

**COB-2023-1349**

**THE INFLUENCE OF PIPE DIAMETER ON LIQUID FILM FEATURES IN  
VERTICAL DOWNWARD ANNULAR FLOW**

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**Abstract.** *The annular two-phase flow is characterized by a gaseous core with dispersed droplets and a liquid film wetting the pipe wall. The film presents structures on its interface with the gaseous core. These structures are classified as disturbance waves and ripples. These waves are affected by the high interfacial shear stresses between the phases and the gas-liquid flow rate variation. The disturbance waves are the interfacial structures that play a role with regard to influencing the flow properties such as the pressure drop, the liquid entrainment and the transfer of momentum, mass, and heat. The knowledge of these flow parameters is essential to the optimization of models and contributes to the enhancement of the monitoring processes in the industry. From previous works, it is known that the pipe diameter affects the flow parameters. Furthermore, although the literature shows several studies on upward vertical annular flows, there is a gap when it comes to researching downward annular flows. Incidentally, most works were based on limited experimental apparatuses concerning the length-to-diameter ratio. In this scenario, an experimental evaluation was conducted to analyze the liquid film parameters in downward vertical air-water annular flow using a rig with two different internal diameters, 26 and 50 mm, and a 14-m long pipe at ambient conditions. Twenty-one annular flow combinations of superficial air and water velocities were investigated for each diameter, ranging from 5 m/s to 15 m/s and 0.05 m/s to 0.25 m/s, respectively. Time series of cross-sectional average liquid thicknesses obtained by a non-intrusive dual ring-shaped conductance sensor were used to provide the fluid film characterization. Moreover, high-speed visualization was used to assess the phenomenological and morphology behavior of the annular flow. The analyses of the liquid film time series provided features such as the average film thickness, film roughness, velocity, frequency, amplitude, length and appearance of the disturbance waves. Individual identification of the disturbance waves was performed to investigate the velocity and frequency regarding the distribution and interaction of the waves. Comparisons of the flow parameters between the flow conditions for the two different diameters showed variations in the frequency and velocity of the disturbance waves, with the larger diameter (50 mm ID) presenting the smallest results.*

**Keywords:** *Annular flow, pipe diameter, liquid film, conductance sensor*

## 1. INTRODUCTION

Annular two-phase flows are characterized by a gaseous core with dispersed droplets and a liquid film wetting the pipe wall. This flow pattern is often observed in pieces of industrial equipment such as nuclear reactor systems, evaporators and condensers, and in the oil and gas industry, notably in gas wells with condensate (Hewitt, G F and Hall-Taylor, 1970; Wallis, 1969). The liquid film presents structures on the gas-liquid interface, classified as disturbance waves and ripples (Chu & Dukler, 1974). The smoothest portion of the liquid film in contact with the pipe wall is identified as *substrate* or *base film*. These waves are affected by the high interfacial shear stresses between the phases and the gas-liquid flow rate variation.

The disturbance waves are interfacial structures that play a role regarding influencing the flow parameters such as the pressure drop, the liquid entrainment and the transfer of momentum, mass, and heat. The knowledge of the flow behavior is essential to the optimization of models and contributes to the progress of the monitoring processes in the industry.

Previous works show that the diameter affects the flow parameters (Weisman et al., 1979). Furthermore, the literature shows many works on upward vertical annular flows and a gap when it comes to the study of downward annular flows (Alves et al., 1991; Azzopardi, 1986; Belt et al., 2009; Cuadros et al., 2019; Zabaras et al., 1986; Zhao et al., 2013). In

this context, experiments were carried out to investigate the effect of pipe diameter on liquid film properties of vertical downward air-water annular flows.

## 2. METHODOLOGY

The experimental tests were conducted at the Multiphase Flow Research Center (NUEM) of the Federal University of Technology – Paraná (UTFPR). An apparatus was designed to carry out measurements in vertical downward annular flows.

The rig has a 26-mm ID and 50-mm ID with a 14-m long test section made of transparent Plexiglas. Special care was taken to obtain the test section alignment ( $90^\circ$ ) using a professional digital inclinometer with an accuracy of  $\pm 0.05^\circ$ . The working fluids used in the tests were air and tap water under room conditions. The experimental evaluation comprised twenty-one (21) combinations (C#) of gas ( $J_G$ ) and liquid ( $J_L$ ) superficial velocities ranging from 0 m/s to 15 m/s and 0.05 m/s to 0.25 m/s, respectively, as presented in Table 1. All twenty-one flow conditions are investigated for both pipe diameters used in the study.

