Packed Column Hydraulics and Continuous Phase Transitions

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Introduction

Currently, no public domain correlation for packed bed hydraulics adequately predicts the pressure drop and flood point for random or structured packings over the full spectrum of vapor and liquid loadings, component physical properties, and column operating conditions normally encountered in industrial practice. Pressure drop is often a critical parameter in column design – for example, in separations involving polymerizable or thermally sensitive components – while flood determines the maximum operational capacity of a column. With this in mind we explore the hypothesis that the flooding locus in a packed column operated countercurrently represents an envelope of second order phase transitions from vapor to liquid continuous operation. We show that an appropriate renormalization of column pressure drop data to the incipient flood point for the particular liquid flowrates examined results in a collapse of these data onto a single "master" curve. This data collapse occurs for virtually all packing types, sizes, and materials of construction. A description of the data reduction procedure will be given. In addition, we will show several examples for specific packings. Further, we will show how these results can be extended to systems with physical properties other than those of the original experimental system.

Pressure Drop as an Example of a Continuous Phase Transition

This paper will expand on the hypothesis presented in earlier articles by Hanley, et al., that the flooding locus in a packed column represents an envelope of continuous phase transitions from gas continuous to liquid continuous operation (or vice versa). Therefore, as with other types of continuous phase transitions, renormalizing packing pressure drop/vapor load/liquid load data to the appropriate flood points should result in a collapse of those data onto a single master curve whose abscissa is fractional approach to flood, F_S/F_S^* (or C_S/C_S^*). Further, since physical laws cannot depend on arbitrarily chosen units of measurement the pressure drop per unit height itself must be renormalized properly. Two potential choices for the appropriate renormalizing factor are the hydrostatic liquid pressure drop per unit height, $\rho_L g$, and the dry pressure drop per unit height for the packing at the same F_S as that for the wet pressure drop, $\Delta p_{dry}(F_S)/Z$. We will show that the first choice is the correct one. The resultant scaled ordinate becomes $[(\Delta p/Z)]_{2\phi}/\rho_L g$. This result has immediate consequences. For example since the pressure drop at flood for water is often taken to be 2" H_2O/ft (~16 mbar/m), then the pressure drop at flood for a liquid with a different density will be $2(\rho_L/\rho_W)$ "H_2O/ft $(16[\rho_L/\rho_W]$ mbar/m). In short, then, we are proposing a transformation of data from a form like that of equation (1)

$$\left(\frac{\Delta p}{Z}\right)_{2\phi} = P\left(F_S, C_L, \nu, \sigma, ...\right) \quad (1)$$

into a dimensionally consistent scaled form given by equation (2)

$$\frac{\left(\frac{\Delta p}{Z}\right)_{2\phi}}{\rho_L g} = S\left(\frac{C_S}{C_S^*(C_L, \nu, \sigma, ...)}\right) \tag{2}$$

Data Analysis

We expect the rescaled two-phase pressure drop to be only a function of the fractional approach to flood. In the figure below, the selected four points should map to a single point when plotted against fractional approach to flood.

