A MODEL FOR TEMPERATURE MEASUREMENT ERRORS IN OFF-GAS CHANNELS

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ABSTRACT

There are uncertainties related to temperature measurements in off-gas channels. These uncertainties are not due to limitations in the precision of the measurement equipment alone, but related to heat transfer processes resulting in unequal temperatures of the gas and the temperature sensor.

A model that considers a cylindrical temperature measurement probe inserted in off-gas cross-flow has been established. For the energy balance of the temperature probe, convective heat transfer from the gas to the temperature probe, thermal radiation from CO_2 and H_2O in the gas, thermal radiation from particles in the gas and thermal radiation from the temperature probe to the walls of the off-gas channel are taken into account. Furthermore, an energy balance for the wall of the off-gas channel has been established. The wall model considers convective and radiative heat transfer from the off-gas to the inner wall, heat transfer by conduction through two wall layers of different thermal conductivity, and heat release at the outside of the channel by convection and thermal radiation.

The main result of the present work is a quantification of how the temperature measurement error in off-gas channels may vary with operating parameters such as the off-gas temperature, the soot/particle concentration in the off-gas, the channel wall thickness, the channel wall thermal conductivity, and geometric parameters such as the diameters of the measurement probe and the off-gas channel.

1 INTRODUCTION

There are uncertainties related to temperature measurements in off-gas channels. These uncertainties are not a result of limitations in the precision of the measurement equipment alone, but due to the interaction between the temperature sensor and the surrounding gas and sidewalls. In process monitoring, for instance, knowledge of the actual gas temperature is important, and the measured temperature may therefore need correction. If the environment surrounding the temperature sensor is isothermal, accurate temperature readings are possible. However, there are frequently ‘cold’ surfaces such as channel sidewalls that will interact with the temperature sensor through thermal radiation, lowering the sensor temperature. Alternatively, if there are hot surfaces or flames that can be viewed by the temperature sensor, a too high temperature may be measured.

The application considered in this study was temperature measurement in an off-gas channel where hot, particle-laden exhaust gas flows, and where the sidewalls are kept at a different temperature from the gas. It was assumed that the temperature probe was sufficiently long so that heat conduction in the temperature sensor could be neglected. This is acceptable for sensors inserted at a distance typically more than 10-15 sensor diameters into the gas stream [1].

The actual temperature of a measurement probe depends typically on

- Convective heat transfer from the gas to the temperature probe.
- Thermal radiation from CO_2 and H_2O in the gas.
- Thermal radiation from particles in the gas.

- Thermal radiation from the temperature probe to the wall of the off-gas channel.

The magnitude of the measurement error will depend on the relative magnitude of the above mechanisms. A calculation model, easily adaptable for spreadsheet implementation was developed and used to evaluate both the magnitude and the sensitivity of the different process conditions on the temperature reading.

2 MODEL FORMULATION

2.1 General

It was assumed that the measurement of the gas temperature takes place in a cylindrical off-gas channel of diameter D using a cylindrical temperature probe of diameter d. The measurement set up is illustrated in Figure 1.

