Development of a Particulate Solids Thermal Mass Flowmeter[†]

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Abstract

An ideal mass flow meter should have the following properties: it should be non-invasive so as not to disrupt the flow profile; it should be easily installed on the conveying line to provide on-line and continuous measurements; it should be able to provide an accurate indication of the mass flow rate regardless of the orientation of the measurement section, inhomogeneities in the solids' distribution, irregularities in the velocity profile, or variations in particle size, moisture content and material properties.

A mass flow meter as described in this paper has been developed which uses a thermal method, a direct, non-invasive approach to measuring the mass flow rate. The thermal method uses the principle of heat transfer to solid particles in a flowing fluid to determine the mass flow rate of particles. The mass flow meter is designed such that temperature sensors are located at two ends of a heated pipe section. In the experiments carried out, measurements of gas and solids' temperature were taken and used to calculate the heat transferred to the solids. The mass flow rate obtained using the thermal mass flow meter was compared to that using load cells. The results obtained are analysed and presented in this paper.

Keywords: gas-solids, pneumatic conveying, heat transfer, thermal mass flow meter

Introduction

Pneumatic conveying has proven to be an efficient and useful method for applications requiring the transportation of bulk solids within processing plants. The process is completely enclosed, using pipes and vessels where the solids are stored. The transporting gas, usually air, is released through a filter at the end of the process. This ensures there is no release of solids into the environment, making it a clean and safe procedure. Another advantage of this process is the fact that the air used as a transporting gas is readily available and does not react with the solids being conveyed. In situations where the use of air is inappropriate, a non-reacting gas such as nitrogen can be used. In various processing plants where pneumatic conveying is employed, the conveying pipes can be constructed in such a way that they span several kilometres and can be installed in a variety of ways, vertically and horizontally. This means any number of plant configurations can make use of the method including multi-storey buildings, or plants with different sections located at a distance from each other.

In pneumatic conveying plants, as in any other system,

optimal control of the processes is achieved by monitoring the parameters within the system. A prerequisite is knowledge of the pressures, temperatures, velocities of gas and solids, the volume of solids within the gas, and the mass flow rate of solids being conveyed. The measurement of the mass flow rate of solids on-line presents quite a number of difficulties. One method of determining the quantity of solids being conveyed is to use a "gain-in-weight" or "loss-in-weight" system where the mass of solids is measured using load cells located at the feed or receiving vessel, respectively. This method is unable to determine the amount of solids passing through a conveying pipe at a given period or position on the line, and is more suitable for batch systems than for continuous flow systems where the mass flow rate is required as the product is being conveyed. The advantage of measuring mass flow rate on-line is the possibility of detecting problems within the conveying line as they occur, for instance a reduction in the mass flow rate along the line may suggest a pipe blockage or solids deposition beginning to occur somewhere along the line. Therefore the possibility of having a device which can determine the mass of solids at any given time during a process is quite attractive.

Research has been ongoing for a number of years towards the development of an "ideal" mass flow meter. For a mass flow meter to be described as ideal it should have the following properties: it should be non-invasive so as not to disrupt the flow profile; it should be easily

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installed on the conveying line to provide on-line and continuous measurements; it should be able to provide a reliable and accurate indication of the mass flow rate regardless of the orientation of the measurement section, inhomogeneities in the solids' distribution, irregularities in the velocity profile, or variations in the particle size, moisture content and material properties (Yan, 1996; Arakaki et al., 2006). Finding all of these properties in one single instrument has not been achieved yet, but research is still ongoing.

The mass flow rate can be measured in two basic ways, directly or inferentially. A direct mass flow meter is one whose sensing element responds to the mass flow rate of solids passing through it, while an inferential mass flow meter obtains the mass flow rate from a calculation of velocity and concentration of solids measured by its sensor (Yan, 1996; Beck et al., 1987). A variety of methods exist for the measurement of solids' concentration and velocity using the inferential method (Carter et al., 2005; Arko et al., 1999; Hrach et al., 2008; Huang et al., 2001), as this has proved to be more easily achievable than obtaining a direct measurement of the mass flow rate. Certain limitations experienced with the use of inferential methods have been presented in the review paper of Zheng and Liu (2010).