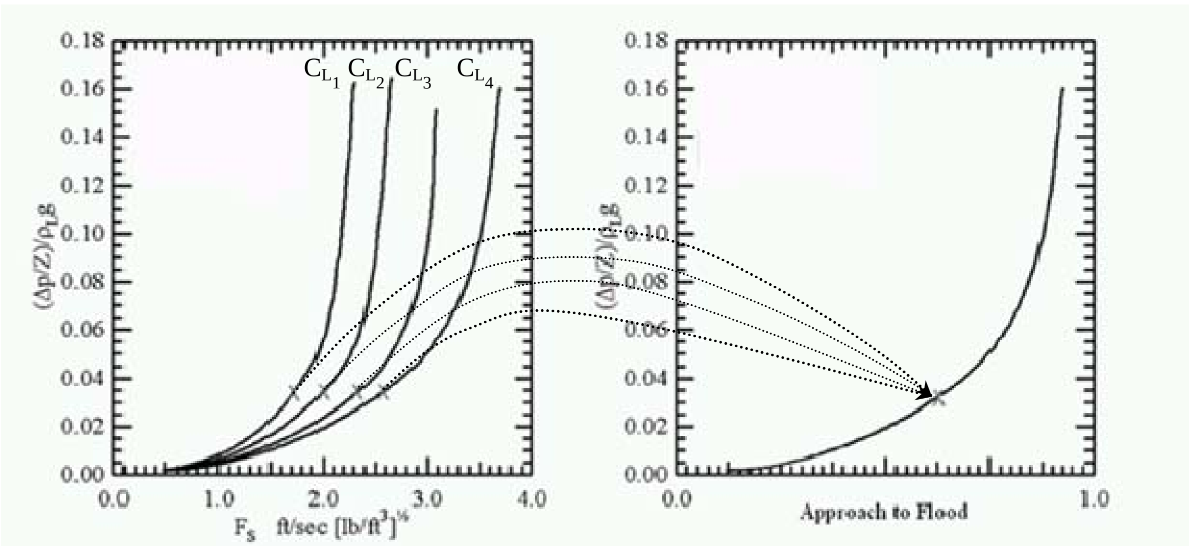


Figure 1: Schematic showing the mapping of $[(\Delta p/Z)_{2\phi}/\rho_L g, F_S, C_L]$ triplets onto a single $((\Delta p/Z)_{2\phi}/\rho_L g, f)$ point, where "f" stands for approach to flood at constant liquid load.

The same mapping should occur for any set of four points at constant pressure drop. This observation leads to the following strategy for finding flooding velocities: flooding velocities are those which minimize the total variance (or total standard deviation) in the calculated fractions of flood among all sets of points with constant pressure drop. For a single set of four points, we would choose the flooding rates - F^*_{Sa}, F^*_{Sb}, F^*_{Sc}, F^*_{Sd} – so that they minimize the expression for the standard deviation, σ:

$$x_a = \frac{F_{Sa}}{F^*_{Sa}} \quad x_b = \frac{F_{Sb}}{F^*_{Sb}} \quad x_c = \frac{F_{Sc}}{F^*_{Sc}} \quad x_d = \frac{F_{Sd}}{F^*_{Sd}} \tag{3}$$

$$\langle x \rangle = (x_a + x_b + x_c + x_d)/4 \tag{4}$$

$$\sigma = \sqrt{\frac{(x_a - \langle x \rangle)^2 + (x_b - \langle x \rangle)^2 + (x_c - \langle x \rangle)^2 + (x_d - \langle x \rangle)^2}{3}} \tag{5}$$

The minimization procedure for this example would be carried out for all sets of four points at constant pressure drop. At least one flooding velocity needs to be fixed at the start of the fit since any multiple of the actual flood velocities will also collapse the data. Least squares can be used to perform the optimization by setting the objective function to be zero for all points (we want the standard deviation or variance to be as close to zero as possible).

The procedure as outlined above assumes that constant pressure drop data across several liquid loads are readily available. In terms of raw data this will rarely be true – experiments are usually not performed in a mode wherein pressure drops are held constant while vapor load is varied at constant liquid load. Instead, most experiments hold the liquid load constant while scanning across the vapor load. Pressure drop is the measured variable. The required constant pressure drop data can be estimated in a number of ways. For example, smooth curves can be drawn through the data and then points at constant pressure drop read off. Alternatively, one could incorporate some type of numerical interpolation procedure (linear, cubic spline, or smoothing spline, for example) into the least squares routine.

Results

We have carried out the procedure described above for air/water data on approximately 200 individual packings, including both random and structured types. In the great majority of cases the data collapse as described above quite well. Figures 2a through 2f below demonstrate that the data collapse occurs for a variety of different packing types across a range of different vendors. Cases do occur, however, where the proposed collapse does not seem to happen. Figures 2g and 2h, for IMTP 40 and FLEXIPAC 1YHC (manufactured by Koch-Glitsch, LP), are examples. It is unclear why certain datasets fail to collapse as expected. It is possible, given the difficulty in performing these types of experiments well, that the datasets themselves are simply in error, perhaps because of flowmeter and/or pressure transducer miscalibrations or because of water in the tap lines leading to the pressure transducer diaphragms.

