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Experimental investigation on heat transfer mechanisms of pneumatically conveyed solids' plugs as a means to mass flow rate measurement

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ABSTRACT

Experiments with a gas–solids dense phase pneumatic pipe flow have been undertaken: (1) to determine the average heat transfer coefficient between a heated wall and a gas–solids dense phase flow; (2) to investigate the heat transfer mechanisms of pneumatically conveyed dense phase flow in detail as the system operates by injecting heat energy into the pipeline to heat the pipe section, as a result, to heat the dense phase gas–solids' plugs, and measuring the resultant change in solids' plug and heated wall's temperatures. The experimental results suggest that the average heat transfer coefficient between the heated wall and the gas–solids dense flow displays an approximately linear relationship with the solids loading ratio. A larger solids' loading ratio results in a higher average heat transfer coefficient. The results have been compared with those of Moriyama et al. although the overlap of data ranges is limited. Experimental results also indicate that the inner wall temperature is able to reflect the energy change when each solids' plug is being through the heated region. The calculated gradient change of the outer wall temperature–time history T_1 measured is consistent with the fluctuation of the wavering of the inner wall temperature along with the present of solids' plugs in the heated region.

1. Introduction

A thermal solids flow meter in general operates by introducing an exterior heat energy into the gas–solid two-phase flow pipeline and measuring the resultant temperature difference with appropriate sensing elements. Several thermal flowmeters for pneumatic conveying pipelines were developed. Li [1] described a inserted thermal mass flow meter for measuring solids' mass flow rate of gas–solids dilute flow. The problems faced this approach were: (1) the sensor probe attrition in the pipeline; (2) invasive measurement. Another approach of mass flowmeter based on heat transfer for a gas–solid dense phase flow was developed by Moriyama [2]. The rig worked by the injection of heat energy into the measuring section. A non-invasive temperature difference sensing was applied. The relationship among the mass flow, the heat transfer coefficient and the temperature difference were analyzed and deduced. The system is unsuitable for applications in which fast dynamic responses are essential [3]. The thermal approach to determine solids' mass flow rate has been driving researchers to investigate and develop continuously since this is a direct and reliable measurement regardless of in homogeneities in solids' distribution, irregularities in velocity profile and variations in particle size or shape.

The heat transfer from the heated wall to the gas–solids dense phase flows in pneumatic conveying pipelines is crucial in the development of thermal mass flowmemter. Findings of the heat transfer between walls and gas–solids suspensions in pneumatic conveying pipelines were demonstrated. A computational and experimental investigation of transient heat transfer in pneumatic transport of granular particles was presented by Li to characterize heat transfer mechanisms in gas–solids flows through pneumatically conveyed pipelines [4,5]. An analysis of the heat transfer coefficient in a turbulent particle dilute pipe flow was conducted by Avila and Cervantes, which suggested that the heat transfer coefficient increased with the particle loading ratio [6]. A study on experiments and calculations was demonstrated to investigate the heat transfer from a heated pipe wall to a single particle with a moving gas stream based on non-invasive temperature measurement [7]. A recent investigation on the two-phase gas–solids flow in pneumatic transport pipe with heat transfer was conducted, in which the predictions of the numerical simulations were validated with published experimental data [8]. To date, more reports involving heat transfer from a hot gas stream to moving solids or from a heated wall to a gas–solid flow have been presented in

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applications of pneumatically conveyed gas–solid flows, but little has been reported on heat transfer mechanisms of pneumatically conveyed solids' plugs, especially in details on the thermal behavior of each solid's plug being traveled through the heated region as a means to mass flow rate measurement by thermal method.

The main objectives in this work are: (1) to characterize the heat transfer and evaluate the average heat transfer coefficient from the heated wall to the solids' plugs in gas–solids dense phase flow with different solids loading ratios, to inform the development of mass flow measurement by thermal techniques; (2) to investigate the heat transfer mechanisms of pneumatically conveyed solids' plugs in detail as the system operates by injecting heat energy into the heated region of the pipeline and measuring the resultant change in solids' plug and heated wall's temperatures.

2. Experimental principle

The rate of heat transported to the suspension Q_{susp} was described as Eq. (1), under the condition of the constant surface temperature of the pipe wall in the case of a pneumatically conveyed gas–solids dilute flow, according to Avila's report [6]. Radiation is neglected since the temperature mentioned here is rather low.

$$Q_{susp} = \bar{h}_{susp} A_{transf} \Delta Tlm_{susp} \tag{1}$$

where, h^{-}_{susp} is the average heat transfer coefficient between the hot wall and a particulate turbulent flow, A_{transf} is the heat transfer surface area, ΔTlm_{susp} is the logarithmic mean temperature difference, i.e. [6]

$$\Delta Tlm_{susp} = \frac{\Delta T_{bulo} - \Delta T_{buli}}{\ln(\Delta T_{bulo}/\Delta T_{buli})} \Delta T_{buli} = T_s - T_{buli} \Delta T_{bulo} = T_s - T_{bulo} \tag{2}$$

The rate of heat transported by the suspension Q_{susp} can be determined by the following relationship, as Eq. (3) [6]:

$$Q_{susp} = (\dot{m}_g c_{pg} + \dot{m}_p c_{pp})(T_{bulo} - T_{buli}) where,$$

$$T_{buli} = \frac{\dot{m}_g c_{pg} T_{mgi} + \dot{m}_p c_{pp} T_{mpi}}{\dot{m}_g c_{pg} + \dot{m}_p c_{pp}}$$

$$T_{bulo} = \frac{\dot{m}_g c_{pg} T_{mgo} + \dot{m}_p c_{pp} T_{mpo}}{\dot{m}_g c_{pg} + \dot{m}_p c_{pp}} \tag{3}$$

where, T_s, the temperature of the pipe surface; T_{buli}, T_{bulo}, the suspension bulk temperatures at the inlet and the outlet of the heated section, respectively; T_{mgi}, T_{mgo}, the gas phase bulk temperatures at the inlet and the outlet of the heated section, respectively; T_{mpi}, T_{mpo}, the solid phase bulk temperatures at the inlet and outlet of the heated section, respectively; $\dot{m}_g$, $\dot{m}_p$, the mass flow rates of the gas and solid phase, respectively; $c_{pg,}$ c_{pp} the specific heat of the gas and the particles, respectively.

