Proceedings of the World Congress on Mechanical, Chemical, and Material Engineering (MCM 2015)
Barcelona, Spain – July 20 - 21, 2015
Paper No. 280

A Comparative Analysis of Interfacial Friction Factor Correlations for Adiabatic Co-Current Gas–Liquid Annular Two-Phase Flow in Large Diameter Pipes

Aliyu M Aliyu, Liyun Lao, Hoi Yeung
Oil and Gas Engineering Centre, School of Energy, Environment, and Agrifood
Cranfield University, Bedfordshire MK43 0AL, United Kingdom
a.m.aliyu@cranfield.ac.uk; l.lao@cranfield.ac.uk; h.yeung@cranfield.ac.uk

Almabrok A Almabrok
Department of Petroleum Engineering, Faculty of Engineering, Sirte University, Libya
Mabrok71@yahoo.com

Abstract **–**There is increasing evidence that gas/liquid two phase flow behaviour in large pipes (with diameter >100 mm) differs from those of smaller pipes. It has therefore become imperative that flow correlations are exclusively derived for large pipes so as to facilitate more accurate prediction of heat transfer and pressure drop in pipes and boilers encountered in the nuclear/process/oil and gas industries. This study focuses on the pipe diameter effect on vertical annular flow, a regime of two-phase flow characterised by liquid flowing along the pipe periphery and the gas and/or mist phase flowing in the pipe core. As such there exists friction at the interface between the core and liquid film on the wall. This interfacial friction is particularly important as it critically influences the behaviour and structure of the flow. This study is based on new large diameter pipe interfacial friction factor data which was obtained from pressure drop and liquid film thickness measurements made in Cranfield University's Serpent Rig (a 101.6 mm internal diameter flow loop) with the fluids co-currently flowing upwards through a 4 m long test section. Ranges of air and water superficial velocities taken were 1.42–28.87 m/s and 0.1–1.0 m/s respectively. Significant discrepancies were found between the published correlations derived using small pipe data and our experimentally determined interfacial friction. We have therefore made attempts to develop a new correlation using a dimensionless liquid film thickness and gas Reynolds number function that well fits the large pipe interfacial friction factor data.

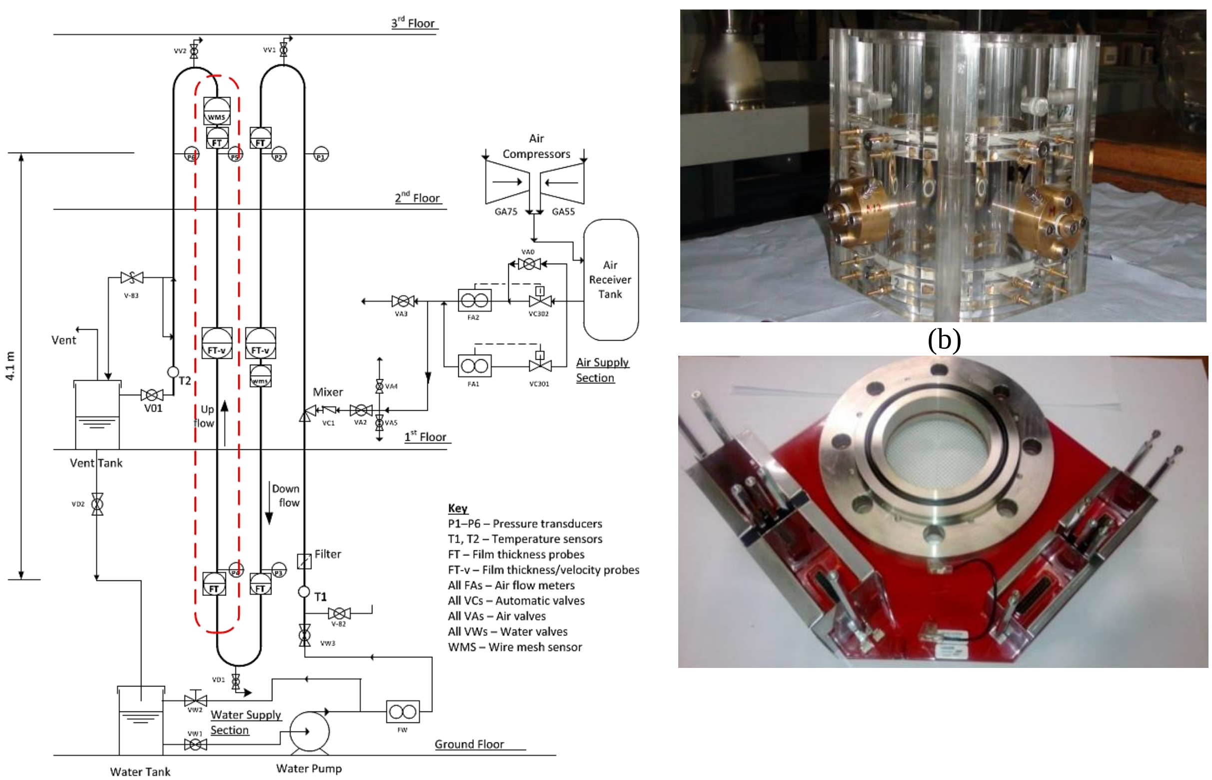
Keywords**:** multiphase flow, liquid film thickness, frictional pressure drop, interfacial shear stress.