The liquid film is investigated in a test section placed at 335D and 205D from the flow inlet, for the D=26 mm and D=50 mm inner pipe diameters, respectively. A non-intrusive dual ring-shaped conductance sensor and a gauge pressure transducer are deployed in the test section. For each combination of superficial phase velocities evaluated in this work, the sensor data acquisition frequency was 10 kHz with a sampling time of 30 s and 100 s for the 26-mm ID and the 50-mm ID, respectively.

A high-speed camera was deployed in the test section for flow visualization. It provided qualitative information to corroborate the liquid film characterization. The flow snapshots were taken at a frame rate of 300 Hz during a 10-s recording session.

Table 1 - Combinations of superficial phase velocities used in the experimental tests.

C#	$J_L$ [m/s]	$J_G$ [m/s]	C#	$J_L$ [m/s]	$J_G$ [m/s]	C#	$J_L$ [m/s]	$J_G$ [m/s]
C01	0.050	5	C08	0.050	10	C15	0.050	15
C02	0.075	5	C09	0.075	10	C16	0.075	15
C03	0.100	5	C10	0.100	10	C17	0.100	15
C04	0.125	5	C11	0.125	10	C18	0.125	15
C05	0.150	5	C12	0.150	10	C19	0.150	15
C06	0.200	5	C13	0.200	10	C20	0.200	15
C07	0.250	5	C14	0.250	10	C21	0.250	15

## 3. RESULTS

The annular flow pattern has an irregular gas-liquid interface with waves (disturbance waves and ripples) and entrainment of bubbles into the liquid film and droplets in the gaseous core. The action of inertia, gravitational force and gas shearing on the interface contributes to the formation of waves.

Figure 1 (a) shows a time series of the liquid film identifying the waves, disturbances waves (DW) and ripples (RP), as well as snapshots of the evolution of one disturbance wave in the flow conditions C14 ( $J_L = 0.25$  m/s and  $J_G = 5$  m/s) in the 26-mm ID, as presented in Figure 1 (b)-(aw).