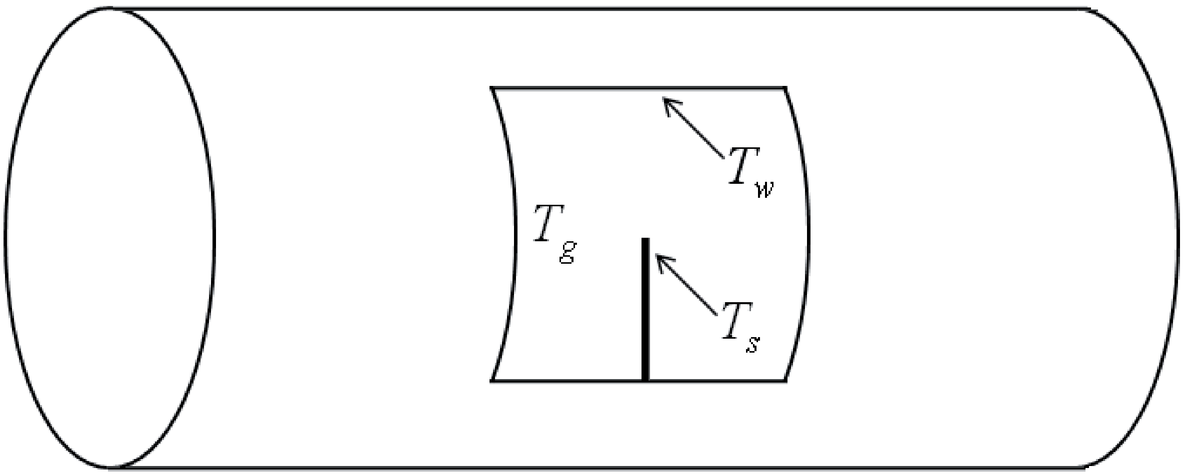

Figure 1: Schematic of temperature measurement in an off-gas channel.

The model consists of an energy balance for the temperature probe that considers heat transfer to the probe by convection from the off-gas, heat transfer to the probe by thermal radiation from gas and particles in the off-gas, and heat transfer from the probe to the channel walls by thermal radiation. Furthermore, an energy balance model for the channel wall was established. This model considers convective and radiative heat transfer with the gas/particle system, heat conduction through the wall and heat loss from the wall to the surroundings (or a coolant). The latter model was used to determine the channel wall inner temperature.

2.2 Energy balance model for the probe

The energy balance for the temperature probe includes heat transfer to the probe by convection from the gas, heat transfer to the probe by thermal radiation from gas and particles, and heat transfer by thermal radiation from the probe to the channel walls. The energy balance may be written as

$$\dot{q}_c + \dot{q}_{g,rad} + \dot{q}_{w,rad} = 0 \qquad (1)$$

where the different terms are described in the following sections.

2.2.1 Convective heat transfer to the probe, $\dot{q}_c$

The heat transfer between the gas and the probe transferred by convection is expressed as:

$$\dot{q}_c = h_c \cdot A_s \cdot \left(T_g - T_s\right) \qquad (2)$$

A_s is the surface area of the temperature sensor, T_g is the real gas temperature and T_s is the sensor temperature. The convective heat transfer coefficient, h_c, may be obtained from a suitable correlation for a cylinder in cross-flow, e.g. [2], valid for $\mathrm{Re}\cdot\mathrm{Pr} > 0.2$, where Re is the Reynolds number and Pr is the Prandtl number:

$$Nu = \frac{h_c \cdot d}{k_g} = 0.3 + \frac{0.62 \cdot \sqrt{\mathrm{Re}} \cdot \mathrm{Pr}^{1/3}}{\left[1+\left(\frac{0.4}{\mathrm{Pr}}\right)^{2/3}\right]^{1/4}} \cdot \left[1+\left(\frac{\mathrm{Re}}{282\cdot 10^3}\right)^{5/8}\right]^{4/5} \quad (3)$$

Here, d is the temperature sensor outer diameter, and is also the length scale in Re. k_g [W/m.K] is the gas thermal conductivity. All gas properties should be evaluated at the film temperature, $T_f = 0.5\left(T_g + T_s\right)$ where T_g and T_s are the gas and sensor temperatures, respectively.