1. Introduction

A large number of experimental studies have been carried out on vertical air–water two-phase annular flow in pipes. This is due to the huge importance annular two-phase flow plays in the nuclear, chemical and petroleum industries where it is generally agreed to be one of the most frequently encountered flow patterns. In investigating annular two-phase flow, the bulk of published works focussed on co-current upward annular flow in small diameter pipes, mostly less than 50 mm in internal diameter. In sharp contrast there have been far fewer studies published on annular two-phase flow in large diameter pipes. This is against the backdrop that annular two-phase flow in large pipes is often encountered in engineering equipment such as gas absorbers, gas condensate pipelines, and in heat transfer equipment like boilers and heat exchangers. It has been noted that there is no guarantee that the use of models developed for these small pipes will accurately predict large diameter flows; and several authors (Oliemans et al. 1985; Kataoka & Ishii 1987;Omebere-Iyari 2006; Kaji & Azzopardi 2010; Peng et al. 2010; Lao et al. 2012; Schlegel et al. 2012) have addressed the need to expand the knowledge to large diameter pipe systems. The contribution of interfacial friction to the two-phase frictional component increases with increasing slip between the phases. Early studies correlated the interfacial friction factor to the ratio of the average wave height to pipe diameter, which has been likened to surface roughness in single-phase flow (e.g. Bergelin et al., 1949; Hewitt & Hall-Taylor, 1970). The interfacial friction factor correlations of Wallis (1969); Moeck (1970); Asali et al. (1985); Fukano & Furukawa (1998); Wongwises & Kongkiatwanitch (2001) among others are based on data from small pipes. We will show that these do not sufficiently model interfacial friction factor data in pipes greater 100 mm internal diameter. We hence propose a new correlation based on data from pipes of 101.6 mm and 127 mm which improves interfacial friction factor predictions for co-current air–water annular flow in large vertical pipelines.

2. Experimental Facility

The two-phase serpent flow loop in the Oil and Gas Engineering Laboratory of Cranfield University (shown in Figure 1) is specially-built test facility used in the study of flow behaviour around upward and downward U-bends. It is divided into three main parts: the fluid (air and water) supply/metering section, the test section, and the separation section. The rig receives measured rates of water and air from the flow metering section to the test rig and finally into the ventilation tank where the air and water are separated. The water is returned back to the storage tank while the air is vented.



