Experimentation and Computational Fluid Dynamics Modelling of Roughness Effects in Flexible Pipelines

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Abstract

Flexible pipes are used to transport hydrocarbons in the subsea oil and gas industry. However, the way flow in rough bore flexible pipes differs from smooth pipe flow has not been widely investigated. The aim of this study is to investigate the effect of flexible pipe roughness through both experimentation and modelling in order to determine if the current industry practice is valid for wall friction on a partially full liquid flow. The driver for this study is for better understanding of co-current gas-liquid flow regimes. Experiments were conducted in open channel flows of water. The flow rate and angle of inclination of the channel were modified to induce different flow regimes. The difference in depth of flow, a manifestation of the roughness, was measured and scrutinised. Computational fluid dynamics (CFD) models were developed to compare with experimental observations. Both experiments and modelling results confirm the flow is affected by wall roughness and show that the roughness value which is currently assigned is not valid for low Reynolds number flows in partially filled pipelines.

1 Introduction

Flexible pipes are used for their ease of installation compared to rigid alternatives. They are constructed using a number of concentric shells alternating between metallic armouring layers and polymer sheaths. The internal layer is formed from a helically wound interlocked strip of stainless steel. This provides collapse resistance yet causes the bore of the pipe to be periodically rough due to the interlock. The roughness affects the flow and is currently accounted for using a 'rule of thumb' measure in calculations. The API Recommended Practice 17B (2002) for unbonded flexible pipes states that the absolute roughness may be calculated as the inner diameter of the pipe divided by 250, or $e = ID/250$. Rearranging yields a constant relative roughness e/ID of 0.004. While usually considered a conservative estimate, there is little else published material regarding the origins of neither the expression nor its validity. The aim of this project is to investigate whether the expression is adequate specifically for partially full pipe flows.

1.1 Project Scope

Experiments were conducted in open channels of water. The flow rate and channel slope could be adjusted resulting in a range of flow regimes, each characterised by a unique depth. The data were collected, processed and plotted against the well known Colebrook-White correlation for roughness in pipes. A PVC channel was used as a control measure, to evoke the hydraulically smooth case, which was compared against expected values for smooth walls. This enabled experiments to be fine-tuned, until satisfactory results were obtained. Experiments were repeated using a rough flexible hose allowing the data to be compared.

To simulate the experimental situation numerically, CFD models of the liquid phase were built. This started with the smooth channel in order to consolidate and compare with expected outputs. This confirmed the validity of assumptions and models used so that rough channel flow could then be confidently modelled.

1.2 Benefit Analysis

Currently, Woodside's operating flexible pipes used as flow lines and risers amount to a length in excess of 100km (Zucaro, 2014). Flexible pipes are being increasingly used offshore, a direct result of the recent growth in subsea engineering. The findings of this study will promote a better understanding of flow and frictional losses in flexible pipeline systems involving two phase flow. The friction factor is directly related to pressure drop, which is used in calculation of the energy cost to drive the flow. Hence, an under predicted value may yield higher than expected costs or reduced production.

1.3 Background Information

Partially full flows differ from full flows in pipes due to two key phenomena. Foremost, the free surface of partial flows can be thought of as a source of instability. As turbulent eddies are produced and transported they are unbound at the surface which is free to undulate. This gives rise to secondary currents, requires energy and causes an earlier transition to turbulence. Additionally, the wall stresses can no longer be considered constant at the wall of a partially full flow. Rather the wall stress distribution is generally considered as dependent on geometry, slope and fluid depth.

For a gas-liquid flow in a horizontal or near horizontal pipeline, a multitude of flow regimes can exist. The regime is dependent on the flow rates of the liquid and gas phases, the properties of the fluids and the pipe. Taitel and Dukler (1976) developed theoretical flow regime maps using analytical models to predict where flow regime transitions occur. The analysis builds on the equilibrium case of smooth stratified flow, Figure 1, which considers the momentum balance of two phase flow on an incline to determine the liquid level h_L. Although it is assumed that the shear force acting on the liquid is identical to open channel flow, full pipe friction factors are used (Taitel & Dukler, 1976).

The Darcy-Weisbach friction factor f is a dimensionless quantity assigned to a particular Reynolds number flow. While a study by the American Society of Civil Engineers (ASCE) does suggest that resistance to flow in open channels may be considered in terms of such a friction factor, it proposes that the governing relationship for the Moody Diagram, the Colebrook-White equation [1], be slightly modified in order to better fit data from a number of sources (Carter, et al., 1963).

