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Importance of output pressure value in measurements of gas flow rates versus pressure input in packed beds of powders

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This brief communication explains relevance of pressure monitoring at the packed bed output and the need of using more then just one transducer across the bed when quadratic relationship between flow rates and pressures is used.

Analysis of experimental results of flow rates measurements through packed bed of cement (described in a separate article) has led to proposal of the following quadratic relationship between flow rates versus set pressures

$$\textbf{Flow rate [Volume/time]} = F = a \cdot (P^2 - P_{ref}^2) \qquad \textbf{(Eq. 1)}$$

where P is the pressure at the input (top) of the packed bed, and the P_{ref} is the pressure reference at the exit from the packed bed. In majority of practical applications, the P_{ref} is the atmospheric pressure or close to it, although different setups may use either a certain vacuum level or some pressure above atmospheric. From literature survey it is clear, that in most experimental work of flow rates measurements, only the pressure differential between the input and output from the bed is involved and somehow the actual value of the output pressure does not seem to play any relevance. Understandably, the linear models are normally involved and only the pressure differential is needed. In cases where compressible fluids and fine powders are involved (smaller interstitial passages) the relationship is no longer linear. It has been attempted to extract additional information from the coefficient a of the proposed quadratic relationship.

Since two different pressure references were used in the previously described experiment work: atmospheric pressure of 102. 20 kPa, and a vacuum level of 7.13 kPa, just out of curiosity, calculations were carried out to obtain radius of such an equivalent capillary which would allow the same flow as the total flow measured through the whole packed bed. The well-known Poisseuille equation corrected for compressible fluids (gases) was used for these calculations for both cases:

$$\textbf{Q [Volume/time]} = \pi \cdot R^4 \cdot (P^2 - P_o^2) / (16 \cdot \mu \cdot h \cdot P_o) \qquad \textbf{(Eq. 2)}$$

where:
Q - flow rate through a capillary [cm^3/s]
R - capillary radius [cm]
μ - dynamic viscosity [Pa · s]
h - height (length) of the packed bed [cm]
P - pressure at the packed bed entrance [kPa]
P_o - pressure at the exit from packed bed (same as P_{ref}) [kPa]

Using a series of set pressure values and the atmospheric pressure as the P_{ref} (or P_o), the calculated radius of capillary was 0.021 cm and it was fairly the same at low flow rates. At higher flow rates the value began showing slightly decreasing trend to about 0.0208 cm. When using a different pressure reference, namely the vacuum level of 7.13 kPa, the radius of the capillary of about 0.013 cm was obtained. Again, the values were fairly the same lower flow rates, and similar trend of slightly decreasing values to about 0.011 cm at higher flow rates. The results of these calculations seemed to be quite interesting at first.

When the flow rate from Eq. 1 is substituted for flow rate in Eq. 2, and both side sides simplified by dividing by ($P^2 - P_o^2$), the following equation is obtained:

$$\mathbf{a = \pi \cdot R^4 / (16 \cdot \mu \cdot h \cdot P_o)} \qquad \textbf{(Eq. 3)}$$

Since the coefficient a from the quadratic equation remains the same for various pressure references, it becomes obvious from this equation that the radius must change to account for different pressure references. Denoting by subscripts 1 and 2 in the two cases, it is easy to see, that

$$\mathbf{R_1^4 / P_{Ref1} = R_2^4 / P_{Ref2}} \qquad \textbf{(Eq. 4)}$$

or in a different form

$$\mathbf{R_1 / R_2 = (P_{Ref1} / P_{Ref2})^{1/4}} \qquad \textbf{(Eq. 5)}$$

As per the example, substituting the pressure values of 102.20 kPa and 7.13 kPa for $P_{ref\ 1}$ and P_{ref2}, respectively, the ratio of the radii was calculated as 1.9457. This value is in approximate agreement with the calculated radii. It needs to be mentioned, that the minimum vacuum level was determined at no flow conditions, so considering limited pumping capacity of a miniature vacuum pump, the actual vacuum pressure when flow was applied was certainly higher then 7.13 kPa, which would improve the agreement.

The Eq. 5 has important practical ramifications. A typical packed bed has some mechanical constrains, like non-zero flow resistance of its support or fixed diameter output port. Applying increasing pressure values at the input to a packed bed consisting of various size particles (fine porous powders) and discharging the gas at a commonly used atmospheric pressure level, the pressure level at the output will start increasing also due to some pressure buildup. Using only a single transducer at the packed bed input and assuming a stable atmospheric pressure at the bed output, or using a differential pressure transducer across the bed does not provide complete information, although such approach can be used for approximate measurements. When using compressible media, the recommended way is use two pressure transducers, one at input and another at output (or a differential one across the bed and another one either at input or output). However, if such option is not available but flow rates measurements are, then comparing radii obtained for different pressure-flow conditions using Eq. 5 can provide information about the exit pressure changes.

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