(b)

(a) (c)

Fig. 1. (a) Cranfield University's Air-water two-phase serpent rig experimental facility (b) Conductance film thickness probe spool (c) Void fraction capacitance Wire Mesh Sensor (WMS)

The test section consists of the flow loop which is an approximately 20 m-long 4-inch (101.6 mm) internal diameter pipeline which includes four ABS plastic vertical upward flowing and downward flowing sections connected by three Perspex 180 degree bends. The two middle 6 m vertical pipes are fitted with various instruments where all data is collected. The left hand arm of the U (highlighted) is the upward flowing section which is the area of interest of this study where all data was collected. Typical test pressures are in the vicinity of 0.2 to 1 barg. A list of instrumentation on the Serpent Rig is as shown in

Table. 1 together with their quoted and estimated uncertainties. Detailed description of these instrumentation (including film thickness probes and Wire Mesh Sensor WMS in Fig. 1 (b) and (c)) can be found in Almabrok (2014).

Table. 1. List of instruments and experimental uncertainties

Instrument	Name	Manufacturer & Model	Uncertainty	Range
Air flow meter 1	FA_1	Rosemount Mass Probar $^1/_2$''	±0.5%	0-150 Sm^3/h
Air flow meter 2	FA_2	Rosemount Mass Probar 1"	±0.5%	150-4250 Sm^3/h
Water flow meter	FW	ABB MMSG-Special	±0.1%	0.06-16 l/s
Pressure sensors	P_1 to P_6	GE Sensing UNIK 5000	±0.02%	0-1.5 barg
Temperature sensors	T_1-T_2	PT 100	±0.5%	0°-100°C
Wire mesh sensor	-	Helmholtz-Zentrum Dresden-Rossendorf (HZDR), CAP200	-	Void fraction 0-100%
Liquid film thickness probes	FT_1-FT_2	Designed and manufactured by PSE	±0.1 mm (±3.3%)	0-3 mm

3. Results and Discussion

3. 1. Flow Regime Identification and Flow Regime Map

The range of the experimental conditions chosen corresponds to conditions in the falling film and annular flow regime characterised by liquid film on the pipe circumference and a gas core (i.e. without liquid droplets entrained) or gas/droplet mixture (i.e. with liquid droplets entrained) in the central area.

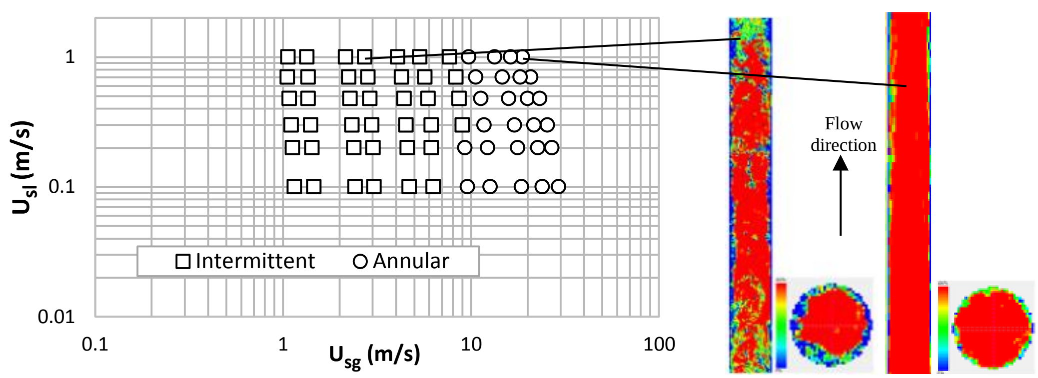
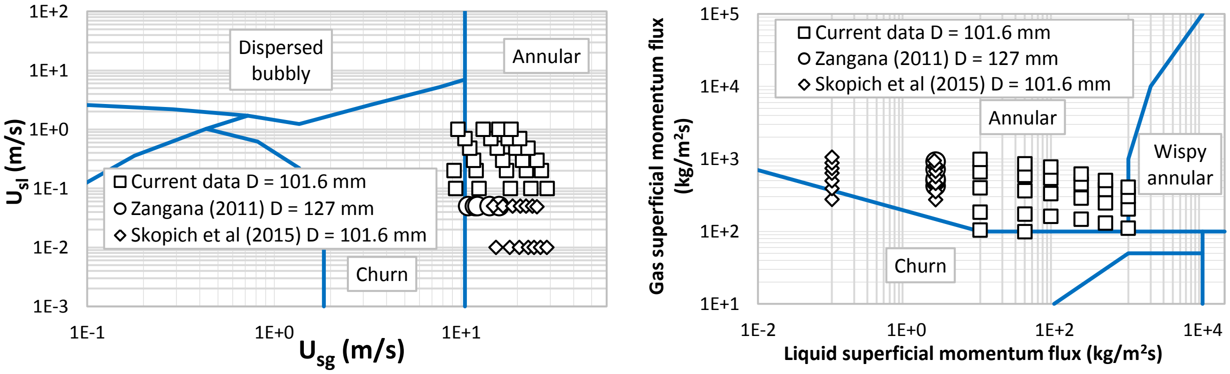


