Experimental investigation of the critical Reynolds number for bubbly two-phase flow

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DOI: 10.13111/2066-8201.2023.15.3.4

Received: 26 July 2023/ Accepted: 16 August 2023/ Published: September 2023

Abstract: *The critical Reynolds number for dispersed bubbly two-phase flows, gas in liquid, was experimentally investigated. In this experiment, the gas was air and the liquid was water. Water flowed upward through a vertical, translucent pipe, and air was introduced into the water prior to the test section by means of a basswood microbubbler. Dye was injected into the water to indicate when the flow transitioned from laminar to turbulent. Mixtures with gas volume fractions up to 10% were tested, and the Reynolds numbers for which the flow transitioned from laminar to turbulent were recorded. The data showed that the critical Reynolds number fell to roughly one-half of its original single-phase liquid value once the gas volume fractions exceeded 0.1%. These results indicate that the presence of even small amounts of bubbles causes pre-mature transition to turbulence.*

Key Words: *transition regime, critical Reynolds number, two-phase flow, bubbles, Reynolds experiment*

1. INTRODUCTION

The motivation for the experimental investigation of the critical Reynolds number for bubbly two-phase flows came from noticing the change of turbomachinery rotordynamic performance while operating with small gas volume fractions [1]. The conjecture was that small gas volume fractions significantly affect laminar-to-turbulent transition. Consequently, earlier transition affects the rotordynamic force coefficients in turbomachinery seals.

A fluid's transition from laminar to turbulent flow has classically been studied by observing a stream of dye in a clear tube. As the fluid's flow rate increases, the laminar stream of dye becomes unstable and oscillates. Further increasing the flow rate results in completely turbulent behavior, in which streamlines swirl and mix due to turbulent eddies. The Reynolds number, $Re = \rho u D/\mu$, is a dimensionless number that indicates whether the flow is laminar, transitioning, or turbulent. The critical Reynolds number, Re_{cr}, is defined as the Reynolds number at which the flow transitions from laminar to turbulent. As determined by Osborne Reynolds' classical experiment [2], single-phase flow transitions to turbulent when $Re_{cr} > 2300$. Work has been done to study the nature and phase distribution in turbulent bubbly two-phase flow. Serizawa [3] experimentally investigated the phase distribution, velocity profile, slip velocity, and pressure drops for various two-phase flows. Lance and Bataille [4] studied dispersed bubbly flow in a vertical square duct for gas volume fractions up to 5%, and found that the presence of bubbles caused increased turbulence kinetic energy in the liquid phase.

Drew and Lahey [5] developed a model to predict the radial phase distribution in pipe flow for both the freestream and boundary layer regions. At the time of writing, no experimental data for the effect of the gas volume fraction on laminar-to-turbulent transition has been found.

To model two-phase flows accurately, $\boldsymbol{Re_{cr}}$ was experimentally determined for flows with gas volume fractions up to 10%. This was accomplished by modifying Reynolds' classic experiment [2] to account for two-phase (air-in-water) flow. The next section presents the experimental setup, followed by a description of the methods used. The Results section summarizes the variation of $\boldsymbol{Re_{cr}}$ with gas volume fraction, $\boldsymbol{\alpha_g}$, and the paper ends by drawing several conclusions.

2. EXPERIMENTAL SETUP

Before introducing bubbles into the experiment, Reynolds' classic experiment was repeated to ensure transition occurred for $Re_{cr} > 2300$. The major components of the original experiment consisted of a reservoir, translucent pipe, valve, and ink delivery system. Water stored in the reservoir was drawn through a translucent 0.6 inch (15.24 mm) inner diameter tube when a valve at the end of the pipe was opened. A bellmouth inlet was fastened to the pipe to allow water to be drawn in so that laminar streamlines were maintained between the water in the reservoir and the pipe. The bellmouth was 3D printed using polyactic acid (PLA), which is a thermoplastic polyester. Water leakage out of the reservoir was prevented by sealing the test section hole with plumber’s putty.

