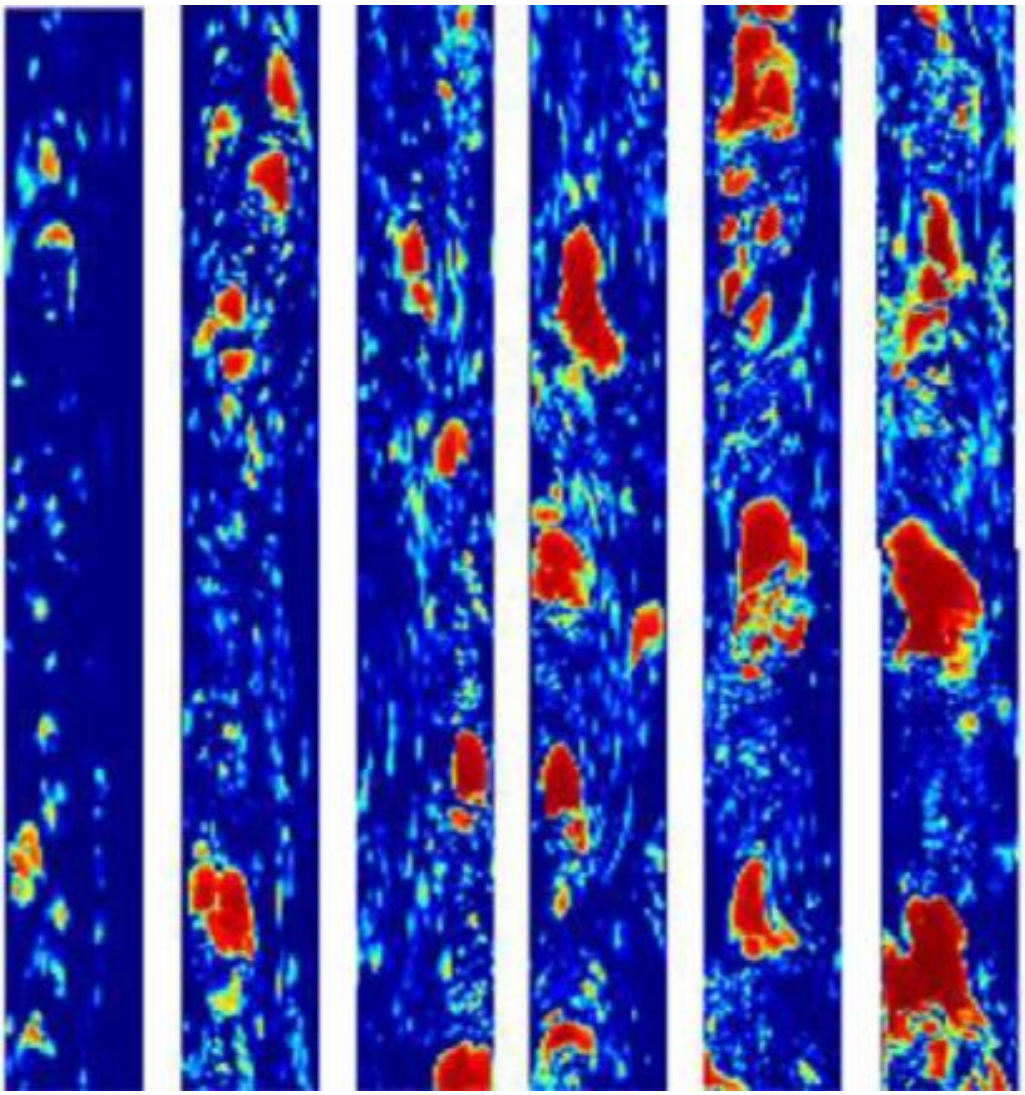


What is Multiphase Flow?

[2016/2017]

The **Scholars** Programme

Instructor **Dr. S. Sharaf**

Pupil Name _____

The Scholars Programme – [2016/2017] – Pupil Feedback Report

Grade	Marks	What this means
1st	70+	Performing to an excellent standard at first year undergraduate level
2:1	60-69	Performing to a good standard at first year undergraduate level
2:2	50-59	Performing to an excellent standard at GCSE level
3rd	40-49	Performing to a good standard at GCSE level
Workings towards a pass	0-39	Workings towards a pass
Did not submit	DNS	No assignment received by The Brilliant Club

Lateness	
Any lateness	10 marks deducted
Plagiarism	
Some plagiarism	10 marks deducted
Moderate plagiarism	20 marks deducted
Extreme plagiarism	Automatic fail

Name of PhD Tutor			
Title of Assignment			
Name of Pupil			
Name of School			
ORIGINAL MARK / 100		**FINAL MARK / 100**	
DEDUCTED MARKS		**FINAL GRADE**	

If marks have been deducted (e.g. late submission, plagiarism) the PhD tutor should give an explanation in this section:

Learning Feedback Comment 1 - *Enter Key Learning Priority Here*	
What you did in relation to this Key Learning Priority *Enter feedback here*	**How you could improve in the future** *Enter feedback here*
Learning Feedback Comment 2 – *Enter Key Learning Priority Here*	
What you did in relation to this Key Learning Priority *Enter feedback here*	**How you could improve in the future** *Enter feedback here*
Learning Feedback Comment 3 – *Enter Key Learning Priority Here*	
What you did in relation to this Key Learning Priority *Enter feedback here*	**How you could improve in the future** *Enter feedback here*
Resilience Comment	
How you showed learning resilience during the course *Enter feedback here*	**How you could build learning resilience in the future** *Enter feedback here*

Contents

Course Rationale Page 4
Mark Scheme Page 5
Glossary of Keywords Page 6
Tutorial 1 Page 7
- Tutorial 1 Assignment – Baseline Test Page 11

Tutorial 2 Page 15
- Tutorial 2 Assignment Page 20

Tutorial 3 Page 21
- Tutorial 3 Assignment Page 28

Tutorial 4 Page 30
- Tutorial 4 Assignment Page 31

Tutorial 5 Page 32
- Final Assignment Page 37

References Page 39
Feedback Tutorial Page 41
Applications Guidance Page 42

Title Page Photograph: Example of a two-phase flow system (Bubble column). Shown time history of phase across a diameter of the bubble column blue is liquid, red is gas. Earliest time at top, later time below. Source Sharaf et al (2016)

Course Rationale

What is multiphase flow? Straightforward answer what isn't single phase flow. When a tap is opened water (liquid) flows. When a cooker in the kitchen is operated, methane (gas) flows and these are examples of single phase flow. What happens when you start mixing phases together and flowing in a certain direction and orientation? It gets more interesting (and more complex!). A phase can be solid, liquid and gas and multiphase flow is when two or more phases flow together as a mixture in a conduit or a pipe which can be horizontal, inclined and vertical and each of these will have their own characteristics and physics to consider. It is arguable that multiphase flows occur more often than single phase flows. Blood can be considered as a multiphase flow. Clouds, oil/gas pipelines, list is endless. Focus will be on gas-liquid (e.g. air-water, air-oil) two phase flow which has many applications in the chemical, oil and nuclear industries. Multiphase flow has Maths, Physics and Engineering combined and will test (and hopefully motivate!) the student in all of these areas and the challenge will be to apply familiar maths or physics concepts in an unfamiliar setting and to a new subject.

Initial tutorials will introduce the students to single phase flow (often called fluid mechanics), while the physics in single phase flow is very different to multiphase flow, it is still important to have an appreciation of essential phenomena such as "Bernoulli" which explains why and how planes fly for example. Subsequent material will get the students thinking about multiphase flow, and then introduce them to basic concepts and technical terms such as "void fraction" or cross-sectional area occupied by a phase inside a pipe and flow patterns or flow regimes such as bubble flow, slug flow, churn flow, annular flow. All background information on multiphase flow will be provided and some slides from undergraduate material will be included. Videos will be provided to demonstrate multiphase flow in action. Experimental techniques will be explained and latest research data and understanding will be shared. Tutorials will be set that contain a mixture of analytical questions and mathematical problems that requires calculations set to university standard. The final assignment will be a case study where the students are asked to size a pipeline using data provided to them. They will be asked to provide a professional report.

Tutorial 1: *Single Phase Flow and Baseline Knowledge Assessment*
(1 hr tutorial plus 1 hr assignment as homework)
Tutorial 2: *Introduction to Multiphase Flow: Flow Patterns*
(1 hr tutorial plus 1 hr assignment as homework)
Tutorial 3: *Multiphase Flow Concepts: Pressure Drop, Void Fraction*
(1 hr tutorial plus 1 hr assignment as homework)
Tutorial 4: *Multiphase Flow: Flow Pattern Maps*
(1 hr tutorial plus 1 hr assignment as homework)
Tutorial 5: *Case study-Multiphase Flow in Industry*
(1 hour tutorial plus ~15 hrs assignment as homework)

Mark Scheme For Final Assignment

Key Skill	1st	2.2	3rd
Data Analysis	▪ Simple Calculations are consistently correct and well presented ▪ Complex calculations which have not been fully demonstrated are convincingly attempted and sometimes correct ▪ Physical Interpretations of numerical values are relevant and inform the work. ▪ Units are comfortably and consistently used correctly.	▪ Simple calculations are well attempted and often correct. ▪ Complex calculations are attempted and some progress ismade ▪ Some attempt is made to interpret results physically ▪ Units are mostly used correctly	▪ Simple calculations are attempted ▪ Formulae are correctly quoted from the course material but not always correctly used ▪ Physical interpretation is lacking or largely misguided ▪ Some attempt to use units
Knowledge and Understanding	▪ Pupils demonstrate accurate, detailed and comprehensive knowledge of key concepts and debates, incorporating the relevant content. ▪ Pupils produce answers which fully address the requirements of the question and demonstrate good contextual awareness. ▪ Pupils provide accurate evidence and independently researched examples to illustrate points made.	▪ Pupils offer some analysis that shows some awareness of differing ideas. ▪ Pupils provide a simple evaluation of key concepts and debates, and make some comparisons. ▪ Pupils make a good attempt at answering the question which partially addresses the requirements of the course, but lacks evidence of independent research and thought.	▪ Pupils demonstrate a basic knowledge of key concepts and debates. ▪ Pupils make a limited attempt at answering the question. ▪ Pupils make limited use of relevant evidence.
Presentation	▪ Report is very well presented and laid out. ▪ Language is concise, clear and in an engaging style ▪ Writing is well structured. ▪ Appropriate technical vocabulary is confidently and correctly used where appropriate	▪ Report is reasonably presented and laid out. ▪ Language is clear and reasonably detailed ▪ Some attempt to appropriately structure writing has been made ▪ Some attempt made to use technical vocabulary	▪ Report is poorly presented and laid out. ▪ Language is readable though not very engaging. ▪ Attempts are made to use Technical vocabulary, but largely incorrect or in an inappropriate context

Marking Criteria For Final Assignment	**Mark**	**Out of**
Introduction		5
Evidence of Referencing		5
Evidence of Research		10
Presentation (Inc Grammar, Neatness, etc)		20
Data Analysis & Interpretation		20
Discussion & Conclusions & Recommendation		20
Knowledge & Understanding & Accuracy		20
Total Mark		**100**

Glossary of Keywords/Nomenclature

Main symbols

A	Area	(m^2)
A_1	Friedel parameter	(-)
A_2	Friedel parameter	(-)
D	Pipe diameter	(m)
d	Diameter	(m)
E_1	CISE parameter	(-)
E_2	CISE parameter	(-)
f	Friction factor	(-)
g	Acceleration due to gravity	(m/s^2)
j	CISE parameter	(-)
L	Length	(m)
$\dot{m}$	Mass flux	(kg/m^2s)
P	Pressure	(kg/ms^2)
Q	Volumetric flow rate	(m^3/s)
r,R	Pipe radius	(m)
Re	Reynolds number	(-)
S	Perimeter	(m)
t	Time	(s)
T	Temperature	(°C)
U	Velocity	(m/s)
U_R	Slip ratio	(-)
u	Velocity	(m/s)
V	Volumetric void fraction	(-)
We	Weber Number	(-)
x_g	Quality	(-)
V	Velocity	(m/s)
z	Axial distance	(m)

Greek symbols

β	Inclination from horizontal	(deg)
ε	Gas or void fraction	(-)
ϕ	Two phase multiplier	(-)
η	Dynamic viscosity	(kg/ms)
μ	Dynamic viscosity	(kg/ms)
ν	Kinematic viscosity	(m^2/s)
ρ	Density	(kg/m^3)
σ	Surface tension	(N/m)
τ	Shear stress	(N/m^2)

Subscripts

l	liquid
lo	all flow as liquid
ls	liquid superficial
m	mixture
g	gas
gs	gas superficial
H	homogeneous
max	maximum
min	minimum
MP	multiphase
r	radial
s	slip
TP	two phase

Tutorial 1 – Single Phase Flow

What is the Purpose of Tutorial 1?

- Introduce the student to single phase flow/Bernoulli's equation and use it as means of checking fundamental skills to tackle subsequent tasks
- These skills will take the form of communication skills, mathematical and numerical skills

Fluid mechanics involves the study of fluids, namely liquids and gases where various properties of the fluid, such as velocity, pressure, density and temperature, are functions of space and time. This is different to solid mechanics with the familiar Newton's equations. One of the most important equations in fluid mechanics is known as the Bernoulli equation. This tutorial is given in a "lecture" format which is typical of University style teaching/tutoring.