2.2.2 Radiative heat transfer from the probe to the wall, $\dot{q}_{w,rad}$

The net radiative heat transfer between two diffuse, gray surfaces without absorption in the gas/particle cloud in an enclosed cavity is expressed as [3]

$$\dot{q}_{12} = \frac{\sigma \cdot \left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_1}{\varepsilon_1 \cdot A_1} + \frac{1}{F_{12}} + \frac{A_1}{A_2} \cdot \frac{1-\varepsilon_2}{\varepsilon_2 \cdot A_2}} \quad (4)$$

Here, σ [W/m.K^4] is the Stefan-Boltzmann constant, ε is radiation emissivity [-] and F [-] is the view factor of surface 2 as seen from surface 1. For a small surface 1 in a large cavity 2 it is apparent that $A_2 >> A_1$, hence $A_1/A_2 \approx 0$ and $F_{12} \approx 1$. Hence, Eq. (4) reduces to

$$\dot{q}_{w,rad} = \varepsilon_s \cdot A_s \cdot \sigma \cdot \left(T_w^4 - T_s^4\right) \quad (5)$$

where ε_s and A_s are the emissivity and surface area of the probe, and T_w and T_s are the inside wall and probe temperatures, respectively.

2.2.3 Radiative heat transfer from the gas and particles to the probe, $\dot{q}_{g,rad}$

The radiative heat transfer from gas and particles to the probe is expressed as [4]:

$$\dot{q}_{g,rad} = \varepsilon_{eff} \cdot \sigma \cdot A_s \cdot \left(T_g^4 - T_s^4\right) \quad (6)$$

where ε_{eff} is an effective emissivity for thermal radiation from gas and particle cloud being at equal temperatures T_g [K]. An empirical correlation for ε_{eff} is given by [5]:

$$\varepsilon_{eff} = 1 - \exp\left[-1.5 \cdot 10^{-3} \cdot C_s \cdot D \cdot T_g\right] \cdot \left(1 - \varepsilon_g\right) \quad (7)$$

where C_s is the soot concentration (in g/m^3). The soot concentration is reported to be typically 0.1 for gas fuels and 0.6 for liquid fuels. D [m] is the channel inside diameter and ε_g [-] is the gas emissivity.

In addition to soot radiation, the gas contains two radiating species of significance, namely H_2O and CO_2. These gases have partly overlapping emission and absorption bands, and need to be considered in combination. A formulation for the calculation of combined CO_2 and H_2O radiation, depending on their relative concentrations is given by [4]. The gas is assumed to behave as a mixture of grey gases and a transparent (non-emitting) medium. According to [4], the gas emissivity ε_g may be expressed as

$$\varepsilon_g = \sum_{i=1}^{n} a_i - \sum_{i=1}^{n} a_i \cdot \exp\left[-k_i \cdot p \cdot L_e\right] \quad (8)$$

where $p = p_{H2O} + p_{CO2}$ [atm] and the mean beam length L_e [m] is

$$L_e = 0.9 \cdot \frac{V}{A} = 0.9 \cdot D \quad (9)$$

and a_i is given by

$$a_i = \sum_{i=1}^{n} b_{j,i} \cdot T^{j-1} \quad (10)$$

Numerical values for k_i and $b_{j,i}$ are given in [4] for different concentrations of CO_2 and H_2O.

2.3 Energy balance model for the gas duct

In calculating the radiative heat transfer between the probe and the gas duct wall, an estimate of the wall inside temperature is required. If known, the wall temperature may be used directly; however, the wall temperature normally would have to be calculated on the basis of material properties and the conditions of surroundings. In the present paragraph, a model for the estimation of the inner wall temperature based on known wall properties and known gas and surrounding properties is given. The model accounts for

- Heat transfer by convection from the gas to the inner wall of the off-gas channel.
- Heat transfer by thermal radiation from gas and particles to the inner wall of the off-gas channel.
- Heat transfer by conduction through two separate layers in the wall. The user may choose to use a single layer by setting the thickness of one of the layers to zero. The default wall properties for the layers in the spreadsheet are those of steel and concrete.
- Heat transfer by convection from the outside of the wall to the surroundings.
- Heat transfer by thermal radiation from the outside of the wall to the surroundings.

For convenience, the included terms are expressed in heat per unit channel length, $\dot{q}'$ [W/m].

