**Gas-liquid flows through porous media in microgravity:**

**Packed Bed Reactor Experiment-2**

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**Abstract**

Experimental results on pressure drop and gas hold-up for gas-liquid flow through packed beds obtained from a second flight on the International Space Station are presented and analyzed. It is found that the gas hold-up is a function of the bed history at low liquid and gas flow rates whereas higher gas hold-up and pressure gradients are observed for the test conditions following a liquid only pre-flow compared to the test conditions following a gas only pre-flow period. Over the range of flow rates tested, the capillary force is the dominant contributor to the pressure gradient and is found to be linear with the superficial liquid velocity but is a much weaker function of the superficial gas velocity. The capillary contribution is also a function of the particle size and varies approximately inversely with the particle diameter within the range of the test conditions.

Keywords: capillary effects, multiphase flow, porous media, microgravity, pressure drop, gas hold-up

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1. **Introduction**

A fundamental understanding of two-phase gas-liquid flows through porous media is important for designing and operating many chemical and biological processing systems. Not surprisingly, many space-based systems or unit operations also involve gas-liquid flows through porous media. In particular, understanding the impact of reduced or zero gravity on the hydrodynamics (pressure drop, as well as distribution and holdup of each phase) is relevant to life support systems, fuel cells, *in-situ* resource utilization, heat pipes, materials processing, production of pharmaceutical-grade water, and transport of nutrients in soils. Some examples of current space systems which involve two-phase flow through fixed porous media include the Volatile Removal Assembly (VRA), the Integrated Advanced Water Recovery System (AWRS), and IntraVenous Water GENeration system (IVGEN). To fully understand how to reliably operate these systems in the reduced gravity environment, NASA has conducted a series of experiments on the International Space Station (ISS) called the Packed Bed Reactor Experiment (PBRE). This work presents experimental data on the second series of tests (PBRE-2) and a preliminary analysis of the phase distribution and pressure gradient.

Results from the original PBRE flights are discussed in (Motil et al, 2020)1 which included two test series using 3 mm Glass and Teflon packing to compare the effects of wettability on pressure drop and phase distribution. PBRE-2 extends these results to include a smaller size glass packing (2 mm) as well as longer duration test runs and a comparison of different pre-flow conditions. In addition, modifications were made to the test facility which are discussed in the experimental section. In this work, we extend the analysis to a wider range of gas and liquid flows (beyond the V-C regime) than were considered in earlier studies1-3.

1. **Experiment and Test Conditions**

­­­­­­­­­­­­­The PBRE was designed to deliver a wide range of tightly controlled gas (nitrogen) and liquid (water) flows to interchangeable test sections. Details of the flow loop and test sections are described in detail in (Motil et al., 2020)1. PBRE-2 used the same gas and liquid flow loop so only the modifications or changes are discussed. For reference, the basic flow schematic is provided in Figure 1. As in the initial experiments, the test column was cylindrical (60 cm long and 5.08 cm in diameter) and constructed out of clear Lexan polycarbonate for flow visualization. During the initial PBRE testing, small pressure oscillations were observed external to the test bed at higher flow rates. To minimize these external disturbances, the inlet mixing head was modified by making the open area mixing chamber shorter in length (from 1.5 cm to 0.5 cm). In addition, the screen at the inlet to the packing was modified to minimize recirculation for the gas and liquid before entering the packing material as shown in Figure 2. The trade off with this modified test section allowed for higher gas and liquid flows without external pressure oscillations but the two phases entering the column were not as well mixed so channeling was observed for the first 10 to 20% of the column length. For both PBRE and PBRE-2, the gas and liquid are introduced at the top center of the mixing section directed toward the packing which is why the initial PBRE design included a section of the screen that was not perforated to increase mixing prior to entering the packing. The strong pressure oscillations observed in microgravity in the mixing section were not observed during ground testing for the original PBRE but adding perforations over the entire screen (PBRE-2) greatly reduced this effect in microgravity.

PBRE-2 used the same glass material for packing, but the particle size was reduced from 3 mm to 2 mm diameter to increase the overall pressure drop in the column. The primary reason for this change was to increase the accuracy of the pressure readings for the lower flow rates. Normal packing size for reactors used on the ISS is in the range of 2-3 mm. As with the initial testing, the packing was randomly distributed and held in place by a spring-loaded perforated end cap. Nitrogen gas and water (liquid) flows were controlled and measured using selectable high and low flow loops.

The diagnostics did not change from the initial experiment and the same pressure transducers and high-speed cameras were used in PBRE-2. Five absolute pressure transducers with an accuracy of +/- 0.14 kPa, spanned the entire column length at equally spaced intervals (Figure 1) to record pressure measurements at a rate of 1000 Hz. Temperatures and pressures were measured at each ﬂuid inlet line just upstream of the mixing chamber, and at the exit of the test section. Two high-speed video cameras were focused on two 10 cm segments along the test section length. One segment was located at the column inlet and the other was near the middle of the test section. Each camera was equipped with a parfocal, 6X zoom capable lens with a field of view from 74.4 mm to 12.5 mm in the axial direction. A variable video frame rate was selected up to a maximum of 150 frames per second. A set of controlled LED strobe lights were used for illumination to improve stopping action (minimize individual image blur).