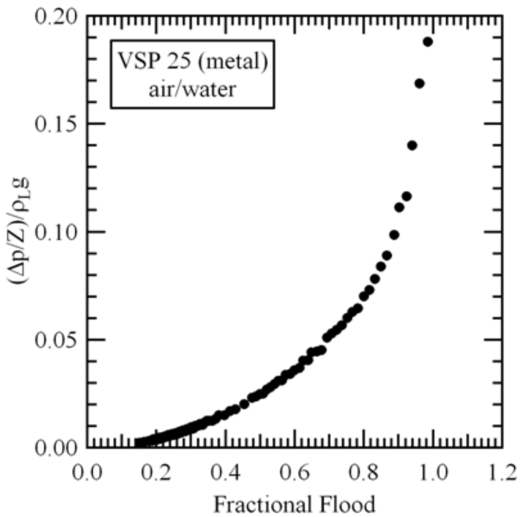
Extensions to Systems Other Than Air/Water

The same type of data collapse observed for air/water would be expected to occur for any gas/liquid combination used to carry out this type of experiment. The absolute values of the gas rates at flood, however, would change primarily due to changes in the physical properties of the liquids used in the experiments. Therefore, in order to be able to predict the pressure drop in systems other than air/water we require a method for adjusting the flood points measured in air/water to values that would occur in a system with different physical properties.

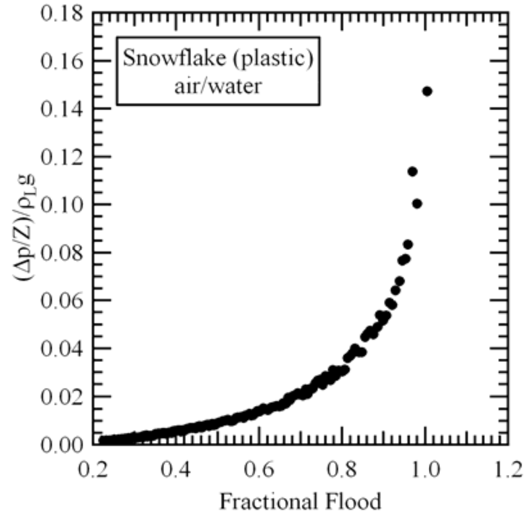
The air/water column flooding data can be fit well with a Wallis-type of equation[1]

$$\sqrt{C_S^*} + m_W \sqrt{C_L^*} = c_W \tag{6}$$

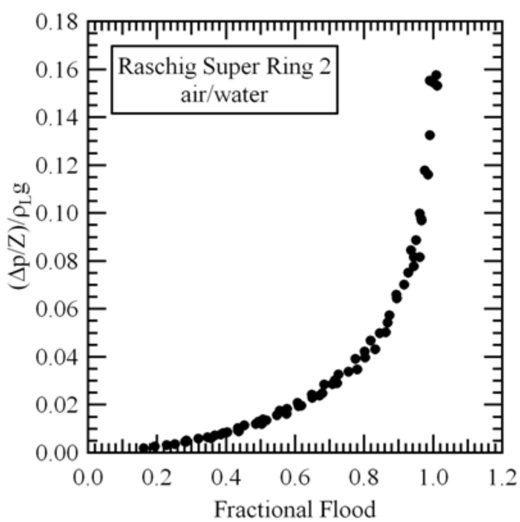
where C_L^* is the superficial liquid velocity at flood, C_S^* is the density corrected superficial vapor velocity at flood, and m_W and c_W are fitting parameters.



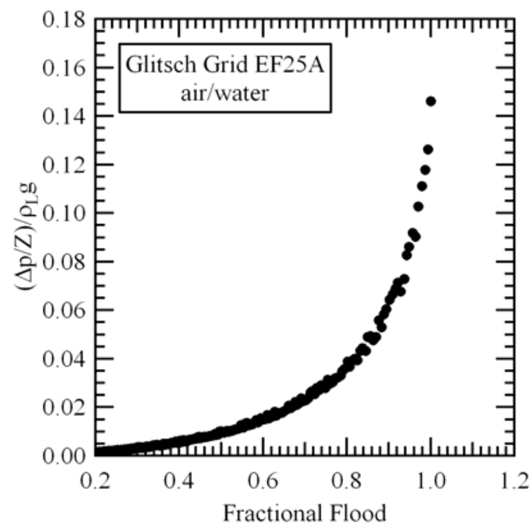
(2a)



