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Detachment velocity: A borderline between different types of particulate plugs

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ABSTRACT

Shaul & Kalman (2014–2015) defined three different types of plugs (Plug-I, II and III) of different particulate materials for dense phase pneumatic conveying. The Present experimental study is undertaken to determine the borderline between Plug-I and the other type of plugs. The borderline is established by using the concept of detachment velocity of the particles from the front of the plug. For the current study, thirty three particulate materials have been tested having the Archimedes number (Ar) in the range of 10^{-3} to10^{6}. The experiments conducted in three transparent Plexiglas pipes of diameters 1 in., 2 in. and 3 in. For each experiment, a single artificial plug of type I of varying length in the range of 10–100 cm was inserted into the test section of 1.5 m length. Further, as the plug flow is a low velocity phenomenon, the Reynolds number (R_e) during experimentation, is varied in the range of 10^{-3} to 10^{2}. The results of the experiments show that for the particulate materials with $Ar > 10^2$, first the phenomenon of detachment occurs at a corresponding velocity and on further increasing the flow rates the plug dissembled. The variation of the detachment velocity is found to be a power function of the Ar number (for $Ar > 10^2$), whereas, the detachment velocity is found to be independent of the pipe diameter and plug length. For materials with $Ar < 10^2$ no detachment of the particles from the plug front is observed and the plug starts to move as Plug-I at a critical air flow-rate and a critical plug length corresponding to respective material.

1. Introduction

Pneumatic conveying of powders through pipelines has been a prevailing practice for transportation in industries. It is done either in dilute phase or in dense phase. These days a shift towards dense phase transportation is observed due to its inherited advantages of low cost and low wear. The most widely used form of dense phase conveying is plug flows, which have an added advantage of low particle attrition along with the other advantages of dense phase pneumatic conveying.

Since the inception of idea of dense phase plug conveying plethora of models have been given for plug flows [4–7]. They all have given theoretical models for the propagation of single plugs through pipelines and pressure drop prediction for the plugs conveying. Recently, Shaul & Kalman [1–3] defined three different types of plugs of particulate materials as shown in Fig.1 for plug flow mode of dense phase pneumatic conveying.

First type (Plug-I) is the one in which the plug covers the whole pipe cross-section and does not leave any stationary particle either behind or in front. However, it may contain a slope of particles in front and rear of the horizontal plug. In the second type (Plug-II) a stationary layer of particles is left at the rear of the plug, while the next plug picks it up. Whereas, third type of plugs (Plug-III) are the small plugs that move over a stationary bed of particles. Shaul & Kalman also gave pressure drop prediction equations for all three types of plugs. The pressure drop required for Plug-I is:

$$\Delta P_{TypeI} = \frac{\left(\frac{2\mu_w^2\rho_b g}{\tan\theta} + \mu_w\rho_b g + \frac{4C_w}{D}\right)e^{\frac{4\mu_{w}kL}{D}} - \frac{4C_w}{D} - \mu_w\rho_b g}{\frac{(1-\varepsilon)4\mu_w k}{D} + \frac{\varepsilon}{L}\left(e^{\frac{4\mu_{w}kL}{D}} - 1\right)}, \quad (1)$$

where, μ_w is coefficient of wall friction, ρ_b is bulk density of the material (kg/m^3), g is gravitational acceleration (m/s^2), θ is repose angle of plug (degrees), C_w is wall cohesion coefficient (Pa), D is internal pipe diameter (m), k is stress ratio, L is plug length (m) and ε is void fraction.

For developing the above equation Shaul and Kalman [3] used the force balance given by previous researchers [4,6,8,9–13] based on analysis of the forces acting on a differential slice of a plug of particulate materials by employing the field of solid mechanics. The forces which were considered by various researchers for force balance were; Pressure Stresses (ΔP), Normal Stresses (σ_a) and Wall Shear Stresses (τ_w). Shaul and Kalman [1] modified the force balance by dividing the pressure

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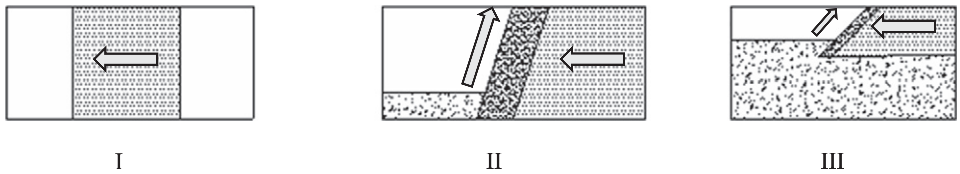

Fig. 1. Three plug types [3].

force to two forces; drag force due to the airflow through the permeable particulate plug ($\varepsilon \Delta P \frac{\pi D^2}{4}$) and pressure force acting directly on the particles [$(1-\varepsilon)\Delta P \frac{\pi D^2}{4}$]. The drag force was applied to the force balance while the direct pressure force was considered as the boundary condition for the stress within the plug.