The energy balance for the duct is expressed as:

$$\dot{q}'_{c,i} + q'_{r,i} + q'_{loss} = 0 \quad (11)$$

2.3.1 Convective heat transfer from the gas to the wall, $\dot{q}'_{c,i}$

The convective heat transfer between the off-gas and the channel duct wall may be expressed as

$$\dot{q}'_{c,i} = h_{c,i} \cdot \frac{A_{w,i}}{L} \cdot \left(T_g - T_{w,i}\right) \quad (12)$$

where $A_{w,i}/L$ is the channel inside surface area per unit length. The convective heat transfer coefficient is determined from a suitable correlation. For large channel diameters the Reynolds number tends to be high, hence care should be taken in choosing a valid correlation. For turbulent flows Gnielinski proposed a correlation valid for $3 \cdot 10^3 < Re < 5 \cdot 10^6$ and $0.5 < Pr < 2000$, extended by [6] for heat transfer enhancement caused by rough surfaces:

$$Nu = \frac{h_{c,i} \cdot D}{k_g} = \frac{\left(\mathrm{Re} - 10^3\right) \cdot \mathrm{Pr} \cdot {c_{f,s}}/{2}}{1 + 12.7 \cdot \left(\mathrm{Pr}^{2/3} - 1\right) \cdot \sqrt{{c_{f,s}}/{2}}} \cdot \left(\frac{c_f}{c_{f,s}}\right)^{0.68 \cdot Pr^{0.215}} \tag{13}$$

where [6]

$$c_{f,s}/2 = \left[2.236 \cdot \ln\left(\mathrm{Re}\right) - 4.639\right]^{-2} \tag{14}$$

and [7]

$$\frac{1}{\sqrt{c_f}} = -3.6 \cdot \lg\left[\frac{6.9}{\mathrm{Re}} + \left(\frac{\delta/D}{3.7}\right)^{1.11}\right] \tag{15}$$

Here, δ is the surface roughness (in m).

2.3.2 Radiative heat transfer from the gas and particles to the wall, $\dot{q}'_{r,i}$

This is similar to the radiation between the gas and the probe, and expressed as

$$\dot{q}'_{r,i} = \varepsilon_{eff} \cdot \sigma \cdot \frac{A_{w,i}}{L} \cdot \left(T_g^4 - T_{w,i}^4\right) \tag{16}$$

where ε_{eff} is calculated from Eq. (6).

2.3.3 Heat transfer by conduction through the wall, $\dot{q}'_w$

Heat is transferred by conduction through two separate layers in the wall (wall and insulation). The inner diameter of the off-gas channel is D, the diameter at the layer interface is D_m and the outer diameter of the off-gas channel is D_o. The thermal resistance of the wall may be then expressed as [3]:

$$R_w = \frac{\ln\left(D_m/D_i\right)}{2 \cdot \pi \cdot L \cdot k_A} + \frac{\ln\left(D_o/D_m\right)}{2 \cdot \pi \cdot L \cdot k_B} \tag{17}$$

where L is the channel length and A and B denotes the two layers. D_m [m] is the outside diameter of layer A and D_o is the outside diameter of layer B. k [W/m.K] is the thermal conductivity of the layer materials. The heat transfer through the wall per unit length is expressed as

$$\dot{q}'_w = \frac{T_{w,i} - T_{w,o}}{R_w \cdot L} = \frac{T_{w,i} - T_{w,o}}{\frac{\ln\left(D_m/D_i\right)}{2 \cdot \pi \cdot k_A} + \frac{\ln\left(D_o/D_m\right)}{2 \cdot \pi \cdot k_B}} \tag{18}$$

2.3.4 Heat transfer at the outside surface of the channel, $\dot{q}'_{loss}$

The heat transferred to the surroundings (or external cooling medium) from the external surface of the gas channel consists of a convective contribution, and a radiative contribution in the case of heat loss to the surroundings:

$$\dot{q}'_{loss} = \left[h_{c,o} \cdot \left(T_{\infty} - T_{w,o} \right) + \varepsilon_{w,o} \cdot \sigma \cdot \left(T_{\infty}^4 - T_{w,o}^4 \right) \right] \cdot \frac{A_{w,o}}{L} \qquad (19)$$