The inner surfaces of the tube and bellmouth were flush. Water pressure to drive the flow originated from hydrostatic pressure in the reservoir. Ink was injected into the test section using a long needle that protruded into the bellmouth. A dye-filled bag was elevated to provide hydrostatic pressure for the dye injection, and the dye flow was controlled by constricting the drip hose. To ensure constant hydrostatic pressure in the test section, the reservoir was continuously filled with water up to a refill line.

The water refill rate was measured using the Brooks Instruments 2530 series 0.25-2.5 gal/min (0.95-9.5 l/min) variable-area, volumetric flow meter for liquids. Figure 1 and Figure 2 show the setup for the single-phase experiment.

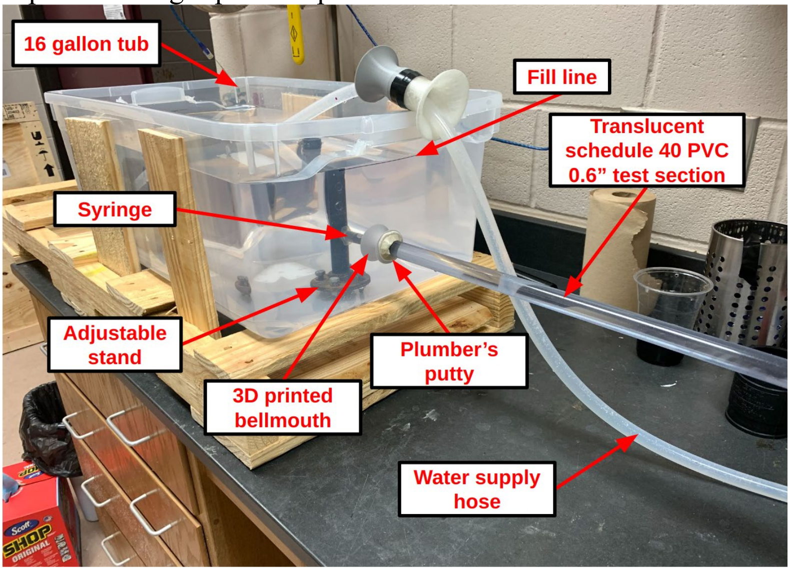

Figure 1: Single-phase experiment apparatus

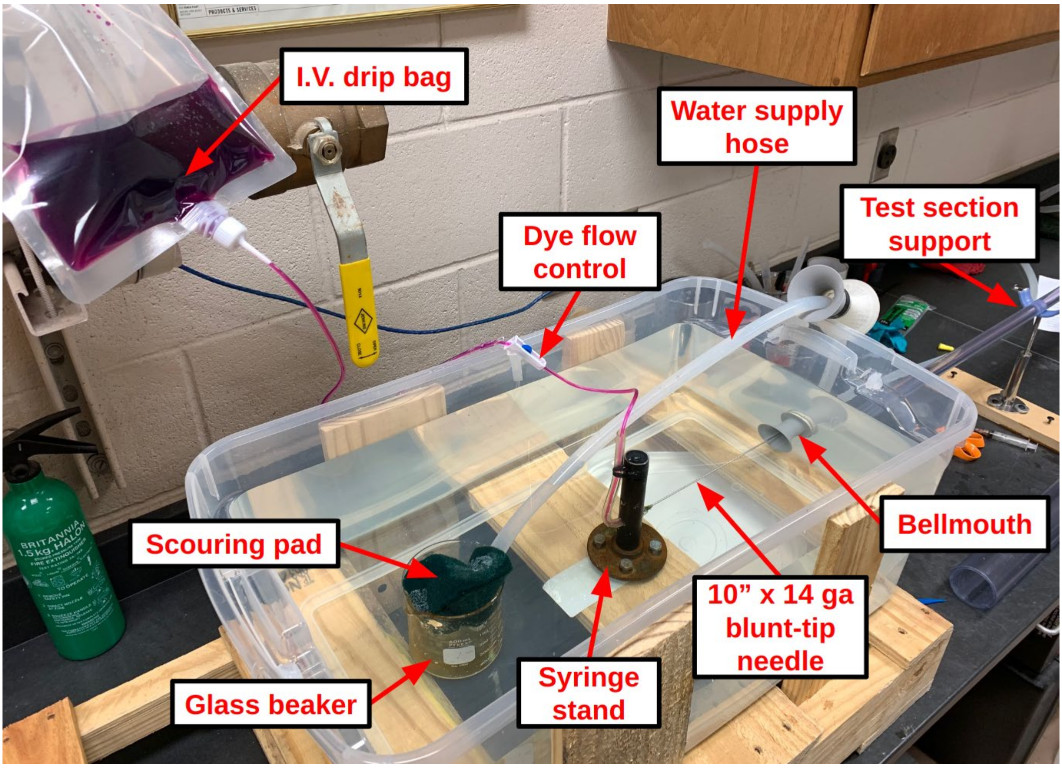

Figure 2: Single-phase experiment apparatus reservoir setup

One major difference between this experiment and Reynolds' classic experiment was the size of the reservoir. Please refer to Table 1 for a complete list of differences. Due to the smaller reservoir of this experiment, the tank was continually refilled to ensure constant hydrostatic pressure in the test section. A mechanical, variable area flow meter was used to measure the volumetric refill rate.

The outlet valve and refill rate was calibrated to ensure that the waterline remained constant when data were recorded.

To reduce turbulence in the reservoir, the water was supplied with a hose inserted into a cup with scouring pads covering the cup, and submerged in the reservoir far from the bellmouth. The most difficult challenge of the single-phase experiment was ensuring that the reservoir water was not disturbed.

Table 1: Single-phase experiment comparison

	water refill	**tube inner diameter**	**tube length**	**tube material**	**bellmouth material**	**tub volume**	**flow rate measure**
Single-Phase Experiment	yes	0.6 in	8 ft	PVC	3D printed PLA (small)	16 gal	flow meter (plunger)
Reynolds 1883	no	0.25 to 1.0 in	4.5 ft	glass	varnished wood (large)	100 gal	volume ÷ time

After making necessary modifications to account for the small reservoir, data were collected, and it was found that transition occurred near $Re = 2300$, in agreement with Reynolds' classic experiment.

It is important to note that "transition" is not a discrete point, but a phenomenon that may occur randomly within a range of Reynolds numbers. Figure 3 shows a straight dye streamline, indicating the flow is laminar. Figure 4 shows a wiggling dye streamline, indicating the flow is transitioning to turbulent.