Although their models, and other models from the literature, may describe accurately the pressure drop required to move the plug for each type of plug flow theoretically, they are developed for only single plug and not for multi-plug conveying, as a real plug flow behaves. Also, they didn't provide any prediction model for the conditions for the existence of each type of the plugs.

Preliminary experiments with artificial creation of Plug-I in an empty pipe have shown that while increasing the airflow rate that is flowing through the stationary plug some of the particles at the top front of the plug may get detached from the plug after acquiring their detachment velocity. Whereas, detachment velocity is the superficial velocity which corresponds to the air flow rate at which the particles from Plug-I front start to separate and fall in front of the static plug. Particles are detached from the top of the plug as the local velocity is higher due to the plug slope at the front and the rear of the plug. Due to this detachment the resistance to the air flow at the top of the plug gets reduced and local air velocity gets increased and bringing more particles to get detached. If we further increase the flow rate the plug gets broken. The falling of the particles in front of the plug and breakage of the plug may actually lead to formation of the stationary layer in between plugs-II or III if it is the case of multi-plug conveying. Therefore, the detachment velocity is defined as the border of existence of Plug-I.

There exists a scarcity of literature related to detachment velocity on plugs. Few works [14–21] are found in literature which mention detachment velocity of particles but in reference to colloids. In those their major focus was on calculation of magnitude of forces required for detachment from colloids and none of them focus on flow mechanics aspect of pneumatic conveying of particles in the form of plugs. Thus, the aim of the current work is to analyze the detachment velocity in detail through extensive experimental study on pipeline plug flows. It will also be tried to obtain few parameters to establish the detachment velocity as a borderline between the plugs, which will ultimately pave way towards a mechanism for multi-plug conveying.

2. Experimental

To obtain various parameters to fit into the plugs suggested by Shaul and Kalman [3], experiments are conducted in Plexiglas pipes of 1 in., 2 in., and 3 in. diameters. The experiments are conducted with 33 different materials, some granular up to 5 mm, and some powders down to 4 μm. The details of experimental test rig, material used and the procedure adopted will be explained in the subsequent sections.

2.1. Test rig

The line diagram of the system as shown in Fig.2 shows all the equipment used for the experiments. The system consists of a compressor (1) of capacity 6–6.5 bar to generate the compressed air for the test rig. One stop valve (2) and a gate valve (3) are provided to control the flow to the flow meters (4) and to the pipes respectively whose overall length is approximately 6 m. The first pipe section (7) which is of 250 mm length is filled with plastic beads for flow straightening. The second pipe section (8) is of 350 mm length and is provided with the pressure transducer (5). The third pipe (9) is 1.5 m long test section which could be separated from the line for the loading and unloading of the artificial plugs. The fourth pipe (10) continues for 4 m up to a cyclone separator (11). All pipes are connected with each other by flanges (13, 14, 15 and 16). The particles after experiment are collected in a collector at the bottom of the cyclone (12). All the data is read and recorded in the Lab-View (6) system. Details regarding utility of the equipment will be explained in Section 2.3.

2.2. Materials

To investigate how the detachment velocity is affected by the particulate materials properties, 33 materials of different properties as

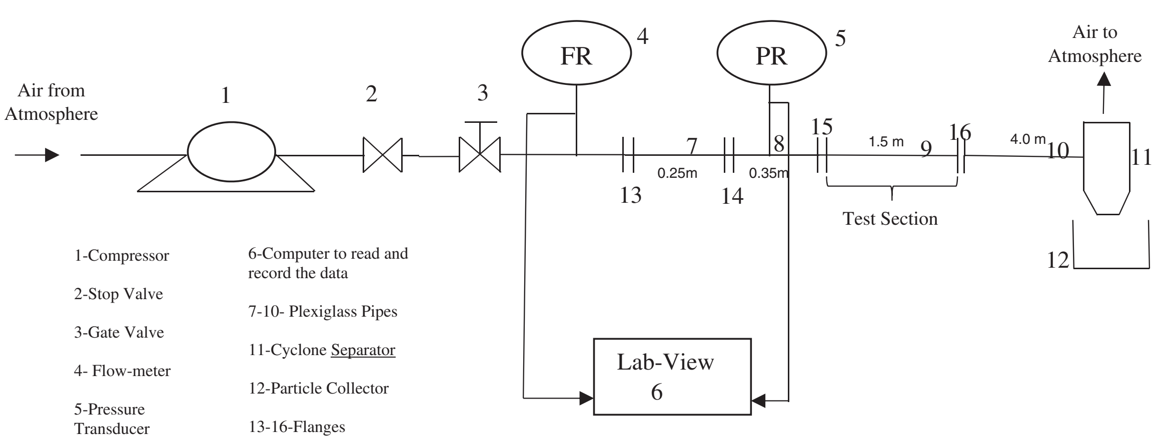

Fig. 2. P&ID of the experimental system.