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Short Communication

The frequency of periodic structures in vertical pneumatic conveying of large particles

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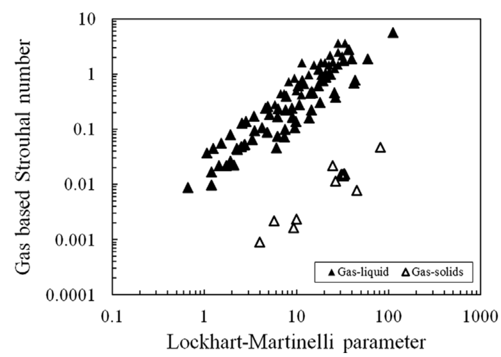
HIGHLIGHTS

- Slug frequency in vertical gas-liquid flow is fitted by a dimensionless equation.
- The limited data for slugs in pneumatic conveying fit a similar equation.
- In a pipeline/bend/riser system, the horizontal section frequency persists.
- A simple equation is presented for the apparent viscosity of solids beds.

GRAPHICAL ABSTRACT



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ABSTRACT

The transport of larger particles, defined as type D in the classification of Geldart (1973), by pneumatic conveying, is characterised by periodic structures, namely slugs. The frequency of these slugs in vertical pipes shows a trend similar to that seen for equivalent structures in gas-liquid flows. A simple equation has been derived to specify the apparent viscosity of the dense particle areas. From the non-dimensional relationship describing the frequency, its dependence on different variables can be identified. It can be inferred that pressure will not have a strong effect on frequency. There is a complication when the piping consists of a horizontal pipe followed by a bend and a vertical section. If there is slug flow in the horizontal pipe, the frequency in the vertical pipe could be the same as that in the horizontal section.

1. Introduction

Like most other combinations of phases, gas-solids flows particularly pneumatic conveying, has been found to exhibit a number of different types of flows. These can be termed flow patterns. Though there is considerable literature on pneumatic conveying much of it focuses on the flow rate/geometry/pressure drop interrelationships. Only a small portion of the papers consider flow patterns. There have been attempts and drawing analogies with gas/liquid flows where there is a much more developed literature. For vertical flows, there have been attempts at analogies in slug, churn and annular flows. Davidson and Harrison (1963) showed that, in fluidized beds, the rise velocity of the single large bubble (slug) could be described by the same relationship as for gas-liquid flow assuming an inviscid liquid. From the results of Azzopardi et al. (2008), who studied the pneumatic conveying of fine coal using Electrical Capacitance Tomography measurements, Azzopardi (2008) identified that there were periodic structures in the flow. These could be seen in the time series of cross-sectionally averaged void fraction. Using the Probability Density Function of these data he found

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typical signatures which, in gas-liquid flows, are accepted as belonging to the flow pattern termed churn flow. Further support for the existence of this flow pattern comes from the fact that the velocities of the periodic structures deviate from the values obtained from the equation of Nicklin et al. which performs well for slug flow. Harris et al. (2002) discuss a film thickness in annular flow. This is a dense layer of particles alongside the wall. The analogy for this flow pattern is weak as in gas liquid flows the film is travelling upwards, drops are created from waves on the liquid film interface and redepositied onto the film. It contrast, for gas/solids flows the particles travel up the centre of the pipe carried by the gas from the fluidized bed at the bottom. When they hit the wall, or rather the "film" they are captured and join the film flowing downwards. For horizontal pipes, Konrad and Davidson (1984) examined the similarity of slug flow between the two phase combinations. They concluded that the movement of the gas bubble relative to the plug of particles (which occupied the entire pipe cross-section) ahead of it was similar to that for the equivalent gas/(inviscid) liquid case. They found the height of the solids layer beneath the large bubble was higher than expected from the gas-liquid analysis. However, this difference could be explained by realising that, unlike the liquid case, the solids did not have a flat interface due to the angle of repose of the particles.

There are two other ways in which we might consider the gas/solid, gas-liquid analogy. The first is through the change of pressure gradient with gas superficial velocity. As discussed by Bi and Grace (1996), it is recognised that in both cases the pressure gradient data passes through a minimum as the gas velocity increases. In Fig. 1 data from pipe of similar diameter are plotted in terms a dimensional gas velocity $u^*_{gs} = \frac{u_{is}\sqrt{\rho_g}}{\sqrt{(\rho_i-\rho_g)gD}}$. For this comparison, data for similar liquid or solids dimensionless velocities were selected. This parameter is defined as $u^*_{is} = \frac{u_{is}\sqrt{\rho_i}}{\sqrt{(\rho_i-\rho_g)gD}}$, where i is l or s. Though there are definite similarities, there are minima around $u_g^* = 1$ – a criterion used to specify the transition between annular and churn flow, there are also distinct differences, the pressure gradient begins to decrease at lower gas flow rates for liquid than for solids – probably because the former can form bubbly flow whilst the latter cannot.