The thermal mass flowmeter

The thermal method of mass flow rate measurement uses the principle of heat transfer to solid particles in a flowing fluid-solid mixture to determine the mass flow rate of particles. Two approaches are used; the first involves a measurement of temperature difference at sensors located before and after a heated region with a constant heat supplied to the system, while in the second method, a constant temperature difference is maintained within the heated region and the heat required to maintain this difference is measured (Zheng and Liu, 2011; Yan, 1996). The mass flow rate is deduced from the relationship between the rate of heat transferred, the measured temperatures, the heat transfer coefficient and the material's thermal conductivity. In his review of mass flow rate measurement methods, Yan (1996) stated that the problems with this method have been found to be poor repeatability of the instrument and a slow dynamic response time. Experiments conducted by Moriyama (1996) using three different measurement methods—cross-correlation, heat transfer and acoustic emission—showed the heat transfer method to have the highest time constant of the three methods. However, research is ongoing to develop the thermal method as it is non-intrusive and expected to provide reliable, on-line, continuous estimates of the mass flow rate. A thermal mass flow meter has been developed which is non-invasive and employs the use of infrared sensors for the temperature

Fig. 1 A thermal mass flow meter (Yan, 1996).

measurement of solids (Zheng et al., 2008).

Thermal mass flow meters have been developed commercially for use in the measurement of liquid and gas mass flow rates (Viswanathan et al., 2002a, 2002b; Han et al., 2005; Kim et al., 2007). A schematic diagram of a thermal mass flow meter is shown in **Fig. 1**.

Heat transfer to gas-solid systems

In a study carried out by Farber and Morley (1957), it was established that the addition of solid particles to a flowing gas increased heat transfer rates when compared to a single phase flow of gas. Using a suspension of air and alumina-silica particles, with carbon tetrachloride vapour as the heat transfer medium, the heat transfer processes occurring in the suspension were investigated. The authors observed an influence of the solids on the gas boundary layer and the heat capacity of the suspension. They concluded that for a constant gas flow rate, the ratio of the increase in the solids' temperature to the increase in gas temperature was a constant and independent of the solids' loading ratio, but increased with increasing gas flow rates or decreasing particle residence times. However, it is important to note that the solids' temperature increase was not a measured value, but was estimated by subtracting the enthalpy increase of the air from the net heat transferred, and dividing this quantity by the weight of the solids flowing and the specific heat of the solids (Farber and Morley, 1957).

The effect of particle size on heat transfer in a gas-solid mixture of air and spherical glass particles was investigated by Farber and Depew (1963). In their study, varying particle sizes of 30, 70, 140 and 200 microns were added to air flowing in a borosilicate glass tube. Using a vertically mounted tube, heat was transferred to the medium using carbon tetrachloride vapour as the heat transfer medium. The results showed a substantial increase in the gas-side heat transfer coefficient for the 30-micron particles, and no visible increase in the heat transfer coefficient for the 200-micron particles; showing that the heat transfer coefficient increased with decreasing particle size. This effect was explained as being due to the fact that increasing solids' sizes prolonged the thermal entry

length, with larger particle sizes having a longer thermal entry length approaching the tube length, therefore the thermal boundary layer was not fully developed within the tube length.

The heat transfer characteristics of a turbulent, dilute, air-solids suspension flow was studied using a uniformly heated pipe and glass beads (Aihara et al., 1997). Measurements of the bulk air-solid suspension temperatures were made using thermocouples at a region stated to be hydrodynamically and thermally fully developed. The results of the Nusselt number showed a dependence on the solids' loading ratio as well as the air flow rates. A decrease in the Nusselt number was observed upon addition of the glass beads to the air flow; however, after reaching a minimum at a critical loading ratio, it began to increase with increasing solid loading ratios.

This effect was also observed by Rajan et al. (2008). Gas-to-particle heat transfer coefficients decreased with solids' feed rate at lower solids' feed rates typical of dilute flow regimes or fast fluidization regimes in packed beds. The same was found to increase with increasing solid feed rates as dense flow regime was approached. Experiments were carried out in a pneumatic conveying test rig consisting of a galvanized iron duct of 54 mm inner diameter and 2.2 m height, fitted with 3 heaters of 5 kW heating capacity. Gypsum was used as the solid medium and hot air as the gas medium (Rajan et al., 2008). Results showed an increase in the air-solid heat transfer coefficient with increasing air velocity in the range between 4.3 m/s and 5.8 m/s; this reached a maximum before decreasing with a further increase in air velocity of about 6.3 m/s. Thermal conductance, defined as the ratio of the heat transfer rate to driving force, was found to increase with solids' feed rate and air velocity (Rajan et al., 2010).

Previous work

Research is ongoing at the Centre for Industrial Bulk Solids Handling in Glasgow on the development of a thermal instrument for solids' mass flow rate measurement. The instrument is made up of a 1-m long pipeline section which is referred to as the heated section. Thermocouples are located upstream and downstream of this section for measurement of the gas temperatures, while infrared sensors are located at similar locations for measurement of the solids' temperatures. The pipe surface temperature is measured using a thermocouple. The heat transferred to the system is controlled within a set band, giving a pulsed heat signal in which the heater is turned off when the pipe wall temperature is above a fixed point, and then turned on when the temperature falls below a fixed value. The instrument described is shown schematically below.

