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A radiation and convection fluxmeter for high temperature applications

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Abstract

Heat flux is an essential parameter for the diagnostic of thermal systems. In high temperature industrial environment, there are difficulties in measuring incident radiation heat flux as well as in differentiating between the convective and radiative components of heat flux on the heat transfer surface. A new method for heat flux measurement is being developed using a porous sensing element. The gas stream flowing through the porous element is used to measure the heat received by the sensor surface exposed to the hot gas environment. A numerical model of sensor with appropriate boundary condition has been developed in order to perform analysis of possible options regarding its design. The analysis includes: geometry of element, physical parameters of gas and solid and gas flow rate through the porous element. For the optimal selection of parameters, an experimental set-up was designed, including the sensor element with respective cooling and monitoring systems and a high temperature radiation source. The experimental set-up was used to obtain calibration curves for a number of sensors. The linear dependency of the heat flux and respective temperature difference of the gas were verified. The accuracy analysis of the sensor reading has proved high linearity of the calibration curve and accuracy of ±5%.

1. Introduction

The energy sustainable development [5] and [7] has imposed a new research for thermal systems to improve their efficiency and reliability. In this respect, attention is focused on the development of new design tools including sophisticated numerical codes for the evaluation of potential options during design. However, even when precaution has been taken in the design of thermal systems their operation is subjected to unpredicted changes leading to the possibility of failures. For this reason, it is of paramount interest to develop adequate monitoring systems dedicated to the on-line assessment of the state of the system.

Recent developments of knowledge-based systems [6,13,21] have opened a challenging option for the development of knowledge-based diagnostic tools for on-line assessment of the state of the system [1,4]. In particular, it was proved that its use in the thermal power system might be very beneficial, resulting in the increase of its efficiency and reliability.

The heat generating within the system and its transfer to the working fluid measure the thermal rating in the thermal system. The heat flux on the heat transfer surface is a parameter used to define the boundary condition of the system during design and operation. For this reason, evaluation of the property of heat flux as design and operation parameters is necessary in order to assess its sensitivity to the different causes leading to the later malfunction of system.

The thermal radiation flux in high temperature gas flow is an important parameter for the assessment of a number of technical systems, including boiler, furnaces, combustion chambers, high temperature regenerators [3,9–11]. Attempts have been made to develop methods for the measurement of the resulting hemispherical radiation heat flux in the environment with substantial convective heat transfer contribution [12]. It was shown that the restriction imposed on the respective methods have limited their application to low temperature and

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Nomenclature

TG	transpiration gas
c_p	specific heat of gas
d	diameter of the instrument
j, m	Specific mass flow rate through the porous disc
q	heat flux at the porous surface disc
Re	Reynolds number
T	temperature
u	gas velocity

Subscripts

g	gas
w	wall
cr	critical
s	surface
total	total
rad	radiation
con	convection
g,1	gas temperature measurement with mass flow rate m_1
g,2	gas temperature measurement with mass flow rate m_2

clean environments. In particular, it was noticed that in the hostile environment existing in most of high temperature equipment's fouling is becoming an additional restriction to the application of the proposed methods. In order to bridge these deficiencies of the available methods for thermal radiation measurement a new method is proposed [2]. The principle of the method may open interesting possibilities for its application in the measurement of relevant parameters in different equipments characterised by a high temperature, harsh environment.

2. Basic working principle

Instrument is made of the porous disc (1) and tube (2), see Fig. 1.

The new sensor is based on the determination of temperature difference of a gas stream flowing through a porous disc exposed to the heat flux to be measured, [2,8,17,18], see Fig. 1. Under stationary conditions, the gas flowing through the porous disc will receive by convection the heat transferred to the disc surface exposed to the high temperature environment. It is known, [14–16] that at a specific gas mass flow rate through the porous disc, the boundary layer of hot gas flowing over porous wall is blown-off. Under this condition the convective heat transfer to the surface becomes practically equal to zero. In the case of an external flow over a porous surface with a laminar boundary layer developing over it, the critical value of the blow-off parameter is

$$\frac{j_{w,cr}\sqrt{Re_g}}{\rho_g w_g} = C. \quad (1)$$

From this it follows:

$$j_{w,cr} = C\frac{\rho_g w_g}{\sqrt{Re_g}}, \quad (2)$$

where C is a constant depending on the geometry of the porous disc surface and direction of the external flow. For a parallel flow to a horizontal infinite surface, $C = 0.62$. Similar relations are available for turbulent boundary layer, see [16].

The heat transfer from the hot gas to the porous disc surface is defined by total heat flux given by

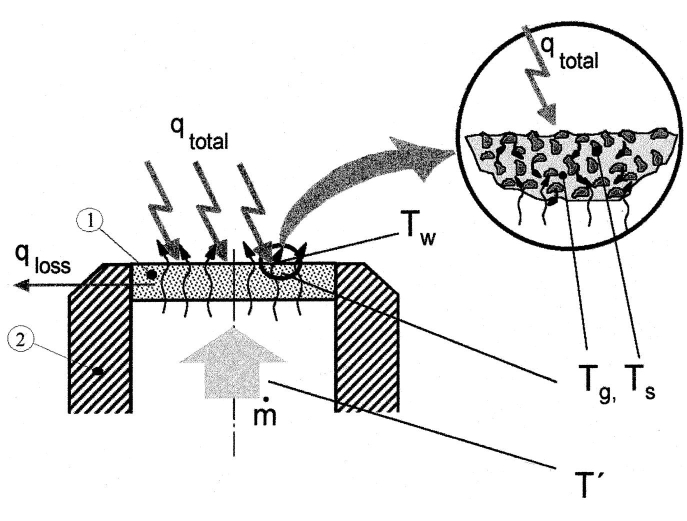

Fig. 1. Working principle of the proposed instrument.