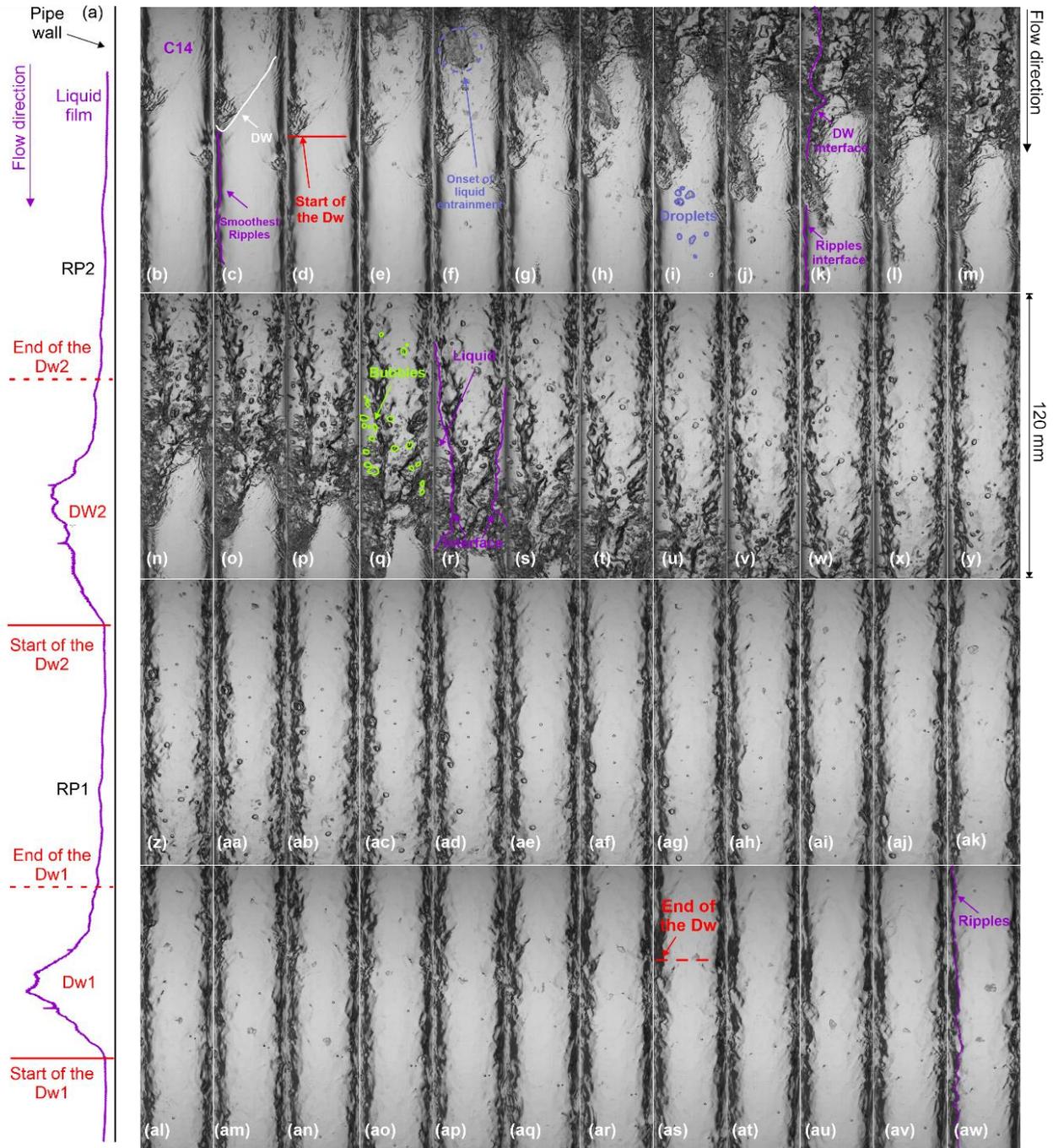


Figure 1 – (a) Time series of the liquid film identifying the disturbance waves (DW) and ripples (RP). (b)-(aw) Evolution of one disturbance wave showing the start, end of the wave, liquid entrainment into the gas core, and bubbles in the liquid film for the flow condition C14 in a 26-mm ID. The elapsed time between each snapshot is 3.33 ms (one frame).

The disturbance waves are three-dimensional, turbulent, non-uniform structures with predominant shapes. These waves have a quite amount of liquid that slips across the substrate in the flow direction. A “pointed-like” structure is observed at the beginning of the disturbance wave, and the many bubbles make the DW to look darker. A large number of bubbles entrapped in the liquid film and droplets entrainment from the disturbance waves into the gas core were observed for all flow conditions evaluated in both diameters, as presented in Figure 2.

