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Establishing Suitable Conditions to Compare Multiphase Flow Laboratories with Different Line Pressures

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Abstract - This paper explores the impact of pipeline pressure variations on the reproducibility of multiphase flow metrology, using experimental results generated as part of the EMPIR MultiFlowMet II project. A test matrix, defined by the gas volume fraction and volumetric flow rate, was repeated at three pressures: 8 barg (Nitrogen), 15 barg (Argon), 30 barg (Argon). The relative change in the volumetric flow rates (gas, liquid, oil, water) is used as a metric to assess the influence of pressure changes. Trends in these deviations are explored relative to both dimensional and dimensionless numbers, so that suitable conditions for laboratory intercomparisons (particularly in cases of incongruent pressure ranges) can be ascertained. As may be expected, these trends are most prominent in the gas volumetric flow rate, and are more pronounced for several dimensionless numbers. Regions of minimal variation due to pressure – such as at high Froude and Reynolds numbers – may be targeted in the aforementioned intercomparisons through careful selection of the fluid properties.

***Keywords*:** multiphase flow metrology; pressure; dimensionless numbers

1. Introduction

Complex multiphase flows – typically including a combination or subset of gas, water, and oil components – are regularly encountered in a number of modern engineering applications, including cooling systems for nuclear power plants [1], and oil and gas pipelines [2]. As such, the ongoing process of transitioning to carbon neutral energy, while also maintaining energy security, is highly dependent on accurate, reliable, and reproducible multiphase flow metrology. The work presented in this paper was developed as part of the wider European Metrology Programme for Innovation and Research (EMPIR) project *16ENG07 – MultiFlowMet II*, which expanded and built upon the results of the European Metrology Research Programme (EMRP) project *ENG58 – MultiFlowMet* [3]. A key output of this project was an intercomparison of three multiphase flow laboratories, which assessed the reproducibility of their flow conditions when measured by a transferable test section and multiphase flow meter (MPFM) [4]; this study expanded the original comparison made in [5]. Across these intercomparisons, best efforts were made to ensure consistency in the operating conditions of the repeated test points. In particular, to account for potential variations between facility operating conditions, two dimensionless numbers – Froude number and Reynolds number – were matched by varying temperature, pressure, and water salinity. The results of this intercomparison demonstrated that reproducibility was largely achieved, though several flow conditions (including conditions close to the phase transition point, and in test points with low gas volume fractions and water-in-liquid ratios) were observed to be more challenging.

The work presented in this paper investigates the influence of a particular laboratory operating condition that may vary between facilities, namely the line pressure. Variations in pressure may lead to a number of changes in the multiphase flow parameters, including gas density and viscosity. Therefore, several important dimensionless numbers (discussed below) will be influenced by this variation, providing an extra challenge in determining the reproducibility of multiphase flow metrology in laboratories with incompatible pressure windows. To alleviate the consequences of these challenges, this paper explores variation in volumetric flow rates for a test matrix that has been repeated at three different pressures. Trends

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in relative deviation as a result of the change in pressure are considered in terms of several dimensionless numbers, to assess potential measures that can be undertaken to improve the quality of such an intercomparison.

2. Experimental Setup

The experimental data used in this study were generated as part of the MultiFlowMet II project, overarching aim of which was to investigate the reproducibility of multiphase flow measurements between laboratories, taking into account differences in the facilities, such as injection and loop geometries, fluid properties, and – of key importance to the presence study – pressure. The data presented here were collected at the DNV GL multiphase flow testing loop in the Netherlands and investigated the influence of pipeline pressure on the volumetric flow rates (gas, liquid, oil, and water).

The DNV GL facility uses a closed flow loop, with all three phases being recirculated. The test section was placed on the suction side of a multiphase pump, which discharges through a series of three separators, with the liquid injected into the gas. The rigid test section was kept in a horizontal orientation and had a 3” internal diameter across its length. A temperature range of 17-19.5°C was maintained throughout the experimental campaign.

An expansive matrix of test points (TPs) was defined for this study in terms of gas volume fraction (GVF) and total volumetric flow rate (Q). An overview of these TPs is presented in Figure 1. As can be observed in this figure, there is some variance around each point of the test matrix. This is a result of variations in water-in-liquid ratio (WLR) for each TP, and the corresponding variations in the volumetric flow rate of the gas, oil, and water phases.