FLOW IN PIPELINES

- Bernoulli's equation

$$\frac{p}{\rho \cdot g} + \frac{V^2}{2 \cdot g} + H = \text{constant}$$

- Conservation of energy

FRICTION LOSS

- Pressure drop

$$\Delta P = \frac{f \cdot \rho \cdot v^2 \cdot L}{2 \cdot D}$$

- f - friction factor related to internal roughness and Reynolds Number

REYNOLDS NUMBER

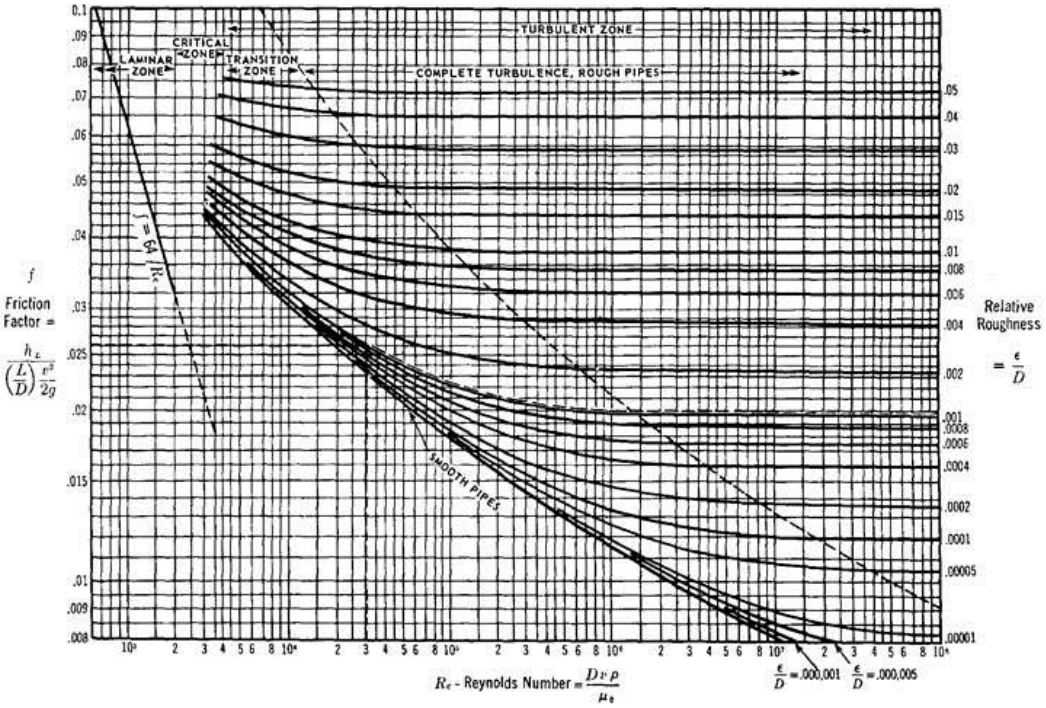
- Ratio of inertial forces to viscous forces

$$\mathbf{Re} = \frac{\rho \cdot \mathbf{V}^2}{\mu \cdot \mathbf{V}/\mathbf{D}}$$

- In its simplest form

$$\mathbf{Re} = \frac{\mathbf{D} \cdot \mathbf{V}}{\upsilon}$$

MOODY DIAGRAM



FRICTION FACTOR

- Laminar flow - Re<2000
- Turbulent flow - Re>2300

$$f = 64 / Re$$

- Colebrook-White equation

$$\frac{1}{\sqrt{f}} = 1.74 - 2 \cdot \log_{10}\left[\frac{2 \cdot k}{D} + \frac{18.7}{Re \cdot \sqrt{f}}\right]$$

PIPE ROUGHNESS

- Absolute roughness values, k
  - clean steel - 0.05 mm (0.002 in)
  - light corrosion - 0.1 mm (0.004i n)
  - heavy corrosion - 1 mm (0.04 in)
  - flexible
    - plastic liner (liquid) - 0.005 mm to 0.01 mm (0.0002 in to 0.0004 in)
    - corrugated liner (gas) - D/250
- Effect of corrosion
  - 406.4 mm (16 in) pipeline - turbulent flow
  - clean steel - f=0.012
  - heavily corroded - f=0.024
  - double the pressure drop

$$\Delta P = \frac{f \cdot \rho \cdot v^2 \cdot L}{2 \cdot D}$$

LIQUID FLOW

- Flow equation

$$\frac{p}{\rho \cdot g} + \frac{V^2}{2 \cdot g} + H + h_f = \text{constant}$$

- Velocity does not change along line - therefore ignore
- Head due to elevation important due to higher density

Line Sizing

Step by Step Calculation

If the agreement is sufficiently good – fine;
If the agreement is poor, assume a new pipe diameter and repeat the calculations.

5. Calculate pressure drop, ΔP and compare with the known available ΔP.
4. Determine friction factor, f from Moody chart or equations.
3. Calculate Re; $Re = \frac{\rho v D}{\mu}$.
2. Determine relative roughness of the pipe, e.
1. Estimate pipe diameter, D.

Pressure Loss Equations

Pressure Drop Calculation

$$\Delta\left(\frac{P}{\rho}\right) + g\Delta z + \frac{\Delta v^2}{2} + gh_L = 0$$

$$\left(\frac{P_2 - P_1}{\rho g}\right) + (z_2 - z_1) + \frac{1}{2g}\left(v_2^2 - v_1^2\right) + h_L = 0$$

$$P_1 - P_2 = \rho g(z_2 - z_1) + \frac{1}{2}\rho\left(v_2^2 - v_1^2\right) + \rho g h_L$$

Bernoulli's equation defines the energy balance for flow problems. p is the fluid pressure (N/m^2), ρ is the density (kg/m^3), g is the gravity constant (m/s^2), V is the flow velocity (m/s) and H is the head (m), L is pipeline length (m), D is pipeline internal diameter (mm), Re = Reynolds number [dimensionless], k = roughness (mm), υ is the kinematic viscosity (m^2/s). Fluid mechanics is a large field and is actively researched. This tutorial is just a brief introduction. More information on fluid mechanics can be found here:

http://www.efm.leeds.ac.uk/CIVE/CIVE1400/Section3/bernoulli.htm

http://www.efm.leeds.ac.uk/CIVE/CIVE1400/PDF/Notes/section_all2.pdf

Assignment 1 – Baseline Test

The homework assignment for the first tutorial is a baseline test to see your initial level of attainment in this subject area. The assignment will test for some or all of the subject specific skills that are required later in the final assignment. However, it is shorter than the final assignment and is will be an introduction to the subject as well as a challenge!

Do not worry too much about doing 'well' or 'badly' on the baseline test, it takes into account the fact that you may not be familiar with the subject area. It is designed to help you and your PhD tutor identify where you are at the start of the programme and to help you measure your progress along the way.

NB-The following exercise will contain non SI units. Unfortunately in some industries e.g. oil/gas this is a reality! Work through the exercise systematically starting with Question 1 to Question 7. Using Excel could be beneficial to lay out your results.

Consider the case, illustrated below, of a pipeline transporting water.

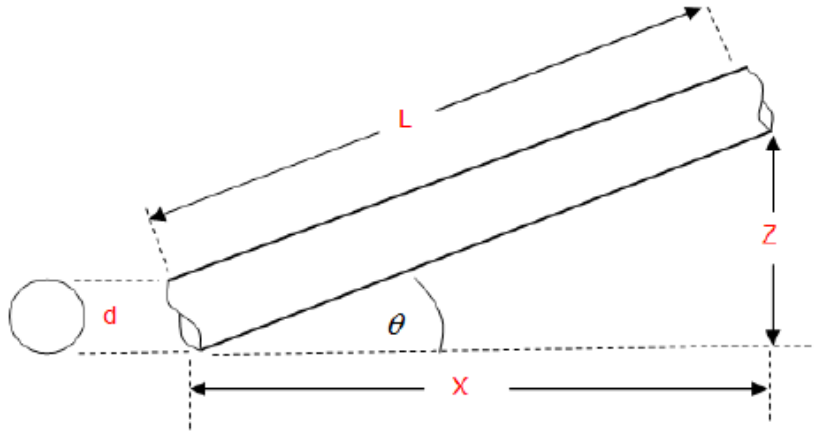


Figure 13 Pipeline transporting water

The pressure change per distance *L* for single phase flow is given by Bernoulli's equation:

$$\left(\frac{dp}{dL}\right)_{total} = \left(\frac{dp}{dL}\right)_{frictional} + \left(\frac{dp}{dL}\right)_{elevational} + \left(\frac{dp}{dL}\right)_{accelerational}$$

Assuming the accelerational term to be zero for your hand calculation, the pressure gradient equation becomes:

$$\left(\frac{dp}{dL}\right)_{total} = \frac{f\rho v^2}{2gd} \text{ (frictional) - } \rho g \sin\theta \text{ (elevational)}$$

where,

ρ = fluid density (lbm/ft^3)

g = gravitational constant

f = moody friction factor

v = fluid velocity (ft/s)

d = pipe inside diameter (ft)

In this exercise, using the data in the table and assuming the flow is isothermal, you perform a hand calculation to determine the delivery pressure of the pipeline using single-phase flow theory.

NOTE: You will need a hand calculator or MS Excel to complete this exercise

Table 2: Water Pipeline Data

Pipeline Data				
Diameter	d	3	in	(= 0.25 ft)
Length	L	20,025	ft	
Elevation Change	Z	1,000	ft	
Horizontal Distance	X	20,000	ft	
Ambient Temperature	T_{amb}	60	degF	
Inclination Angle	q	2.866	°	(=.05002 radians)
Roughness	e	0.0015	in	
Relative Roughness	ε/d	0.0005	in	
Fluid Data				
Water viscosity	μ_w	1.2	cp	(= 8.06e-4 lb/ft-s)
Water density	ρ_w	63.7	lbm/ft^3	

Table 2: Water Pipeline Data

Operating Data				
Source Temperature	T_{inlet}	60	degF	
Inlet Pressure	P_{in}	1,200	psia	
Water Flowrate	Q_w	6,000	BPD	(= 0.39 ft^3/s)
Constants				
Gravitational	g	32.2	ft/s^2	

1. Calculate the water velocity:

$$v = \frac{Q_w}{\left(\frac{\pi d^2}{4}\right)} = _____ \text{ ft/s}$$

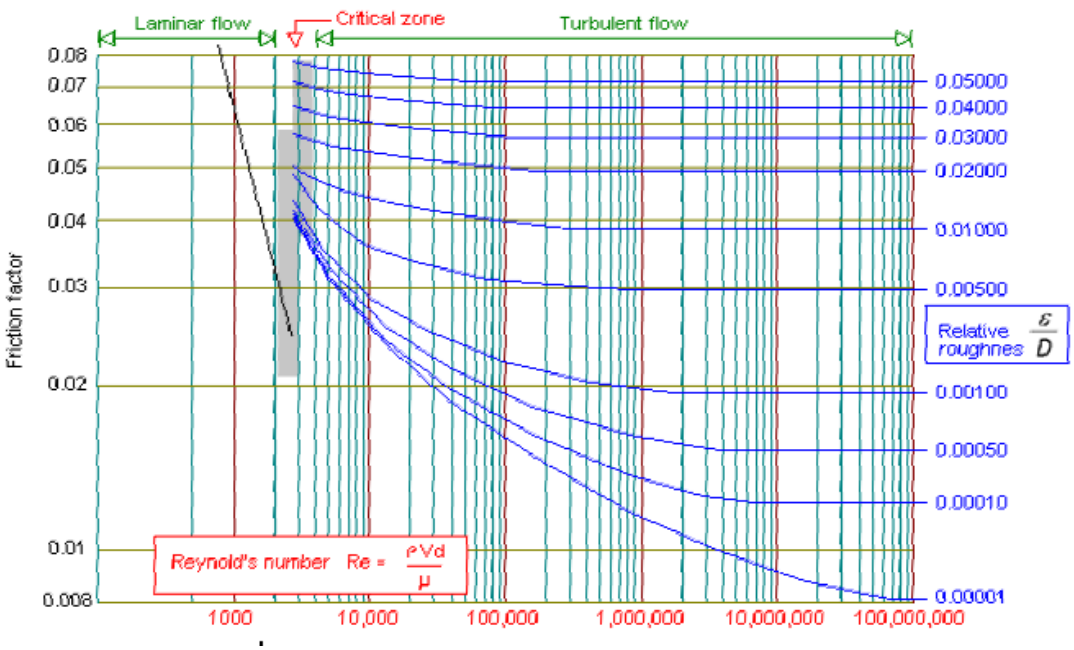
2. Calculate the Reynold's number:

$$\mathrm{Re} = \frac{\rho v d}{\mu} = _____$$

- Is the flow laminar or turbulent? (See the Moody Diagram on the following page.)

3. Lookup the friction factor using the Moody diagram shown below.

f = _____



4. Evaluate the frictional pressure term, $\frac{f\rho v^2}{2gd}$:

$\left(\frac{dp}{dL}\right)_{friction}$ = _____ psf/ft /144 = _____ psi/ft

For the given length of pipe, L,

$dp_{friction}$ = _____ psi

5. Evaluate the elevational pressure term, $\rho \sin\theta$

NOTE: If using Excel, be sure the angle is in radians.

