Pearson BTEC Level _ Higher Nationals in Engineering (RQF)

Unit 64: Thermofluids

Unit Workbook 4

in a series of 4 for this unit

Learning Outcome 4

Fluid Systems and Hydraulic Machines

Contents

INTRODUCTION

Analyse fluid systems and hydraulic machines

- *Fluid systems:*
  - Characteristics of fluid flow: laminar and turbulent flow, Reynolds number.
  - Friction factors: relative roughness of pipe, use of Moody diagrams.
  - Head losses across various industrial pipe fittings and valves, use of Bernoulli's Equation and Darcy's Formula.
- *Hydraulic machines:*
  - Turbines: Pelton wheel, Kaplan turbine, Francis wheel.
  - Pumps: centrifugal, reciprocating.
- *Analysis of systems:*
  - Dimensional analysis: verification of equations for torque, power and flow rate.
  - Application of dimensional analysis to determine the characteristics of a scale model.
  - Use of Buckingham Pi Theorem.

GUIDANCE

This document is prepared to break the unit material down into bite size chunks. You will see the learning outcomes above treated in their own sections. Therein you will encounter the following structures;

Purpose — Explains *why* you need to study the current section of material. Quite often learners are put off by material which does not initially seem to be relevant to a topic or profession. Once you understand the importance of new learning or theory you will embrace the concepts more readily.

Theory — Conveys new material to you in a straightforward fashion. To support the treatments in this section you are strongly advised to follow the given hyperlinks, which may be useful documents or applications on the web.

Example — The examples/worked examples are presented in a knowledge-building order. Make sure you follow them all through. If you are feeling confident then you might like to treat an example as a question, in which case cover it up and have a go yourself. Many of the examples given resemble assignment questions which will come your way, so follow them through diligently.

Question — Questions should not be avoided if you are determined to learn. Please do take the time to tackle each of the given questions, in the order in which they are presented. The order is important, as further knowledge and confidence is built upon previous knowledge and confidence. As an Online Learner it is important that the answers to questions are immediately available to you. Contact your Unit Tutor if you need help.

Challenge — You can really cement your new knowledge by undertaking the challenges. A challenge could be to download software and perform an exercise. An alternative challenge might involve a practical activity or other form of research.

Video — Videos on the web can be very useful supplements to your distance learning efforts. Wherever an online video(s) will help you then it will be hyperlinked at the appropriate point.

4.1 Fluid Flow

Fluid flow can be broken down into two terms, either laminar or turbulent. Knowing whether a fluid is laminar or not is very important in figuring out its characteristics.

4.1.1 Laminar Flow

Laminar flow is the name given to a "smooth" flow. Consider the pipe shown in Fig.4.1, the arrows in the image show the direction that the fluid travels, and it can be considered that a laminar flow are all parallel to each other. Laminar flow is also simpler to calculate, as it can also be assumed that the flow's velocity, pressure at each point is constant.

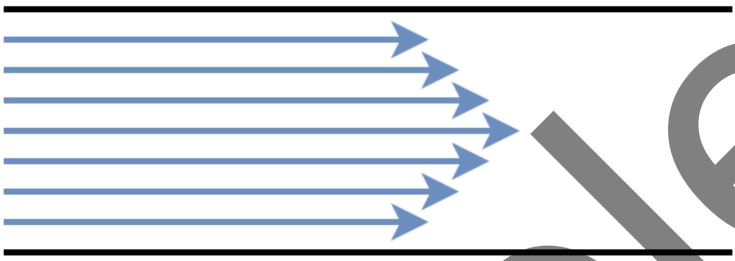

Figure 4.1: Laminar flow through a pipe

Laminar flow typically occurs in very small flow channels, where a relatively high viscosity fluid flows slowly. Examples of this are oil through a small pipe, or blood through the capillaries (not arteries or veins). The URL below shows a laminar flow.

https://www.youtube.com/watch?v=9opbBlbXN8c

4.1.2 Turbulent Flow

Turbulent flow, on the other hand, is disordered and the flow paths will often cross and mix. The velocity of turbulent flow is constantly changing in direction and magnitude, but the general direction will not change. The constant changes in velocity result in "eddy currents", which are swirls in the flow. Fig.4.2 shows turbulent flow through a pipe.