2.4 Solution procedure

i. Gas channel inside temperature

The inner wall temperature is determined from the energy balance, Eq. (11). However, the different terms are nonlinear functions of the unknown inner wall temperature ($T_{w,i}$) and external wall temperature ($T_{w,o}$). These two temperatures are linked via Eq. (18). An iterative procedure is necessary, in which $\dot{q}'_w = \dot{q}'_{c,i} + \dot{q}'_{r,i}$ is calculated by guessing $T_{w,i}$, and $T_{w,o}$ is then obtained from Eq. (18). Then, from Eq. (19) $\dot{q}'_{loss}$ can be calculated. A converged solution is obtained when $T_{w,i}$ is chosen such that $\dot{q}'_w = -\dot{q}'_{loss}$.

ii. The temperature sensor temperature

The solution procedure is straightforward, in the sense that the energy balance for the sensor, Eq. (1) must be satisfied. This is most effectively performed by iterating on the unknown sensor temperature T_s until Eq. (1) is satisfied.

3 RESULTS AND DISCUSSION

In the following the error reading of a cylindrical temperature probe inserted into a hot gas stream with cold side walls is investigated by using the above model. A typical exhaust gas from a ferrosilicon plant is used, with gas composition as shown in Table 1.

Table 1: Composition for ferrosilicon furnace flue gas.

Species	Volume fraction	Partial pressure
H_2O	0.06	0.06 atm
CO_2	0.06	0.06 atm
O_2	0.15	0.15 atm
N_2	0.73	0.73 atm

The physical properties of the gas were determined from an in-house database, and are shown in Figure 2.

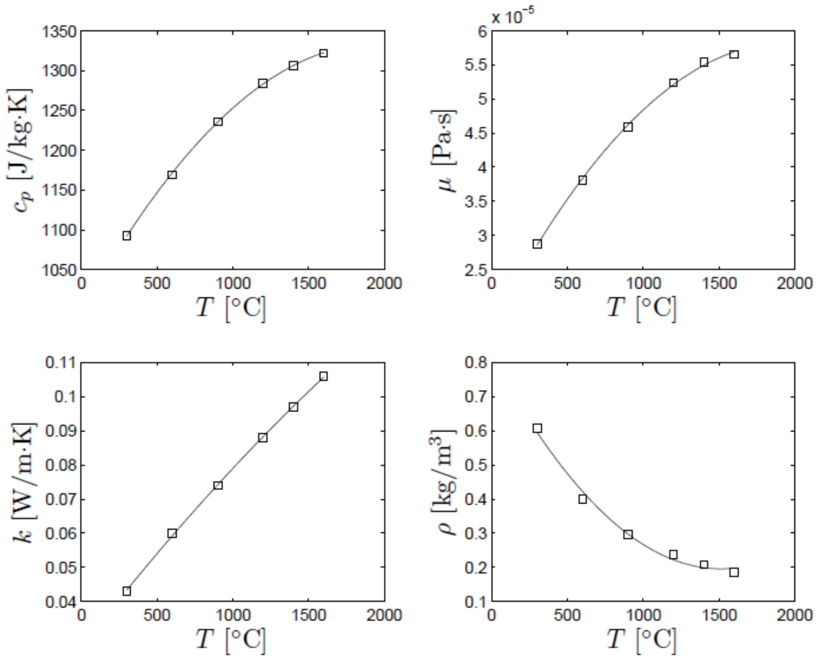

Figure 2: Physical properties for ferrosilicon furnace flue gas.