The average heat transfer coefficient from the hot wall to the particulate flow h^{-}_{susp}can be deduced from Eqs. (1)–(3) in terms of "measurable" quantities, which can be calculated and obtained from experimental data according to Eq. (4) [6]:

$$\bar{h}_{susp} = \frac{(\dot{m}_g c_{pg} + \dot{m}_p c_{pp})(T_{bulo} - T_{buli})}{A_{transf}((\Delta T_{bulo} - \Delta T_{buli})/\ln(\Delta T_{bulo}/\Delta T_{buli}))} \tag{4}$$

For practical purposes, the single-phase bulk temperatures of the gas (T_{mgi} and T_{mgo}) and the solids (T_{mpi} and T_{mpo}), and the mass flow rate of the gas and solid phase ($\dot{m}_g$and $\dot{m}_p$) in Eq. (3) were taken as those values could be measured by the appropriate transducers in experiments of the work.

3. Experimental rig and materials

The experimental rig applied in lab scale is shown in Fig. 1, which comprises a lab-scale vacuum pneumatic conveying pipeline along with a heated region and several transducers. Solids' plugs are conveyed in a gas stream through a pipeline with a heated region from the hopper to the receiving vessel where the gas is separated from the particulates. The gas in the conveying pipeline is controlled by adjusting the amount of gas fed into the vacuum line via the bypass gas valve. This control of the conveying gas enables adjustments of the solids' velocity and solids' plug structure in the pipeline.

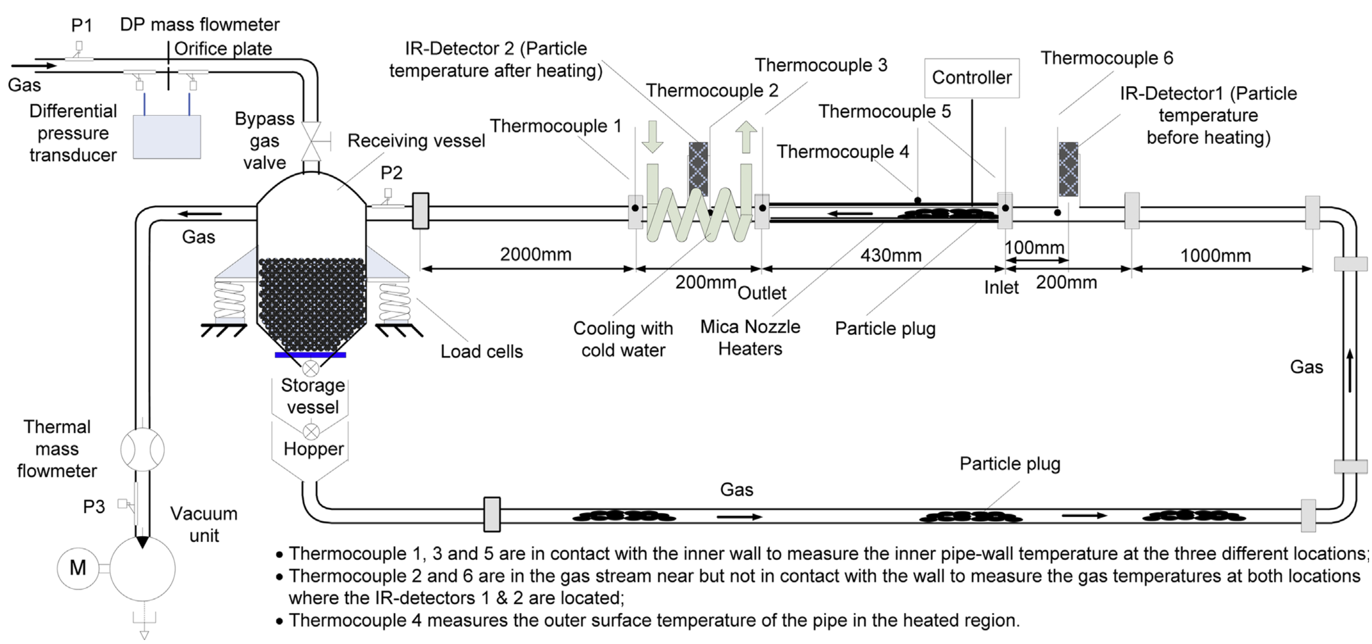

Fig. 1. Experimental rig, T_{mgi}—gas temperature at the inlet of the heated region; T_{mpi}—particles' temperature at the inlet of the heated region; T_{wr1}—pipe wall temperature at the inlet of the heated region; T_{mgo}—gas temperature at the outlet of the heated region; T_{mpo}—particles' temperature at the outlet of the heated region; T_{wl1}—Pipe wall temperature at the outlet of the heated region; T_{surf}—the temperature of the outer surface of the heated pipe section.