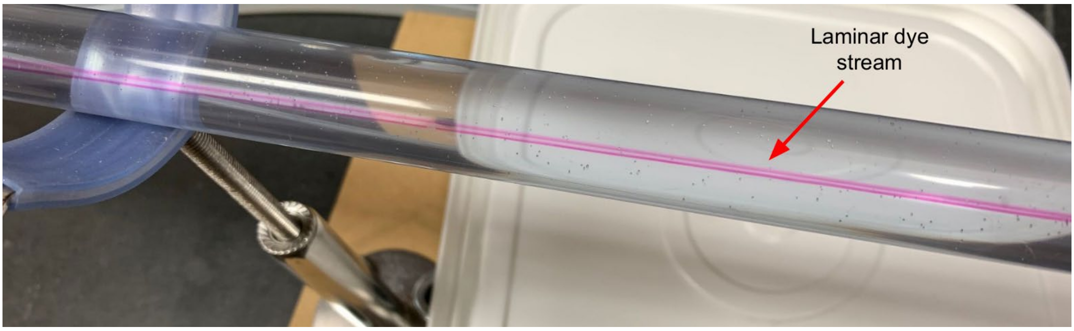

Figure 3: Laminar flow occurring in single-phase flow

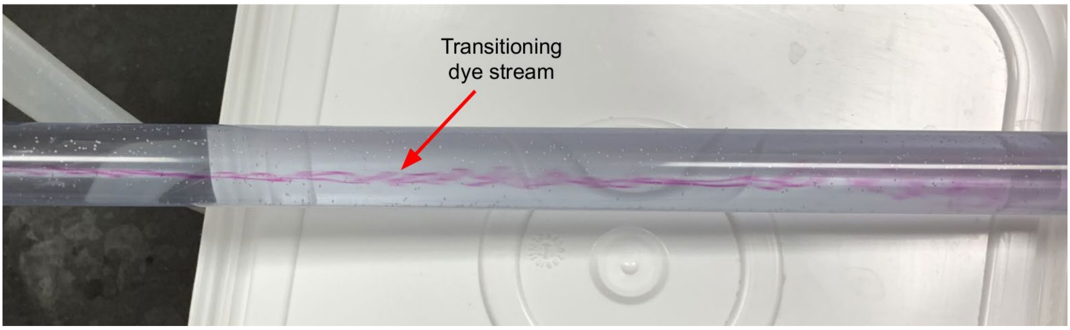

Figure 4: Transitional flow occurring in single-phase flow

To determine the variation of Re_{cr} with gas volume fraction, α_g, bubbles were introduced to the flow.

It was quickly discovered that any effort to introduce bubbles to the horizontal apparatus resulted in the bubbles rising abruptly to the top of the test section, causing an air pocket to form. It was concluded that a vertical test section was necessary.

The 0.8 inch (20.3 mm) diameter test section was tilted vertically and a 4 inch (101.6 mm) diameter "mixing" section was used to introduce bubbles to the flow. A schematic of the apparatus is shown in Figure 5.

Water was supplied from the lab sink after passing through a variable area volumetric flow meter.

The mixing section smoothly transitioned to the test section by way of a 3D printed ABS reducer. This reducer acted similarly to the bellmouth in the single-phase experiment by preserving laminar streamlines incoming from the mixing section.

Potassium permanganate dye was supplied via a 10-inch-long (254 mm) needle that was bent through a hole drilled in the mixing section.

The needle was connected to an intravenous drip system that was raised above the highest point of the test section to ensure sufficient dye pressure. A scouring pad was originally used to dampen any disturbances in the mixing section due to refill water, but it was later deemed unnecessary.