The second way in which the links between gas-liquid and gas/solids flow might be examined is via the frequency of the periodic structures which occur in both these flows. The present paper will consider the frequency of periodic structures in gas/solids flow (concentrating on slug flow in pneumatic conveying) and seeks a method of describing them. The next section provides background on the relationships between frequency and other relevant parameters in gas-liquid flows.

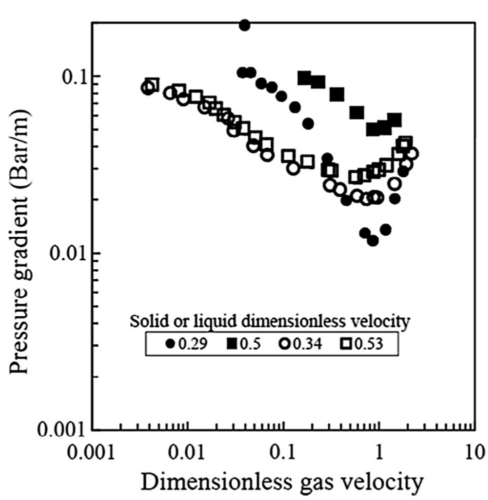

Fig. 1. Effect of gas and solids or liquid dimensionless velocities on pressure gradient. Solids: closed symbols- data of Lippert (1966) – pipe diameter = 40 mm; liquid: open symbols – data of Spedding and Van Nguyen (1975) – pipe diameter = 45.5 mm.

2. Gas-liquid flow information

As background it is important to examine the work carried out in the gas-liquid field. There, four main flow patterns are recognised in vertical pipes: bubbly, slug, churn and annular. The periodic structures in these are void waves (variations axially and in time of the concentration of bubbles), slugs/large bubbles, huge waves (as defined by Sekoguchi and Mori, 1997) and disturbance waves on the wall film respectively. Slug and annular flows also exist in horizontal pipes. Data on the frequency of these has been gathered and work has been carried out to find ways of correlating them. Now, if data are taken far from flow pattern transition boundaries, there will only be one periodic structure involved for each combination of phase flow rates. However, Sekoguchi and Mori (1997) showed that across boundaries then more than one periodic structure can be present with the frequency of one increasing and that of the other decreasing. An early way of correlating frequency was used for disturbance waves in vertical annular flow by Nedderman and Shearer (1963) employing a Strouhal number (fD/u) and a liquid Reynolds number. This was developed further by Azzopardi (2006). To handle a wider range of periodic structures Azzopardi and Baker (2003) used plots of a Strouhal number versus Lockhart-Martinelli parameter, X_{LM}. This last is the square root of the ratio of the frictional pressure drop for the liquid and gas phases and is defined in detail in the Appendix. Given that slug flow is the main flow pattern of interest in the present work, a selection of data from that type of flow has been collected and plotted using the gas superficial velocity in the Strouhal number. This is illustrated in Fig. 2 and shows that there is some correlation of the data plotted in this way. There is an obvious displacement between the air-water and air-silicone oil data, probably due to the difference in surface tension (0.073/0.02 N/m). A further dimensionless group is probably required to draw the data together. However, as will be discussed below, gas-solids is probably equivalent to a zero surface tension liquid, there is not much point pursuing that aspect in the present work. As will be discussed below, there is also an interest in slug flow in horizontal pipes. To elucidate whether there is an effect of orientation, data

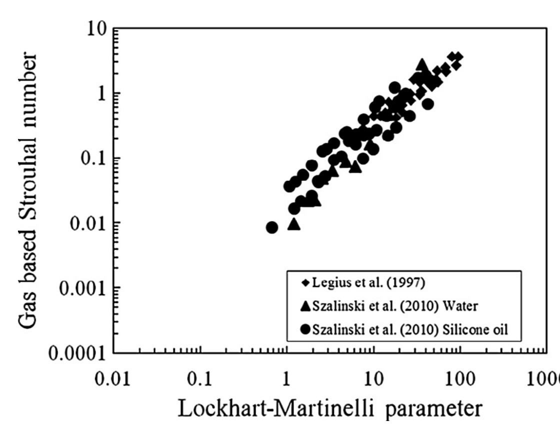

Fig. 2. Relationship between the gas-based Strouhal number and the Lockhart-Martinelli parameter for gas-liquid flow at lower gas flow rate with bubbly and slug flow patterns. Legius et al. (1997) used air-water in a 50 mm diameter pipe. Szalinski et al. (2010) used a 67 mm diameter pipe with air and either water or a silicone oil of 5 mPa s viscosity.