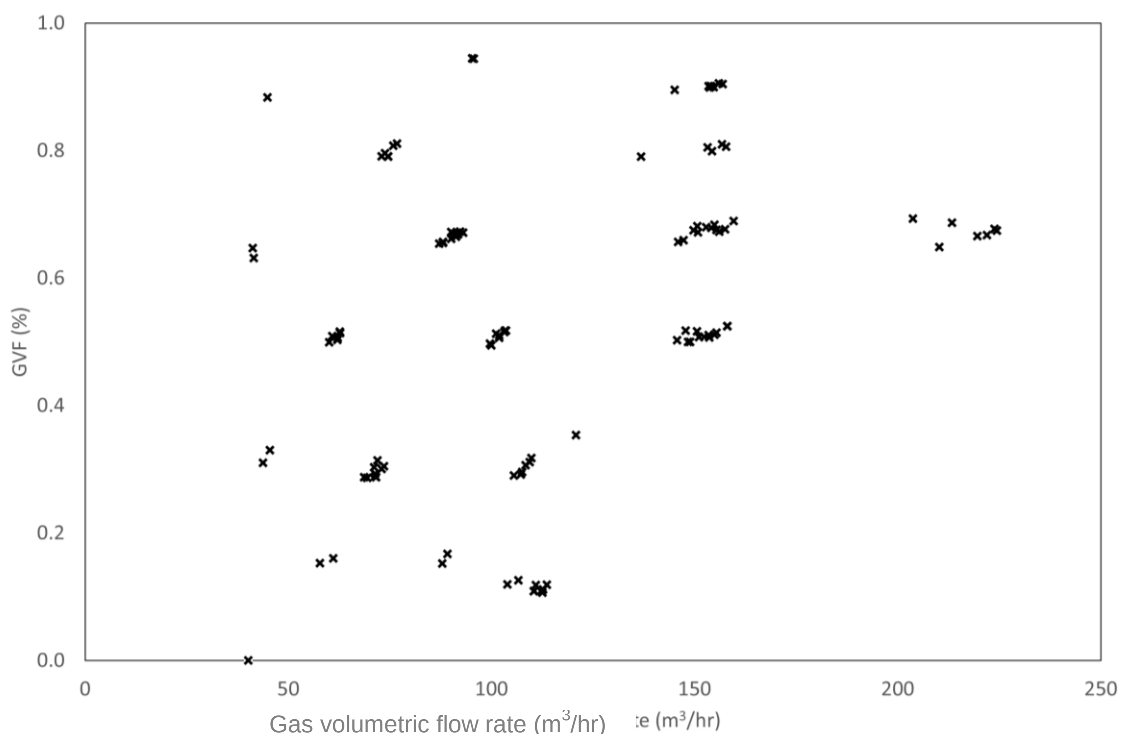

Figure 1: Overview of test points included in the present analysis.

The primary aim of this investigation is to establish trends in the relative deviation of volumetric flow rates due to changes in pressure. As such, the above test matrix has been repeated at three pressures for inert gas: Nitrogen at 8 barg and Argon at 15 and 30 barg. The deviation due to changes in pressure is calculated for the two higher pressure cases, relative to the low-pressure case, as follows:

$$\Delta Q = \frac{Q^{Ar} - Q^{N}}{Q^{Ar}},$$

where Q^{Ar} and Q^{N} denote the volumetric flow rates for the higher pressure (Argon, 15 or 30 barg) and lower pressure (Nitrogen, 8 barg) test runs.

A number of dimensionless numbers for this analysis include Reynolds number, Froude number, Weber Number, Euler number, and Ruark number. Various forces acting on the multiphase flow system are combined to formulate these dimensionless numbers. Inertia force ratio to viscous, gravity and surface tension forces are Reynolds number, Froude number and Weber number, respectively. The ratio of pressure force to inertia force is called the Euler number. The ratio of one phase's density to another phase's density in a multiphase flow system is called density ratio. These dimensionless parameters are presented in equations 1-5 in the form of gas-phase, oil-phase, water-phase and liquid-phase.