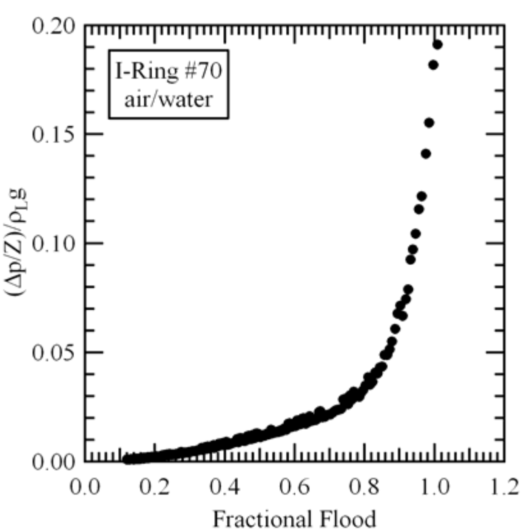
(2b)



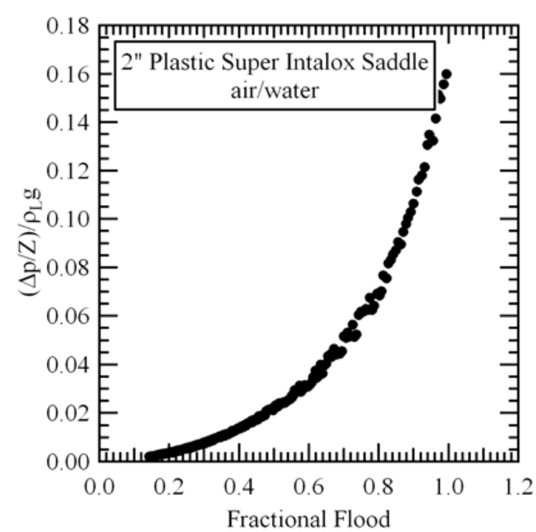
(2c)



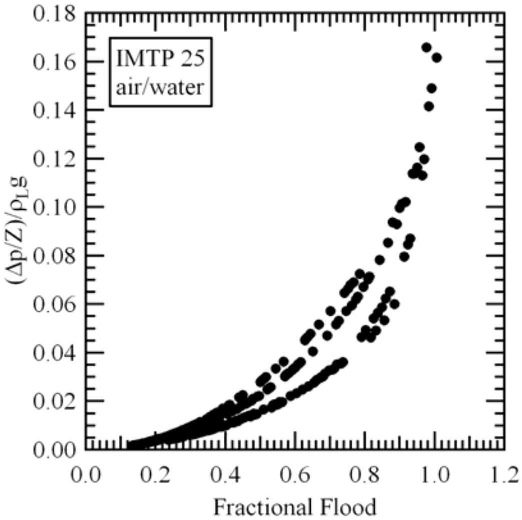
(2d)



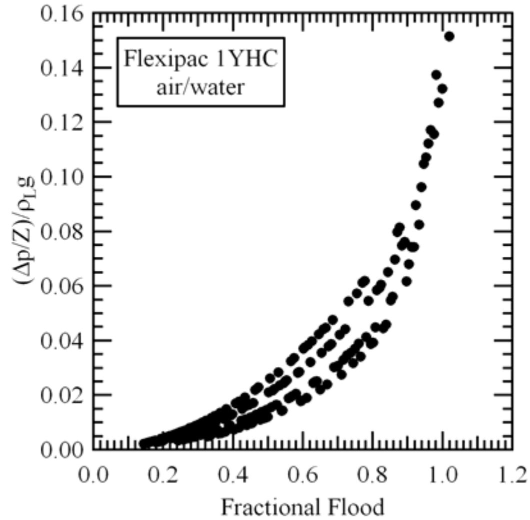
(2e)



(2f)



(2g)



(2h)