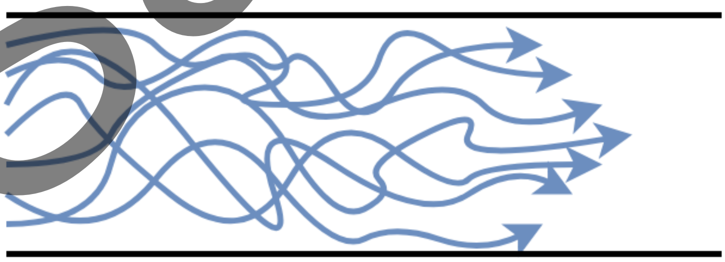

Figure 4.2: Turbulent flow through a pipe

There are far more examples of turbulent flow in systems, such as oil transport pipes and blood through arteries and veins. Turbulent flow also includes air over an aerofoil.

4.1.3 The Reynold's Number

They Reynold's number (Re) is a dimensionless constant that is used to describe fluid flow. The Reynold's number is calculated using Eq.4.1, and is a ratio of inertia forces to viscous forces.

$$\mathrm{Re} = \frac{\rho \mathrm{uL}}{\mu} = \frac{uL}{v} \qquad \text{(Eq.4.1)}$$

Where:

- ρ is the density of the fluid $(\mathrm{kg/m^3})$
- u is the velocity of the fluid $(\mathrm{m/s})$
- L is the length of that you are measuring over (m)
- μ is the dynamic viscosity $(\mathrm{Pa \cdot s})$
- v is the kinematic viscosity $(\mathrm{m^2/s})$

The corresponding value for the Reynold's number defines the flow as:

- $\mathrm{Re} < 2000$: Flow is laminar
- $\mathrm{Re} = 2000$: Known as the critical Reynold's number, flow is no longer laminar and will start to transition towards turbulent flow
- $2000 < \mathrm{Re} < 4000$: Flow is considered transitional, or unstable, it is not laminar, but it is not fully turbulent yet either.
- $4000 < \mathrm{Re}$: Flow is turbulent

Example 1

Give the flow characteristic of:

a) Honey $(1450\mathrm{kg/m^3}, 14.095\mathrm{Pa \cdot s})$ flowing through a $3\mathrm{m}$ length of pipe at $0.3\mathrm{m/s}$.
b) Castor oil $(961\mathrm{kg/m^3}, 950\mathrm{cP})$ flowing through $1\mathrm{m}$ length of pipe at $2\mathrm{m/s}$
c) Water $(1000kg/m^3, 1cP)$ flowing through a $1m$ length of pipe at $0.3m/s$.

Answers:

a) Re is given as:

$$\mathrm{Re} = \frac{\rho \mathrm{uL}}{\mu} = \frac{1450(0.3)(3)}{14.095} = 92.6$$

The flow is laminar

b) $950\mathrm{cP} = 0.95\mathrm{Pa \cdot s}$, so Re is:

$$\mathrm{Re} = \frac{961(1)(2)}{0.95} = 2023$$

The flow is transitional

c) $1\mathrm{cP} = 0.001\mathrm{Pa \cdot s}$, so Re is:

$$\mathrm{Re} = \frac{1000(1)(0.3)}{1\backslash \mathrm{cdot}\ 10^{-3}} = 300000$$

The flow is turbulent

4.2 Head Losses in Pipes

No system is 100% efficient, and pipework is no exception, frictional losses occur as the surface of the water and the surface of the pipe make contact with each other.

Head losses in particular describe the loss of pressure in the system, consider the pipework in Fig.4.3 below, this method is a simple pressure measurement without the use of electronics. The head losses refer to the height lost at each gauge, the further along the pipe, the more frictional losses occur, this loss in pressure means that the height that the water reaches in the gauge lowers, and as such $h_1 > h_2 > h_3$ in Fig.4.3.

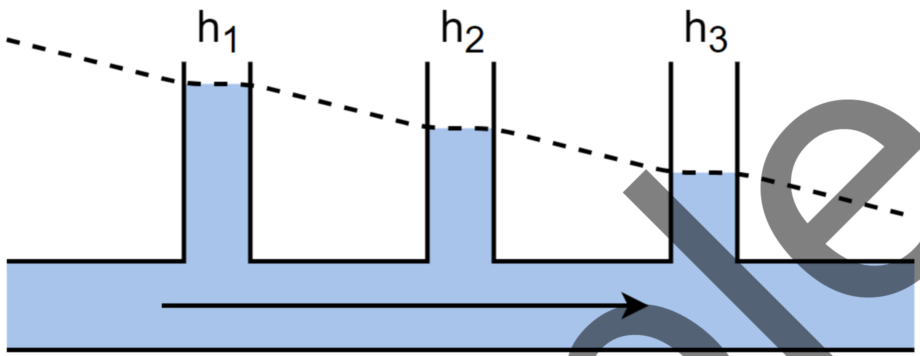

Figure 4.3: Head losses in pipes

4.2.1 Surface Roughness

Head losses in pipes can have a range of reasons, one important aspect to consider is the relative roughness of the pipe. Fig.4.4 shows the effect surface roughness can have on the flow, the rough surface keeps some of the flow contained within the crevices, while these streamlines can make their way back into the flow, it requires more forces and pressures to get them back on the right track, meaning there are more head losses, compared to the perfectly smooth pipe.