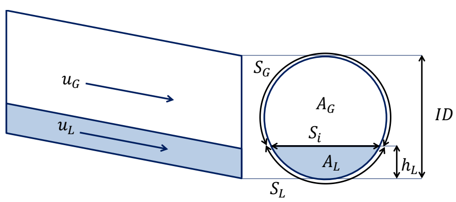

Figure 1 Equilibrium stratified flow (Taitel & Dukler, 1976)

$$\frac{1}{\sqrt{f}} = -2\ \log_{10}\left(\frac{e}{14.8R_h} + \frac{2.52}{R_e\sqrt{f}}\right) \qquad [1]$$

In the case of partial flows, the length scale is the hydraulic radius which is the ratio of cross sectional area to wetted perimeter, $R_h = A/P$. This is used in the definition of Reynolds number R_e and relative roughness e/R_h.

2 Process

2.1 Experiments

Experimental data were collected and processed in order to determine if the industry measure of $ID/250$ is appropriate. The key variables were channel slope, flow rate and depth. These can be manipulated into friction factor, Reynolds number and relative roughness.

A schematic of the experimental setup is shown in Figure 2. A cut circular PVC pipe of 17 diameters in length conveys the open channel of water. The channel, being hinged at the upstream end, can be inclined using a mechanical jack at the centre. The channel is supplied with water by means of a centrifugal pump with variable speed drive. The flow rate is measured using an ultrasonic flow meter which is entirely external and installed at the recirculation pipe downstream of the pump. Since an actual flexible pipe was not available for experiments, a flexible hose was installed which has a similar roughness form as shown in Figure 3. The orientation of the pipe was selected to be that which least resists the flow.