$$Re_i = \frac{\rho_i v_{si} d}{\mu_i}, \qquad for\ i = g, o, w, l \tag{1}$$

$$Fr_g^2 = \frac{v_{sg}^2}{gd}\left(\frac{\rho_g}{\rho_l - \rho_g}\right),\ Fr_i^2 = \frac{v_{si}^2}{gd}\left(\frac{\rho_i}{\rho_i - \rho_g}\right),\ \ for\ i = o, w, l \tag{2}$$

$$We_g = \frac{\rho_g v_{sg}^2 d}{\sigma_{gl}}, \qquad We_i = \frac{\rho_i v_{si}^2 d}{\sigma_{gi}}, \qquad for\ i = o, w, l \tag{3}$$

$$Eu_i = \frac{\Delta p}{\rho_i v_{si}^2}, \qquad for\ i = g, o, w, l \tag{4}$$

$$\mathrm{R}u_i = \frac{\rho_i v_{si}^2}{\Delta p}, \qquad for\ i = g, o, w, l \tag{5}$$

where Re, Fr, We, Eu, and ρ are Reynolds number, Froude number, Weber number, Euler number and density, respectively. The subscripts $_{g,\ o,\ w}$ and $_l$ are gas, oil, water and liquid phases, respectively. The subscripts v_{sg}, v_{so}, v_{sw} and v_{sl} are superficial gas velocity, superficial oil velocity, superficial water velocity, and superficial liquid velocity, respectively. The subscripts $_{gl}$, $_{go}$, and $_{gw}$ are gas-liquid phase, gas-oil phase, and gas-water phase, respectively. The letter d and g are pipe diameter and acceleration due to gravity, respectively.

3. Results and Discussion

After consideration of the gas, liquid, oil, and water volumetric flow rates, it was gas flow rate (ΔQ_g) that showed the greatest variation with changes in both dimensional and dimensionless parameters. This is consistent with the fact that these deviations are a result of the change in pressure. The percentage change in ΔQ_g versus GVF and WLR are shown in Figure 2 and Figure 3, respectively. The ΔQ_g variation reduces as the percentage of GVF increases, as shown in Figure 2; also, the variation appears to reduce with increasing WLR in Figure 3, though lesser than the reduction observed in Figure 2. In both cases, there is no clear division between the 15 barg and 30 barg deviations, suggesting that there is no directly proportional relationship between the two. Although these initial figures provide some interesting insight, it must be noted that intercomparisons between laboratories typically consider a range of GVF and WLR test points. As such, the subsequent discussion will focus on non-dimensional parameters that could be matched through changes in fluid parameters other than pressure and inlet conditions.

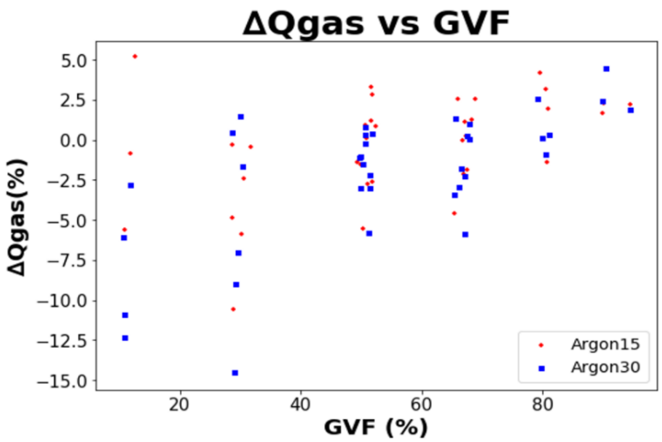

Figure 2: The percentage change in gas flow rate (ΔQ_g) due to pressure variation as a function GVF

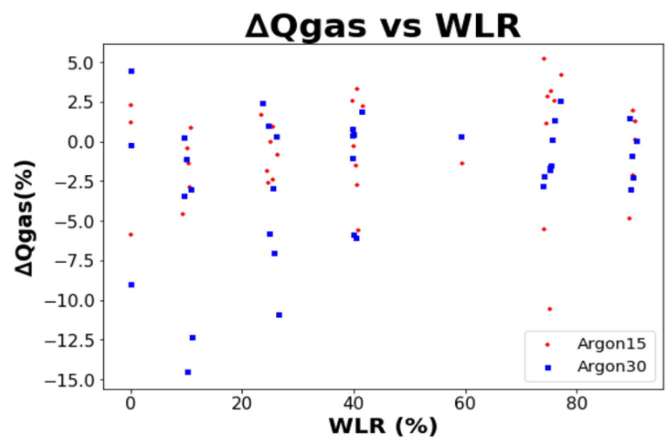

Figure 3: The percentage change in gas flow rate (ΔQ_g) due to pressure variation as a function WLR