$\left(\frac{dp}{dL}\right)_{friction}$ = _____ psf/ft /144 = _____ psi/ft

For the given length of pipe, *L*,

$dp_{elevation}$ = _____ psi

6. Add the frictional and elevational terms to determine the total pressure term:

$\left(\frac{dp}{dL}\right)_{total}$ = _____ psf/ft /144 = _____ psi/ft

For the given length of pipe, *L*,

dp_{total} = _____ psi

7. Calculate the outlet pressure given the inlet pressure: $P_{out} = P_{in} - dp_{total}$ = _____ psia

Answers for Tutorial 1

Pipeline Data							
Diameter	d	3	in	0.25	ft	0.0762	m
Length	L	20,025	ft				
Elevation	Z	1000	ft				
Hor Distance	X	20000	ft				
Ambient T	Tamb	60	degF				
Inclination	q	2.866	°				
Roughness	e	0.0015	in	0.0000381	m		
Rel Roughness	e/d	0.0005		0.0000127	m		
Fluid Data							
Water Viscosity	Muw	1.2	cp	8.06E-04	lb/fts		
Water Density	rhow	63.7	lbm/ft3				
Operating Data							
Source Temp	Tinlet	60	degF				
Inlet Pressure	Pin	1200	psia				
Water flowrate	Qw	6000	BPD	0.39	ft3/s		
		953.8951	m3/d				
Contants		0.01104	m3/s	0.3898899	ft3/s		
Gravity	g	32.2	ft/s2				
Velocity							
v	7.9450148	ft/s					
Dimensionless Numbers							
Re	1.57E+05						
Friction Factor							
f	1.93E-02	Using GOALSEEK					
Frictional Pressure Drop							
(dp/dL)f	4.8125436	psf/ft	0.03342	psi/ft			
For a given length of pipe							
dp (friction)	669.24434	psi					
gravitational Pressure Drop							
(dp/dL)g	3.1850178	psf/ft	0.022118	psi/ft			
For a given length of pipe							
dp (gravitational)	442.91654	psi					
Total Pressure drop							
Ptotal	1112.1609	psi					
Outlet Pressure							
Pout	87.839122	psia	6.05787	bar			

Tutorial 2 – Multiphase Flow and Multiphase Flow Patterns

What is the Purpose of Tutorial 2?

- Introduce Multiphase Flow and applications and brief history
- Discuss Flow patterns or flow regimes
  - -Flow patterns in vertical flow
  - -Flow patterns in horizontal flow

Introduction

Multiphase flows are ubiquitous, which makes them arguably more important than single phase systems. However, they must be treated as an entirely separate subject as they are significantly more complex than single phase systems. Examples of multiphase systems can be found in many fields and applications, some of which are obvious, and others less so. Volcanoes, weather systems and fizzy drinks are all examples of multiphase systems. Study of multiphase flow has been described as a black art, where challenges include the mechanisms of multiphase flow propagation along a pipe, how to pump a mixture comprising gas and liquid and how to measure the mixture's flowrate (King, 1990). Multiphase flow is still a relatively new subject area, with around half a century of research behind it. It is also a fairly specialised field of engineering, with many avenues that have not yet been explored. However, this is changing with the rapid advancement of technology, computational power and modern instrumentation.

It is possible to have two, three or even four phase systems and this is not to be confused with the traditional physics based definition of phases of matter. In this case, a phase is a macroscopic state of matter which is homogeneous in chemical composition and physical structure (Corradini, 1998). The three main phases are solid, liquid and gas (ignoring plasma as a phase). For example a four phase gas-liquid-liquid-solid system, consisting of gas-water-oil-sand, is common in the oil and gas industry. This project is focused on investigating two-phase gas-liquid flow, which again has many important industrial applications, such as in the chemical, nuclear and petroleum industries. Within two phase flows it is possible to have several combinations, which are gas-solid, gas-liquid, liquid-liquid and liquid-solid. It is also possible to have multi-component flow, for example in blood flow the plasma/platelet corpuscles can be described as two phase/multi-component flow (Corradini, 1998). Table shows a summary adapted from Crowe (1998):

Component	**Phase**	
	Single Phase Flow	***Multiphase Flow***
Single	*Single-phase, Single component* Flow of water, oil and O_2.	*Two-phase, Single component* Flow of water and steam.
Multiple	*Single-phase, multi component* Flow of air and liquid polymer mixture.	*Multi-phase, multi component* Flow of air, water and particles.

Table 2.1 - Single phase vs. multiphase, single vs. multi component, Crowe (1998).

A brief historical note

Examples of two-phase flows can be found throughout the history of science. Hero's Turbine, or 'Aeolipile', as shown in Figure 2.1 was invented around two thousand years ago by the Greek scientist Hero of Alexandria.

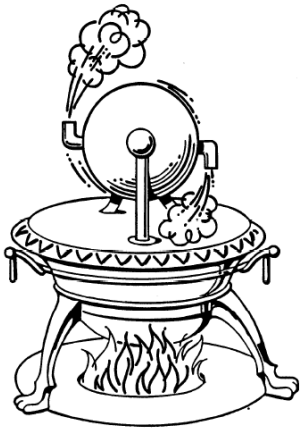


Figure 2.1 -Early examples of two-phase flows: Hero's Turbine

Hero's turbine was primarily a toy, where a ball was suspended on a pivot and a flame heated a small reservoir of water underneath the ball until it turned to steam. The steam was then directed to exit from nozzles located on the ball, which caused the ball to rotate due to Newton's laws. This principle was initially used to open temple doors and was also the precursor to the jet and steam engines. It is interesting to note that Akagawa et al. (1984) studied this device two thousand years later.

Introduction to Gas-Liquid flow

Gas-liquid flow is arguably the most complicated system to analyse out of the four possible combinations of two-phase flow, due to the infinitely deformable interface between the gas and liquid phases. There is the added complication that the gas phase is also compressible. Gas-liquid flows can occur in horizontal, vertical and inclined pipes, where each of these orientations will have its own characteristics, pressure drops and flow patterns. This section considers vertical gas-liquid flow, with both the gas and liquid "mixture" travelling upwards against gravity, which is known as co-current flow. It is important to note that this is on the "macro" scale, and that in the "micro" scale in vertical gas-liquid flow, the term "micro-gravity" is often used to indicate that in very small diameter pipes the gravity is negligible.

Gas-liquid two-phase flow is encountered in many important industrial applications in the oil, gas, chemical and nuclear industries. Applications include (Chisholm, 1983):

- Water tube boilers and reboilers.
- Water reactors in the nuclear industry.
- Gas lift pumps and oil wells; geothermal wells and volcanoes.
- Oil and gas transportation pipes and processing equipment.
- Refrigerators and process condensers.

Flow Patterns-Vertical Flow

When two fluids with different physical properties flow simultaneously in a pipe, there is a wide range of possible resulting flow patterns. The surface tension and gravity are the crucial physical parameters in determining the flow pattern in the pipe. The surface tension keeps the pipe walls wet, and it also encourages small liquid drops and small gas bubbles to be spherical in nature. The result of the gravitational force is that the liquid tends to be pulled to the bottom of the pipe (Ghajar, 2005). The multiphase flow may be classified as diabatic or adiabatic, which means it occurs with or without heat addition or removal at the channel wall. An example of adiabatic flow without heat transfer would be gas-oil or air-water flow in pipelines, which is the type of flow that will be investigated and analysed in this project. In this type of flow, the flow patterns change as the inlet mass flow rates of the gas or liquid are altered or as the velocity and void distributions develop along the channel. This is in contrast with diabatic flow, where boiling, dryout and phase change can occur (Corradini, 1998). Many different names have been given to these various patterns, with as many as 84 having been reported in the literature (Rouhani et al, 1983). The variations in nomenclature are partly due to the subjective nature of flow pattern definitions, and partly due to the variety of names given to what are essentially the same geometric flow patterns. However, these classifications can be reduced to five main flow patterns as shown in Figure 2.2, which is in contrast to one-phase flow, where their characterisation as laminar, transitional or turbulent is much simpler. For two-phase flow, bubbly and annular flows are often labelled as “continuous flow” whereas slug and churn flow are termed as “intermittent flow”. These flow patterns are dependent on various parameters, which are volumetric flow rate of each phase, pressure, density, viscosity and surface tension of the phases, pipe inclination and pipe diameter (Delhaye et al, 1979).

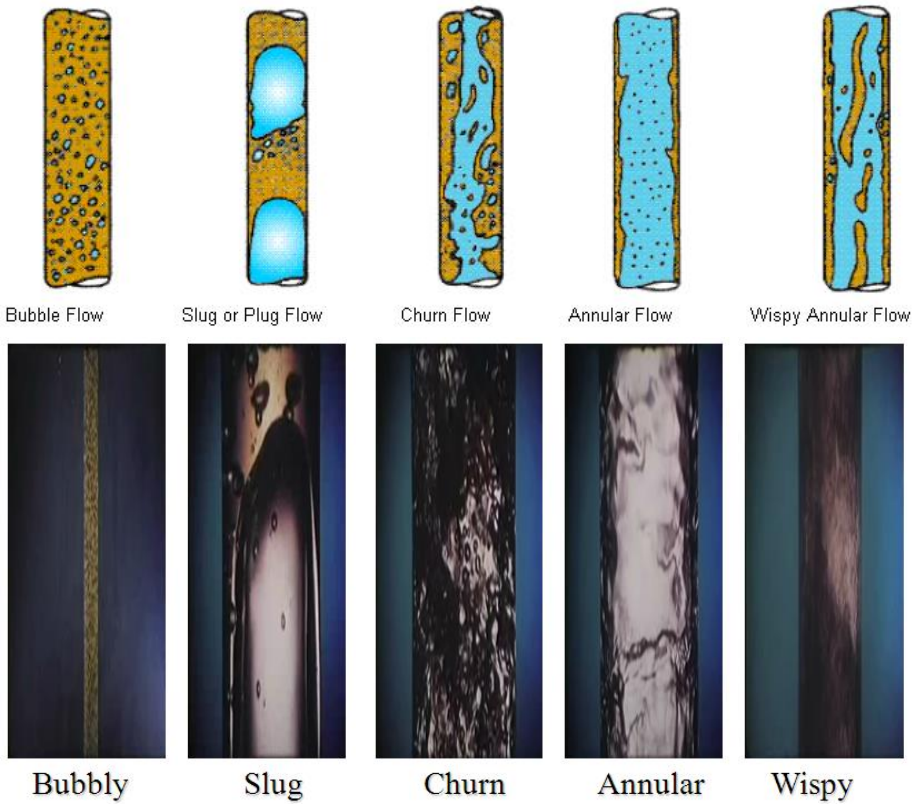


Figure 0.2 -Two-phase flow patterns; gas flow rate increasing from left to right (Sources: www.thermapedia.com, 2011 & Rhodes (1980))

Bubble Flow

Many bubbles can be observed as the gas is dispersed in the form of discrete bubbles in the *continuous* liquid phase. These bubbles vary in size and shape and generally are non-uniform in size and concentration. However, they are much smaller than the diameter of the tube itself and they rise inside the liquid due to buoyancy, which promotes collisions. In some circumstances, they congregate at the pipe centre, and in others, they are distributed near the pipe walls. The sizes of the bubbles and the distribution of their sizes are important parameters that need to be considered. The importance of bubble size has only been recognised comparatively recently (Song et al, 1995). In any bubble flow, two opposing processes are at work, which are bubble coalescence as a result of bubble collisions, and bubble break up as a result of turbulence in the liquid phase. At low liquid velocities when turbulence is small, bubble coalescence dominates and the equilibrium bubble size is large. These larger bubbles have distorted, constantly varying shapes, and they rise with a spiral or zigzag trajectory, which promotes collisions. At higher velocities turbulence is increased, and the equilibrium bubble size is smaller. These smaller bubbles are essentially spherical, and they rise rectilinearly, reducing the number of collisions. This leads to the two sub-regimes described above being termed as “discrete bubble” (low turbulence) and “dispersed or poly-dispersed bubble” (high turbulence).

Slug or Plug Flow

With an increasing gas void fraction, the proximity of the bubbles becomes closer such that bubbles collide and coalesce to form larger bubbles, with the bubble size tending towards that of the channel (cross-section of the pipe). These bubbles have a characteristic shape similar to a bullet, with a hemispherical nose and a blunt tail end. They are commonly referred to as “Taylor bubbles” or sometimes “Dumitrescu bubbles”, and are considered as the “plugs”. The Taylor bubbles are separated from one another by “slugs”` of liquid and small bubbles may be present. Small bubbles may also be present in the wake behind the slug regions. The behaviour of the entrained gas travelling in between the Taylor bubbles is not well understood. Taylor bubbles are surrounded by a thin liquid film, situated between them and the tube wall, which may flow downward due to the force of gravity even though the net flow of fluid is upward. Therefore, slug flow displays *intermittency* in the flow direction, which results in a significant change in the shear stress/frictional pressure gradient, resulting in negative values that are not consistent with some correlations.

Churn flow

Increasing the superficial gas velocity results in the structure of the flow becoming unstable after the break down of the Taylor bubbles. The gas-liquid mixture travels up and down in an oscillatory or churning motion, but with a net upward flow. The instability is the result of the relative parity of the gravity and shear forces acting in opposing directions on the thin film of liquid surrounding the Taylor bubbles. This flow pattern is in fact an intermediate pattern between the slug flow and annular flow regimes (Figure 0.3).