For the initial PBRE test conditions, a pre-flow “liquid flush” was used to establish similar initial conditions prior to testing. PBRE-2 ran a series of tests using the same liquid pre-flow conditions which consisted of flowing liquid at 150 kg/hr for 30 seconds, followed by 20 kg/hr for 120 seconds and then flowing the selected gas and liquid flow rates dictated by test conditions for a duration long enough to establish pseudo-steady flow conditions throughout the column. Over 200 test points were recorded spanning the full range of gas and liquid flows available (0 to 1 kg/hr for gas and 1 to 150 kg/hr for liquid). In addition, PBRE-2 duplicated these test conditions using a “gas flush” pre-flow (this pre-flow was not performed during the initial PBRE testing). The gas pre-flow conditions consisted of flowing gas at 0.1 kg/hr for 30 seconds, followed by 0.3 kg/hr for an additional 30 seconds and then flowing the selected gas-liquid test condition for a duration long enough to establish steady flow throughout the column as with the liquid pre-flow or “liquid flush”.

For each run, and after the liquid or gas flush period is completed, the selected liquid and gas test flows are applied and controlled until an equivalent of 150% of the bed void volume was passed through the column to ensure steady flow conditions were achieved. The water and gas flow into the mixing head region of the packed bed where the two fluids are mixed. The liquid-gas mixture in turn flows through the screen into the packed bed. The absolute pressure of the single-phase liquid (water) is measured using pressure transducer PT7 while the pressure in the gas flow stream is measured using PT6. The pressure gradient along the column is measured by the difference in absolute pressures between PT1 and PT5. Since the spacing between PT1 and PT5 is 0.56m, the accuracy of our measured pressure gradient is +/-0.25kPa/m]. The two-phase stream exits the packed bed and enters the two-phase vortex separator where the gas and liquid are separated. The liquid is recirculated, and the gas is vented into the ISS cabin. Pressure data for PT1 through PT5 are recorded at a high data rate (1000 Hz). Video imaging was recorded at 100 fps for each of the test conditions. Sample recorded pressure traces of pressure transduce just before the bed exit (PT5) as a function of time are shown in Figure 3 at various selected liquid and gas flow rates.

1. **Flow Regimes in Microgravity**

The flow pattern data presented here are based primarily on video observations, analysis of pressure traces (amplitude and frequency of pressure fluctuations), and similar observations of the flow patterns in normal gravity (with co-current up and down flows but with Bond numbers of less than unity). Some typical pressure traces of PT5 at selected gas and liquid flow rates are shown in Figure 3. An approximate flow regime map (and the entire test matrix of 232 experiments) is shown in Figure 4. At high liquid flow rates (10 kg/hr to 150 kg/hr or liquid superficial velocities greater than about 1 mm/s), the two main flow patterns are well known and are the same as those observed in low gravity aircraft and earlier ISS experiments, namely, dispersed bubble flow (DB) and pulse (P) flow. It should be noted that these two patterns also exist in normal gravity co-current down flow, but at different flow rates. At high liquid inertia, increasing the gas flow rate results in transitioning from the DB regime to the P regime. The pressure signals in figures 3C and 3D show this transition. The pressure signal in Figure 3C shows more regular fluctuations at a lower gas flow rate compared to a typical pressure signal in pulse flow which is indicative of the passage of the more frequent liquid-gas slugs in the packed bed and leads to higher amplitude and frequency pressure fluctuations (Figure 3D). The pressure signal standard deviation is plotted as a function of liquid flow rate in Figure 3E and shows that at liquid flow rates greater than about 20 kg/hr, the standard deviation increases beyond the accuracy of the pressure transducer (+/-0.14 kPa) which is an indication of the pulse flow. Since dispersed bubble and pulse flow patterns have already been discussed in the literature, we refer to these studies1,4-5. The aircraft-based correlation4 appears to give a fair description of the observed transition and may be expressed as:

*(1)* where the constant Λ depends on the packing size and fluid properties. Based on the literature correlations4,5, for the packing size and fluids used in PBRE-2, this constant was estimated to be about 3.4. The line represented by Eq. (1) is shown as a dashed line in Figure 4.

At low liquid flow rates (1 kg/hr to 10 kg/hr or liquid superficial velocities smaller than about 1 mm/s) and low gas flow rates, video observations close to the column wall showed the presence of small (less than or equal to the particle size) as well as large bubbles (spanning more than several particles). It is hypothesized that bubble coalescence takes place leading to large bubbles whose presence extends throughout the bed. We refer to this flow regime as the “large bubble” (LB) regime. This regime is like that observed in normal gravity (at low Bond numbers) co-current up-flow at stationary or very low liquid flow rates and low gas flow rates6 (except that the bubbles appearing in microgravity are larger). The pressure trace in Figure 3A shows a uniform pressure signal with several spikes correlating to the release of large bubbles trapped in the packing. As discussed later, in this regime of low gas and liquid flow rates, it is found that the time required to fully reach a steady (or periodic/intermittent) flow pattern is of the order of several minutes (and may even be longer at the lowest flow rates we used). However, most of our experiments only included a pre-flow time to sufficiently replace the void area in the bed with the selected test conditions followed by a short test duration (30 to 60 s). In this flow regime, it was observed that gas accumulates in the form of long bubbles which are broken up and released so that the gas fraction in the bed is oscillatory with a period that depends on the flow rates.