Among several parameters tested, the percentage change in gas flow rate (ΔQ_g) versus the gas-phase Reynolds number (Re_g), gas-phase Froude number (Fr_g), gas-phase Weber number (We_{gl}), gas-phase Euler number (Eu_g), and gas-phase Ruark number (Ru_g) (inverse to gas-phase Euler number) show interesting trends for further discussion. These trends are presented in Figure 4 to Figure 18.

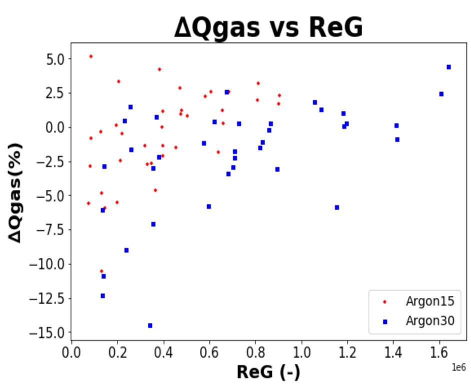

Figure 4: The percentage change in gas flow rate (ΔQ_g) versus gas-phase Reynolds number (Re_g)

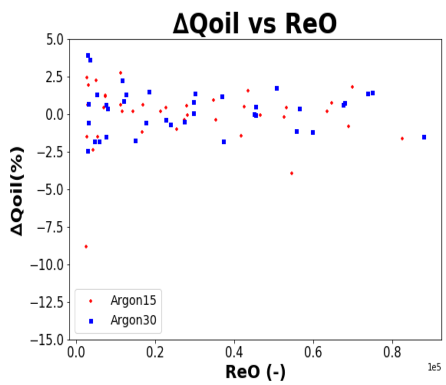

Figure 5: The percentage change in oil flow rate (ΔQ_o) versus oil-phase Reynolds number (Re_o)

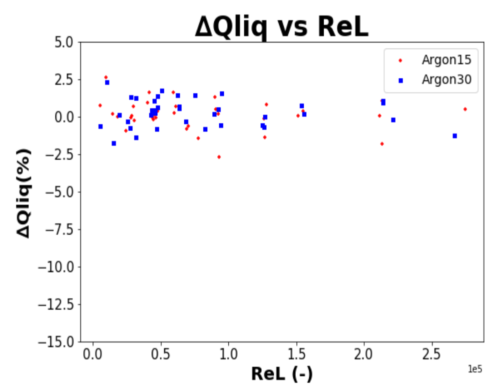

Figure 6: The percentage change in liquid flow rate (ΔQ_l) versus liquid-phase Reynolds number (Re_l)

Figure 4 shows that the spread of ΔQ_g deviations decreases as the Re_g increases. Similar decreases are observed for ΔQ_o and ΔQ_l, Figure 5 & Figure 6. The reductions in deviation of both ΔQ_o and ΔQ_l are lesser than ΔQ_g. At low Reynolds number, the most significant variation is observed in all volumetric flow rates. For ΔQ_g, the deviation window narrows down at high Re_g, which implies a reduction in the effect of pressure on reproducibility. Both ΔQ_o and ΔQ_l show a similar trend but with lesser magnitude comparatively. For intercomparisons between laboratories operating at different pressures, a flow condition with a high Reynold number must be aimed to minimise pressure effect on reproducibility. This can be achieved by increasing the superficial gas velocity, increasing the operating pressure, which will increase the gas density and gas viscosity, but the increase in gas viscosity will be insignificant compared to the increase in gas density. An increase in operating temperature will reduce the oil and liquid viscosity, which will increase the Re_o and Re_l. An increase in salinity will rise water density and viscosity. A water salinity of 75‰ achieved by adding common salt (9% water weight) to the water tank, changed water density from 999 kg/m^3 to 1065 kg/m^3 and viscosity from 0.985 mPa s to 1.246 mPa s at 23.5 °C [6] [7].