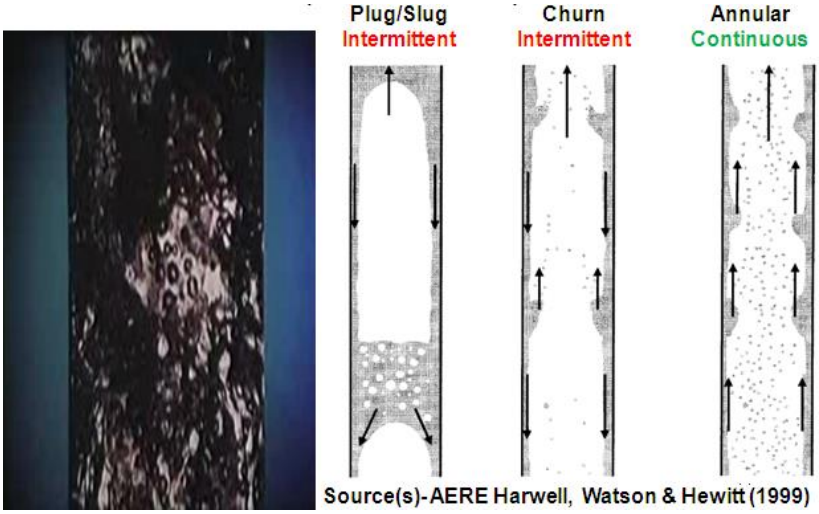


Figure 0.3-Slug/Churn/Annular in a cross-section of pipe

Churn flow is an important pattern, which often covers a fairly wide range of gas flow rates. At the lower end of the range, churn flow may be regarded as a broken-up form of slug flow, with occasional bridging across the tube by the liquid phase. At the higher end of the range of gas flow rates, churn flow may be considered as a degenerate form of annular flow, with variation in the direction of the film flow and very large waves being formed on the interface as shown in Figure 0.3. In this higher range, the term 'semi-annular flow' has sometimes been applied. A mechanistic description of the gas-liquid interaction in the churn flow regime is very difficult.

Annular Flow

Once the interfacial shear of the high velocity gas on the liquid film becomes dominant over the gravitational force, the liquid is expelled from the centre of the tube and flows as a thin film on the wall, which forms an annular ring of liquid, "wetting" the wall. The gas flows together with the liquid as a continuous phase up the centre of the tube, as shown in Figure 0.3. The interface between them is disturbed by high frequency waves and ripples. Waves are formed on the surface of the liquid film and the amplitude of the waves increases as the gas velocity increases. In addition, liquid may be entrained in the gas core as small droplets, and the fraction of liquid that is entrained may be balanced by the re-deposition of droplets from the gas core onto the liquid film. The liquid phase is always moving upwards, whether as droplets or a film, which is what distinguishes annular flow from churn flow, although in both flow patterns there is a continuous gas core. Pure annular flow, without any entrained droplets present at all, is probably not realisable in practice for most gas-liquid applications.

Wispy-Annular Flow

This unusual flow pattern was first identified by Bennett et al. in 1965. If the liquid flow rate is increased further, large liquid objects may be observed within the gas core. These have been termed 'wisps'. Their appearance has been compared to ectoplasm. This has been classified as a separate flow pattern by Hewitt-Roberts (1969) although several other flow maps don't refer to it. Hawkes et al. (2000, 2001) have suggested that the wisps arise from agglomeration of the drops that must be present in large concentrations within the gas core. Under some circumstances, bubbles of gas may be entrained in the liquid film. This flow pattern is important in a wide range of industrial applications, such as in nuclear reactors and power station boilers.

Flow Patterns-Horizontal Flow

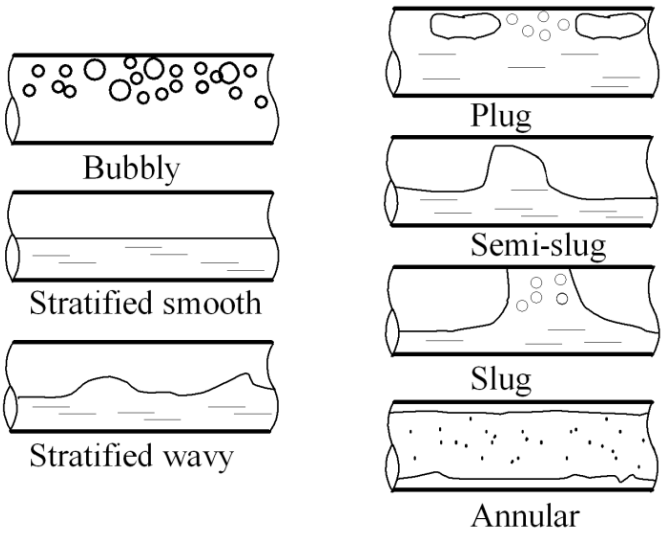


Figure 2.4-Flow patterns in horizontal flow

When gravity acts perpendicularly to the tube axis separation of the phases can occur. This increases the possible number of flow patterns, as shown schematically in Figure 2.4. **Bubbly flow**, like the equivalent pattern in vertical flow, consists of gas bubbles dispersed in a liquid continuum. However, except at very high liquid velocities when the intensity of the turbulence is enough to disperse the bubbles about the cross section, gravity tends to make bubbles accumulate in the upper part of the pipe as illustrated. In **Stratified flow** liquid flows in the lower part of the pipe with the gas above it. The interface is smooth. An increase of gas velocity causes waves to form on the interface of stratified flow to yield **Wavy flows. Plug flow** is characterised by bullet shaped gas bubbles as seen in vertical flow. However here they travel along the top of the pipe. **Slug flow**, like plug flow, is intermittent. The gas bubbles are bigger whilst the liquid slugs contain many smaller bubbles. At large levels of aeration, they are called **frothy** surges or **semi-slug**, if the surges do not fill the pipe completely. However, this might be more correctly considered as part of wavy flow. A continuous gas core with a complete wall film characterises **Annular flow.** As in vertical flow, some of the liquid can be entrained as drops in the gas core. Gravity causes the film to be thicker on the bottom of the pipe but as the gas velocity is increased the film becomes circumferentially more uniform.

Assignment Two

1. We will as a group watch the informative video gas-liquid flow. Much of the information in this tutorial will be demonstrated in the video where the flow patterns are videoed. Try to take notes as you watch the video.

2. Attempt the following exercise if possible and with care: get some fizzy drink (preferably 7up or carbonated water) and put a little in a cup and put a salted peanut inside and let it settle to the bottom, what do you observe happens? Can you offer an explanation why?

3. How do the flow patterns differ between horizontal and vertical flow? Why do you think they are different?

4. Sciencedirect is the defacto website for downloading research papers. Have a look at it and download the following paper: doi:10.1016/j.ijmultiphaseflow.2015.09.005. It is available under open access of EPSRC. Read the paper and summarise what you understood from it in a paragraph or two. This exercise will give you practice in reading and understanding scientific papers and this is an essential skill for University and Research learning!

Tutorial 3 – Multiphase Flow Concepts

What is the Purpose of Tutorial 3?

- Introduce further multiphase concepts
  - -Void Fraction
  - -Pressure drop (not single phase)

Void Fraction

The void or gas fraction ε_g is a dimensionless quantity that varies between 0 to 1, or is sometimes expressed as a percentage between 0-100%, which indicates the fraction of a geometry or temporal domain occupied by the gas phase. It is probably the most significant quantity that could be measured in two-phase flow (Bertola, 2003). It is sometimes referred to as "liquid hold-up", which is equal to 1- ε_g. Void fraction is a function of many parameters, such as the fluid physical properties, pipe dimensions, angle of inclination, phase flow rates and system pressure. It is an important quantity in two-phase pressure drop prediction, flow pattern transitions, heat transfer and sizing of process and control equipment, such as slug catchers, separators, two-phase pumps and control valves. The gas fraction will change progressively along the pipe length, due to the change in fluid pressure and temperature (Saleh 2002). The void fraction will determine the two-phase density, two-phase viscosity and the relative average velocity between the two phases. Understanding where the liquid or gas is located inside the pipe and how it is distributed (the phase distribution) is of great importance to many industries. A **local** time-averaged void fraction may be determined by measuring the cumulative residence time of the gas phase over a total time interval t. Such a measurement may be made using electrical or optical probes (Hewitt 1978). Alternatively, at any instant of time, a line passing through the channel normal to the channel axis will lie partly in the liquid phase and partly in the gas phase. An instantaneous line-averaged or **chordal** void fraction may be defined as the length of the line submerged in the gas phase over the total length of the line within the channel. Such a measurement may be made using the attenuation of an x-ray or γ-ray beam (Hewitt 1978). Similarly, an instantaneous **area** (or volume) averaged void fraction may be defined as the area (or volume) of the channel occupied by the gas phase divided by the cross sectional area (or total volume) of the channel. The **volume** averaged gas fraction may be measured using quick-closing valves at the entrance and exit of the channel (Hewitt 1978). The space and time averaged gas fractions will be equal only in the circumstance when the flow is steady and one-dimensional. These definitions are summarised in Figure (Thome, 2004).

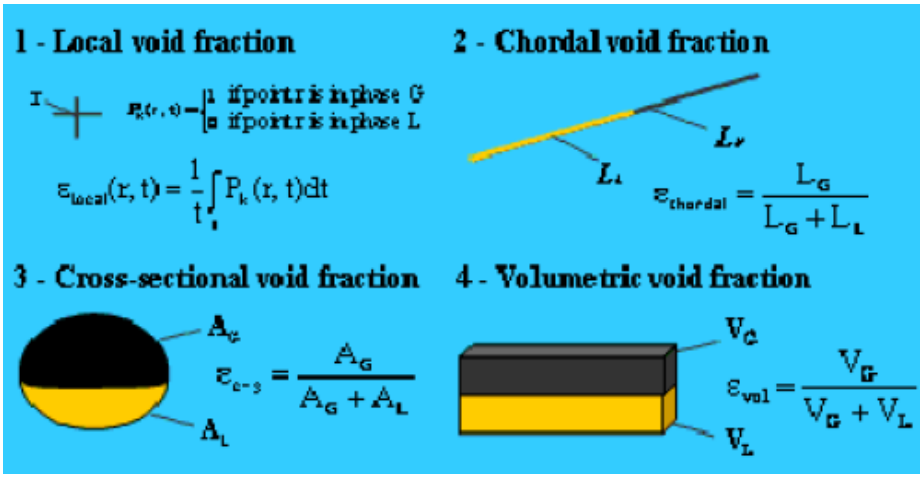


Figure 3.1-The different definitions of void fraction, Thome (2004)

It is important to differentiate between the different types of void fraction, as occasionally they are treated as being the same in some literature, which is clearly not correct. A general expression for the void fraction can be derived as follows (Azzopardi, 2003, 2006), where the flow rate and cross-sectional area can be eliminated:

$$\varepsilon_g = \frac{1}{1 + U_R \dfrac{\rho_g (1 - x_g)}{\rho_l x_g}} \tag{3.1}$$

$$U_R = \frac{u_g}{u_l} = \frac{U_{gs}(1 - \varepsilon_g)}{U_{ls}\varepsilon_g} \tag{3.2}$$

$$\frac{u_g}{u_l} = \frac{Q_g / A_g}{Q_l / A_l} \tag{3.3}$$

From equation (3.1), the higher the quality x_g the bigger the void fraction will be. U_R is known as the slip ratio or velocity ratio, which is a dimensionless quantity. In this report, ε_g is generally the cross-sectional void fraction. Note that u_g *and* u_l are the true phase velocities in equation (3.2). When $u_g = u_l$ then $U_R = 1$ in equation (3.1) and this is known as the homogeneous flow model. The homogeneous void or gas fraction is given as (Azzopardi, 2003, 2006):

$$\varepsilon_{g\,H} = \frac{1}{1 + \dfrac{U_{ls}}{U_{gs}}} = \frac{1}{1 + \dfrac{(1 - x_g)}{x_g}\dfrac{\rho_g}{\rho_l}} \tag{3.4}$$

The gas phase tends to travel faster than the liquid phase, for example in annular flow the gas core would flow faster than the liquid film on the pipe wall. This is because $\rho_l > \rho_g$. which implies $U_R > 1$ and this will be known as the separated flow model. At this stage ε_g is unknown, therefore U_{ls} *and* U_{gs} can be calculated, and these are known as the phase superficial velocities. These are the theoretical velocities each phase would possess if it flowed on its own within the entire pipe cross-section, and they can be calculated as long as the flow rate of each phase is known. The mixture velocity is defined as the sum of these two superficial velocities, which are given for the gas and liquid as:

$$U_{gs} = \frac{Q_g}{A_g + A_l} = \frac{\dot{m}\, x_g}{\rho_g}; \quad U_{ls} = \frac{Q_l}{A_g + A_l} = \frac{\dot{m}(1 - x_g)}{\rho_l} \tag{3.5}$$

The quality can also be expressed in terms of the superficial velocities as follows:

$$x_g = \frac{U_{gs}\rho_g}{U_{gs}\rho_g + U_{ls}\rho_l} \tag{3.6}$$

In order to calculate ε_g, it is first necessary to determine U_R when $U_R > 1$.

Slip Ratio U_R.

Several correlations have been reported for U_R. Some of these are empirical, and some analytical. Examples of these can be found in works by, Zivi (1964), Zuber (1967), CISE (1970), Smith (1971), Chisholm (1972) and HTFS. Details of two of these correlations by Chisholm and CISE are given below. Correlations have in general been derived from data

obtained from small diameter pipes and correlations must be treated with care when they are applied to large diameter pipes where clearly errors can be generated.