Fig. 2. Flow regime map by visual observation at the top position where the length to diameter ratio, L/D = 39, with reconstructed WMS images for $U_{sl} = 1.0\ m/s$; $U_{sg} = 2.7$ and 18.6 m/s showing intermittent and annular flow regimes respectively. For the images, red colour signifies air while blue is water.

The flow regime map based on the test superficial liquid and gas velocities for upward flow is illustrated in Figure 2. The flow regime identification was done using visual observation of the flow configuration during tests, high speed/reconstructed videos and images of the flow made via transparent Perspex sections provided at the top, middle and bottom sections of the test rig; and analysis of the Probability Distribution Functions PDFs of the WMS void fractions. As can be seen, upward annular flow region is limited to high gas superficial velocities, and flow regimes marked as intermittent were characterised by highly oscillatory and rough gas–liquid interface. These observations are consistent with the earlier study of Almabrok (2014) who worked on the same experimental setup.

3. 2. Literature Data

Large pipe literature data was obtained from the works of Zangana (2011) and Skopich et al. (2015) who worked on air/water upflow annular flow in vertical pipes of 127 and 101.6 mm internal diameter. As shown in Fig. 3, their experiments fall in the annular flow regime. Zangana made simultaneous measurements of wall shear stress (using uni- and multi-directional hot wire probes), liquid film thickness (using pin probes), and pressure gradient. He observed that the onset of annular flow occurred at the same dimensionless gas velocity as it would in smaller pipes and that the total pressure gradient for given liquid and gas superficieal velocities fall as the pipe diameter increases.



(a) (b)

Fig. 3. Flow regime maps (a) Taitel and Dukler (1976) (b) Hewitt and Roberts (1969) showing experimental conditions for data points obtained for this study and those from the literature.

Similarly, in the work of Skopich et al. (2015) measurements were made of time averaged pressure gradient, liquid holdup, and cross-sectionally averaged liquid film thickness; in order to study liquid loading phenomenon in gas transport pipes. Liquid holdup measurements were made using quick closing valves in the middle of the 15.4 m long test section. They noted that discrepancies observed between experimental pressure gradient, liquid holdup and mechanistic model predictions are due to inaccurate flow regime prediction occasioned by the different regime transitions in different pipe scales.

3. 3. Calculation of Interfacial Properties from Experimental Measurements

A total of 45 data points were obtained for this study in the range of Re_G = 59000–400000 and Re_L = 1100–113000. The interfacial friction factor is estimated from measured pressure gradient by taking a momentum balance at the gas–liquid interface with the assumption that the flow is fully developed:

$$f_i = \frac{2\tau_i}{\rho_G U_{sg}^2} \tag{1}$$

where τ_i is the interfacial friction factor is estimated from the measured pressure gradient by

$$\tau_i = \left(-\frac{dP}{dz} - \rho_c g\right)\frac{D-2t}{4} \tag{2}$$

This equation assumes a uniform film thickness around the pipe cross-section. Here it should be noted that since there is significant droplet entrainment in the gas core, pure gas properties are replaced by linearly phase-averaged density of droplet laden gas core:

$$\rho_c = (1-\varepsilon_c)\rho_L + \varepsilon_c \rho_g \tag{3}$$

Core flow viscosity was also calculated using a linear phase-averaged mixing rule as defined by Cicchitti et al. (1960); Hewitt & Hall-Taylor (1970); recently used by Cioncolini et al. (2009) and Cioncolini & Thome (2010); where ε_c is the gas core void fraction estimated as:

$$\varepsilon_c = \frac{\varepsilon}{\varepsilon+\gamma(1-\varepsilon)} \text{ where } \gamma = e\frac{\varepsilon}{(1-\varepsilon)}\frac{1-x}{x}\frac{\rho_g}{\rho_L} \quad (4)$$