As the gas flow rate is increased, the large bubbles overlap and form gas channels that extend from the inlet to the exit of the column. We term this flow regime as “gas channeling” (GC) regime. This regime was also observed in normal gravity up-flow experiments7-13. Our video observations (limited to near wall region) were not clear enough to determine the transition between the LB and GC regime, but it appears that Eq. (1) is a fair approximation. While we observed weak pulsing in the GC regime, the transition between GC and P regimes is not as sharp as it is that between LB and DB regimes. Figure 3B shows that as the gas flow rate increases, the pressure trace exhibit higher amplitude fluctuations on the order of ~0.4 kPa compared to the LB regime (Figure 3A) at the same liquid flow rate indicative of bubble coalescence and formation of a gas channel. The vertical dotted line in Figure 4 represents an approximate transition boundary between the low and high interaction regimes. These low and high interaction regimes are delineated based on the pressure gradient plots shown in Figure 5, where the pressure gradient is plotted as a function of the liquid flow rate for two fixed gas flow rates of 0.1 and 1.0 kg/hr. It is observed that the pressure gradient is small and nearly independent of the liquid flow rate in the range of 1-10 kg/hr, and this behavior is also observed for other gas flow rates between 0.1 kg/hr and 1.0 kg/hr. For gas flow rates below 0.1 kg/hr, the pressure gradient in the low interaction regime is too small and below the accuracy of our measurement, though it is observed that it increases linearly with liquid flow rate (for L>20 kg/hr). For all the gas flow rates used, it is observed that the pressure gradient increases sharply with the liquid flow rate in the high interaction regime (10 to 150 kg/hr).

It should be emphasized again that the flow regime map shown in Figure 4 is only approximate. Further understanding of the flow patterns, their evolution with time and along the bed as well as the impact of the packing wetting characteristics on transition boundaries requires a detailed analysis of pressure traces (e.g. power spectrum, auto- and cross-correlations). This, along with further experiments with improved diagnostics remain to be the subject of future work.

1. **Experimental Results on Pressure Drop**
   1. ***Single-Phase Flow in Porous Media in Microgravity***

Prior to conducting any two-phase flow experiments, the column was flooded with liquid and we conducted liquid-only flow experiments to determine the single-phase Ergun equation coefficients. The overall apparent bed porosity was measured in normal gravity (before flight) to be 0.34. However, the local bed porosity between pressure transducers during the experiment is the relevant parameter which could not be measured. Using only the highest six liquid flow rates for which the measured pressure gradient was accurate (i.e. -ΔP/Z values greater than 0.5 kPa/m), the coefficients of the linear and quadratic terms (in liquid velocity) in the pressure gradient equation:

*(2a)*

are estimated (using *dp* = 0.002 m, *ρl* = 997 kg/m3, and *μl* = 0.00089 Pa-s) as:

*(2b)*

As these relations are not sufficient to determine the three unknown constants (*CV, CI, ε*), we varied *ε* in an acceptable range (0.34 < *ε* <0.37) and based on other considerations (e.g. reported literature values of porosity for packed beds of uniform spheres and theoretical considerations, see Scott and Kilgour14) to fix the dry bed porosity ε=0.358 and determined *CV* =150.8, *CI* =1.78. Thus, the single-phase friction factor is taken as:

;  *(3a)*

where:

*(3b)*

results in the following expression for the single-phase pressure gradient:

*(3c)*

[Note: *ReLS* is the Reynolds number based on the superficial liquid velocity while *Re\*LS* is *ReLS* divided by (1-*ε*). Figure S-1 in the Supplementary Material shows a fit of the single-phase Ergun equation to measured data].

* 1. ***General Considerations on two-phase friction factor***

Because of the modifications discussed earlier, we believe that the pressure drop data obtained over the entire range of gas and liquid flow rates for PBRE-2 is more accurate than that for PBRE. This is especially true at the highest six liquid flow rates where the pressure gradient is at least 1 kPa/m (and higher than the accuracy of our measurement) at all gas flow rates used in PBRE-2. Thus, in this manuscript, we restrict the pressure drop analysis to this range of liquid flow rates, where the flow patterns observed are mostly bubbly and pulse flows. This restriction allows us to compare the measured pressure gradient with aircraft (and 1-g) experiments and assess the impact of capillary effects. The more interesting case of low liquid flow rates, corresponding to the viscous-capillary regime will be discussed in a subsequent manuscript.