Figure 3 shows the temperature error reading for a case with pure gas (no particles) flowing at 10 m/s in a 2 m inside diameter channel and where the gas channel wall is maintained at 300ºC. Figure 3 shows the influence in the temperature error caused by different emissivities of the temperature probe. At emissivity of 0, there is no thermal radiation from the probe to the cold walls, hence the error is zero. Increasing the emissivity increases the heat loss from the probe, thereby increasing the error reading. The temperature error increases as the gas temperature increases. This is due to the increased temperature difference between the probe and the wall, where heat is lost by thermal radiation.

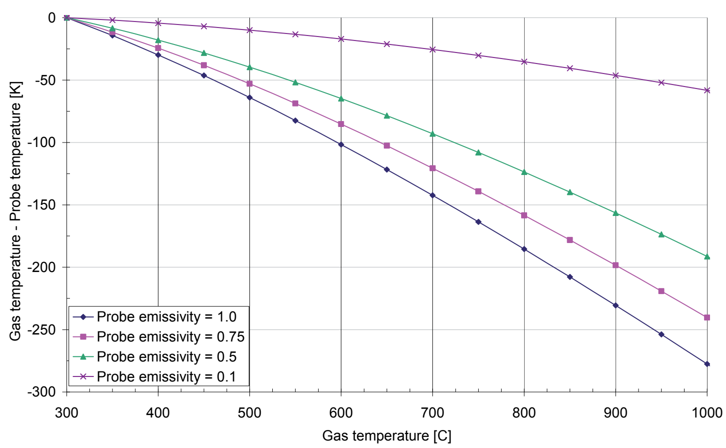

Figure 3: Influence of probe emissivity on temperature reading error.

Figure 4 illustrates the influence of gas radiation on the probe error reading. For a situation with no gas radiation (no CO_2 or H_2O) in the gas the net heat transfer to the probe is less than for the case with radiation. As a consequence, the probe temperature is lower, yielding a higher temperature reading error. A similar behaviour is observed when decreasing the gas velocity, which decreases the heat transfer coefficient between the gas and the probe and thereby reducing the probe temperature.

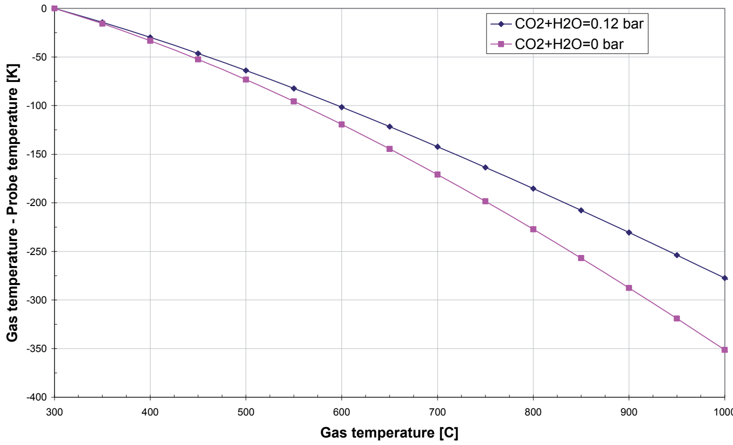

Figure 4: Influence of gas radiation on temperature reading error.

Figure 5 shows the influence of soot concentration on the temperature error reading. As expected, soot will have a positive effect since it effectively increases heat transfer to the probe due to thermal radiation. A soot concentration of 0.1 is representative for a relatively clean flue gas (e.g. from combustion of natural gas), and a concentration of 0.6 is representative of luminous oil flames [5].