And ε being the cross-sectionally averaged void fraction; γ is the droplet holdup, estimated by ignoring the slip between the entrained droplets and the gas; e is the entrained droplet fraction; and x is the gas quality.

3. 4. Comparison of Experimental Interfacial Friction Factor with Published Correlations and New Empirical Correlation

Wallis's (1969) developed a correlation for interfacial friction factor in vertically upwards annular two-phase flow which solely depends on the relative liquid film thickness as follows:

$$f_i = 0.005(1 + 300t/D) \quad (5)$$

Since then, a number of Wallis-type empirical relations have been developed such as that by (Moeck 1970) for the disturbance wave regime. Noting that existing correlations do not adequately cater for thick films at low gas Reynolds numbers, Fore et al. (2000) combined new data obtained at high pressures in a 5.08 × 101.6 mm rectangular duct with those of Asali (1983) and Fore & Dukler (1995) to obtain a new correlation for f_i as follows:

$$f_i = 0.005[1 + 300(t/D - 0.0015)] \quad (6)$$

In order to account for a change in liquid viscosity, Fukano and Furukawa (1998) carried out experiments in a 26 mm diameter pipe with air/water and air/glycerol mixtures; they proposed a correlation which was within ±15% of the experimental data as:

$$f_i = 0.425(12 + \nu_l/\nu_w)(1 + 12t/D)^8 \quad (7)$$

Where ν_l and ν_w are liquid kinematic viscosity of liquid and water at 20˚C. We however illustrate that these equations do not amply represent our large pipe friction factor as well as those of Zangana (2011) and Skopich et al. (2015) as shown in Fig. 4. While there is reasonable agreement at high interfacial shear stress regions where the film is smooth, a sharp change in slope of the experimental data lead to large deviations at lower interfacial shear stresses due to the rougher gas–liquid interface of thicker films. The reason for the deviations (apart from the difference in hydrodynamics occurring in different pipe scales) could be that the increasing influence of the gas velocity has been ignored. Therefore another group of relations were proposed that comprise the gas Reynolds number. These include those of Hori et al. (1978), Asali et al. (1985), Fukano et al. (1991) and Wongwises & Kongkiatwanitch (2001).

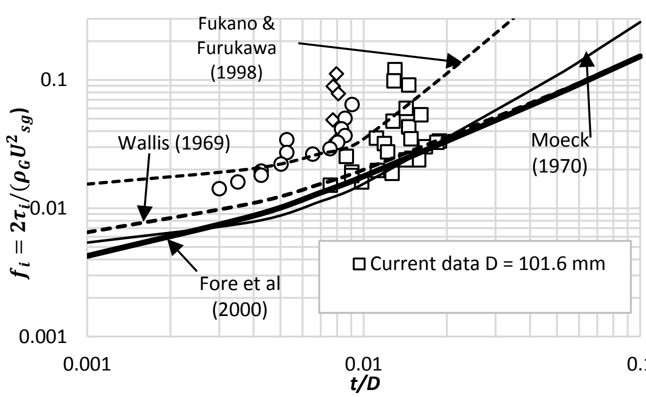
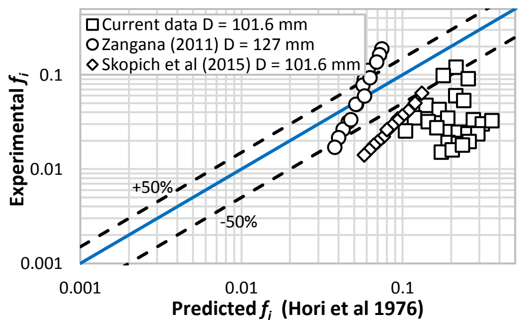
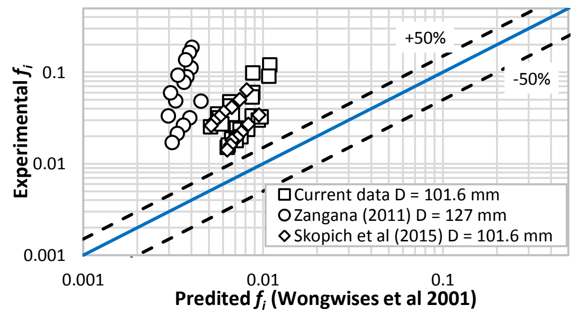