Chisholm Correlation

Chisholm's correlation provides a very simple, reasonably accurate result, and is useful for determining a quick estimate of U_R:

$$U_R = \left[1 - x_g\left(1 - \frac{\rho_l}{\rho_g}\right)\right]^{0.5} \tag{3.7}$$

CISE Correlation

Premoli et al. (1970), also known as the CISE correlation, yielded a more complicated expression for U_R. CISE correlation is generally the most accurate applicable correlation (Whalley 1987, Hills et al 1997), and it is summarised below.

$$U_R = 1 + E_1\left(\frac{j}{1+E_2 j}\right)^{0.5} \quad \text{for } \frac{j}{1+E_2 j} > E_2 \tag{3.8}$$

$$U_R = 1 \text{ for homogeneous flow} \tag{3.9}$$

$$\text{where } j = \frac{\varepsilon_{gH}}{1-\varepsilon_{gH}} \tag{3.10}$$

$$E_1 = 1.578\,\mathrm{Re}^{-0.19}\left(\frac{\rho_l}{\rho_g}\right)^{0.22} \tag{3.11}$$

$$E_2 = 0.0273\mathrm{We}\ \ \mathrm{Re}^{-0.51}\left(\frac{\rho_l}{\rho_g}\right)^{-0.08} \tag{3.12}$$

Re and Weber numbers used here are defined as

$$\mathrm{Re} = \frac{(\dot{m}_g + \dot{m}_l)D_t}{\eta_l} \qquad We = \frac{(\dot{m}_g + \dot{m}_l)^2 D_t}{\sigma\rho_l} \tag{3.13}$$

Pressure Drop

Apart from the void fraction, the next important quantity that requires definition for two-phase flow is the pressure drop. There are several methodologies for calculating the pressure drop, and these will be explained in this section. Calculating the pressure drop is a major requirement for two phase flow, which is involved in the calculation of flow rates under a given head loss, and of pumping requirements for a given flow rate. For many years, when the structure of gas/liquid flows were not well understood, methods for calculation of pressure drop were produced by fitting the constants in equations using experimental data. Whilst this might be acceptable when the fluids are essentially the same, such as stream/water, and the process is one of interpolation, it is more difficult and dangerous to take large steps to new fluids or geometries. Use of larger databases does help but there really is a need for more physical understanding. Another problem which might make data fitting difficult and which might be the source of difference between experiments, accounting for some of the scatter in the data from ostensibly the same

experimental conditions, concerns the question as to whether a given flow is fully developed. Some experiments on vertical pipes indicate that as much as 200 pipe diameters are needed to establish fully developed flow, and such a length is rarely provided in experimental rigs. While it might be possible to establish a set of data in fully developed flow, the practical value would be small since very few industrial two-phase flow systems have more than 200 diameters of straight, uninterrupted pipe run without bends, T-junctions or other fittings.

The pressure will vary from one flow pattern to another. The onset of slug flow is accompanied by a sharp decrease in the pressure gradient down to a minimum value (Owen 1986). As the gas velocity is further increased, the pressure gradient initially increases significantly with the onset of churn flow. It reaches a maximum and then drops, subsequently passing through a minimum value. Eventually the pressure gradient increases again with the onset of annular flow as the gas flow rate increases, as shown in Figure3.2. The figure also shows how the various correlations described earlier compare with experimental data from Owen (1986). Most perform well except for the homogeneous approximation. The downward part of the curve will be dominated by gravity as the flow rate is low, and hence flow-dependent frictional losses will also be low. This continues up to a minimum value, and then the frictional pressure drop will exceed the gravitational forces at the higher flow rates. From an industrial perspective, some flow patterns are considered to be more beneficial than others depending on the situation and application. For example, bubbly flow is desirable in chemical reactors and in the oil and gas industry. The reason for this slug and churn flows can cause pressure fluctuations, hence significant vibration and potential damage to equipment and pipework, meaning in some cases expensive solutions such as slug catchers may be required. However, slug and churn flows may be favoured over bubbly/mist flows which are difficult to deal with by separators due to the presence of very small bubbles and drops. Slug flow can also assist in cleaning up pipes by acting as a virtual “pig”, and can also aid solid transportation. Annular flow is a particularly stable type of flow and can be found in many industries. For example it may be applied to cool down pipes through the formation of the liquid film on the pipe wall.

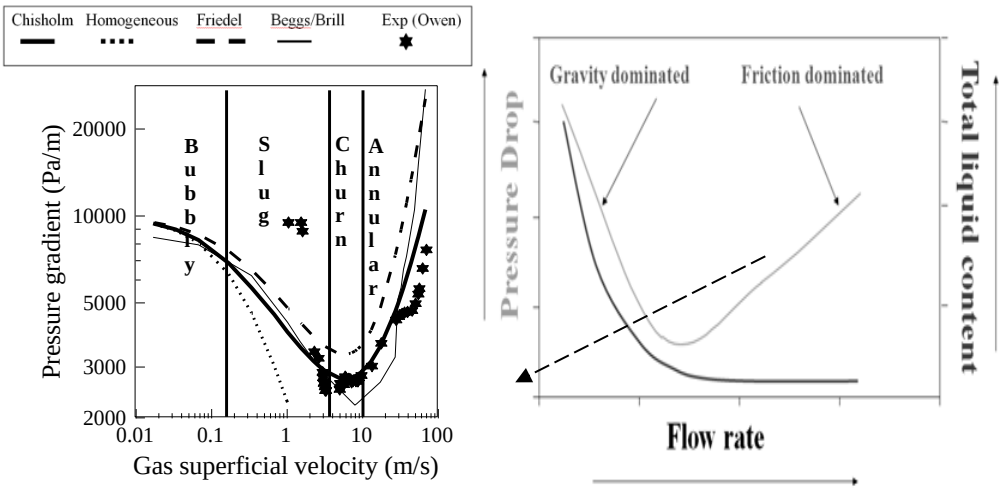


Figure 3.2-Pressure gradient of air-water mixture in a vertical tube. Azzopardi (2010)

The downward part of the curve will be dominated by gravity as the flow rate is low, and hence flow-dependent frictional losses will also be low. This continues up to a minimum value, and then the frictional pressure drop will

exceed the gravitational forces at the higher flow rates. From an industrial perspective, some flow patterns are considered to be more beneficial than others depending on the situation and application. For example, bubbly flow is desirable in chemical reactors and in the oil and gas industry. The reason for this slug and churn flows can cause pressure fluctuations, hence significant vibration and potential damage to equipment and pipework, meaning in some cases expensive solutions such as slug catchers may be required. However, slug and churn flows may be favoured over bubbly/mist flows which are difficult to deal with by separators due to the presence of very small bubbles and drops. Slug flow can also assist in cleaning up pipes by acting as a virtual "pig", and can also aid solid transportation. Annular flow is a particularly stable type of flow and can be found in many industries. For example it may be applied to cool down pipes through the formation of the liquid film on the pipe wall.

Homogeneous Flow

The simplest approach to analysing two-phase flow is homogeneous flow, where the liquid and gas are replaced by a theoretical single phase fluid travelling with one velocity (equivalent to the liquid and gas phases travelling with equal velocities). The phase temperatures and pressures are also assumed to be equal. The corresponding pressure drop for homogeneous flow is (Whalley, 1987 and Hewitt, 1998):

Change in momentum= Wall Shear Stress+Gravitational Force+Pressure Force

$$-\frac{dp}{dz} = -\left(\frac{dp}{dz}\right)_{friction} - \left(\frac{dp}{dz}\right)_{gravitation} - \left(\frac{dp}{dz}\right)_{acceleration} \tag{3.14}$$

$$-\frac{dp}{dz} = \bar{\tau}\frac{P}{S} + \rho_H g \sin\beta + \dot{m}^2 \frac{d}{dz}\left(\frac{1}{\rho_H}\right) \tag{3.15}$$

You may recognise equation (3.14) as it is very similar to the one used in Tutorial 1.

Separated Flow

For separated flow, the two phases are no longer assumed to flow with same velocities. Essentially, this is a 1D approach i.e. all changes occur along the pipe. A "generalised" equation is given by (Hewitt 1998, Azzopardi 2006):

$$-\frac{dp}{dz} = \bar{\tau}\frac{P}{S} + \rho_{MP} g \sin\beta + \dot{m}^2 \frac{d}{dz}\left[\sum_{s=1}^{n} \frac{\dot{x}_s^2}{\rho_s \varepsilon_s}\right] \tag{3.16}$$

The pressure drop equation can also be written as (see Appendix A for more details):

$$-\Delta p = \int_{z_1}^{z_2} \frac{4 f_{lo}}{d} \frac{\dot{m}^2}{2\rho_l} \phi_{lo}^2 \, dz + \int_{z_1}^{z_2} [\varepsilon_g \rho_g + (1-\varepsilon_g)\rho_l] \, g \sin\beta \, dz + \left[\dot{m}^2 \left(\frac{x_g^2}{\varepsilon_g' \rho_g} + \frac{(1-x_g)^2}{(1-\varepsilon_g')\rho_l}\right)\right]_{z_1}^{z_2} \tag{3.17}$$

In vertical flow the majority of pressure loss will be due to the gravity or head of liquid at low quality values. It should be noted that for higher velocities and quality, frictional and accelerational losses contribute a greater part to the total pressure drop, and therefore cannot be neglected at the higher flow rates (Saleh, 2002, Takacs, 2005). The

accelerational term tends to be important when there is a phase change in the form of evaporation or condensation. In this handbook, the accelerational term will be assumed to be small and can be neglected; hence equation (3.17) can be simplified to:

$$-\Delta p = \int_{z_1}^{z_2} \frac{4 f_{lo}}{d} \frac{\dot{m}^2}{2 \rho_l} \phi_{lo}^2 \, dz + \int_{z_1}^{z_2} [\varepsilon_g \rho_g + (1-\varepsilon_g) \rho_l] \, g \, dz \qquad (3.18)$$

From equation (2.13), the gravitational pressure drop can be seen to be dependent on ε_g and therefore as ε_g is increased, the gravitational pressure drop decreases. This is behind the use of artificial gas lift in vertical facilities in the oil industry. As the gas is injected into the system, the void fraction is increased, therefore the gravitational pressure drop decreases, and this subsequently reduces the pumping power requirements.

Beggs and Brill (1973) published an alternative equation for the pressure drop based on the homogeneous model, that includes an accelerational component:

$$-\frac{dp}{dz} = \frac{g \sin\beta \, [\rho_g \varepsilon_g + \rho_l (1-\varepsilon_g)] + \dfrac{f_{TP} \dot{m} (U_{gs} + U_{ls})}{2 D_t}}{1 - [\rho_g \varepsilon_g + \rho_l (1-\varepsilon_g)] \dfrac{(U_{gs} + U_{ls}) U_{gs}}{p}} \qquad (3.18a)$$

Frictional Pressure Drop

The two phase frictional pressure drop can be considered as the product of a single phase frictional pressure gradient multiplied by a two phase multiplier ϕ_{lo}^2:

$$-\Delta p_{frictional} = \int_{z_1}^{z_2} \frac{4 f_{lo}}{d} \frac{\dot{m}^2}{2 \rho_l} \phi_{lo}^2 \, dz = \frac{4 f_{lo}}{d} \frac{\dot{m}^2}{2 \rho_l} \int_{z_1}^{z_2} \phi_{lo}^2 \, dz \qquad (3.19)$$

It is not possible to measure the frictional pressure drop directly, so this term is obtained by subtracting the measured acceleration (unless this is neglected) and gravity components from the measured total pressure drop. There are many frictional pressure drop correlations presented in the literature, for example Martinelli-Nelson (1948), Lockhart-Martinelli (1949), Bankoff (1960), Duckler (1964), Thom (1964), Baroczy (1966), Chawla (1968), Gronnerud (1972), Beggs and Brill (1973), Chisholm (1973), Friedel (1979), Muller-Steinhagen and Heck (1986).

Hewitt (1998) reported that Whalley (1980) made an extensive comparison and evaluation between various published correlations and the HTFS proprietary database (which consisted of over 25,000 data points). The following recommendations were made:

- $\frac{\eta_l}{\eta_g} < 1000$ and $\dot{m} < 2000$ kg/m^{2}s, then Friedel (1979) correlation should be used.
- $\frac{\eta_l}{\eta_g} > 1000$ and $\dot{m} > 100$ kg/m^{2}s, then Chisholm (1973) correlation should be used.

- $\frac{\eta_l}{\eta_g}$ > 1000 and $\dot{m}$ < 100 kg/m^{2}s, then Lockhart-Martinelli (1949) should be used.

Friedel Correlation

For most fluids, $\frac{\eta_l}{\eta_g}$ < 1000. For example, for the two-phase air-water mixture then: $\frac{\eta_l}{\eta_g}$ =53.867 (at normal pressure). The Friedel (1979) correlation is therefore recommended, which is a fairly complicated expression:

$$\phi_{lo}^2 = A_1 + A_2 \qquad (3.20)$$

where $$A_1 = (1 - x_g)^2 + x_g^2 \frac{\rho_l}{\rho_g} \frac{f_{go}}{f_{lo}} \qquad (3.21)$$

and $$A_2 = \frac{3.24\ x_g^{0.78}\ (1 - x_g)^{0.224} \left(\frac{\rho_l}{\rho_g}\right)^{0.91} \left(\frac{\eta_g}{\eta_l}\right)^{0.19} \left(1 - \frac{\eta_g}{\eta_l}\right)^{0.7}}{Fr^{0.045}\ We^{0.035}} \qquad (3.22)$$

for horizontal and vertically upward flow. In these equations, f_{lo} and f_{go} are the single phase friction factors if all the flow were liquid or gas respectively and $We = \frac{\dot{m}_{TP}^2 D_t}{\rho_{TPH}\ \sigma}$ where ρ_{TPH} is the homogeneous two-phase density

$$\rho_{TPH} = \left(\frac{x_g}{\rho_g} + \frac{(1 - x_g)}{\rho_l}\right)^{-1} \qquad (3.23)$$

Assignment Three

1. A steam-water mixture flows in a 11/2" (0.0381 m) vertical pipe at a pressure of 20 bar. The mass flux is 500 kg m^{-2} s^{-1} and the mass quality 0.2. Calculate the void fraction and mean density using homogeneous flow theory. Data for steam-water at 20 bar are below. [**Ans: 0.955, 47.7 kg m^{-3}**]

2. (i) Repeat the calculation of question 1(a) using:
   a) Chisholm's correlation, eqn (3.7). [**Ans: 0.834, 149.1 kg m^{-3}**]
   b) The CISE correlation, eqn (3.8-3.13). [**Ans: 0.885, 106.1 kg m^{-3}**]
   c) What do you understand is meant by the word correlation?