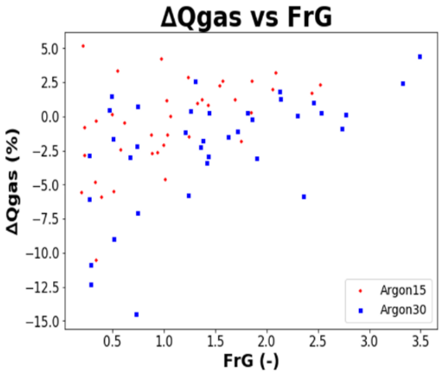

Figure 7: The percentage change in gas flow rate (ΔQ_g) versus gas-phase Froude number (Fr_g)

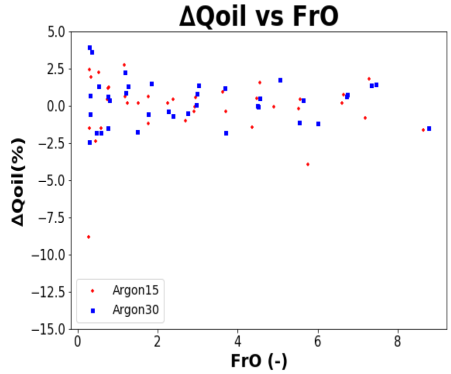

Figure 8: The percentage change in oil flow rate (ΔQ_o) versus oil-phase Froude number (Fr_o)

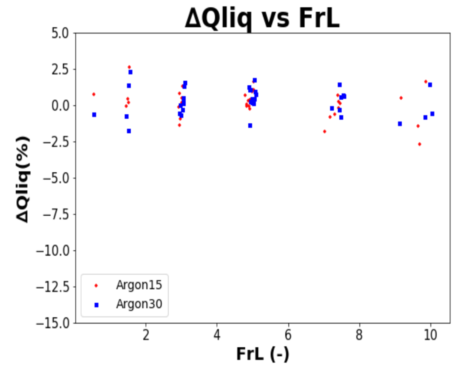

Figure 9: The percentage change in liquid flow rate (ΔQ_l) versus liquid-phase Froude number (Fr_l)

Figure 7 shows that the deviation in percentage change of gas flow rate narrows down as the gas-phase Froude number increases. The trends presented in Figure 8 & Figure 9 do not narrow down significantly with increasing oil-phase Froude number and liquid-phase Froude number. The largest deviation is observed in volumetric flow rates at low Froude number. For ΔQ_g, the deviation window narrows down at high Fr_g, the test points in this region indicate a reduction of pressure effect on reproducibility at high Fr_g. Similar trends are observed for Fr_o and Fr_l, though their trends do not narrow down significantly as the Fr_g. Therefore, flow conditions with high Fr_g values should be targeted in ensuring intercomparisons between laboratories with differences in pressure. A high Froude number can be achieved by increasing superficial velocity.

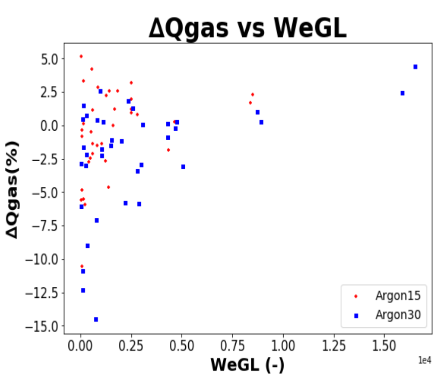

Figure 10: The percentage change in gas flow rate (ΔQ_g) versus gas-phase Weber number (We_{gl})

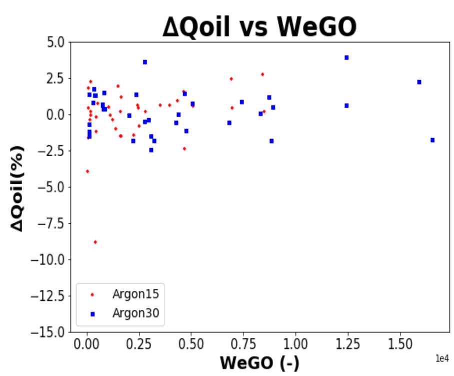

Figure 11: The percentage change in oil flow rate (ΔQ_o) versus oil-phase Weber number (We_{gl})