Fig. 4. comparison of measured friction factors with Wallis, Moeck, Fukano & Furukawa, and Fore et al. correlations.

These correlations do not describe the collected large pipe data satisfactorily either; with a large part the predictions of Hori et al. (Fig. 5a) and Fukano et al. falling outside the ±50% error band. Consistent underpredictions were obtained using the models of Wongwises & Kongkiatwanitch (Fig. 5b) and that of Asali et al. even though the latter gave better predictions at low shear region.



(a)



(b)

Fig. 5. Experimental vs friction factors predicted with Hori et al., Asali et al., Fukano et al., and Wongwises & Kongkiatwanitch correlations

These form the premise for a separate correlation of the large pipe friction data. It was important to capture the effect of the flowing gas with the insertion of the gas Reynolds number (based on superficial velocity) in any new correlation going by the deficiencies of Equations **Error! Reference source not found.**) – **Error! Reference source not found.**) (Fig. 4). Also, the effect of pipe diameter is represented by inclusion of a gas Froude number. Thus, the friction factor is assumed to follow a power law function:

$$f_i = \alpha \, Re_g^{\beta} Re_l^{\gamma} Fr_g^{\delta} (t/D)^{\varepsilon} \tag{8}$$

Multiple non-linear regression was applied to determine the factor α and indices $\beta - \varepsilon$ such that the following correlation was obtained for interfacial friction factor:

$$f_i = 6059 \, Re_g^{-0.05} Re_l^{-0.38} Fr_g^{-1.6} (t/D)^{0.7} \tag{9}$$

Equation **Error! Reference source not found.**) produces a better fit to the experimental data as can be seen in Fig. 6 with 73% of all predicted points within 50% of the experimental values when compared to the existing correlations.

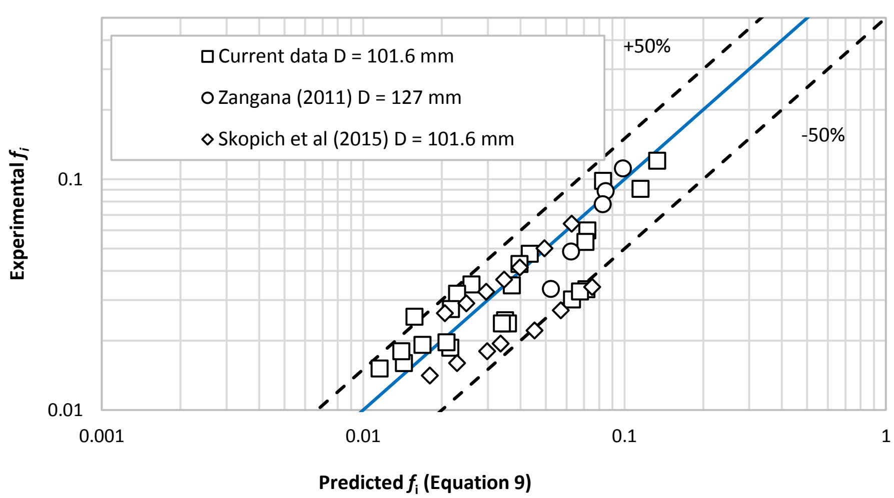


Fig. 6. Comparison of new correlation with experimental data

4. Conclusion

Experiments were performed to obtain pressure gradient and film thickness data for annular two-phase flow in large diameter vertical pipes. Published correlations did not sufficiently describe the interfacial friction factors calculated from the data and those from other sources. As such, a new correlation has been proposed that enhanced the prediction and hence better frictional pressure gradient estimation in industrial scale gas condensate pipes and boilers. It is simple and can be easily incorporated into existing flow simulator codes for improved prediction in the annular flow regime.