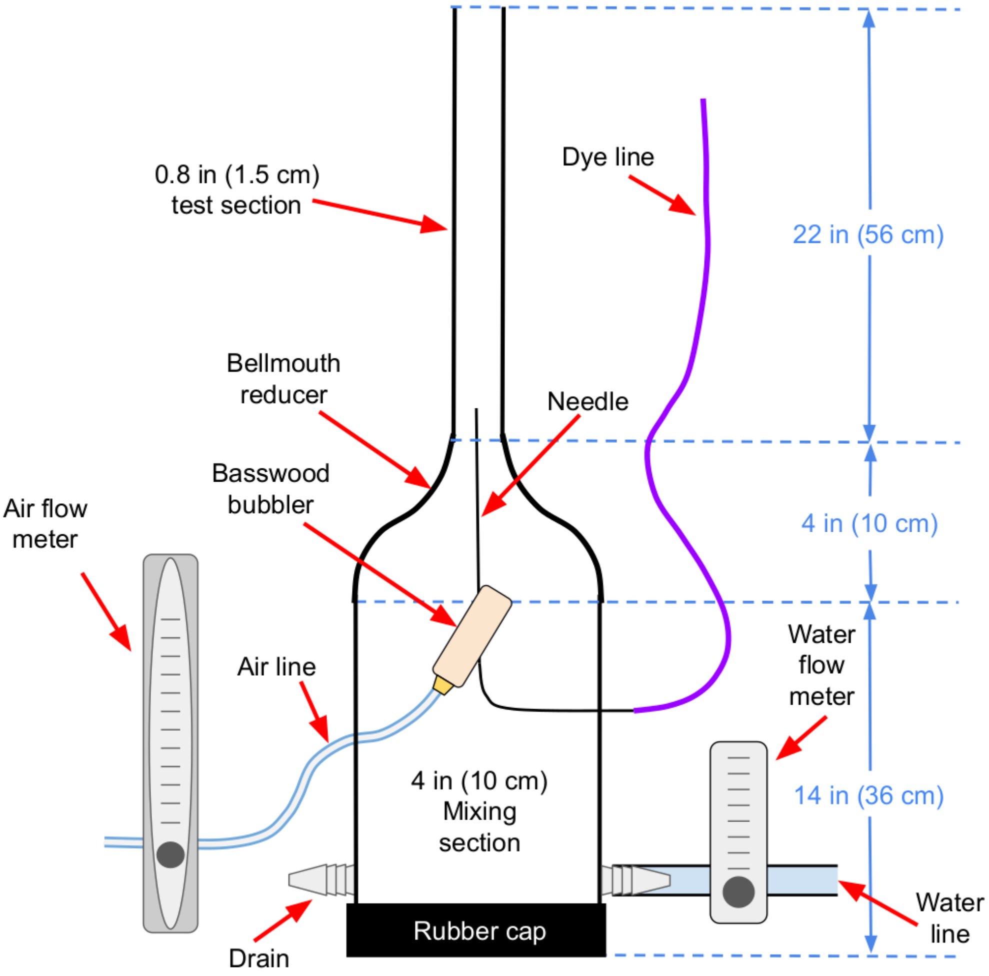

Figure 5: Two-phase experiment apparatus schematic

Due to the high water pressure in the mixing section caused by the water column, compressed shop air was used to introduce air into the system. The air was regulated and measured via a Brooks Instruments 1255 SHO-RATE (0-855 ccm air) variable area mechanical flow meter.

An air stone designed for aerating fish tanks was first used as a bubbler, but it was soon discovered that the bubbles were too large. Large bubbles were problematic because they oscillated horizontally as they rose, due to their high buoyancy. Their buoyant force caused a high relative velocity between the phases in the direction of flow, which is not representative of all two-phase flows.

A venturi nozzle was also used to mix air and water to form bubbles, but the velocity of the mixture from the nozzle caused excessive turbulence in the mixing section.

Thus, hand-made microbubblers were constructed using basswood, which has diffusive porosity. Epoxy resin was used to cover the pores in the longitudinal direction, forcing air transversally through the wood grain, resulting in tiny bubbles.

Brass airline hose connectors were epoxied into countersunk holes in the wood to connect the wood to the air source. A basswood microbubbler is shown in Figure 6.

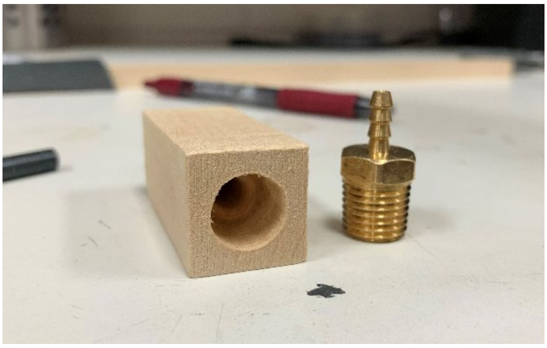

Figure 6: Basswood microbubbler

Bubblers with various shapes, sizes, epoxies, and hole sizes were used for testing. It was found that larger microbubblers with larger holes drilled inside produced consistently small bubbles. Additionally, the bubblers would become water logged and would aerate most effectively if they were dried out thoroughly before use. When collecting data, a single bubbler was positioned a few inches below the reducer and needle, and typically positioned diagonally or horizontally to prevent bubbles from accumulating on the epoxy seal. The bubbler was positioned so that most bubbles would flow directly through the test section, as opposed to sticking to the reducer.