   (ii) What do you infer from the calculations carried out in (1) and (2)?

3. (Advanced question) The pipe of question 1(a) is 10 m long, and the inlet pressure is 20 bar. Calculate the pressure loss in (a) horizontal and (b) vertically upward flow, using the Friedel correlation for the two-phase multiplier and the CISE correlation for void fraction. The relative pipe roughness may be taken as 0.008, which, for Reynolds numbers in excess of 10^5, leads to a single-phase friction factor of 8.8×10^{-3}, independent of Re.

   [**Ans: (a) Horiz = 0.294 bar, (b) Vert = 0.398 bar**].

Physical property data are below for steam-water at 20 bar

Temperature = 212°C

ρ_l = 849.3 kg m^{-3}	ρ_g = 9.997 kg m^{-3}.
η_l = 1.270×10^{-4} kg m^{-1} s^{-1}	η_g = 1.603×10^{-5} kg m^{-1} s^{-1}
h_l = 910.7 kJ kg^{-1}	h_g = 2797 kJ kg^{-1}
c_{Pl} = 4.563 kJ kg^{-1} K^{-1}	c_{Pg} = 3.087 kJ kg^{-1} K^{-1}
σ = 0.03501 N m^{-1}	

Tutorial 4 – Multiphase Flow Pattern Maps

What is the Purpose of Tutorial 4?

- Introduce flow pattern maps and their significance
  - Flow maps for vertical flow
  - Flow maps for horizontal flow

Vertical Flow in Pipes

Early work often represented the observed flow patterns on two dimensional diagram in terms of system variables. The most common variables used are the liquid and gas superficial velocities (volumetric flow rate/cross sectional area of the pipe). Since variables other than the superficial velocities are known to affect the flow pattern, maps of this kind are specific to a particular combination of fluids and geometry. However, they are simple to use, and unlike the case of single-phase Newtonian flow where the single parameter of Reynolds number brings all flows together, it is by no means clear exactly which other variables should be included. No reliable universal flow map has yet been produced. The commonest way of constructing a flow map is to identify the flow pattern at a set of conditions covering the field, and then to sketch in boundary lines separating the different patterns. Because of problems in correctly identifying flow patterns, it often happens that a few experimental points lie on the wrong side of these lines, and the lines would be better regarded as transition zones, of indeterminate width. This should always be remembered when using maps on which only the boundary lines appear.

For **vertical upflow**, flow pattern maps based on superficial velocities have been published since the 1960's and are still being produced. Some workers have presented maps where the superficial velocities are modified by factors in the form of ratios of actual physical properties to standard values raised to different powers. One of the most popular flow pattern maps for vertical flow is that of Roberts-Hewitt (1969), as shown in Figure 4.1. This map was constructed using data from a 0.032m diameter pipe for air-water at 0.4-4.5 bar(g), and from steam-water data by Bennett et al. (1965) for a 0.0127m diameter pipe at elevated pressures of 35 and 70 bar(g). The map uses the momentum flux for gas ($\rho_g U_{gs}^2$) against liquid ($\rho_l U_{ls}^2$) instead of the superficial velocities of liquid against gas to cover a wider variety of fluids and geometries, in order to take into account the densities of the phases.

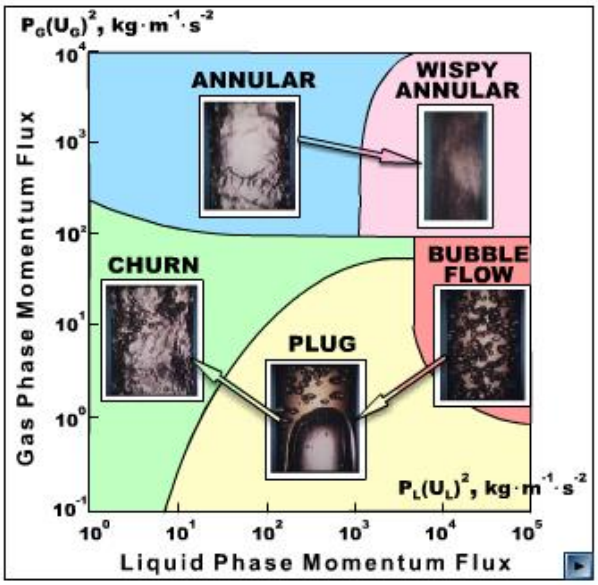
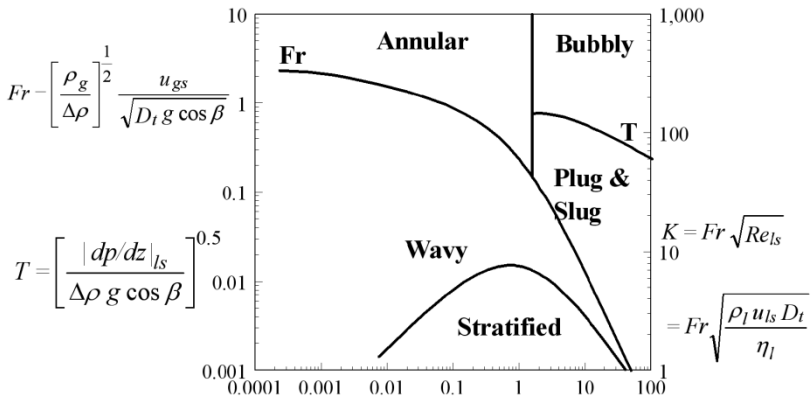


Figure 4.1 -Hewitt and Roberts flow pattern map (1969).

Horizontal Flow in Pipes

In **horizontal flows** the flow pattern map of Baker (1954) still has great popularity. To its credit, it is simple and based on industrially relevant data (gas/condensate flows at high pressure in 5"-10" lines). Subsequent work has shown some of its transition boundaries to be poor. Much more popular is the composite map of Taitel and Dukler (1976) illustrated in Figure 4.2.



$$X^2 = \frac{(dp_F/dz)_l}{(dp_F/dz)_g}$$

Figure 4.2-Flow pattern map of Taitel and Dukler (1976) for horizontal flow

The approach for transitions in horizontal and near horizontal pipes which was first suggested by Taitel and Dukler (1976), starts with an estimation of the position of the interface that would be present were the flow stratified. This was obtained from force/momentum balances on each phase. The pressure gradient is eliminated by combining the two equations. Wall and interfacial shear stresses are defined as if the flow is in channels of non-circular section. After careful non-dimensionalisation, the resulting equation can be solved to yield the position of the interface. The growth or decay of a perturbation of the interface, say an upwelling, to the effect of gas velocity (making it rise by the Bernoulli effect) and gravity (pulling it down) was then modelled. The conditions at which the perturbation rose gave the flow rates at the flow pattern transition between stratified and annular or slug. The transition between the latter two patterns was taken to be when the pipe was half full. If the interface was above the horizontal diameter, then slug flow would ensue, lower liquid levels, it was suggested, would result in annular flow. The stratified smooth to stratified wavy transition is also obtained from analysis of the stability of the interface. Taitel and Dukler (1976) made a significant step forward. They concluded that a single pair of axes was not sufficient, and produced the map of Figure 4.2. The approach produced models for the individual transitions and from these both appropriate axes and the transition curves were determined. The method has been tested against a wide range of experimental data. Reasonable agreement was obtained for air/water in a range of pipe sizes. However, the stratified/non-stratified transition was poorly predicted for high pressure hydrocarbon systems and air flowing in combination with a liquid whose viscosity was 0.15 Pa s.

Assignment Four

Precursor: Watch the gas-liquid video again to gain a further understanding of flowmaps.

1. 0.5 kg s^{-1} of a water-steam mixture flows at 20 bar pressure up a vertical tube of diameter 1" (0.0254 m). Physical property data are below for steam-water at 20 bar. Using the Hewitt and Roberts flow pattern map determine the flow pattern to be expected when the mass quality is:

   (a) x_g = 1% and (b) x_g = 20%.

   c) Sketch on the map how the operating point would vary if the mass flow rate was steadily increased at a constant mass quality of 1%.

   d) If 0.5 kg s^{-1} of mixture flows up a 1" pipe, what is the minimum quality to avoid the possibility of pulsating flow (plug/slug or churn)? [**Ans: 0.032**]

2. (Extension) Repeat 1 (a) to (d) with the pipe horizontal, using the Baker map.
   A version with log-log grid is below. [**Ans for (d): 0.028**]

   On baker map figure:

$$\lambda = \left(\frac{\rho_g}{\rho_{air}} \frac{\rho_l}{\rho_{water}} \right)^{\frac{1}{2}} \quad \text{and} \quad \psi = \frac{\sigma_{water}}{\sigma} \left(\frac{\mu_l}{\mu_{water}} \left[\frac{\rho_{water}}{\rho_l} \right]^2 \right)^{\frac{1}{3}}$$

   where ρ_{air} = 1.23 kg m^{-3}, ρ_{water} = 1000 kg m^{-3}, μ_{water} = 10^{-3} kg m^{-1} s^{-1} and σ_{water} = 0.072 N m^{-1}.

   Physical property data are below for steam-water at 20 bar

   Temperature = 212°C

   ρ_l = 849.3 kg m^{-3} ρ_g = 9.997 kg m^{-3}.

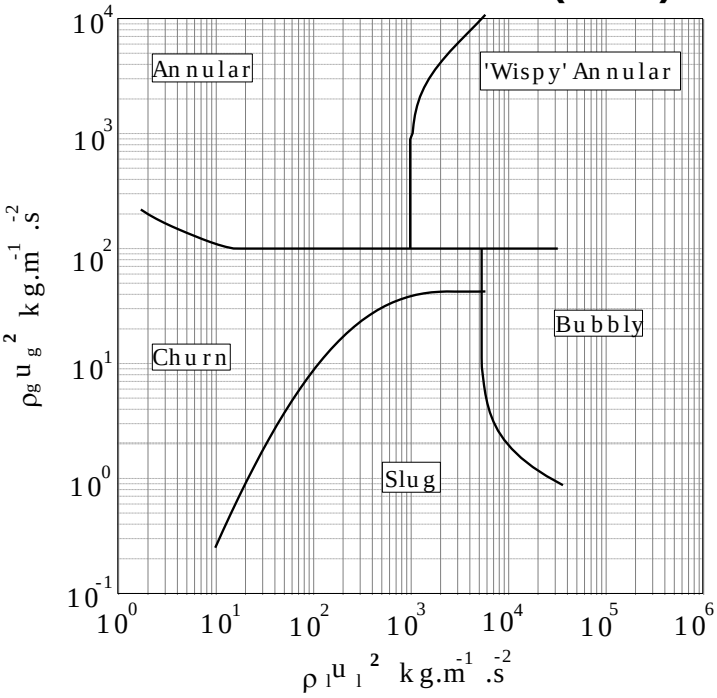
   η_l = 1.270x10^{-4} kg m^{-1} s^{-1} η_g = 1.603x10^{-5} kg m^{-1} s^{-1}

   h_l = 910.7 kJ kg^{-1} h_g = 2797 kJ kg^{-1}

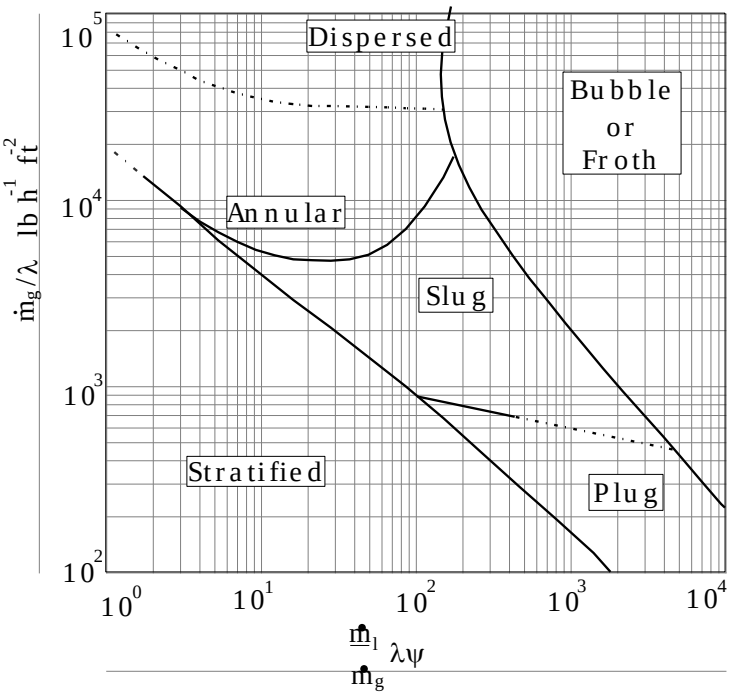
   c_{Pl} = 4.563 kJ kg^{-1} K^{-1} c_{Pg} = 3.087 kJ kg^{-1} K^{-1}

   σ = 0.03501 N m^{-1}

Hewitt and Roberts (1969)



Baker (1954)



Tutorial 5 – Multiphase Flow In Industry

What is the Purpose of Tutorial 5?