Acknowledgement

Aliyu M Aliyu gratefully acknowledges the funding provided by the Petroleum Technology Development Fund, Abuja, Nigeria for his doctoral studies.

References

Almabrok, A. (2014). Gas - Liquid Two-Phase Flow in up and down Vertical Pipes. *PhD Thesis*, Cranfield University.

Asali, J C. (1983). Entrainment in Vertical Gas-Liquid Annular Flows. *Univ of Illinois,* Urbana.

Asali, J C., Hanratty, T J., & Andreussi, P. (1985). Interfacial Drag and Film Height for Vertical Annular Flow. *American Institute of Chemical Engineers: AIChE Journal*, 31 (6), 895–902. DOI:10.1002/aic.690310604.

Bergelin, O P., Kegel, P K., Carpenter, F G., & Gazley, C Jr. (1949). Co-Curreint Gas Liquid Flow. II. Flow in Vertical Tubes. *Heat Transfer and Fluid Mechanics Institute*, 19–28.

Cicchitti, A., Lombardi, C., Silvestri, M., Soldaini, G., & Zavattarelli, R. (1960). Two-Phase Cooling Experiments - Pressure Drop, Heat Transfer and Burnout Measurements. *Energia Nucleare,* 7(6), 407–25.

Cioncolini, A., & Thome, J. R. (2010). Prediction of the Entrained Liquid Fraction in Vertical Annular Gas–liquid Two-Phase Flow. *International Journal of Multiphase Flow,* 36(4), 293–302. DOI:10.1016/j.ijmultiphaseflow.2009.11.011. http://linkinghub.elsevier.com/retrieve/pii/S0301932209001918.

Cioncolini, A., Thome, J. R., & Lombardi, C. (2009). Unified Macro-to-Microscale Method to Predict Two-Phase Frictional Pressure Drops of Annular Flows. *International Journal of Multiphase Flow*, 35(12), 1138–48. DOI:10.1016/j.ijmultiphaseflow.2009.07.005. http://linkinghub.elsevier.com/retrieve/pii/S030193220900127X.

Fore, L B., Beus, S G., & Bauer, R C. (2000). Interfacial Friction in Gas-Liquid Annular Flow: Analogies to Full and Transition Roughness. *International Journal of Multiphase Flow,* 26.

Fore, L B., & Dukler, A. E. (1995). Droplet Deposition and Momentum Transfer in Annular Flow. *American Institute of Chemical Engineers AIChE Journal,* 41(9), 2040–46. doi:10.1002/aic.690410904. http://dx.doi.org/10.1002/aic.690410904.

Fukano, T., & Furukawa, T. (1998). Prediction of the Effects of Liquid Viscosity on Interfacial Shear Stress and Frictional Pressure Drop in Vertical Upward Gas–liquid Annular Flow. *International Journal of Multiphase Flow,* 24(4), 587–603. DOI:http://dx.doi.org/10.1016/S0301-9322(97)00070-0. http://www.sciencedirect.com/science/article/pii/S0301932297000700.

Fukano, T., Kawakami, Y., Qusaka, A., & Tominaga, A. (1991). Interfacial Shear Stress and Holdup in an Air - Water Annular Two-Phase Flow. *Proceedings of the ASME-JSME Thermal Engineering Joint Conference,* 2(217), 17-22.

Hewitt, G F., & Hall-Taylor, N S. (1970). *Annular Two-Phase Flow,*. Oxford; New York: Pergamon Press.

Hewitt, G F., & Roberts, D N. (1969). Studies of Two Phase Patterns by Simultaneous X-Ray and Flash Photography. Harwell, Berkshire.