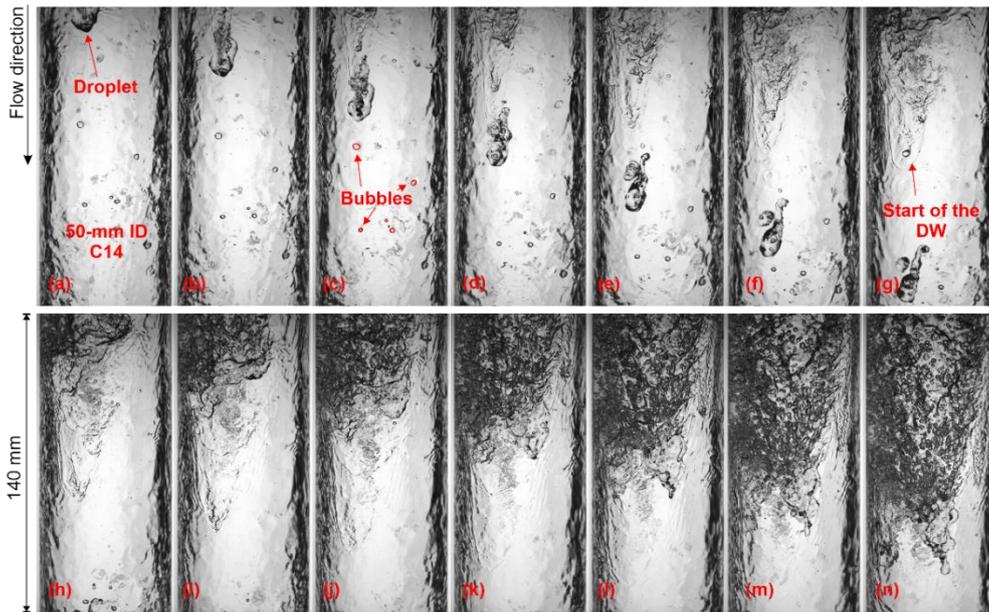


Figure 2 - Evolution of one disturbance wave and droplet for the flow condition C14 in a 50-mm ID. The elapsed time between each snapshot is 3.33 ms (one frame).

Figure 3 shows the liquid film time signals as a function of the superficial phase velocities for two different flow combinations, C07 and C21, for both diameters.

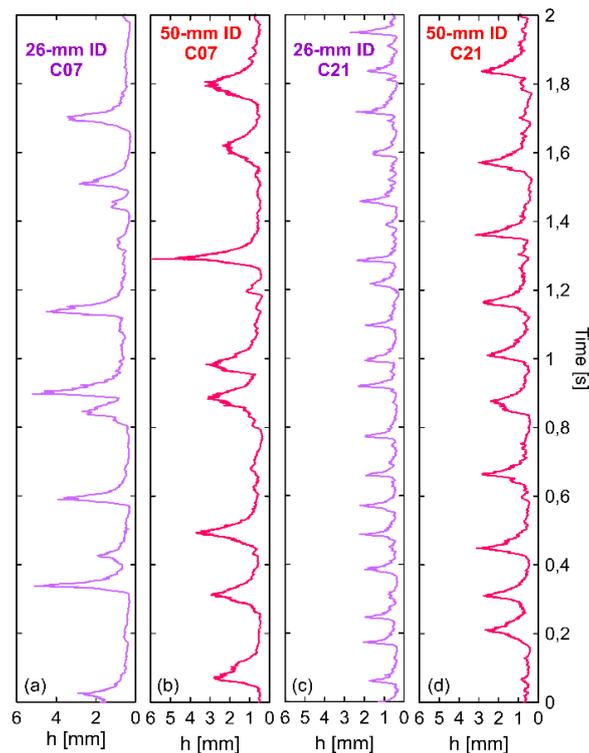


Figure 3 – Time signal of the liquid film for two different flow combinations, C07 and C21, in both diameters tested.

Depending on the superficial phase velocities for both diameters, the disturbance waves can be more frequent and showing changes in their shapes concerning their amplitudes and lengths that fluctuate with time. Comparing the effect of the pipe diameter for the same flow condition, it is observed a more expressive variation in the wave parameters, as for example the DW frequency for the highest superficial gas velocity (C21), as presented in Figure 3 (c) and (d).

Figure 4 shows the averaged liquid thickness for both diameters analyzed as a function of the superficial phase velocities for all flow conditions investigated. The average liquid thickness has a well-defined trend regarding the

superficial phase velocities, increasing with the superficial liquid velocity ( $J_L$ ) while  $J_G$  remains constant. Moreover, in the opposite effect, a reduction in the average liquid thickness was observed with the superficial gas velocity increase.