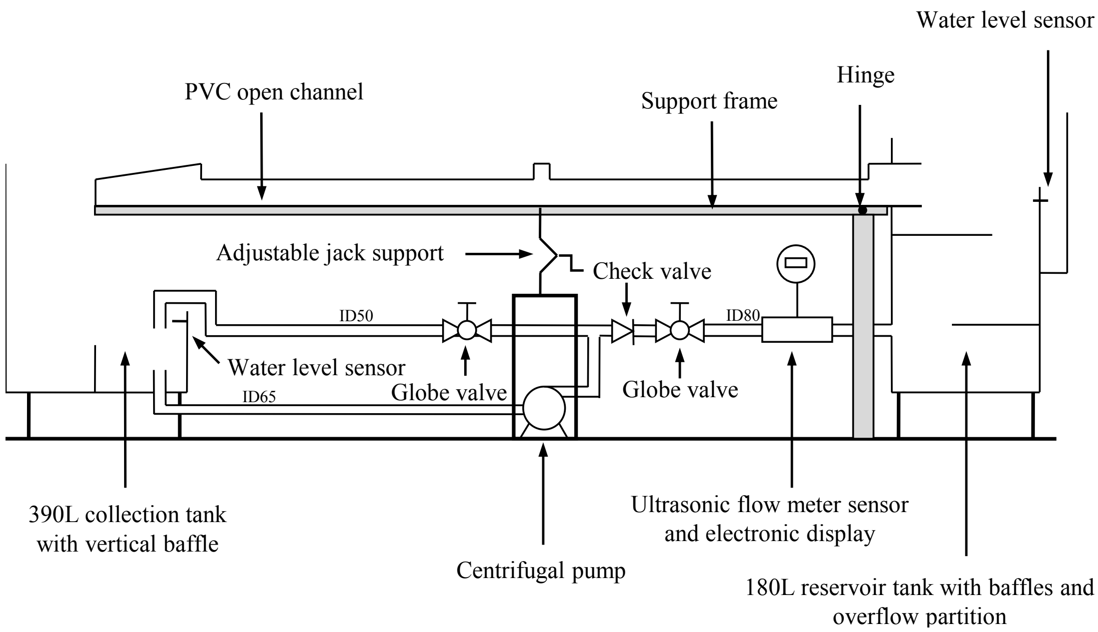

Figure 2 Experimental setup

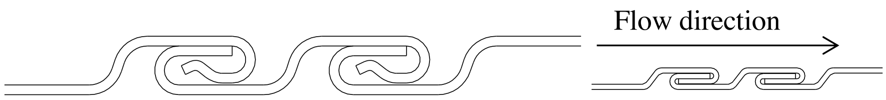

Figure 3 Comparison of flexible pipe size compared to hose used for experiments

2.2 Modelling

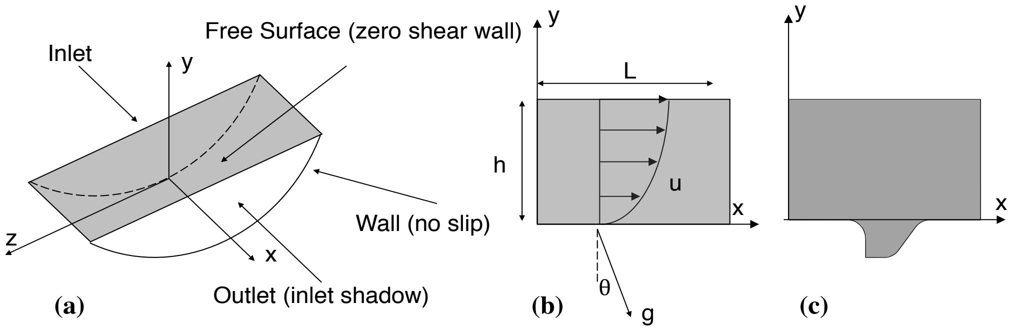

Figure 4 (a) Fluid domain and boundary conditions, (b) Direction of gravitational acceleration and velocity profile, (c) incorporation of wall roughness

The ANSYS software package Workbench (v14.5) has been used for all CFD procedures. Only the water phase is modelled. As such, the water depth and channel slope are predetermined for each simulation. The flow rate develops naturally according to these input conditions. This can then be compared to the depth, slope and flow rates from experiments.

To simulate fully developed flow, a segment of fluid with length L is defined with a translationally periodic boundary condition applied to the inlet and outlet faces as shown in Figure 4a. For the rough channel, the wall is modified to incorporate the profile of the interlock (Figure 4c). Since the rough pipe geometry is also periodic, the flow domain is streamwise periodic allowing the periodic boundary condition to remain suitable. The selected turbulence model is SST k-ω. Since it is not possible to replicate the ripples generated at the free surface using a steady state solver, it has been assumed that the free surface is fixed and parallel to the xz plane. This surface is assigned a zero shear wall boundary condition. The channel wall has a no slip boundary condition applied.

To generate flow, gravity must act on the fluid. This is achieved by applying the gravitational body force at an angle θ to the vertical which corresponds to a particular channel slope, shown in Figure 4c.

3 Results and Discussion

3.1 Experimental Results

A summary of the range of values tested is presented in Table 1. The number of data points collected was 92 and 108 for the smooth and rough channels respectively. Reynolds numbers were in the range of 8000 – 90 000 for all cases.

	Smooth		Rough	
	min	max	min	max
Flow rate (L/s)	0.17	3.39	0.2	3.01
Slope (degrees)	0.9	1.4	0.9	1.6
Depth (%ID)	3.3	14.0	3.8	15.4
Hydraulic radius (mm)	4.71	19.05	5.09	19.58

Table 1 Summary of experimental ranges tested

Data is plotted as friction factor against Reynolds number as in the Moody diagram, with curves of constant relative roughness fitted using the minimised sum of the squared residuals. The general trend of the data is as expected, with a slight decrease in friction factor as Reynolds number increases. The relative roughness value for the smooth channel is slightly larger than what is predicted, with a relative roughness value of 0.006 compared to the theoretical hydraulically smooth value of 0.00005. This is expected due to the non perfect nature of the experimental situation. Comparatively, there is a definite increase in calculated friction factors for the rough channel. This confirms that the flow is indeed influenced by the presence of the roughness.

The constant relative roughness curves suggested by the Colebrook-White equation do not fit the data well, at low Reynolds numbers the predicted friction factors are lower than observed in experiments.

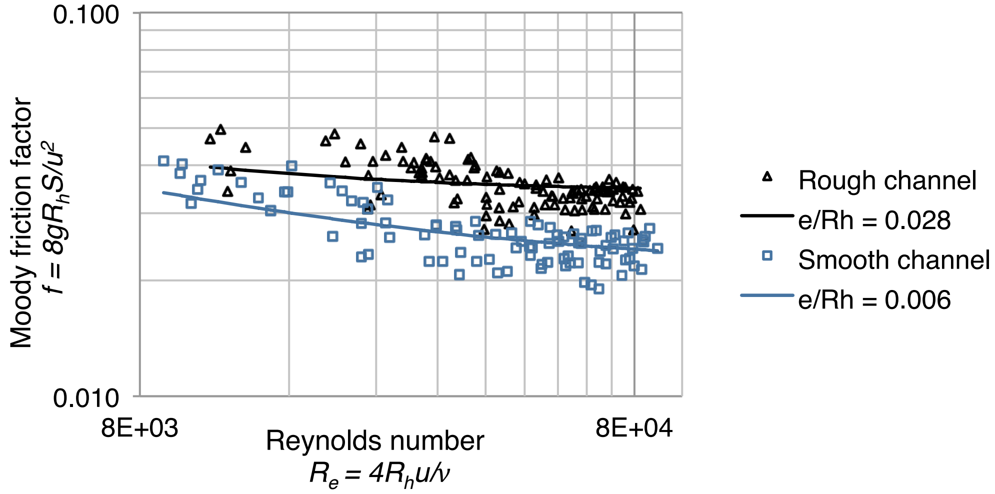

Figure 4 Smooth and rough channel data fitted with curves of constant relative roughness