As discussed by Motil et al.4, the two-phase pressure drop in porous media can be expressed in terms of a modified Ergun equation (Eq. 4), which is written as the sum of an Ergun-type single-phase friction factor and a “dynamic phase interaction term” that models the complex effects of introducing a gas phase (and the associated capillary effects):

*(4)*

The dimensionless numbers in Equation 4 are defined as follows:

[The modified dimensionless group with a star is defined by dividing the group as defined above by the volume fraction of the packing, e.g. and so forth]. Motil et al.4 used the aircraft pressure drop data to fit the constants in Eq. (4). Their data did not cover the regime of low gas flow rates, in contrast to the case of PBRE and PBRE-2 experiments. For example, the lowest *Re\*GS* in aircraft experiments was about 10 while the highest was 267, compared to 0.023 and 23 in PBRE-2 experiments. The best-fit constants for aircraft-based data were , and *CS* = 0.8, while the single-phase Ergun constants were taken as *CV* = 180, *CI* = 1.8. We observe that for the range of flow rates used in the aircraft data, inertial effects are significant and due to the short duration (~ 20s) of the experiment, it is likely that capillary contribution was underestimated. A second difference between the aircraft and ISS experiments is that the former covered a wide range of Suratman numbers (by varying liquid viscosity, surface tension, and particle size), while the Suratman number was not varied in PBRE-2. For these reasons, to fit our experimental data, we retain the form of Equation (4), but rewrite it in a form suitable for PBRE experiments:

*(6)*

Eq. (6) may also be expressed in terms of the Capillary number as

*(7)* where

When Eq. (6) is written in the form of the overall pressure gradient (which is the summation of viscous, inertial, and capillary contributions), we obtain:

Viscous Inertial Capillary *(8)*

We note that the capillary contribution to the pressure gradient goes to zero in the limit of zero gas flow rate or zero interfacial tension. However, when the gas flow rate is finite, capillary forces play a more significant role in determining the pressure drop as well as other variables such as phase distribution and liquid hold-up, especially when the liquid inertia forces are much smaller compared to viscous forces.

Since the liquid phase Suratman number was not varied in PBRE experiments, the exponent on the Suratman number in Eq. (6) was taken to be same as that obtained in the aircraft-based experiments (γ = 2/3), while the other two exponents and the constant *CS* was fitted to the pressure drop data.

* 1. ***Modified Two-Phase Friction Factor in Microgravity***

Figure 5 shows plots of the pressure gradient as a function of liquid flow rate at various fixed gas flow rates. Whereas Figure 6 shows the capillary contribution to pressure drop as a function of *ULS* for different values of *UGS*. As stated in section 3, it is clear that over the entire range of gas flow rates of the experiments, the pressure gradient is a linear function of the liquid flow rate (for L>20 kg/hr) and so the liquid superficial velocity. Therefore, the exponent on the modified liquid Reynolds number or the Capillary number in Eqs. 6 and 7 is estimated as *β = -1*. Thus, the capillary contribution to pressure drop varies inversely with the modified liquid Reynolds number or Capillary number, which is not a surprising result.

Figure 7 shows the dependence of the pressure gradient on gas flow rate at various fixed liquid flow rates for both liquid and gas flush runs. We observe that the pressure gradient is a weak function of the gas flow rate. Using this and other data (shown in the Supplementary Material), we determine the exponent on the modified gas Reynolds number to be *α=0.2.* Comparing this value to that obtained in the aircraft experiments (0.5), we note the much weaker dependence. As pointed out earlier, this may be due to the much lower gas flow rates used in PBRE-2 experiments. In summary, the capillary contribution of the pressure gradient and two-phase friction factor are of the form:

*(9a)*

*(9b)*

Using the complete data set of the six highest liquid flow rates and all gas flow rates, this correlation was found to fit the data well (with the fit being better for liquid flush experiments than gas flush) with the constant *CS* = 0.26. Table 1 shows the experimental and calculated pressure gradients for different gas and liquid flow rates and compares the contribution of the capillary, viscous, and inertial terms to the pressure gradient. It can be observed that the capillary contribution is much larger than the viscous and inertial contributions and increases with increasing gas flow rate and decreasing liquid flow rate. It reaches to 90% of the total pressure gradient at the highest gas flow rates tested. It is the dominant contribution to the pressure drop (>50%) in the entire range of flow rates listed in Table 1. It is also interesting to observe that at the highest liquid flow rate (L = 150 kg/hr) for which the viscous and inertial contributions are the same for liquid only flow (or in the transition regime), the capillary contribution dominates even at the lowest gas rate (G = 0.001). At a lower liquid flow rate (L = 20 kg/hr) for which the viscous contribution (is about 90%) and dominates over inertia for liquid only flow, capillary contribution dominates again at the lowest gas rate (G = 0.001 kg/hr).

The proposed pressure gradient equations are valid for the bubbly flow regime. However, as it can be seen from the last column of Table 1, the calculated no-slip gas fraction is much higher than the acceptable values for bubbly flow regime in some range of the experiments and it seems that pulse flow may occur in the bed which can affect the pressure drop. A no-slip condition was assumed in the bed for calculating the gas fraction which was estimated as the ratio of gas volume fraction to the total volume fraction. It was also reported by Colin et al.15 that the gas-liquid local velocity difference is expected to be minimal in the absence of a body force such as gravity.