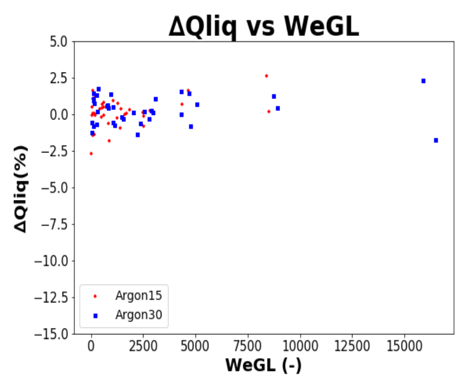

Figure 12: The percentage change in liquid flow rate (ΔQ_l) versus gas-phase Weber number (We_{gl})

Increasing the Weber number narrows down the deviation of the gas flow rate, as shown in Figure 10, but the deviations in both oil and liquid flow rates remain broad, particularly for higher pressure data i.e. Argon 30 bar, as presented in Figure 11& Figure 12. The widest variation observed in the gas flow rate is at low Weber number. For ΔQ_g, the deviation window narrows down at high We_{gl}, implying less effect of pressure on reproducibility for test points in the region. Therefore, high We_{gl} should be aimed at to minimise the pressure effect when intercomparing laboratories with different operating pressures. Usually, increasing operating pressure will raise the gas density and superficial gas velocity, and increase these parameters will increase the We_{gl}. The trends of ΔQ_o and ΔQ_l do not show an apparent reduction of pressure effect on reproducibility, as shown in Figure 11 and Figure 12.

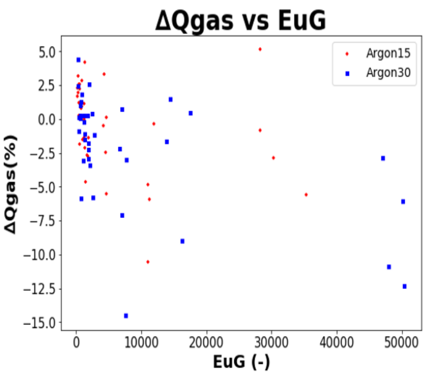

Figure 13: The percentage change in gas flow rate (ΔQ_g) versus gas-phase Euler number (Eu_g)

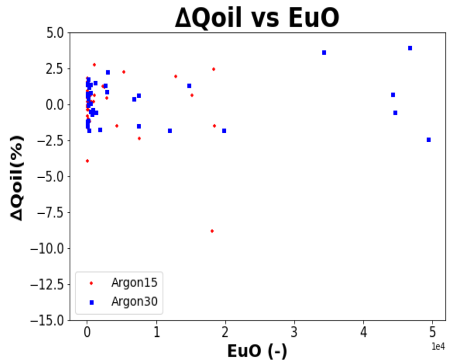

Figure 14: The percentage change in oil flow rate (ΔQ_o) versus oil-phase Euler number (Eu_o)

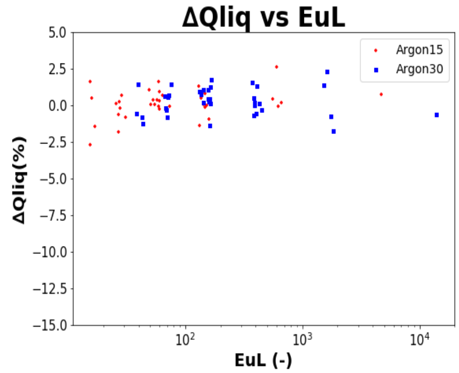

Figure 15: The percentage change in liquid flow rate (ΔQ_l) versus liquid-phase Euler number (Eu_l)

Increasing the Euler number, the deviation of ΔQ_g remains significantly high, particularly for higher pressure case i.e. Argon 30 bar, as shown in Figure 13. A similar observation for both ΔQ_o and ΔQ_l, as shown in Figure 14 & Figure 15. The largest deviation in all the volumetric flow rates is observed, usually at a low Euler number.