Hori, K., Nakasamomi, M., Nishikawa, K., & Sekoguchi, K. (1978). Study of Ripple Region in Annular Two-Phase Flow (Third Report, Effect of Liquid Viscosity on Gas-Liquid Interfacial Character and Friction Factor). *Trans. Jap. Soc. Mech. Eng.* 44(387), 3847–56.

Kaji, R., & Azzopardi, B.J. (2010). The Effect of Pipe Diameter on the Structure of Gas/liquid Flow in Vertical Pipes. *International Journal of Multiphase Flow,* 36(4), 303–13. DOI:10.1016/j.ijmultiphaseflow.2009.11.010. http://linkinghub.elsevier.com/retrieve/pii/S0301932209001906.

Kataoka, I., & Ishii, M. (1987). Drift Flux Model for Large Diameter Pipe and New Correlation for Pool Void Fraction. *Int. J. Heat Mass Transfer,* 30(9), 1927–39.

Lao, L., Xing, L., & Yeung, H. (2012). Behaviours of Elongated Bubbles in a Large Diameter Riser. *Multiphase,* 8, 381–92.

Moeck, E. O. (1970). Annular-Dispersed Two-Phase Flow and Critical Heat Flux. McGill University. http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/01/002/1002083.pdf.

Oliemans, R. V. A., Pots, B. F. M., & Trompe, N. (1986). Modelling of Annular Dispersed Two-Phase Flow in Vertical Pipes. *International Journal of Multiphase Flow,* 12(5), 711–32.

Omebere-Iyari, N. K. (2006). The Effect of Pipe Diameter and Pressure in Vertical Two-Phase Flow. *University of Nottingham.*

Peng, D. J., Ahmad, M., Hale, C. P., Matar, O. K., & Hewitt, G. F. (2010). Flow Regime Transitions in Large Diameter Pipes. *7th International Conference on Multiphase Flow*, 1–9.

Sawant, P., Ishii, M., & Mori, M. (2008). Droplet Entrainment Correlation in Vertical Upward Co-Current Annular Two-Phase Flow. *Nuclear Engineering and Design,* 238(6), 1342–52. DOI:10.1016/j.nucengdes.2007.10.005. http://linkinghub.elsevier.com/retrieve/pii/S0029549307005304.

Schlegel, J.P., Miwa, S., Chen, S., Hibiki, T., & Ishii, M. (2012). Experimental Study of Two-Phase Flow Structure in Large Diameter Pipes. *Experimental Thermal and Fluid Science*, 41, 12–22. DOI:10.1016/j.expthermflusci.2012.01.034. http://linkinghub.elsevier.com/retrieve/pii/S0894177712000465.

Skopich, A., Pereyra, E., Sarica, C., & Kelkar, M. (2015). Pipe-Diameter Effect on Liquid Loading in Vertical Gas Wells. *SPE Production and Operations*, 30(2). 164–76. https://www.onepetro.org/download/journal-paper/SPE-164477-PA?id=journal-paper%2FSPE-164477-PA.

Taitel, Y., & Dukler, A. E. (1976). A Model for Predicting Flow Regime Transitions in Horizontal and near Horizontal Gas-Liquid Flow. *American Institute of Chemical Engineers AIChE Journal*, 22(1), 47–55. DOI:10.1002/aic.690220105. http://dx.doi.org/10.1002/aic.690220105.

Wallis, G. B. (1969). Annular Two-Phase Flow - Part II (additional Effects). *ASME* 69.

Wongwises, S., & Kongkiatwanitch, W. (2001). Interfacial Friction Factor in Vertical Upward Gas-Liquid Annular Two-Phase Follow. *International Communications in Heat and Mass Transfer,* 28(3), 323–36. DOI:10.1016/S0735-1933(01)00238-X. http://linkinghub.elsevier.com/retrieve/pii/S073519330100238X.

Zangana, M. H. S. (2011). Film Behaviour of Vertical Gas-Liquid Flow in a Large Diameter Pipe. *University of Nottingham.* http://eprints.nottingham.ac.uk/12782/1/546275.pdf.