The operation of a thermal mass flow meter is based on the principle of heat transfer to a medium; in this case a mixture of solids in air. To provide an understanding of this, a study was carried out on the heat transfer mechanisms to solids flow. Zheng et al. (2008) reports the results of a numerical analysis and experimental studies carried out to analyse the heat transferred to a flowing gas from the heated wall, and then from the heated gas to a single particle passing through the region. This study proposed that the heat generated was transferred along the pipe wall axially and radially by conduction, and then from the pipe wall to the gas and then to the solid particle by convection.

In another study, the heat transfer coefficient from a heated wall to a gas-particulate plug flow was investigated experimentally and numerically (Zheng et al., 2007). The results showed that the heat transfer coefficient increased approximately linearly with the solids' loading ratio, this being consistent with Zheng et al.'s hypothesis that a higher solids loading provides more carriers for heat

Fig. 2 Schematic diagram of the thermal mass flow meter.

transfer.

The operation of the thermal mass flow meter was further investigated with experiments conducted under dilute phase flow conditions, conveying ordinary Portland cement on an industrial-scale pneumatic rig (McGlinchey et al., 2010; McGlinchey et al., 2013). Using an energy balance approach between the heat entering the system and the heat taken by the gas-particulate mixture, a measure of the mass flow rate was obtained which was then compared to measurements obtained from load cells. The results showed good agreement between the thermal mass flow meter and the load cells; however, some important observations were made. The analysis showed that the temperature of solids being measured by the infrared sensors was affected by the ambient temperature around the sensor (Kato et al., 2012). Therefore a method to control the infrared sensor temperature was developed using cooling water which was passed through a copper pipe coiled around the steel conveying line.

The following section describes further measurements carried out on the industrial-scale pneumatic conveying rig as a means to further understand the principle of operation of the thermal mass flow meter under development.

Experimental procedure

A schematic diagram of the experimental rig used is shown in **Fig. 3**.

The experimental system is the same as that described in a previous publication (McGlinchey et al., 2013). The pipeline is of mild steel nominal bore 50 mm, with a total length of about 50 m, of which 5 m is vertically up, the remainder in the horizontal plane, and included five 90-degree standard radius bends. The measurement system as shown in **Fig. 2** was positioned at least 5 m from any bend. Ordinary Portland cement with a mean particle size of 25 μm was conveyed in a range of dilute phase conditions with mass flow rates of air ranging from 0.4 kg/s to 0.14 kg/s and solid loading ratios in the range 4 to 136. The thermal properties of ordinary Portland cement are listed in **Table 1**. The mass flow rate of solids used to compare the results from the thermal instrument was obtained from load cells at the receiving vessel.

The experimental procedure was as follows. Compressed air was supplied to the test rig via the pressure control valve PRV1 shown in **Fig. 2**. The gas mass flow rate at the outset was determined using a combination of a

Fig. 3 Schematic diagram of industrial-scale test rig.

Table 1 Properties of Granular Material

Properties of Ordinary Portland Cement	
Particle size	25 mm
Density	1500 kg/m ³
Thermal conductivity	0.29 W/mK
Specific heat capacity	0.84 kJ/kgK

Source: Holman, 2010

number of nozzles to achieve the required flow rate. Once the gas flow rate had been established, the measurement and data acquisition system was turned on. A program developed using LabVIEW and the National Instruments DAQ system was used to control the heater to maintain the pipe wall temperature within a fixed band. After the system had reached a stable condition, solids were inserted into the conveying line from the blow tank. A record of the temperatures of the pipe wall, the gas and solids was acquired, as well as the pressure drop within the system and the mass of solids obtained from load cells located at the receiving vessel.

Results and analysis

The amount of heat transferred to a system is defined as a product of the mass of the system, its specific heat capacity and the difference in temperatures measured before and after heat is transferred. The heat transferred to a gas-solid suspension is a function of the specific heat capacity of the suspension, the temperature difference and also the mass flow rate of the suspension.

Using the energy balance method (McGlinchey et al., 2013), the following equation was used to calculate a factor corresponding to the mass flow rate of solids measured by the thermal instrument. The rate at which heat is transferred to the system is given by:

$$Q = \dot{E}_{in} + S_{heater} m_{heater} \frac{\Delta T_{heater}}{\Delta t} \quad (1)$$

and the rate at which heat is taken up by the gas-solids suspension is given by:

$$Q = S_{susp} \frac{m_{susp}}{\Delta t} \Delta T_{susp} \quad (2)$$

where $\dot{E}_{in}$ is the energy supplied to the heating system.