* 1. ***Gas Hold-up in Porous Media: Gas Flush vs Liquid Flush***

As stated in the experimental section, another difference between PBRE-2 and PBRE was that in addition to the liquid flush runs in PBRE-2, all test runs were repeated and preceded with a gas flush before beginning each test run. As stated by Motil et al.1, the highest available liquid flow rate was used in the liquid flush runs but it was not sufficient to force any trapped gas bubbles through the bed as the liquid inertia was not adequate to move the bubble. During the liquid flush, the dominant forces acting on the trapped bubble are due to liquid inertia and capillarity, the relevant dimensionless group is the Weber number (which is the ratio of inertial to capillary forces acting on the bubble; See Eq. 5c.).

If *WeLS* >> 1, the inertial force will dislodge the bubble, while for *WeLS* << 1, the bubble remains and may influence the subsequent experiment. For the highest liquid flow rate used during flushing (150 kg/hr), we estimated to be much smaller than unity. The same observation also applies to gas flush experiments. However, based on the flow pattern map, we conjecture that the high velocity of the gas during flushing, creates a gas channel in the center of the bed, possibly displacing the liquid as well as any trapped bubble (but leaving pendular liquid bridges near particle to particle contact points). Unfortunately, we do not have video observations to support or refute this conjecture, but it is clear that the observed pressure gradient in PBRE experiments is certainly influenced by the bed history.

Higher pressure gradients were observed in the liquid flush runs compared to the gas flush runs throughout the whole flow range (Figure 8). In Figure7, the pressure gradient is plotted versus gas superficial velocity at different liquid superficial velocities for both liquid flush and gas flush tests, and the experimental results are compared with the correlation. As explained above, the higher pressure gradient in the liquid flush cases is probably a result of higher gas hold-up which is attributed to stuck bubbles in liquid flush tests, and which are released from the bed in gas-flush tests. The removal of these stagnant bubbles by the gas flush preceding the test consequently leads to lower gas hold-ups and pressure gradients.

The difference in the pressure gradient between the liquid and gas flush run results in the limit of zero gas flow rate and various liquid flow rates shows that different fractions of void space are occupied by bubbles in the liquid-flush and gas-flush runs. Figure 8 (a) shows this difference in pressure gradients at two low gas flow rates and liquid flow rate of L = 70 kg/hr. The bed porosity was estimated for each liquid flow rate at approximately zero gas flow rate by solving the single phase (liquid only) Ergun equation for the porosity using the extrapolated pressure gradient (at zero gas flow rate). As can be seen in Figure 8 (b) the bed porosity is almost independent of the liquid flow rate and is about 0.305 for the gas flush and 0.263 for the liquid flush experiments, whereas it was 0.358 for the single-phase experiment measured with a fully flooded bed (prior to introducing gas). Thus, the average gas hold-up (defined as the volume percent of the total void volume in the bed) for the gas-flush run is calculated as 14.8% whereas it is 26.6% for the liquid flush run. It is also observed that the gas hold-up (and pressure gradient) appears to be independent of the column initial condition (gas or liquid flush) only at high liquid flow rates. However, at low liquid flow rates, the data indicate that the column history is important in determining the gas hold-up (and hence the pressure gradient).

The two-phase friction factor is plotted versus the modified liquid Reynolds number *Re\*LS* at fixed modified gas Reynolds numbers *Re\*GS* in Figure 9 in a log-log scale. As can be seen from both Figures 7 and 9, the developed correlation fits the experimental data over the full range of both gas and liquid flows and the accuracy is high at higher flow rates where liquid flush and gas flush data approach a single asymptote.

* 1. ***The Effect of Particle Size on Capillary Pressure Gradient***

The capillary contribution of the total pressure gradient was also compared between PBRE (3 mm sized particles) and PBRE-2 (2 mm sized particles) versus liquid superficial velocity for liquid flush runs in Figure 10. It was observed that this contribution is almost 1.5 to 2 times higher for the PBRE-2 data which is consistent with the proposed empirical correlation:

*(* *-ΔP/Z)cap* ~ *(10)*

Figure 10 also illustrates that the pressure gradient is proportional to the liquid superficial velocity and the constant of proportionality depends to a lesser extent on the gas superficial velocity. As discussed in Motil et al.1, the capillary contribution to the pressure gradient is much larger than the viscous contribution for these flow rates.

1. **Summary and Conclusions**

The PBRE-2 experiment was run on the International Space Station with a smaller packing diameter and with gas and liquid flush initialization of each of the runs in the test matrix which encompassed 400 gas-liquid flow rate combinations. Modifications to the inlet section eliminated the pressure oscillations observed in earlier experiments. Video observations, pressure traces, and pressure drop data indicate that within the range of gas and liquid flow rates examined, there are four main flow regimes, namely dispersed bubble flow, pulse flow, gas channeling, and large bubble regime. The most interesting (and practically relevant) of these flow regimes is that of the large bubble regime observed at very low liquid and gas flow rates. Our preliminary data indicate that this regime is intermittent in nature with times scales of the order of several minutes (depending on the flow rates) and is dominated by capillary effects. The accuracy of our pressure measurements or the duration of the experiments was not sufficient to characterize this regime in any detail quantitatively, but it could be a topic for future microgravity (or normal gravity) based investigations. The pressure drop data from PBRE-2 at higher liquid flow rates were analyzed in terms of a modified two-phase friction factor which encompasses contribution from viscous, inertial, and capillary forces. Moreover, the effects of liquid and gas flush preceding the runs on the gas holdup in the packed bed were assessed. Finally, the effects of the packing particle diameter on the capillary contribution to the overall pressure drop were analyzed. The main conclusions are listed below:

