



The influence of windows on infra-red temperature measurements for solids' mass flow rate determination

M. Kato, J.R. Pugh*, D. McGlinchey

School of Engineering and Built Environment, Glasgow Caledonian University, 70 Cowcaddens Road, Glasgow, G4 0BA, United Kingdom

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ABSTRACT

Thermal mass flow meters can, in theory, be used in pneumatic conveying applications to provide a reliable monitoring of the mass flow rate of solids being transported in a stream of gas. Accurate measurement of temperature is necessary for the mass flow rate to be reliably determined. Direct measurement of temperature of particulate solids being conveyed pneumatically can be achieved, in principle, with the use of infra-red (IR) detectors. This has been done in previous work for the measurement of solids' temperatures in a pneumatic conveying line where windows were employed. This paper investigates the influence of windows on the temperature measurement process. We investigate specifically the effect of dust deposited on the window surface in conjunction with the window temperature. The results show that if the window is not ideal, measurements of temperatures above the temperature of the window will be below actual, and measurement of target temperatures below the window temperature will be higher than actual. A simple assumption that a non-ideal window would attenuate the IR signal and result in lower temperature measurements is therefore, not valid. An analysis is offered that explains the results obtained.

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1. Introduction

Pneumatic conveying applications often require the accurate measurement of the mass flow rate of solids being transported. An online method of measurement which provides reliable data is highly desirable and has been the subject of study for a number of researchers [1–3]. Studies have shown that a thermal mass flow meter would, in theory, provide reliable data over a range of flow regimes; and thus previous work has concentrated on the development of a thermal mass flow meter [4,5]. The operation of such an instrument is based on the principle of heat transfer to the solid particles, and therefore, a reliable and accurate measurement of the solids' temperature is a necessary component for accurate determination of the mass flow rate.

Contact methods of temperature measurement such as thermocouples [6–9] and resistance thermometers [10] have been used in a number of applications. When a sensing probe is inserted into a conveying pipe, the solids come into contact with it when in motion. Due to the high velocities of these particles, the sensors are more prone to wear and degradation. The time response of the sensors also needs to be taken into consideration, as there needs to be

an interaction between the particles and the sensor head for an accurate measurement. Non-contact methods provide the advantage that they are non-invasive and therefore, not at risk of degradation by the particles. This method is based on the measurement of thermal energy radiated by heated particles. The temperature ranges of interest are such that the thermal radiation emitted is in the infrared region, and a number of devices exist and have been used for infrared temperature measurements [5,11–14].

When using infrared devices, the target must remain visible to the sensor at infrared wavelengths [15]. The sensor must be protected from the pressure inside the conveying line in a pneumatic process where particles are being conveyed in a stream of air at a pressure above or below the atmospheric pressure. A window is used to contain the pressure within the line. The choice of window is usually based on the wavelength of interest; the window's absorption coefficient, its transmissivity, and its cost.

Zinc Selenide (ZnSe) windows have a low absorption coefficient [16] at infrared wavelengths; which provides the advantage that almost all the radiation from the target passes through the window and onto the sensor. Harris [17], in his review of durable windows (in the 3–5 μm range) states that the main limitation of using these windows is the emission of radiation from the window itself, which can sometimes exceed the signal from the target. A study on the fouling of windows used in combustion chambers carried out by Ranner et al. [18] showed that the thermal conductivity of the window influenced the measurement of formed carbon deposits. Fischer et al. [19] also state that the temperature of

* Corresponding author. Tel.: +44 0 141 331 3670; fax: +44 0 141 331 3690.

E-mail addresses: mary.kato@gcu.ac.uk (M. Kato), j.r.pugh@gcu.ac.uk (J.R. Pugh), d.mcglinchey@gcu.ac.uk (D. McGlinchey).

the instrument can itself lead to uncertainties in the measurement of interest.

In experiments by the authors and others [4], infrared temperature measurement was used to infer solids' mass flow rate. However, one of the data points was inconsistent with the others. As Zinc Selenide (ZnSe) windows were being used it was not inconceivable that in this case a deposition of dust on the window may have affected the infrared temperature measurements. However, the direction of the inconsistency did not accord with an attenuation of the infrared radiation due to a dirty window. This experiment and subsequent explanation were required to explain fully the inconsistency.

2. Theory

Infrared (IR) detectors measure the temperature of an object by detecting the radiation it emits. All objects above a temperature of absolute zero emit radiation, the power of which is proportional to the fourth power of their absolute temperature according to the Stefan–Boltzmann law. In the case of an ideal emitter, this is represented by:

$$W = A\sigma T^4, \quad (1)$$

where W represents the total power radiated in Watts; σ is the Stefan–Boltzmann constant $= 5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4}$; A is the surface area of the object in m^2 ; and T represents the temperature of the target in Kelvin, K.