This tutorial and subsequent assignment will test the student understanding of multiphase flow and concepts covered during the course and in the tutorials, by asking them to size a multiphase pipeline. They will be asked to present their results as a professional report.

What is Flow Assurance?

Flow Assurance is the study and design of fluid flow operations to ensure that fluid is transported from one point to another in a safe, efficient and economical matter. Fluid flow is driven by the existence of a pressure gradient but there are numerous factors which affect the flow of fluids including hydrate formation, slugging, wax, erosion and corrosion (all to be discussed in this document.). All of this leads to flow assurance being one of the most diverse and critical challenges in the modern oil and gas industry (especially in deepwater production due to the extremities of the ambient conditions). Figure 5.1 shows all the different issues that have to be considered for designing and understanding any flow assurance system.

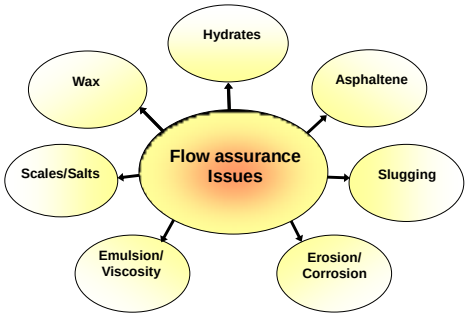


Figure 5.1 - Flow Assurance Design Challenges

Applications and problems

There is a need to predict the behaviour of multiphase flows in large diameter pipes in onshore and offshore production facilities. Multiphase flow can occur in various locations in an offshore facility, such as in the bottom of the well, in the pipelines along the sea bed and up the riser to the separator (Figure 5.2). It can be seen from this figure that the pipes can be horizontal, inclined or vertical, and flow assurance engineers are tasked with ensuring continuous and maximum oil production in the most cost effective way. The flow assurance engineer often relies on complex number crunching software based on information provided by the client for example compositions of the fluid. The Engineer uses the software to deduce the inlet pressure if the outlet pressure is known for example, or predict if there will be slugs in the pipeline, and this assists in sizing pipelines. Significant amount of research is currently taking place in multiphase flow to improve the understanding of this complex subject. For example large scale multiphase research facilities have been built at the University of Nottingham. State of the art instrumentation is being used, such as the wire mesh sensor (WMS) and electrical capacitance tomography (ECT). These instruments vary in temporal resolution, spatial resolution, intrusiveness to flow and cost. Further information on the experimental techniques in multiphase flow can be found in Sharaf (2011).

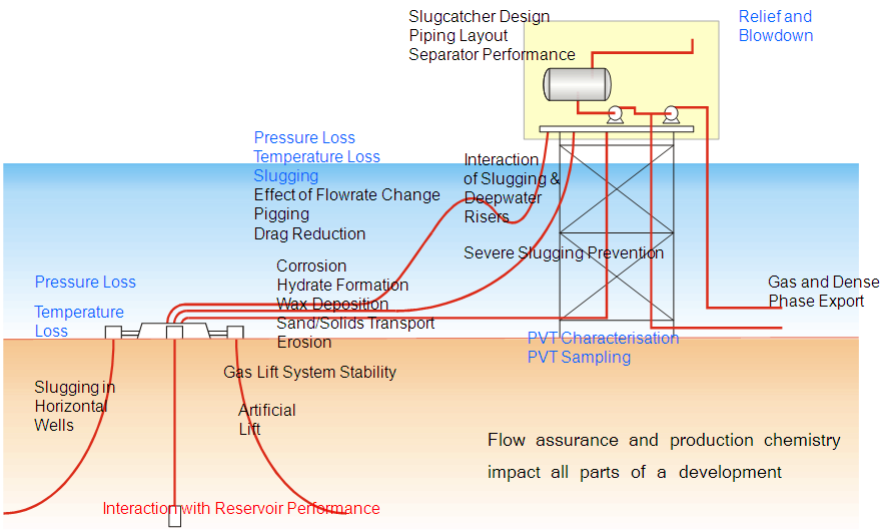


Figure 5.2 - Schematic of an offshore oil facility

Selecting a riser or a well tube below the sea bed with an incorrect diameter could have a significant impact on the rate of oil/gas extraction and hence production and profitability, due to it being too small or too large. The pipes must also be designed correctly for example with the right amount of insulation to ensure temperatures don't allow the formation of hydrates and wax, which can block the pipe and stop production. The costs from rectifying these problems and replacing pipelines after the rig is built can run into many millions of dollars, meaning it is vital that the engineers get it right at the design stage. The recent oil spillage in the Gulf of Mexico demonstrated the need for accurate predictions in this field and the prevention of equipment failures; otherwise the financial and environmental costs of clean-up operations are huge and potentially catastrophic.

Multiphase flow in pipelines is very complex and difficult to predict as it exhibits many phenomena that aren't encountered in single phase flow, such as backflow, phase change, phase mixing and different flow patterns. Some flow patterns can result in serious problems such as slugging (severe or hydrodynamic). With some pipe lengths running up to several kilometres, more than one flow pattern may be present in the same pipe. For example, an oil pipe may just have oil flowing at the bottom, whereas higher up the pipe, the pressure drops and bubbles start to form, creating a multiphase mixture (Figure 5.3).

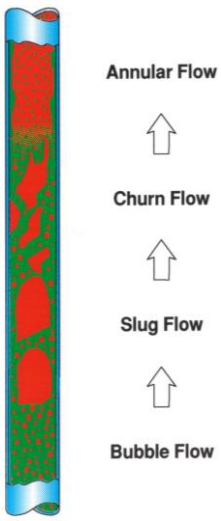


Figure 5.3 – Multiphase flow regimes in well tubing as pressure declines

Therefore, another important consideration is the prediction of this pressure drop. As the oil is extracted, reservoirs will drop in pressure and in the amount of oil they produce over time. The amount of water -watercut- will increase as the oil decreases. Flow assurance engineers are required to ensure the economic viability of a well, and to ask whether it is still profitable to extract oil from a well with a watercut of 99% for example. Surprisingly, often it is.

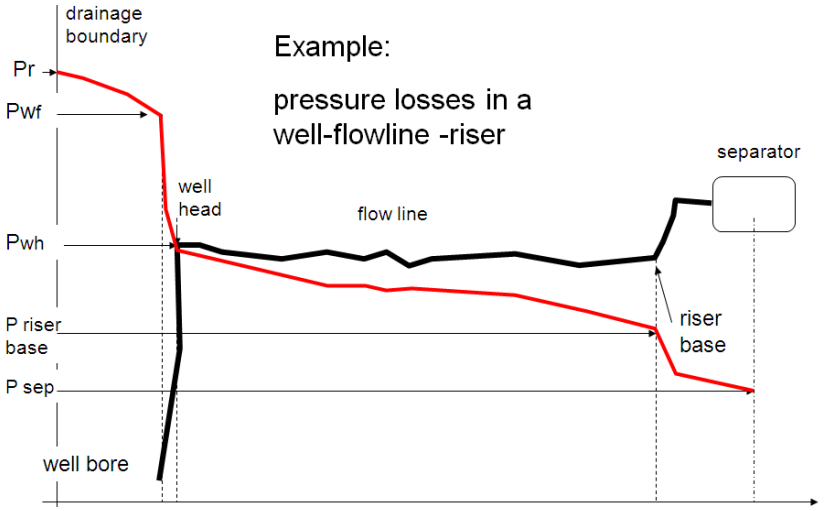


Figure 5.4 -Pressure drop, from the well to the pipeline to the riser (Source: Olga Training documentation).

Figure 5.4 shows an example of the variation in pressure drop in a full offshore system, starting from the well, through to the pipeline, and finally going up the riser. The pressure is constantly dropping, and applying single phase pressure drop predictions will result in errors. It is clear from the gradients of the lines that the vertical pipes have bigger pressure drops than the horizontal pipes. This is due mainly to gravity, which would have less of an impact on horizontal pipes. Large diameter pipes are being used in offshore oil and gas rigs to minimise these pressure drops in particular due to frictional losses and turbulence in order to maximise flowrates and hence oil production. Multiphase flow in pipes can be transient, i.e. time varying as well as steady state, meaning that different modelling techniques are required. Examples of transient flow conditions include shut down/re-start of wells, slugging, variable flow rates, pigging, blow-down, tube ruptures, valve failures and tripping of pumps/compressors. In this handbook it is assumed that conditions are constant or steady-state. The riser is essentially a vertical or near-vertical pipe, connecting the sea-bed collection pipe network (the flowlines) to a sea-surface installation, which is typically a floating receiving and processing vessel, sometimes known as an FPSO (Figure 5.5). These are often used for extracting oil and gas from wells if the depth is too great to build a platform cost effectively.

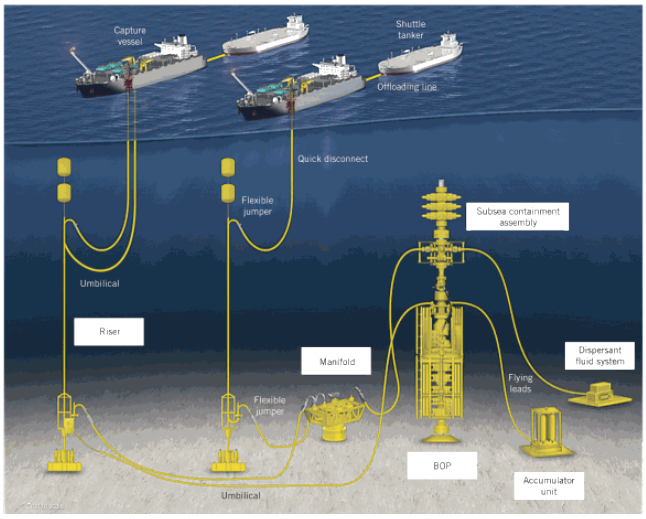


Figure 5.5 -Offshore oil/gas extraction (Source: www.marinelog.com, 2010)

The oil and gas industry is currently operating in extremely challenging economic conditions, with the oil price having experienced significant fluctuations over the past few years. A recent article (The Engineer, 2009) stated that each person in the UK uses around 125kWhr of energy every day. This is equivalent to 125 40 Watt light bulbs on around the clock. If half of the available UK land space was covered with wind farms, this would generate around 800W per person, or 20kWhr per day, which is still significantly less than recent demand. The trend in this demand is upwards.

This is the scale of the energy crisis globally, and it is believed that in the short to medium term, the reliance on oil and gas for energy will continue until viable alternative energy sources are developed and commercially tapped. These energy alternatives are essential, as oil and gas are finite resources. Investments in oil and gas offshore systems have been, and will continue to be, huge (around $35 billion up to 2005), with the riser systems accounting for around 20% of the costs. Current multiphase research methods have been based on measurements from smaller diameter tubes (typically 25-75 mm) and on the interpretation of these measurements in terms of the flow patterns occurring in such tubes. However, the limited amount of data available shows that the flow patterns in larger tubes may be quite different, and that the detailed phenomena may also vary within a given flow pattern. For example, there is some evidence to suggest that slug flow of the normal type, with liquid slugs separated by Taylor bubbles of classical shape, may not exist in large pipes. This can be seen in Figure 5.6 (Prasser et al, 2007a), which also shows the difference in wave structures (Azzopardi et al, 1983).

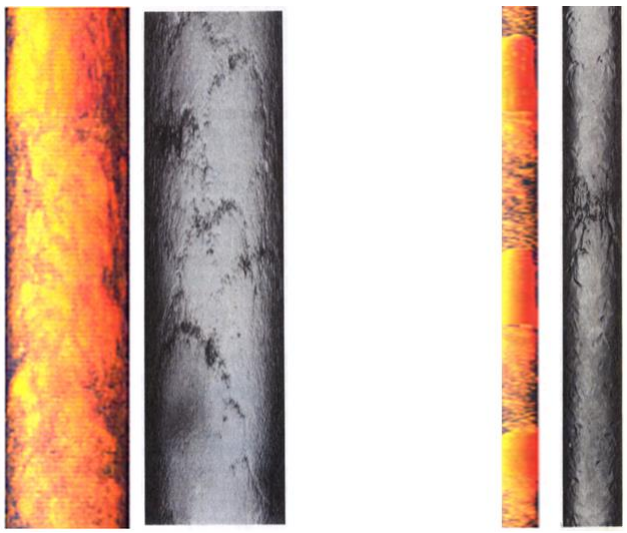


Figure 5.6 -Differences between large diameter (>100mm) and small diameter pipes (<100mm). Taylor bubbles not evident in tube on left. Also shown are wave profiles.

Bubble size distributions measured by Prasser et al. (2004) also displayed significant differences for small diameter and large diameter pipes (Figure 5.7). The second peak for 200mm diameter pipes is broader and less prominent than for 50mm pipes as shown in Figure 2.6 below. Offshore risers were relatively short and had modest diameters. However, as the oil and gas fields are being depleted, and as demand for oil and gas continues to grow globally, the oil and gas companies are being forced to look further afield for replacement reserves with the potential for economic development.