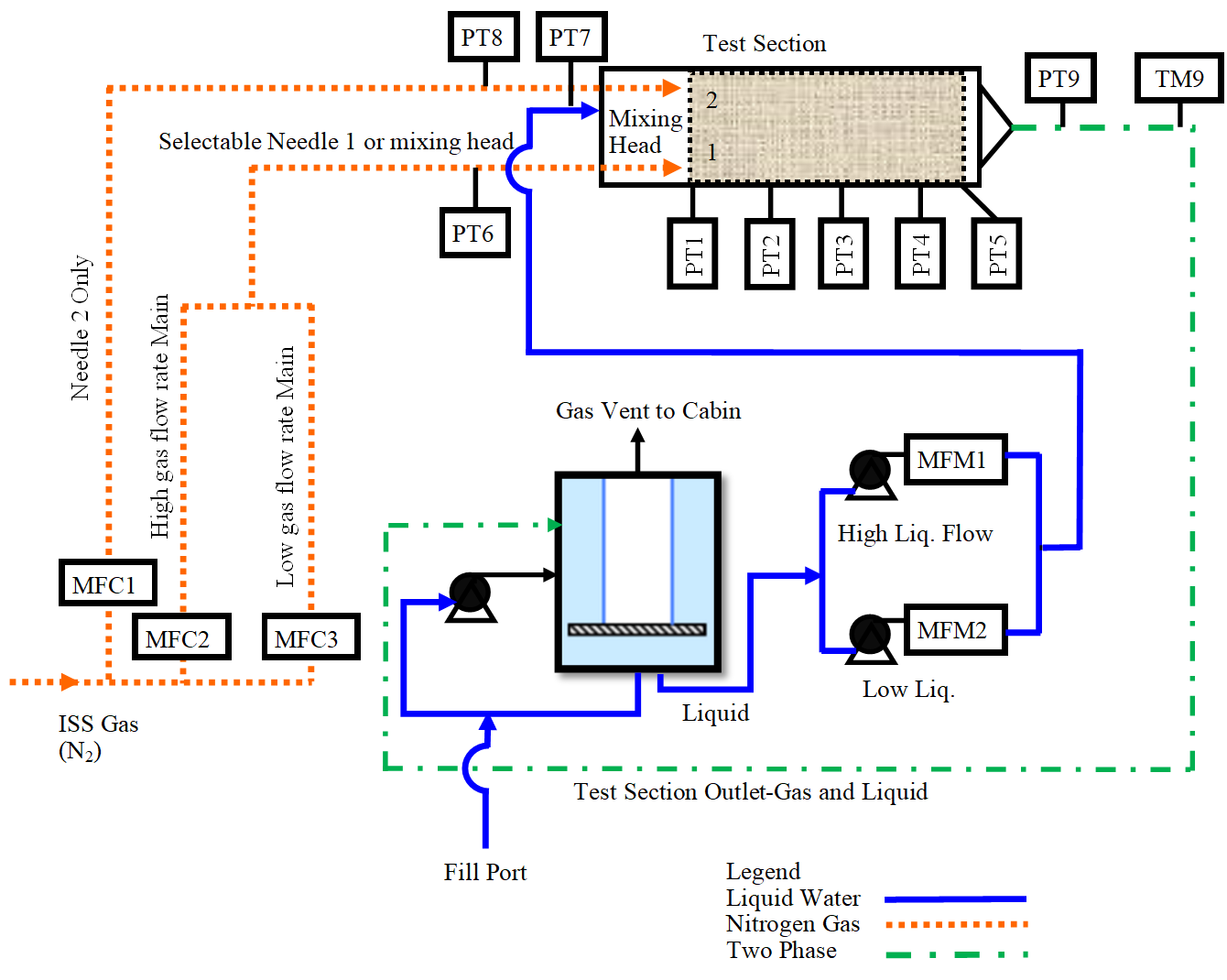
* Gas accumulation was observed over longer run times, especially at lower flow rates.
* The average gas hold-up for the gas-flush run is calculated as 14.8% whereas it is 26.6% for the liquid flush run.
* Bed porosity was shown to be almost independent of the liquid flow rate and is about 30.5% for the gas flush and 26.3% for the liquid flush experiments, whereas it was 35.8% for the single-phase experiment done before introducing the gas into the bed.
* Capillary contribution to the pressure gradient is greater in PBRE-2 because of the smaller particle diameter. The capillary contribution to the pressure drop is found to be proportional to the inverse of the Capillary number. It is the dominant contribution even at the highest gas and liquid flow rates studied.
* A modified friction factor correlation is developed, and it showed good agreement with the data from PBRE-2.

For future PBRE testing, the authors recommend that more accurate pressure transducers be used for the low flow rates and perhaps replacing absolute pressure transducers with differential ones that satisfy the pressure accuracy requirement. In addition, longer duration runs (of the order of several minutes to an hour depending on the flow rates) are recommended in order to assess and capture gas accumulation in the bed more accurately. Finally, for future PBRE beds, the authors strongly recommend the adoption of void fraction visualization for a better assessment of gas accumulation and its effects on the pressure gradient.