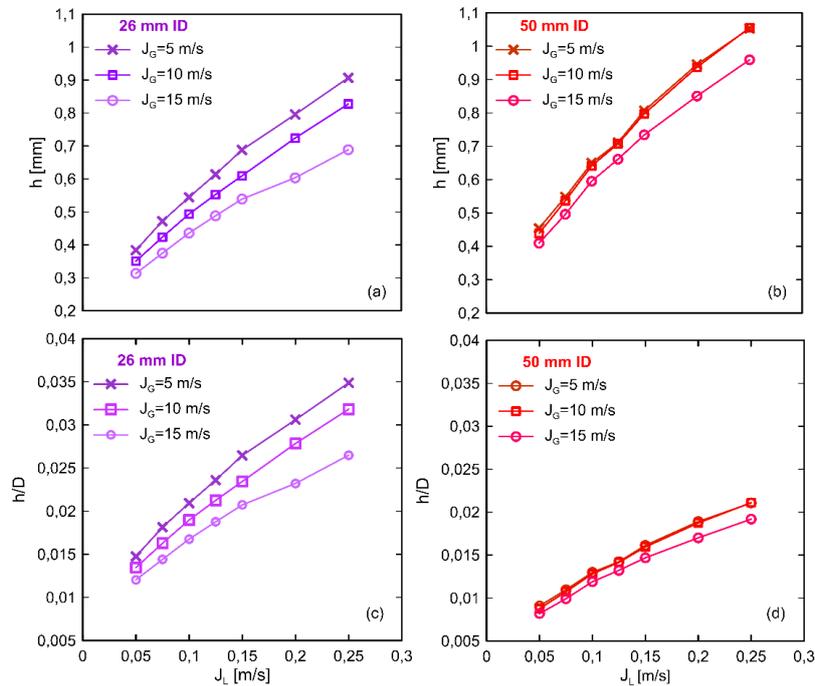


Figure 4 – Averaged liquid film thickness ( $h$ ) and dimensionless averaged liquid film thickness ( $h/D$ ) as a function of the superficial phase velocities for both pipe diameters analyzed.

Interestingly, for the largest diameter (50 mm), a similar liquid thickness result was obtained for the annular flow condition with  $J_G = 5$  m/s and  $J_G = 10$  m/s in all superficial liquid velocities range, as can be observed in Figure 4 (b). These results suggest that a larger diameter needs a higher shear interaction because of the increasing gas-liquid interface in the circumferential direction.

Furthermore, Figure 4 (c) and (d) show the dimensionless averaged liquid film ( $h/D$ ) where the 50-mm ID presents the smallest value for all flow conditions investigated in comparison with the results obtained for the 26-mm-ID.

Figure 5 presents the shape of the disturbance waves and ripples regarding the amplitude and length for all the phase flow rates evaluated. The geometrical features of the waves are obtained by overlapping each identified wave in the liquid film time signal. The waves are three-dimensional and non-uniform structures, and therefore the appearance acquired by the time signal of the liquid film is the mean liquid height variation in the circumferential direction.

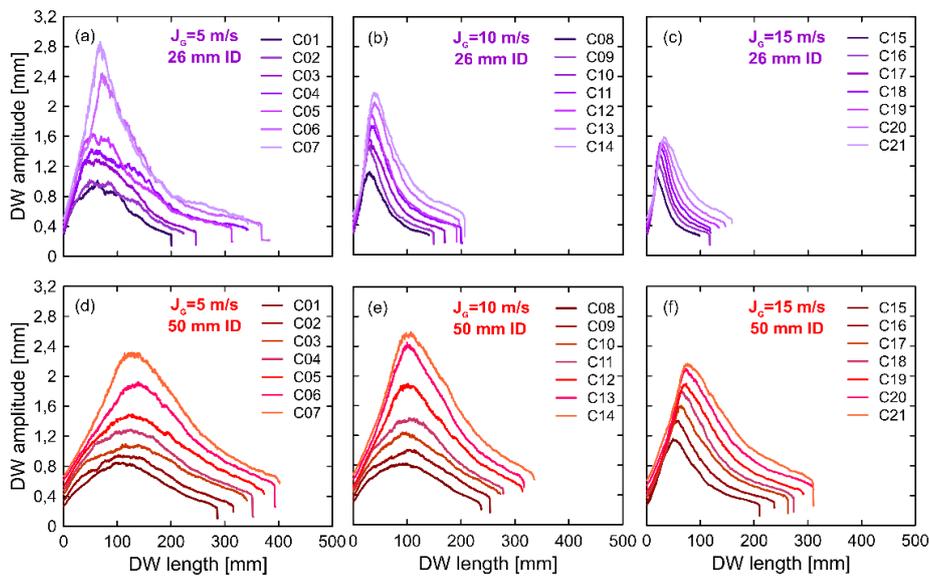


Figure 5 – Median shape of the disturbance wave as a function of the superficial phase velocities.

From the obtained representation of the median shapes of the disturbance waves, two distinct formats are identified regarding the front and rear parts of the waves. The front of the wave is the region that extends from the beginning of the wave until the maximum liquid height is reached, whereas the rear is the region from the maximum liquid height to the end of the wave.