It was found that bubbles readily stuck to any surface they contacted, then accumulated and broke off into large bubbles. These surfaces included the needle, reducer, test section, and the epoxy seal on the bubblers. No solution was found to entirely prevent bubbles from sticking, but lifting the apparatus upwards and then pushing it down quickly onto its rubber cap at the base of the mixing section helped plunge any accumulated bubbles out of the system.

3. METHODS

The basswood microbubblers took minutes to aerate once fully pressurized, resulting in a time-consuming process to calibrate the air flow meter to a constant flow rate. Therefore, controlling the volumetric flow rate of the air was much more difficult compared to that of the water. Because of this, the volumetric air flow rate was calibrated first, and then the water flow rate was incrementally increased until transition occurred. For a given air and water flow rate, transition was defined as the case at which the ink trail was noticeably and consistently laminar and straight for the first six inches (152.4 mm) of the test section, and then oscillatory and swirling afterward, as shown in Figure 7. Critical Reynolds number, Re_{cr}, was then calculated from the water flow rate, and the gas volume fraction, α_g, was calculated using the volumetric flow rates of the liquid and gas phase, $\alpha_g = \dot{V}_g / \left(\dot{V}_g + \dot{V}_l\right)$. Once Re_{cr} was determined for a given air flow rate, the air flow rate was incremented, and the process continued. These steps continued until no water flow rate could produce a stream of dye that was defined to be in transition.

Due to the nature of turbulence, especially in bubbly two-phase flows, it was difficult to find the exact flow rate to cause transition six inches (152.4 mm) into the test section. Sometimes, a change of ±0.05 gal/min seemed to have no effect on the state of the dye.

Before each data set was collected, Re_{cr} was observed for pure liquid flow $\left(\alpha_g = 0\right)$. Re_{cr} was found to be near 3750 for flows without air. This result might be explained by the favorable pressure gradient present in the vertical test section. Attempts were made to change the pressure in the test section by changing the outlet height. Although lowering the height of the outlet hose decreased the hydrostatic pressure within the test section, it did not have an effect on the pressure gradient, and the high Re_{cr} for $\alpha_g = 0$ did not change. The final apparatus used for collecting data used an outlet above the apparatus to prevent an air pocket forming in the outlet hose.

4. RESULTS

Eight data sets were gathered over the course of a two-week period. Most data points were recorded on video for later analysis. After each data set was recorded, the apparatus was taken apart and re-built, usually with a new microbubbler.

Constant re-adjustment to the setup was needed to ensure the bubbles were well-mixed, and to prevent bubbles from accumulating on surfaces. Transition occurring for two-phase flow is depicted in Figure 7.

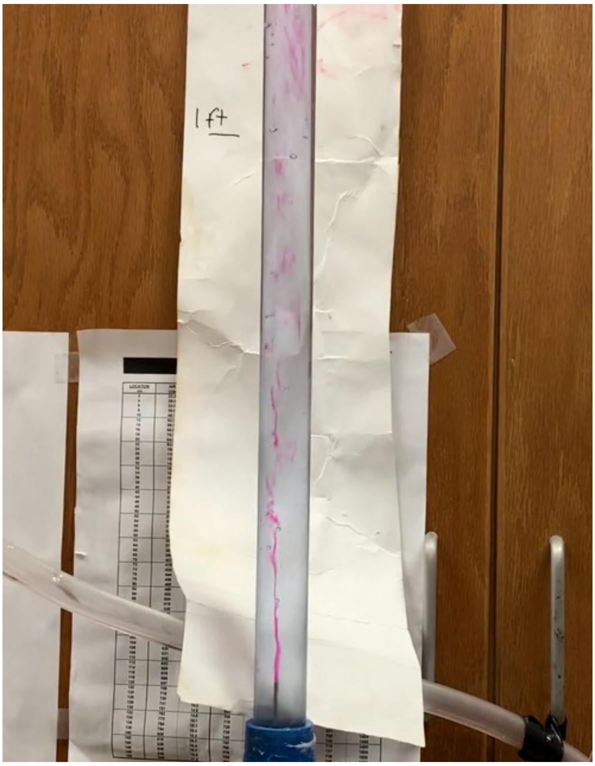

Figure 7: Transition in two-phase flow with gas volume fraction less than 1%

The final results for the two-phase experiment are shown in Figure 8. Re_{cr} dropped significantly with even small amounts of gas, despite the favorable pressure gradient from the vertical flow.