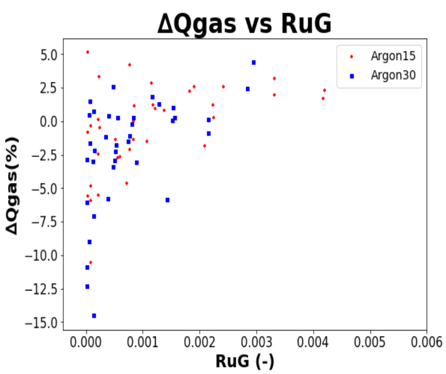

Figure 16: The percentage change in gas flow rate (ΔQ_g) versus gas-phase Ruark number (Ru_g)

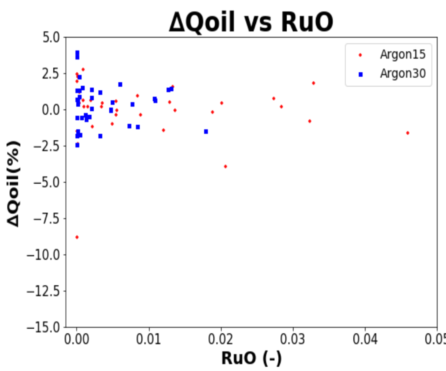

Figure 17: The percentage change in oil flow rate (ΔQ_o) versus oil-phase Ruark number (Ru_o)

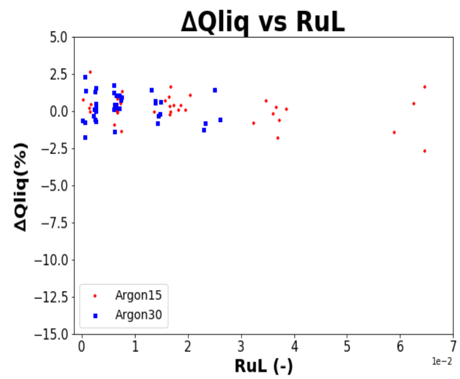

Figure 18: The percentage change in liquid flow rate (ΔQ_l) versus liquid-phase Ruark number (Ru_l)

Increasing the Ruark number, the deviation of ΔQg reduces, as shown in Figure 16, but the deviations for ΔQo and ΔQl remain broad, particularly the low-pressure case, i.e. Argon 15 bar, as shown in Figure 17 and Figure 18. The variation is largest at low-Ruark number for ΔQg and ΔQo but remains broad for ΔQl even at high-Ruark number. For ΔQg, the deviation window narrows down at high Rug, suggesting that the effect of pressure on reproducibility would be reduced for test points with high Ruark number. Similar trends can be observed for Ruo, though trends for Rul are less clear. Therefore, intercomparisons between laboratories with differences in pressure should primarily target flow conditions with high Rug values; this could be achieved by increasing the superficial gas velocity, operating at high pressure to ensure high gas density and minimising the difference in the operating pressures between the two laboratories.

4. Conclusions

This paper explores variations in volumetric flow rates as a result of changes in pressure, particularly focusing on trends with respect to dimensional and dimensionless parameters. This work contributes to wider discussions regarding reproducibility of multiphase flow measurement between laboratories and focuses specifically on steps that can be made to improve the outcomes of intercomparisons with differing operating pressures. Initial consideration of trends as a function of GVF and WLR showed that the influence of pressure was reduced for higher GVF values, though this information cannot be used to minimise this influence across a comprehensive test matrix, as GVF is typically varied. As such, this paper considered trends with respect to dimensionless parameters, as these are more readily altered through changes in the fluid characteristics.

The deviation of ΔQ_g was observed to be the highest of all the variations of volumetric flow rates, which was consistent with the focus on pressure. However, the deviations were largest, for all the volumetric flow rates (gas, liquid, oil), at lower values of the dimensionless parameters considered. Therefore, by adapting the fluid parameters to increase the Froude and Reynolds number, in particular, it will be possible for future laboratory intercomparisons to remove some of the uncertainty introduced by incompatible pressure ranges.

Increasing the operating pressure will increase the superficial gas velocity and gas density, which raise the value of Re_g, Fr_g, We_{gl} and Ru_g, leading to a narrow window with a low effect of pressure on reproducibility. An increase in operating temperature significantly reduces the liquids' viscosity, thereby boosting the value of Re_o, Re_w and Re_l, which would boost intercomparisons between laboratories operating at different pressures by reducing effect of pressure at high Reynold numbers.

Acknowledgements

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