At a time when the electrical input to the heater is off ($\dot{E}_{in} = 0$) and the pipe wall temperature change is approximately linear with time, and if we assume the specific heats of the heater and the suspension to be relatively constant, the mass flow rate of the suspension can be obtained by equating (1) and (2) and rearranging the result

to give:

$$\dot{m}_{susp} = Const * \frac{\Delta T_{heater} / \Delta t}{\Delta T_{susp}} \quad (3)$$

where the constant value is given by:

$$Const = \frac{S_{heater} m_{heater}}{S_{susp}} \quad (4)$$

Assuming a value of –1 kgs for the constant (so that the results can be viewed in the positive graph axes), the following results were obtained for tests carried out over a range of air mass flow rates and varying solid loading ratios. Results shown have been made dimensionless by dividing by corresponding air mass flow rates.

The results above show the thermal instrument's response to varying air flow rates and solid loading ratios. The mass flow rate factor from the thermal instrument was obtained using **Eqn. 3**. The graph shows three distinctive regions: Region 1, where an approximately linear relationship can be observed between the thermal instrument and the load cells; Region 2, where a very low solids' temperature difference causes the measured mass flow rate to be uncharacteristically high for the given solids' loading; and Region 3, where we can observe a gradual approach to dense phase flow conditions.

This factor obtained from the thermal instrument is dependent on the change in wall surface temperature with time, as well as the heat taken in by the solids which is measured by the infrared sensors, assuming the specific heats of the heater and the suspension remain constant. According to the equation, a high mass flow rate is recorded by the thermal instrument when the change in wall temperature with time is high. This gradient should increase with increasing air mass flow rates. In addition to this, if the heat taken in by the solids as measured by the temperature difference is a low value, then a high mass flow rate should also be observed. An increasing solids' loading ratio will reduce the relative air mass flow rate influence and hence the temperature gradient per time at the wall for a given test, however, this does not fully explain the observed results. This may be due to the measurement method of the infrared sensors. For accurate temperature measurement of moving solids using an infrared sensor, it is necessary for the solids to completely fill the viewing window of the sensor. At low solids loading ratios, it is possible that this requirement is not met, and therefore the results obtained in this range are being affected by the temperature of the inner pipe wall. See **Fig. 4**, Region 2. At high solids loading ratios the measurement may be biased to detection of a solids fraction in non-suspension mode which would be hotter than a bulk temperature. See **Fig. 4**, Region 3.

Fig. 4 Results obtained for the mass flow rates of solids using the thermal instrument. The legend shows the different air mass flow rates used.

Conclusions

Investigation of the operation of a thermal mass flow meter was carried out by analysing tests performed on a pneumatic conveying rig with air flow rates between 0.04 kg/s to 0.14 kg/s, and solid loading ratios in the range 4 to 136. Results have shown a dependency of the mass flow rate measurements on the solid loading ratio. The thermal mass flow meter shows promise as a direct mass flow rate measurement instrument. Further tests and investigations are ongoing to characterise the operation of the mass flow meter.

Nomenclature

$\dot{E}_{in}$	electrical input rate to heater (W)
m_{heater}	mass of heater (kg)
m_{susp}	mass of gas-solids suspension (kg)
$\dot{m}_{susp}$	mass flow rate of gas-solids suspension (kg/s)
Q	heat energy rate (W)
S_{heater}	specific heat capacity of heater (J/kgK)
S_{susp}	specific heat capacity of gas-solids suspension (J/kgK)
Δt	change in time (s)
ΔT_{heater}	change in temperature of heated wall (K)
ΔT_{susp}	change in temperature of gas-solids suspension (K)

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Author's short biography

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Mary Kato is a research student at Glasgow Caledonian University, working with the Centre for Industrial Bulk Solids Handling where she is investigating heat transfer in particulate systems at the PhD research level. With a background in chemical engineering, she proceeded to study applied instrumentation & control and completed an MSc. She has published works on the influence of windows on infra-red temperature measurement towards the development of a thermal mass flow meter.

John Pugh

John Pugh is a professor at Glasgow Caledonian University. He has pursued an interest in instrumentation and measurement for over thirty five years—with at least twenty years in the area of instrumentation for bulk solids handling. Current research work is on the development of solids' two-phase mass flow measurement, and he also maintains an interest in industrial weighing. He is vice-president (Learned Society matters) of the Institute of Measurement and Control in the UK, and chair of the institute's Learned Society Board. He has published over eighty papers and conference proceedings—around 30 in the area of solids handling.

Don McGlinchey

Professor Don McGlinchey is the head of the Centre for Industrial Bulk Solids Handling at GCU. He is an academic of international standing in the particulate solids handling community. He has undertaken consultancy projects for both multinational companies and small to medium enterprises, and has delivered short courses in Sweden, USA and the UK. Don has also presented at international academic conferences in China, India and Europe. He is a chartered physicist with a PhD on the subject of the effect of vibration on particulate materials. Don is the editor of two books and has authored over 50 research articles.