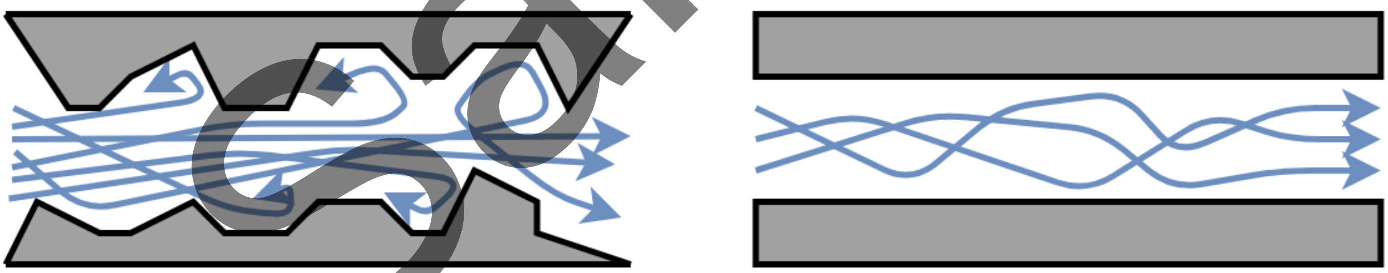

Figure 4.4: Turbulent flow through a rough (left) and smooth (right) pipe

The relative roughness of a pipe is defined Eq.4.2, where k is the average height of the surface irregularities (some sources will use ϵ), and d is the diameter of the pipe.

$$\text{Relative Roughness} = \frac{k}{d} \qquad \text{(Eq.4.2)}$$

Fig.4.5 gives a graphical demonstration of the dimensions.

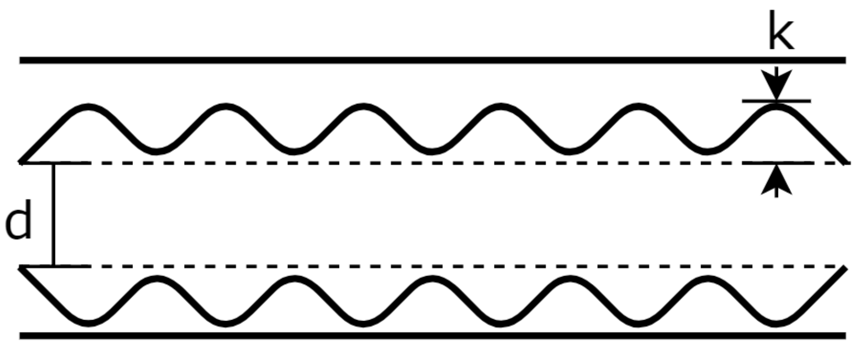

Figure 4.5: The measurement of the diameter and height of irregularities in a pipe.

4.2.2 Moody Diagrams

Moody diagrams is a diagram to measure the coefficient of friction in pipes (noted in this workbook as f, some sources will use λ). Calculating the coefficient of friction depends on both the flow in the pipe and its relative roughness.

The equations used for calculating f are:

Laminar: $f = \frac{16}{Re}$ (Eq.4.3)

Turbulent Smooth pipes: $f = 0.079Re^{-0.25}$ (Eq.4.4)

Turbulent Rough pipes: $\frac{1}{\sqrt{f}} = -3.6log_{10}\left[\frac{6.9}{Re} + \left(\frac{k}{3.71d}\right)^{1.11}\right]$ (Eq.4.5)

These equations are quite long to calculate, with the exception of the laminar equation (Eq.4.3). So alternatively, the Moody chart is available for reference, the Moody chart is a graph that has already plot the values for the friction factor across a range of Reynold's numbers and relative roughness to give a quick (and fairly accurate) estimate. Fig.4.6 shows a Moody chart, the lines show the variation of friction factor at a given relative roughness, but a varying Reynold's number. Most Moody diagrams will also include an absolute roughness value for some materials, the absolute roughness value is a typical estimate for ϵ for certain materials.