3.2 CFD Modelling Results

CFD results show that the friction is less than observed in experiments, with the smooth wall showing less frictional resistance than predicted by the Colebrook-White equation due to the controlled nature of the computational environment. Again, there is a distinct shift upwards shown in the friction factors of the rough channel compared to the smooth indicating that the flow is affected by the presence of the roughness.

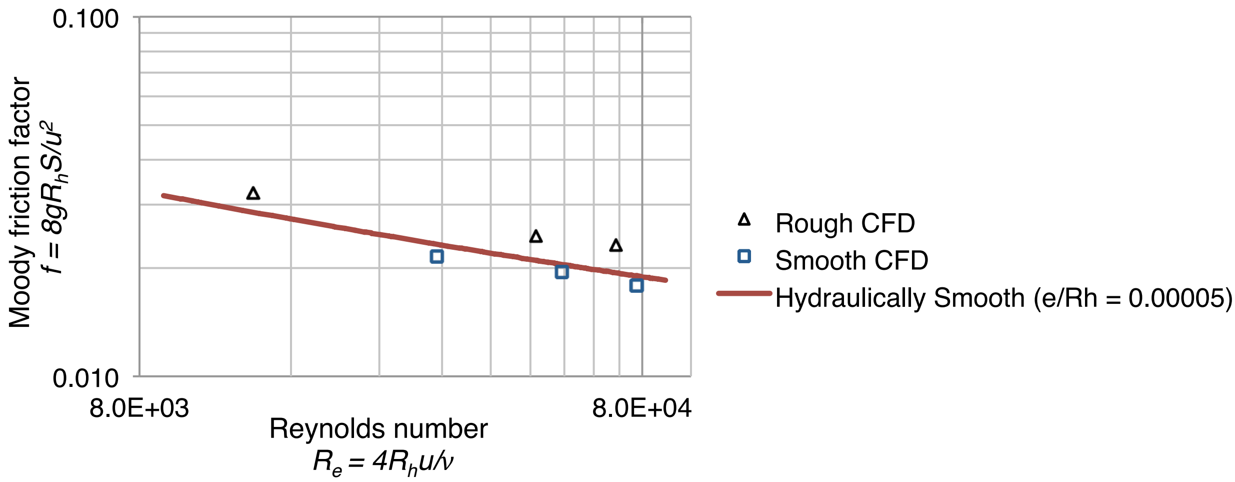

Figure 5 CFD friction factors for the smooth and rough channels

3.3 Appropriate Correlation for Roughness

In the ASCE study, there are correlations for roughness proposed to better suit data in open channels. Two suggested are by authors Keulegan and Robinson. These were tested for both the experimental and CFD data and shown to be more suitable. In the case of experiments, Table 2, a smaller sum of the squared residual indicates a better fit. For the CFD results, the better fit is indicated by more constant relative roughness values for the 3 cases, shown in Table 3. In experiments, the Robinson correlation was the best fit, however the Robinson formula was not applicable to CFD results because the relative roughness values calculated were negative. However, the relationship suggested by Keulegan shows that the relative roughness values are more constant. In both cases the apparent relative roughness is reduced when a formula for open channels is used.

Experimental	e/R_h	Sum squared residual
Colebrook-White	0.028	0.0020
Keulegan	0.025	0.0022
Robinson	0.021	0.0017

Table 2 Experimental constant relative

CFD	Colebrook-White	Keulegan
Low R_e	0.009	0.005
Med R_e	0.005	0.003
High R_e	0.004	0.003

Table 3 *e/R_h* values calculated directly for the 3 CFD cases simulated

4. Conclusions and Future Work

Experimental data and modelling results show that curves of constant relative roughness using the Colebrook-White formula (full pipe flow) may not be appropriate to account for roughness in flexible pipes when the liquid phase is flowing partially full. Rather, alternative correlations developed from open channel data may be used. Since there is no agreed correlation for friction factor in open channels in the literature, this should be further investigated.

5. Acknowledgements

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