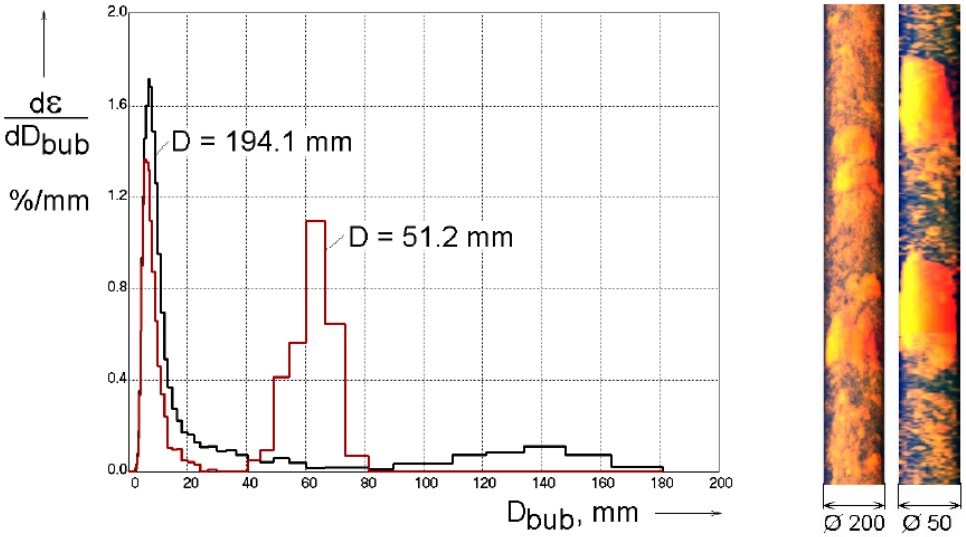


Figure 5.7 - Comparison of bubble size distributions for 50mm and 200mm diameter pipes, superficial gas/liquid velocities of 0.53 m/s and 1 m/s respectively.

This has led to an increased interest in deeper waters, harsher environments and more remote locations, most notably in the Gulf of Mexico, the Brazilian Campos basin, west of the Shetland Isles and the Angolan Aptian basin. Many of the major deepwater developments are located in water depths exceeding 1km, for example Elf's Girassol exploration field at 1300m and Petrobras' Roncador project at 1500-2000m. To transport the fluid produced from systems such as these with the available pressure driving forces has led naturally to the specification of risers of much greater diameter (typically 300 mm) than those used previously (typically 75 mm). Shell recently broke the record for the deepest drilling and production facility in the world with the Perdido project, located in the Gulf of Mexico. This facility will be operating in waters over 2200m deep, and drilling a further 2400m below the sea bed, as shown in Figure 5.8. Therefore, the trend for the oil and gas industry is clear, with a shift towards longer and larger diameter pipes in deeper waters, to remote places with extreme environmental conditions.

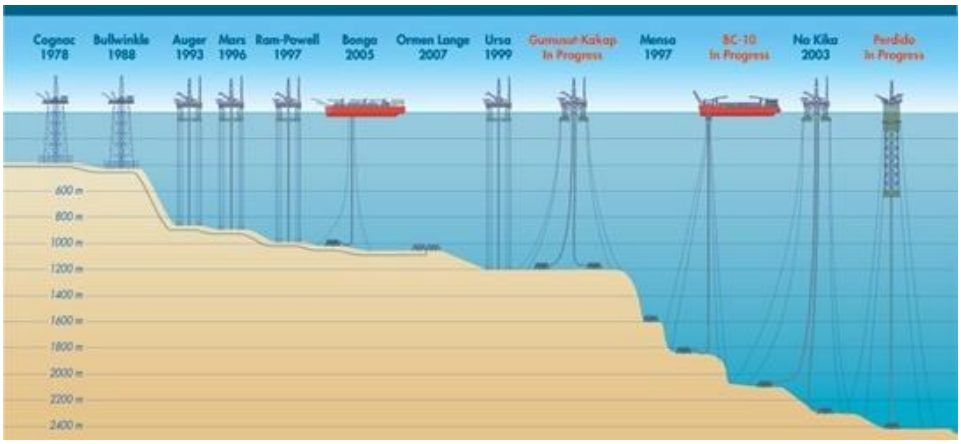


Figure 5.8 -Deepwater Milestones (Source: www.Shell.com, 2011)

Tutorial 5 – Homework: Final Assignment

Multiphase Pipelines in Hilly Terrain

Oil companies are now international operations. This produces a wide range of situations which have to be dealt with from political, geographical and climatical points of view. An interesting example arises from the Columbian fields being developed by an international oil-gas operator. These are in the foothills of the Andes and consequently the flow-lines which deliver the hydrocarbons from the wellhead to a Central Processing Facility have to pass up and down some significant elevation changes. Sizing of the flow-lines is critical to both the maximum production rates that can be delivered through them and also to their operability at lower flowrates once the field comes "off plateau".

What are the relevant parameters when predicting pressure drop? (Report)

What part will flow pattern play in pressure drop prediction? (Report)

Which flow patterns are not favoured in industry and why? (Report)

Though actual pipe lines will go up and down several mountains, for the purpose of this assignment consider a pipe line that covers a single up slope. Assume that the reservoir can work against a back or inlet pressure of up to 900psia at the well head **what pipe size (internal diameter or ID to the nearest inch) would you recommend? Explain your results and findings (Report).**

THE SPREADSHEET:

You will all receive a copy of the work book "casestudy1.xls" to help you with this case study. The idea is that you use this spread sheet to perform the calculations, giving you more time to analyse the results thoroughly. The spread sheet has been set up to compare the results of three pressure drop calculation methods – the homogeneous method, the Fridel/CISE method, and the Beggs and Brill method.

Using the spread sheet:

1. Before you can use the spread sheet you MUST convert the data given in the question into suitable SI units. Place your answers in cells G6 : G15. Conversions for the gas and liquid flow rates are entered in cells G18 : I20.
2. Place your choice of pipe diameter in cell B3 and the corresponding pressure drops for each method are given at the end of the sheet [Hint: Here you can vary the pipe diameter e.g. 6, 8, 10 inches…etc].
3. Using the spread sheet investigate the effect of pipeline diameter on pressure drop for the three flowrates [Hint: You can produce a graph of pressure drop vs diameter and from this make deductions].
4. Compare the results obtained for each method by drawing your own graphs, either by hand or within EXCEL.

Which calculation method did you use for your final answer and why? (Report)

USEFUL DATA:

Up slope:	Increase in elevation: 200m
	Length of pipeline: 2000m

A typical flowline will be producing at a range of rates, therefore it is important to carry out calculations at the maximum and minimum expected flowrates as well as the mean value.

Parameter	Mean	Maximum	Minimum
Oil Production (bbd)	25000	40000	10000
Gas to Oil Ratio (GOR) (scf/barrel)	2000	4500	1400

PHYSICAL PROPERTIES:

Specific gravity of oil	0.85
Gas gravity	0.76
Oil viscosity @ 180 ^{o}F	1.00cP
Gas viscosity @ 180 ^{o}F	1.00cP
Surface tension	12dyn/sm
Outlet pressure	650psia

[Hint: Look at the at inlet and outlet pressures and deduce a "pressure drop" limit to deduce the pipe diameter]

Assume constant fluid temperature of 180 ^{o}F

To calculate the friction factor use the following:

$$f_{SP} = f_{ns} = \left[2\log\left(\frac{Re_{ns}}{4.5223\log Re_{ns} - 3.8215} \right) \right]^{-2}$$

$$Re_{ns} = \frac{\left[\rho_l\left(1-\varepsilon_{gH}\right)+\rho_g\varepsilon_{gH}\right]\left(u_{gs}+u_{ls}\right)D_t}{\left(1-\varepsilon_{gH}\right)\eta_l+\varepsilon_{gH}\eta_g}$$

Please produce a technical report with the following format:

- Title Page
- Abstract
- Table of Contents
- Introduction
- Results
- Conclusions
- References
- Appendix

TIPS FOR REPORT

-Address all the questions in **BOLD** in your report.
-Please reference your work. Suggested method-Harvard Style: For this booklet, this style of referencing was used.
-Do NOT just copy and paste material from references. Summarise. Screenshots can sometimes be useful.
-Please list the parameters you used for your case study.
-Do your own research. Ask for any journal/academic papers that might be of interest/useful.
-Use third person/passive form. Do not waffle. Concise technical report.
-Aim not to exceed 10 pages and around 2500-3000 words (excluding appendix).
-Imagine Chief Engineer is reading your report!

We will go through an example report in class so that you know what is expected.

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Tutorial 6 – Feedback

What is the Purpose of Tutorial 6?

- Reflect on skills learned on the programme with a view to encouraging resilience
- Receive feedback on final assignment

What are the key questions?

- What strengths have I demonstrated in my work and what areas of development are there left for me to address?
- What steps do I need to take to improve my academic output?

Activity 2 – Marking your own

Using the mark scheme, identify three things you did well and three things you could improve.

What went well?

1.

2.

3.

What could be improved?

1.

2.

3.

Activity 3 – Responding to feedback

Read through your feedback sheet and highlight on your assignment where you received positive feedback (one colour) and areas for improvement (different colour). You might find it helpful to annotate this with a brief comment or two.

(Acknowledgement: The structure and the activities in this feedback tutorial were first designed by Hannah Manktelow in January 2015. We have repeated them here as they demonstrate thoughtful and excellent planning, and can be used by all tutors to ensure a successful and productive feedback tutorial.)

University Applications Guidance

For course choices and careers information: www.brightknowledge.org.uk

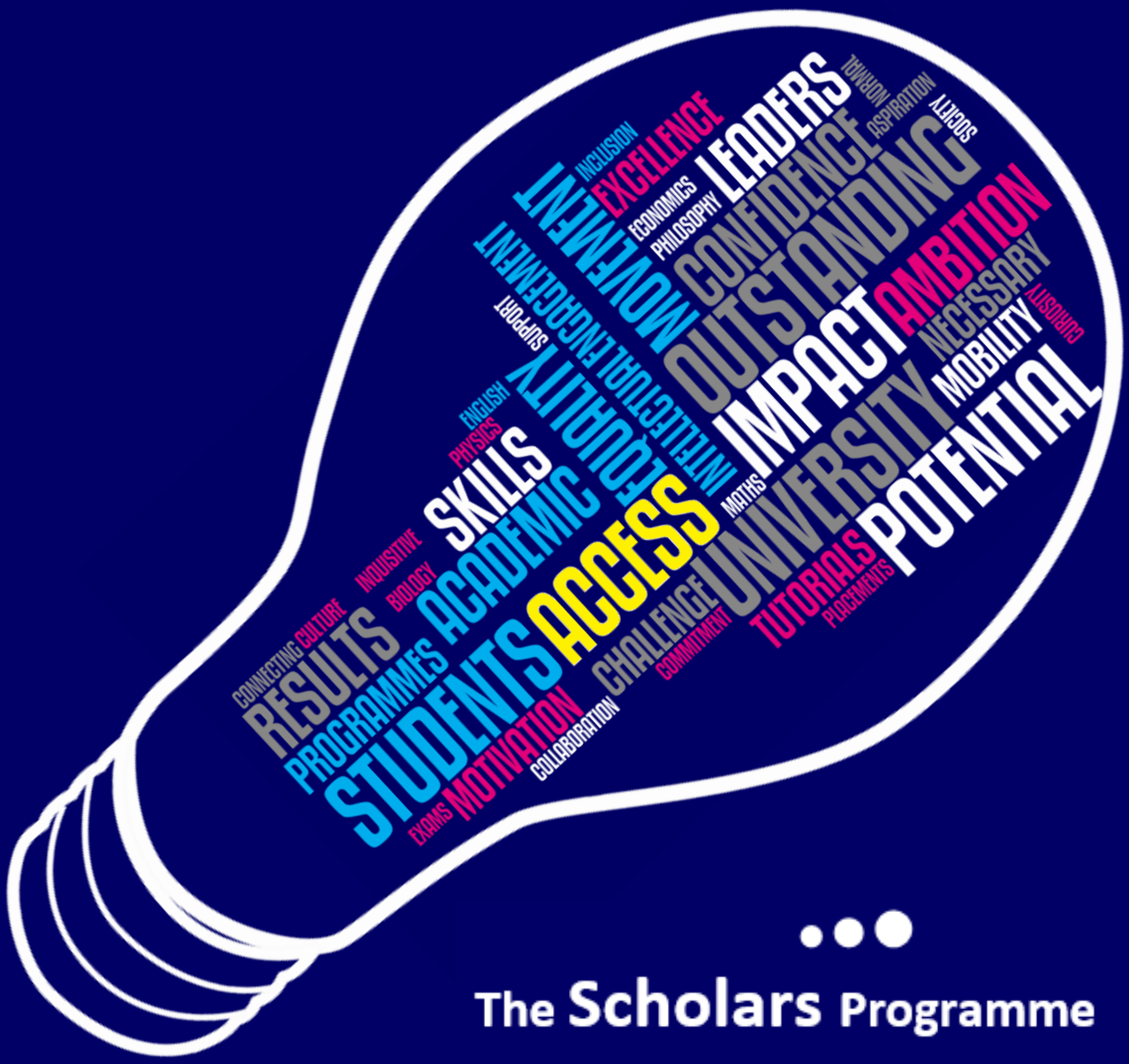
For information and statistics on universities and course: www.unistats.direct.gov.uk

For comprehensive information on universities, including rankings: www.thecompleteuniversityguide.co.uk

PLEASE NOTE – The Scholars Programme is designed to support the university applications process at your school. The work you complete for the programme should add to your schoolwork rather than detract from it. Please be aware of deadlines and try to manage your workload appropriately. If you are worried about the Scholars Programme interfering with your schoolwork then please speak to your teacher.

Subject Specific Top Tips for Strengthening your application

What could you read around the subject?
Suggestions of podcasts/videos that can be found online? Are there any age-appropriate, good films on this topic?
What cheap or free events and talks would it be good to attend?



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