Example 2

Let's say for an example, the Reynold's number of a given flow is $7 \cdot 10^5$, and the absolute roughness is 0.25mm with a diameter of 62.5mm. The friction factor will be ~ 0.007 (maybe 0.0071, shown as a red dot in Fig.4.7), or using the Eq.4.6, knowing that the pipe is rough and turbulent.

$$\frac{1}{\sqrt{f}} = -3.6\log_{10}\left[\frac{6.9}{\text{Re}} + \left(\frac{\text{k}}{3.71\text{d}}\right)^{1.11}\right] = -3.6\log_{10}\left[\frac{6.9}{7 \cdot 10^5} + \left(\frac{0.25 \cdot 10^{-3}}{3.71 \cdot 62.5 \cdot 10^{-3}}\right)^{1.11}\right] = 11.827$$

$$f = \left(\frac{1}{11.827}\right)^2 = 0.00715$$

Which means the estimate from the Moody diagram is very close.

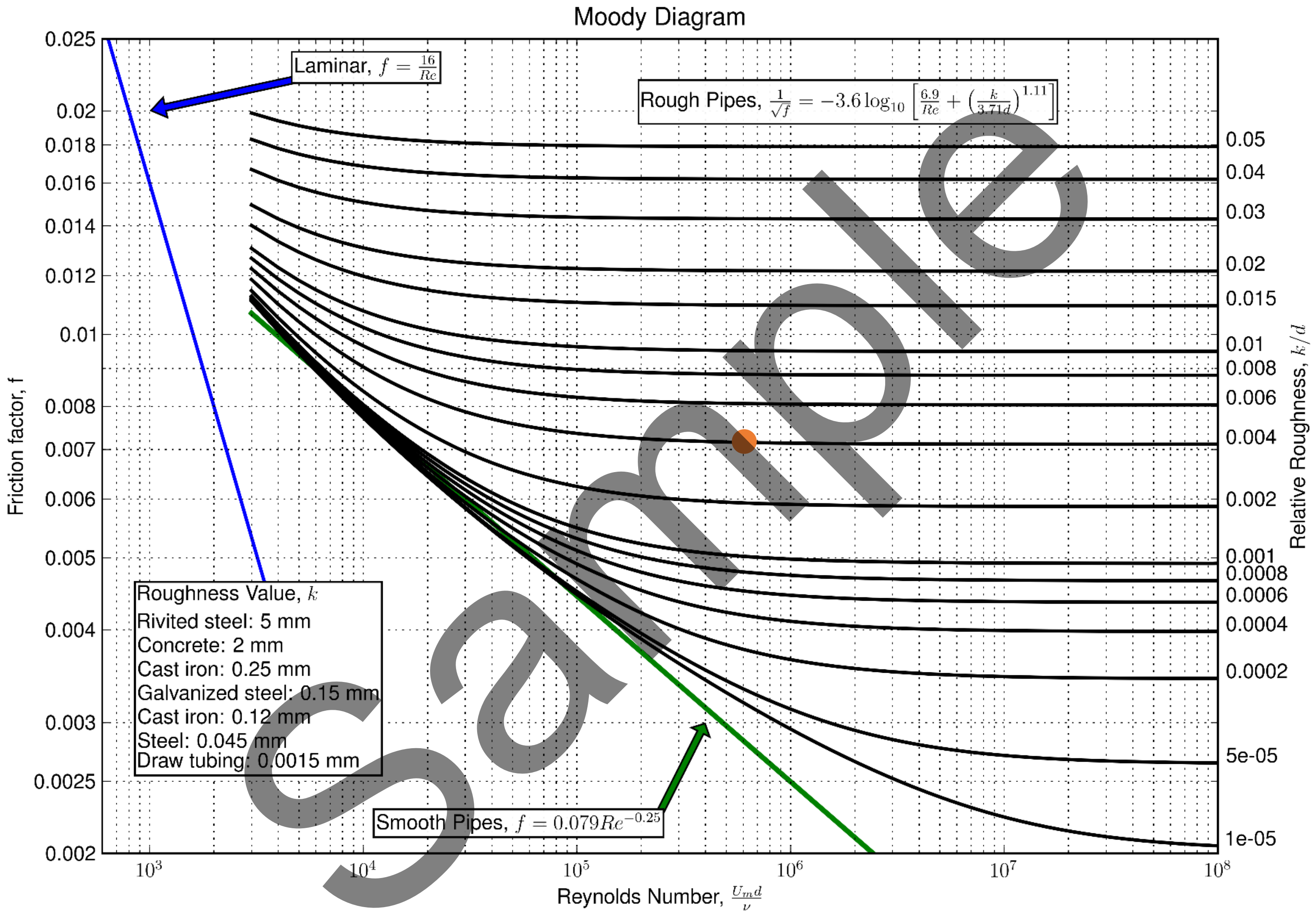

Figure 4.7: Moody Diagram