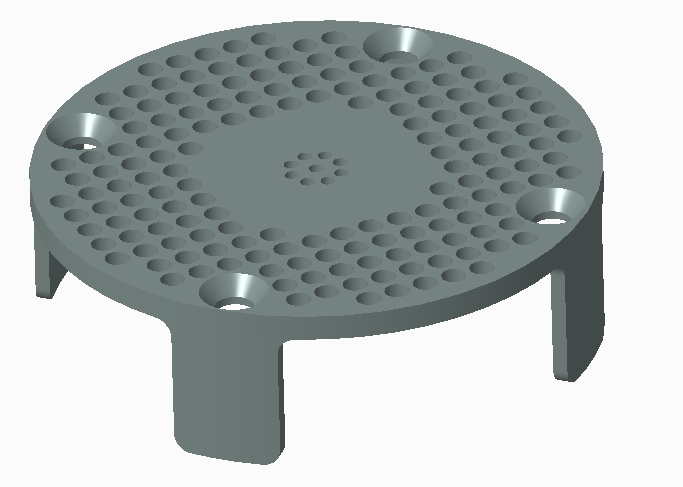
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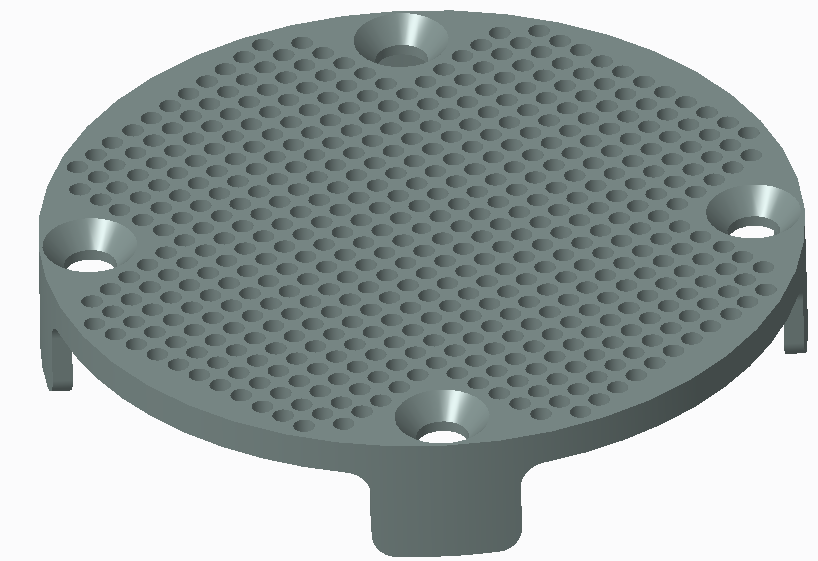
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**Figure 1:** Schematic diagram of the Packed Bed Reactor Experiment-2 (PBRE-2)





**Figure 2:** Original inlet screen with 1.5 cm standoff legs which establish the open mixing area prior to flow entering the bed (top) and the modified inlet screen with holes over the entire area as well as 0.5 cm standoff legs for shorter mixing zone (bottom). The large holes are attachment points.

|  |  |
| --- | --- |
|  |  |
| A-Large Bubble  L=7.5 kg/hr, G=0.05 kg/hr | B-Gas Channeling  L=1 kg/hr, G=1 kg/hr |
|  |  |
| C-Dispersed Bubble  L=70 kg/her, G=.03 kg/hr | D-Pulse Flow  L=125 kg/hr, G=1 kg/hr |
|  |  |
| E-Standard Deviation (σPressure) of pressure signal as a function of liquid flow rate for three gas flow rates |  |

**Figure 3:**  Pressure traces of the pressure transducer 5 as a function of time at different flow regimes

**Figure 4:** Approximate map of the flow regimes observed in the microgravity PBRE experiment

**Figure 5:** Measuredpressure gradient versus liquid flow rate for G=0.001 and 0.01 kg/hr (top) and G=0.1 and 1.0 kg/hr (bottom)

**Figure 6:** Estimated capillary pressure gradient as a function of liquid superficial velocity at various fixed gas flow rates