Tilting the test section vertically resulted in a favorable pressure gradient within the flow, meaning that the static pressure decreased in the direction of the flow.

A favorable pressure gradient tends to have a laminarizing effect on flows, and caused transition to occur for Reynolds numbers up to $Re_{cr} = 3750$.

However, it was found that bubbles in liquid significantly reduced Re_{cr}, despite the favorable pressure gradient.

This phenomenon of bubbles inducing premature transition is in agreement with the experimental measurements reported by Tran et al. [5].

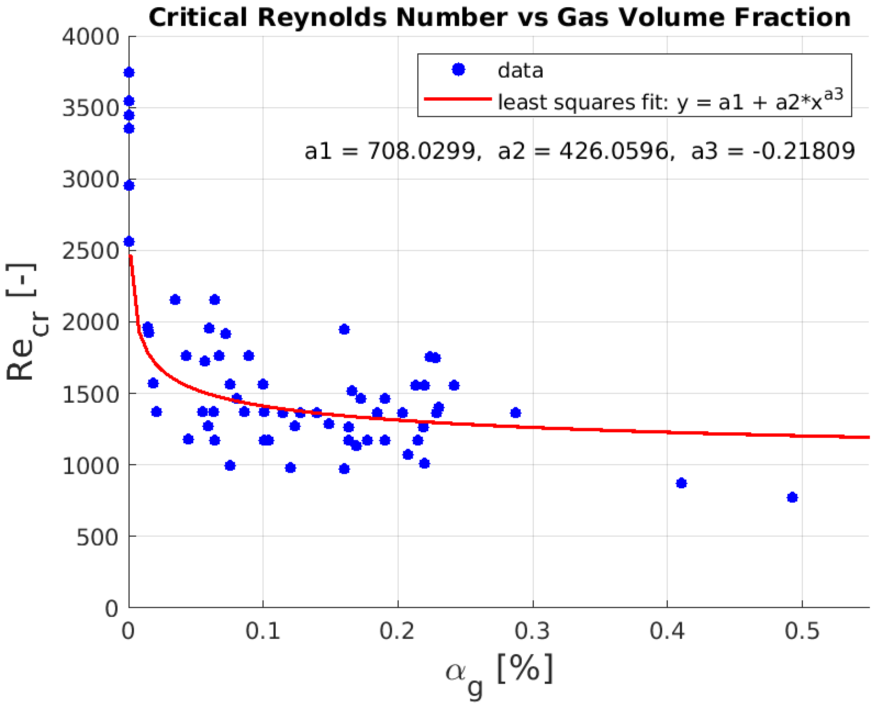

Figure 8: Critical Reynolds number vs. gas volume fraction for bubbly two-phase pipe flow

A second observation is the lack of substantial data beyond $\alpha_g = 0.3\%$. It was rare for transition to occur for $\alpha_g > 0.3\%$, for at that point the flow was completely turbulent.

The two data points beyond this could be considered outliers. These points were most likely caused from the bubbles being positioned towards the wall of the pipe, preventing the dye from making contact with the bubbles at the beginning of the test section where the dye was observed.

A third observation is the significant spread of data. This might be attributed to variation in bubble placement, but it is understood that Re_{cr} is not a discrete phenomenon.

5. CONCLUSIONS

The data suggest that introducing a finite amount of bubbles, even if the bubbles are considered small, causes Re_{cr} to drop to roughly half of the single-phase value.

Further increasing α_g resulted in a slight decrease in Re_{cr}, but significant changes in Re_{cr} occurred between. $0 < \alpha_g < 0.1\%$

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