Figure 2: Data collapse: a) VFF metal VSP #25[2], b) Koch-Glitsch plastic Intalox Snowflake packing[3], c) Raschig Super Ring No. 2[4], d) Koch-Glitsch Grid EF25A[5], e) Sulzer I-Ring #70[6], f) Koch-Glitsch 2" plastic Super Intalox Saddle[2], g) Koch-Glitsch metal IMTP 40[7], and h) Koch-Glitsch FLEXIPAC 1YHC[8]

Hanley[9] showed that

$$m = \mathbf{M}\left(\frac{d_e^2 \rho_L\, g}{\sigma}, \frac{d_H^3 \rho_L^2\, g}{\eta_L^2}\right) = \mathbf{M}(\mathrm{Bo}, \mathrm{Ga}) \qquad c = \mathbf{C}\left(\frac{d_e^2 \rho_L\, g}{\sigma}, \frac{d_H^3 \rho_L^2\, g}{\eta_L^2}\right) = \mathbf{C}(\mathrm{Bo}, \mathrm{Ga}) \tag{7}$$

where "Bo" is the Bond number and "Ga" is the Galilei number. Because the functional forms for the dependence of the Wallis parameters on the Bond and Galilei number are unknown, let us assume for the sake of simplicity that the Wallis equation parameters are power laws of the Bond and Galilei numbers

$$m \propto (\mathrm{Ga})^a (\mathrm{Bo})^b \qquad c \propto (\mathrm{Ga})^x (\mathrm{Bo})^y \tag{8}$$

Two limiting cases arise: 1) the Galilei number dominates flooding, or 2) the Bond number dominates. In each limiting case we are able to make a remarkable observation – the effects of the liquid's physical properties on the flood locus can be quantified by observing the effects of the equivalent diameter on the Wallis parameters "c_W" and "m_W" for a geometrically similar packing family using air/water data only.

Figure 3 presents an example showing the variation in the Wallis parameters c_W and m_W with the equivalent diameter of the packing. The power law exponents, a and b or x and y, are easily determined for case 1 or case 2 above. We have examined flood point data for a number or non-aqueous systems. In Figure 4 the percent difference between the reported flood points and calculated flood points based on the dimensionless Galilei and Bond number corrections are presented. Figure 4a demonstrates that the Galilei number (which involves the liquid's viscosity) fails to adequately account for liquid physical property effects when the Galilei number is small. Figure 4b, on the other hand, shows that reasonable flood point physical property corrections can be made to air/water flood data for the complete range of Bond numbers (involving the liquid's surface tension) covered by these data.

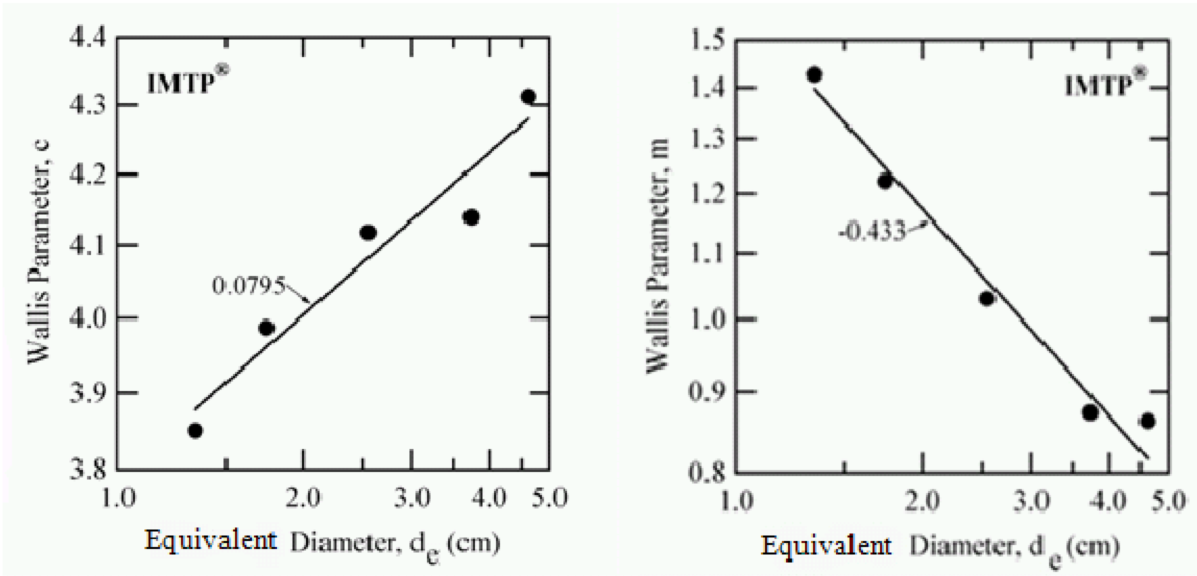


Figure 3: Variation of the air/water Wallis constants with equivalent diameter for IMTP random packing family.