**Figure 7:** Measured pressure gradient as a function of gas superficial velocity for fixed liquid flow rates

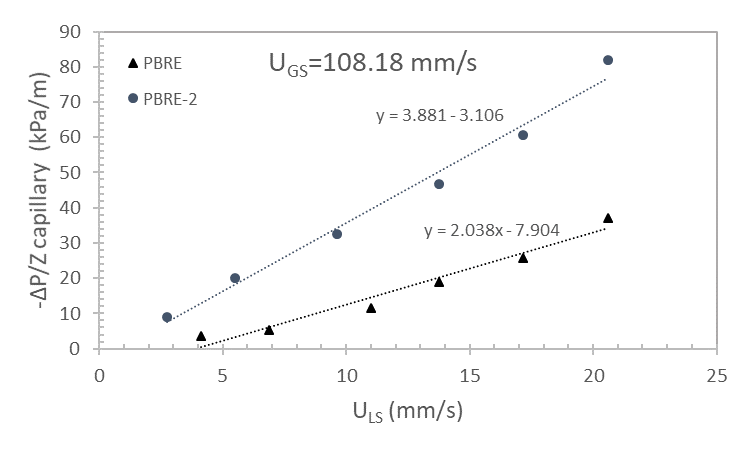
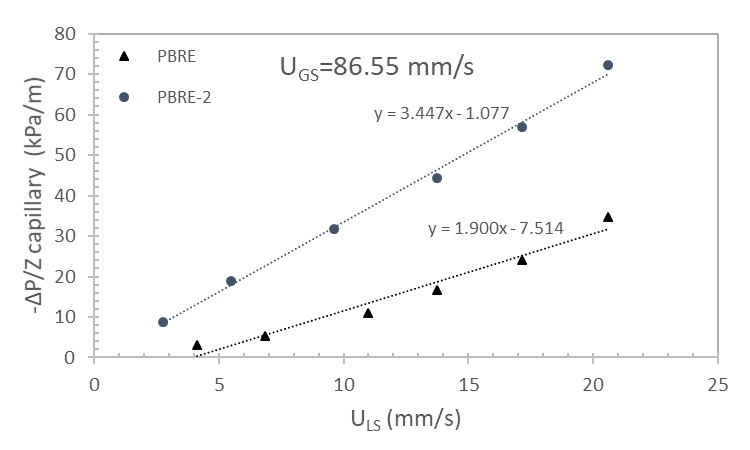
**(b)**

**(a)**

**Figure 8:** (a) Pressure gradient in the limit of low gas flow rate; (b) Estimated bed porosity in gas and liquid flush experiments

**Figure 9:** Two-phase friction factor as a function of Re\*LS at different gas flow rates

**Figure 10:** Comparison of capillary contributions to pressure drop in PBRE (3 mm) and PBRE-2 experiments (2 mm)



**Table 1:** Estimated pressure gradient contributions and no slip gas fraction at selected gas and liquid superficial velocities

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| ULS (mm/s) | UGS  (mm/s) | Experimental -ΔP/Z  (Pa/m) | Calculated -ΔP/Z (Pa/m) | Capillary -ΔP/Z (%) | Viscous -ΔP/Z (%) | Inertial -ΔP/Z (%) | No-Slip Gas Fraction  (%) |
| 2.75 | 0.11 | 3219 | 3059 | 69.9 | 27.0 | 3.1 | 3.8 |
| 2.75 | 3.25 | 4745 | 5142 | 82.1 | 16.1 | 1.8 | 54.1 |
| 2.75 | 10.82 | 5765 | 6292 | 85.4 | 13.1 | 1.5 | 79.7 |
| 2.75 | 108.19 | 9916 | 9433 | 90.2 | 8.8 | 1.0 | 97.5 |
| 5.50 | 0.11 | 6228 | 6306 | 67.8 | 26.2 | 5.9 | 1.9 |
| 5.50 | 3.25 | 13585 | 10472 | 80.6 | 15.8 | 3.6 | 37.1 |
| 5.50 | 10.82 | 15767 | 12771 | 84.1 | 13.0 | 2.9 | 66.3 |
| 5.50 | 108.19 | 22101 | 19053 | 89.3 | 8.7 | 2.0 | 95.2 |
| 9.62 | 0.11 | 15563 | 11527 | 64.9 | 25.1 | 10.0 | 1.1 |
| 9.62 | 3.25 | 23254 | 18818 | 78.5 | 15.4 | 6.1 | 25.2 |
| 9.62 | 10.82 | 27149 | 22841 | 82.3 | 12.7 | 5.0 | 52.9 |
| 9.62 | 108.19 | 36478 | 33835 | 88.0 | 8.6 | 3.4 | 91.8 |
| 13.74 | 0.11 | 23454 | 17170 | 62.3 | 24.1 | 13.7 | 0.8 |
| 13.74 | 3.25 | 30777 | 27587 | 76.5 | 15.0 | 8.5 | 19.1 |
| 13.74 | 10.82 | 36438 | 33333 | 80.6 | 12.4 | 7.0 | 70.3 |
| 13.74 | 108.19 | 53287 | 49039 | 86.8 | 8.4 | 4.8 | 88.7 |
| 17.18 | 0.11 | 25536 | 16691 | 60.2 | 23.3 | 16.5 | 0.6 |
| 17.18 | 3.25 | 37079 | 28233 | 74.9 | 14.7 | 10.4 | 15.9 |
| 17.18 | 10.82 | 44997 | 36151 | 79.2 | 12.2 | 8.6 | 38.6 |
| 17.18 | 108.19 | 69439 | 60594 | 85.8 | 8.3 | 5.9 | 86.3 |
| 20.61 | 0.11 | 32968 | 27514 | 58.3 | 22.5 | 19.2 | 0.5 |
| 20.61 | 3.25 | 44062 | 43138 | 73.4 | 14.4 | 12.2 | 13.6 |
| 20.61 | 10.82 | 51501 | 51758 | 77.8 | 12.0 | 10.2 | 34.4 |
| 20.61 | 108.19 | 93346 | 75317 | 84.8 | 8.2 | 7.0 | 84.0 |