Eq. (1) describes the radiation obtained from an ideal emitter, known as a 'blackbody', at a given temperature. A blackbody is an object that absorbs the entire radiation incident on its surface. Most real objects, however, are not perfect absorbers of radiative energy. The radiative power obtained from real bodies is given by:

$$W = \varepsilon A\sigma T^4, \quad (2)$$

where ' ε ' is a dimensionless factor called the emissivity and is the ratio of the radiation observed from a real body to that from a blackbody at the same temperature [20]. A blackbody has an emissivity equal to 1. A real body has lower values depending on its material characteristics. For instance, a shiny surface will have a far lower emissivity than a darkened surface.

From Kirchhoff's law of thermal radiation, emissivity equals absorptivity at thermal equilibrium [20]. Absorptivity in this case refers to the fraction of incident radiation that is absorbed by the object's surface. A blackbody can absorb the entire incident radiation hitting its surface. A real body is characterised by two other properties in addition to the absorptivity; the reflectivity and the transmissivity. Reflectivity describes the fraction of incident radiation reflected by a surface. Transmissivity is the fraction of incident radiation that passes through a body. This property is important in transparent objects such as lenses and optical viewing windows. An opaque object has no transmissivity. A high transmissivity means that the object (lens or optical window) allows a large proportion of the radiation observed from a target to pass through it to reach the IR detector for measurement. In pneumatic conveying operations, zinc selenide windows have been used to accommodate pressure differences between the inside of the pipe and the detector outside [5]. Unless an optical window has a transmittance equal to 100%, it is likely that the temperature obtained from the radiation energy observed will be attenuated by a few degrees Kelvin. This attenuation is caused by the window absorbing a fraction of the emitted radiation from the target. A great portion of the signal will be lost if the window exhibits a high absorptivity (Fig. 1).

For every solid, applying the principle of energy conservation [21], the properties discussed above are related by the Eq. (3) below:

$$\alpha + \rho + \tau = 1, \quad (3)$$

where α = absorptivity, ρ = reflectivity and τ = transmissivity.

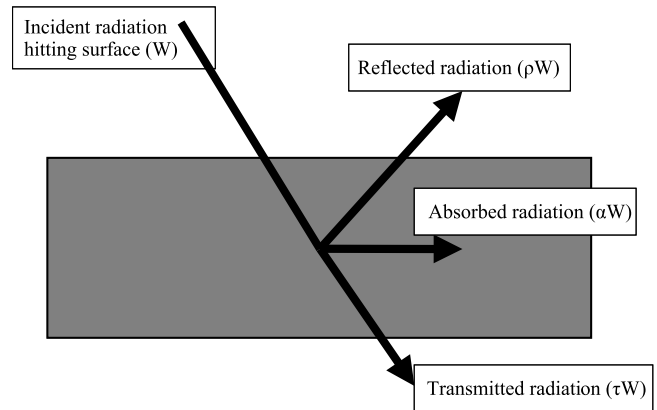


Fig. 1. Incident radiation on a surface.

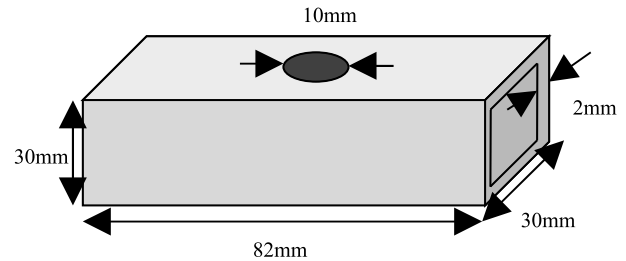


Fig. 2. Hollow metal channel used as target.

IR detectors measure temperature through the detection of thermal radiation from a surface. A collection area is defined on the surface; this is called the spot size which changes as a function of distance between the target and the detector. As this distance increases, the size of the collection area increases, and as long as the target completely fills it; the increase in area compensates for any reduction in the radiation collected as a result of increasing distance. Therefore, the amount of radiation collected (and hence the temperature measured) will be independent of distance as long as the condition previously mentioned (that the target completely fills the collection area) is met.

3. Experimental procedure

A blackbody cavity has been constructed using a darkened, hollow metal channel with a hole drilled in the centre of one side. Incident radiation entering the hole is largely absorbed by the opposite face and most reflected radiation will finally be absorbed by the other internal surfaces. The fraction of radiation leaving the hole is small, thus approximating a blackbody.

The IR detector used was an IN 510-N model from IMPAC Lumasense Technologies. Voltage was supplied to the device at 20 V. The parameters of the IR device were configured via an RS232 connection to a computer running the Infracore software, also provided by IMPAC. Furthermore, the measurements from the sensor were acquired and displayed using the same RS232 connection.

Heat was supplied to the target using a Stuart Heat-Stir SB162 heat source. Direct contact measurement of the target temperature was achieved using an RS 206-3722 K-type thermocouple. The sensor head of the IR device was held in place using clamps on a retort stand. The distance from the sensor head to the target was approximately 100 mm. At this distance, the characteristics are such that the temperature is obtained from a region of diameter 10 mm (the spot size) aligned with the blackbody hole. Measurements were recorded as the target was gradually heated to approximately 333 K.

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