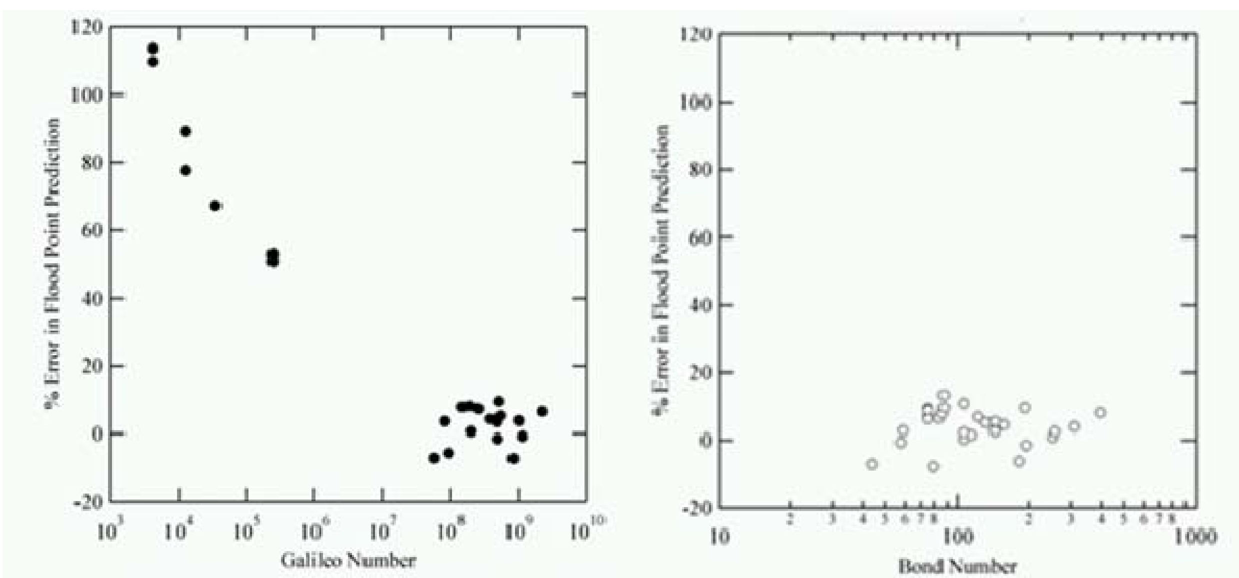


Figure 4: a) flood data presented as percent error in the calculated flood point versus Galileo number, and b) the same data displayed as percent error in the calculated flood point versus Bond number.

Comparison to Experiment for Non-Aqueous Systems

Figure 5 is a comparison of pressure drop predictions for three different packings in three different chemical systems with experimental data taken on these same packings and systems. It is important to note that the original two-phase pressure drop data on which these predictions were made were taken in air/water. Clearly the pressure drop predictions are in line with experiment. Further, the capacity of the columns in these experiments has also been adequately captured.