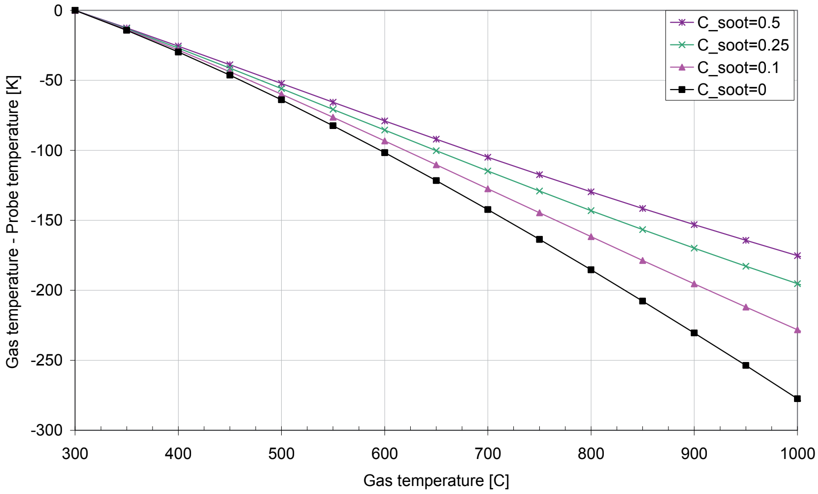

Figure 5: Influence of soot concentration on temperature reading error.

Figure 6 shows the behaviour of a system where the channel wall temperature is insulated with a 12 cm brick layer (with thermal conductivity of 1 W/mK) and exposed to the surroundings at 30ºC. On the external wall there are convection losses (heat transfer coefficient of 5W/m^{2}K) and thermal radiation losses (emissivity of 0.9). On the inside there is convective heat transfer between the gas and the wall (radiation is neglected in this calculation). With this, the wall temperature is allowed to vary according to the energy balance shown in section 2.3. The brick insulation will ensure that the inner steel wall has a temperature much closer to the gas temperature, hence reducing the heat loss from the temperature to the wall by themal radiation. As shown, the error reading is significantly reduced for all cases with elevated temperature, and that an increased soot concentration in the gas further reduces the error reading. A similar trend is observed when increasing the gas velocity, increasing the heat transfer to the probe and wall and thereby reducing the temperature differences.

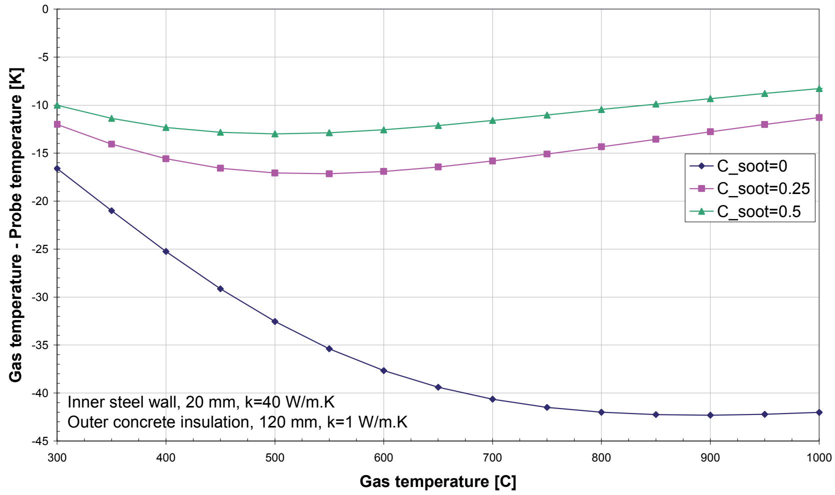

Figure 6: Physical properties for ferrosilicon furnace flue gas.

4 CONCLUSIONS

A model for the error in temperature readings of cylindrical temperature sensors placed inside a gas channel with different gas and channel wall temperatures is developed. The model is essentially an energy balance model, including the effects of thermal radiation from the temperature probe, gas convection, gas thermal radiation, and the influence of thermal radiation from particles suspended in the gas. A separate model was developed to describe the channel wall temperature as a function of internal convection heat transfer and external convection and radiation heat losses. Calculations show that the error in temperature measurement increases with the temperature difference between the gas and the wall, and that thermal radiation from the gas and particles tends to reduce the error. Insulating the channel wall reduces the temperature difference between the gas and wall, thereby reducing the heat loss from the temperature sensor and reducing the temperature error.

5 REFERENCES

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