In this context, the first shape is characterized by a steep front of liquid, increasing until it reaches the maximum height (the peak of the disturbance wave). After that, the liquid decreases to the film thickness of the ripples, indicating the end of the DW, as observed for the flow conditions C06 to C21 in the results for the 26-mm ID pipe, as illustrated in Figure 5(a)-(c). On the other hand, the wave format presented by the flow combinations C01 to C05 shows a gradual variation of the liquid amplitude between the front and rear of the disturbance wave.

For the 50-mm ID wave format results, the two formats previously discussed can also be observed. However, there is a difference in the disturbance wave format for the same flow condition evaluated for each diameter, as it can be observed in the flow conditions with  $J_G = 10$  m/s where there is a transition between the two wave formats identified in the range variation of the superficial liquid velocity.

Moreover, comparing the same flow combination, the amplitude and the length of the disturbance wave tend to increase for the 50-mm ID. An exception is observed for the flow condition C06 and C07 in the 26-mm ID with the highest amplitude. This behavior could possibly be associated with the annular flow wave regime transition. A more detailed investigation of the effect of the diameter in features of the disturbance waves will be investigated in future works.

#### 4. CONCLUSIONS

In this work, an investigation of downward vertical air-water annular flows was carried out. This investigation aimed at evaluating the effect of the pipe diameter on features of the disturbance waves. The liquid film analysis was conducted by measurements using a non-intrusive conductance sensor and visualization with a high-speed camera in 26-mm ID and 50-mm ID, 14-m long pipes. In summary, the significant findings of this work are that the pipe diameter affects the disturbance wave shape when analyzed for the same flow condition of superficial phase velocities. Furthermore, a larger diameter needs a higher shear interaction because of the increasing gas-liquid interface in the circumferential direction.

#### 5. REFERENCES

- Alves, I. N., Caetano, E. F., Minami, K., & Shoham, O. (1991). Modeling annular flow behavior for gas wells. *SPE Production Engineering*, 6(4), 435–440. <https://doi.org/10.2118/20384-PA>
- Azzopardi, B. J. (1986). Disturbance wave frequencies, velocities and spacing in vertical annular two-phase flow. *Nuclear Engineering and Design*, 92, 121–133.
- Belt, R. J., Van't Westende, J. M. C., & Portela, L. M. (2009). Prediction of the interfacial shear-stress in vertical annular flow. *International Journal of Multiphase Flow*, 35(7), 689–697. <https://doi.org/10.1016/j.ijmultiphaseflow.2008.12.003>
- Chu, K. J., & Dukler, A. E. (1974). Statistical characteristics of thin, wavy films: Part II. Studies of the substrate and its wave structure. *AIChE Journal*, 20(4), 695–706. <https://doi.org/10.1002/aic.690200410>
- Cuadros, J. L., Rivera, Y., Berna, C., Escrivá, A., Muñoz-Cobo, J. L., Monrós-Andreu, G., & Chiva, S. (2019). Characterization of the gas-liquid interfacial waves in vertical upward co-current annular flows. *Nuclear Engineering and Design*, 346(July 2018), 112–130. <https://doi.org/10.1016/j.nucengdes.2019.03.008>
- Hewitt, G F and Hall-Taylor, N. S. (1970). *Annular Two-Phase Flow*. Pergamon Press.
- Wallis, G. B. (1969). *One Dimensional Two-Phase Flow*.
- Weisman, J., Duncan, D., Gibson, J., & Crawford, T. (1979). EFFECTS OF FLUID PROPERTIES AND PIPE DIAMETER ON TWO-PHASE FLOW PATTERNS IN HORIZONTAL LINES. *Int. J. Multiphase Flow*, 5, 437–462.
- Zabaras, G., Dukler, A. E., & Moalem-Marón, D. (1986). Vertical upward cocurrent gas-liquid annular flow. *AIChE Journal*, 32(5), 829–843. <https://doi.org/10.1002/aic.690320513>
- Zhao, Y., Markides, C. N., Matar, O. K., & Hewitt, G. F. (2013). Disturbance wave development in two-phase gas-liquid upwards vertical annular flow. *International Journal of Multiphase Flow*, 55, 111–129. <https://doi.org/10.1016/j.ijmultiphaseflow.2013.04.001>

#### 6. RESPONSIBILITY NOTICE

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