F_B$$

$$C_D \frac{\rho_{air}}{2} A V_\infty^2 = (\rho_s - \rho_{air}) V g$$

$A = \frac{\pi}{4} d^2$

$V = \frac{\pi}{6} d^3$ $\Longrightarrow$ $V_\infty = \sqrt{\frac{2g(\rho_s - \rho_{air})4d}{6 C_D \rho_{air}}} = ?$

$$Re = \frac{\rho_{air} V_\infty d}{\eta_{air}} = \frac{V_\infty d}{\nu_{air}}$$

since $V_\infty = ? \Longrightarrow Re = ?$ we assume $\Longrightarrow C_{D_1} = 0.2$

(as a smooth sphere would have both small skin & form drag)

$$V_{\infty_1} = \sqrt{\frac{2(9.81\frac{m}{s^2})(1050-1.28)\frac{Kg}{m^3}\cdot 4(0.2m)}{6(0.2)(1.28\frac{Kg}{m^3})}} = 103.5\ m/s$$

$$Re_1 = \frac{103.5\frac{m}{s}(0.2m)}{1.6\times10^{-5}\frac{m^2}{s}} \simeq 1.3\times10^{6}$$

at $Re_1 \Rightarrow \boxed{C_D \simeq 0.2}$ ✓

So our initial assumption was correct.

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Question 7 … Wind energy **Points: 10**

The torque of a windmill can be generated by rotating blades with a certain speed v.

a) Assuming the wind is moving from left to right, indicate the direction of rotation of the windmill shown in the picture. Is it clockwise or counter clockwise?

We Know it from the leading edge.

b) Provide a velocity polygon and a schematic representation of the different forces, i.e. magnitude and direction, acting on the blade. Use the template below and a ruler (!!!) to draw the polygons.

How is torque generated? Give rationale.

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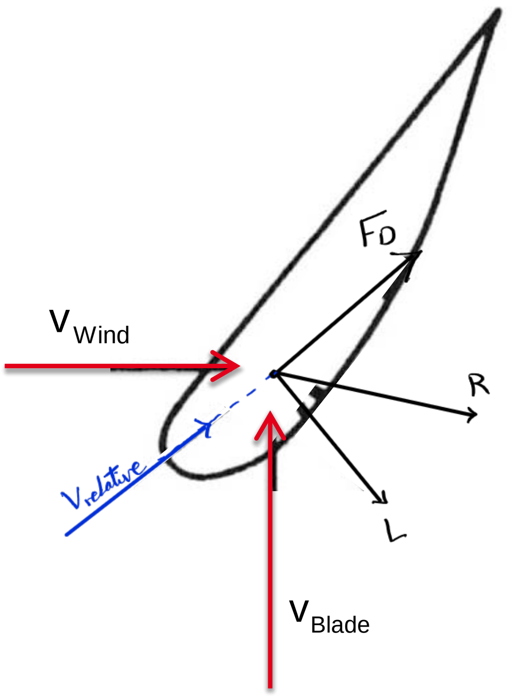

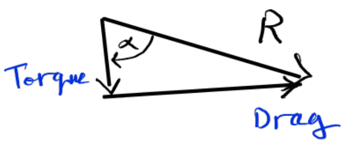

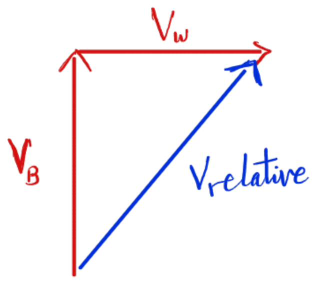

The Torque is generated from the resultant force times $\cos(\alpha)$ where the thust $= R\sin(\alpha)$

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End of exam