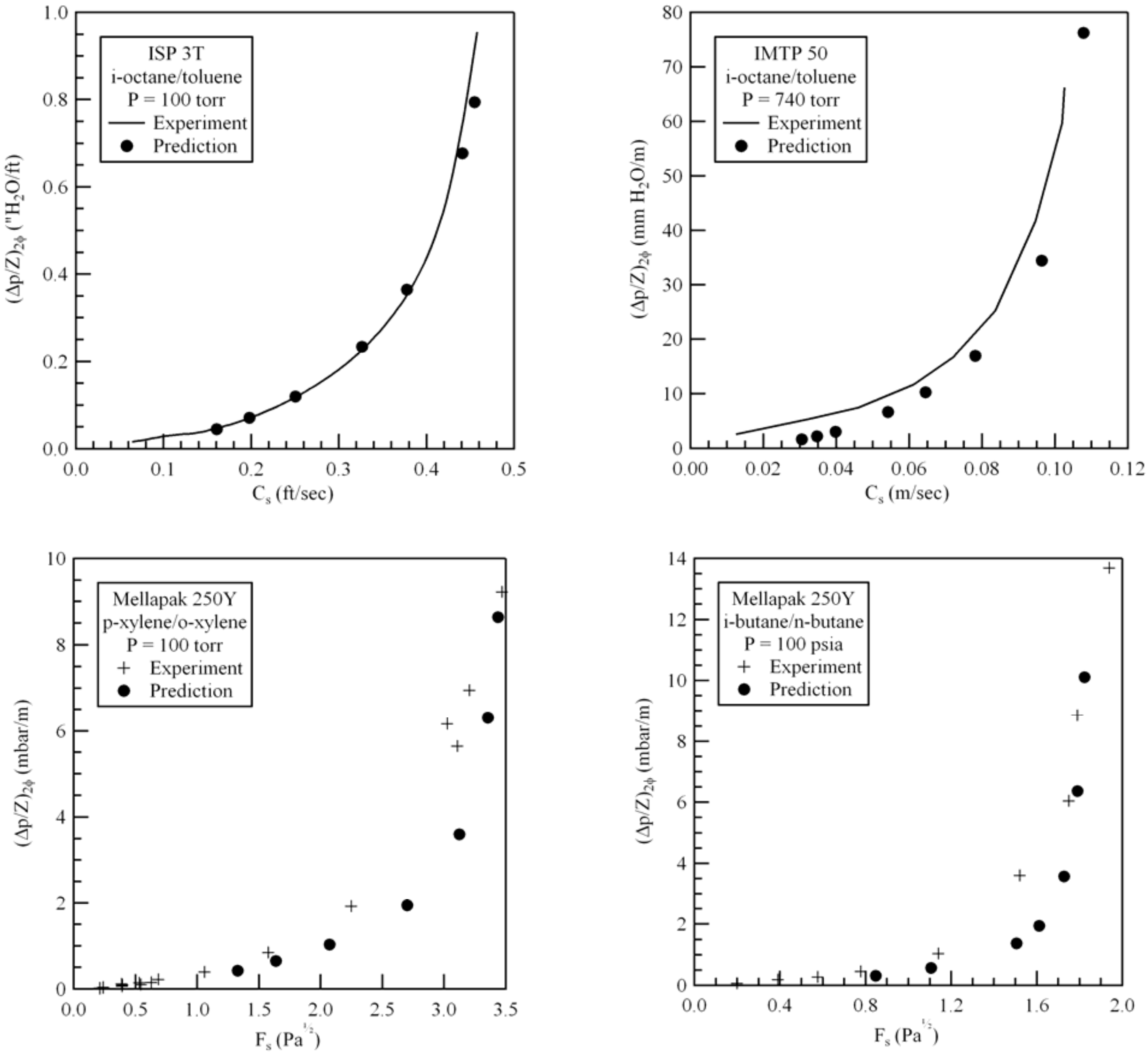


Figure 5: Comparison of model predictions to experiment for: a) i-octane/toluene at 100 torr for ISP 3T structured packing[10], b) i-octane/toluene at 740 torr for IMTP 50 random packing[11], c) p-xylene/o-xylene at 100 torr for MELLAPAK 250Y structured packing[12], c) i-butane/n-butane at 100 psia for MELLAPAK 250Y structured packing[12].

Conclusion

A two-phase pressure drop prediction method for packings has been developed. It is based on the observation that packed column flooding is an example of a continuous phase transition and that, therefore, we can expect a level of universal behavior in the pressure drop/approach to flood regardless of the actual vapor and liquid loads involved. Predictions by this method are superior to those made via other literature models because they capture both the magnitude of the pressure drop as well as the approach to flood for the column without need for empirical correction. The success of the data renormalization procedure described in this paper is further proof of the crucial role played by the continuous phase transition commonly referred to as flooding in packed column hydraulics.

References

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