$$q_{tot} = q_R + q_{con}. \quad (3)$$

By the change of gas mass flow rate through the porous disc, two situations are possible, namely:

1. When the critical flow through the porous disc is attained, the boundary layer at the porous surface will be blown-off, so that convective heat flux will become negligible and

$$q_{tot} = q_R. \quad (4)$$

If the emitted radiation is taken into account, the heat flux from the porous media material is

$$\alpha q_R - \varepsilon\sigma T_w^4 = j_{w,cr} c_p (T_w - T'). \quad (5)$$

Under assumption that the radiation emitted by the porous surface is small in comparison with incident radiation then

$$\alpha q_R = j_{w,cr} c_p (T_w - T'). \quad (6)$$

2. When the critical mass flow rate through the porous disc is lower than the critical mass flow rate, then

$$\alpha q_R + \chi q_{con} = j_w c_p (T_w - T'). \quad (7)$$

If the measurement of radiation heat flux is performed for the same conditions before the measurement with sub-critical gas mass flow rate in the disc, it may be written as

$$q_{con} = q_{tot} - q_R. \quad (8)$$

This will give the possibility to determine the convective heat flux of the hot gas flowing above the porous disc surface. It should be stressed here that the determination of the convection heat flux component does not require a null BOG mass flow rate. Actually, a sub-critical BOG mass flow rate (different form zero) is enough since the response of the heat transfer coefficient as a function of the BOG mass flow rate is known. This is an important remark because the blow-off gas plays different roles on the instrument operation and not only by the blowing-off of the boundary layer.

Consequently, the total heat flux (convection and radiation) of the sensing element can be determined by using a sub-critical gas mass flow rate. Considering that the radiative component can be determined using a critical or over-critical gas mass flow rate, two consecutive measurements at different mass flow rates are enough to determine the convective and radiative components of the total heat flux since $q_{tot} = q_{rad} + q_{conv}$. This is a new concept in heat flux measurement.

The determination of the heat flux can be made based on different mathematical formulations. Each one has specific advantages, related with specific applications. By now three different formulations have been developed:

1. Energy balance mode.
2. Modified energy balance mode.
3. Transient mode.

The energy balance mode is the simpler and more intuitive formulation. It is considered as the basic formulation. The modified energy balance mode, is similar to the previous mode, but there is no need to measure the blow-off gas inlet temperature. This formulation is particularly suitable when low blow of gas mass flow rates is required. Under these conditions the assumption of $T_s = T_g$ may be false at the porous disc entrance. The transient formulation is completely different from the previous formulations and it may be advantageous when short response times are required, since the heat flux to be measured can be determined before the gage reaches the stationary regime. The three formulations are discussed in detail in the next paragraphs.

2.1. Energy balance mode

The energy balance mode of measurement is based on the determination of a gas temperature difference in the porous disc and gas mass flow rate. Considering the system as defined in Fig. 1, under steady-state conditions, $q_{loss} = 0$ and with an over-critical Transpiration Gas (TG) mass flow rate being used, the energy balance equation after standard simplifications is

$$q_{rad} = \frac{\dot{m}}{\alpha \cdot A_F} \cdot c_p \cdot (T_{g,o} - T_{g,i}). \quad (9)$$

The measurement of the temperature difference between the two surfaces of porous disc together with the TG mass flow rate is enough to determine the total hemispherical radiation flux if α is known.

This method does not require calibration if the total hemispherical absorptivity of the porous disc surface is known. However, a correct choice of the porous sensing element characteristics and operating conditions is required in order to make realistic assumptions.

2.2. Modified energy balance mode

When high radiation heat fluxes have to be measured, the above analysis may not be valid. Actually, under high flux environments, to keep the back surface temperature independent of the incident heat flux it may require either unrealistic porous disc thickness or unrealistic TG mass flow rate. To overcome this difficulty, a modified energy balance mode of measurement may be considered.

The modified energy balance formulation is based on the measurement of two gas mass flow rates and respective outlet temperatures, assuming as valid, all the above-discussed assumptions except the independence of temperature of the porous disc backside to the incident radiation. Under the same heat flux the measurement is performed with two different flow rates. The energy balance for these two cases may be written for a fixed heat flux, q_{rad} as:

$$q_{rad} = \frac{\dot{m}_1}{\alpha \cdot A_F} \cdot c_p \cdot (T_{g,o,1,} - T_{g,i}), \quad (10)$$

$$q_{rad} = \frac{\dot{m}_2}{\alpha \cdot A_F} \cdot c_p \cdot (T_{g,o,2} - T_{g,i}), \quad (11)$$

where $T_{g,i}$ is the TG temperature somewhere upstream to the porous disc as shown in Fig. 1.

Making T_g, explicit in Eq. (10) and substituting in Eq. (11) it is obtained as

$$q_{rad} = \frac{\dot{m}_2}{\dot{m}_2 - \dot{m}_1} \cdot \frac{\dot{m}_1}{\alpha \cdot A_F} \cdot c_p \cdot (T_{g,o,1} - T_{g,o,2}). \tag{12}$$

From the above equation it may be concluded that the incident radiation flux can be determined, without knowing the inlet TG temperature, by making two consecutive readings at different TG mass flow rates and the corresponding gas outlet temperatures.

This operation mode has the advantage to make possible the radiation flux measurement without the knowledge of TG inlet temperature. However, two steady-state measurements of the temperature on porous disc surface, at two different TG mass flow rates are required. This is not compatible with the need for short response time or time-dependent radiation flux measurements, unless and instrument composed of two sensing elements with the possibility of working with different TG mass flow rates is considered. However, for the measurement of high radiation fluxes under steady conditions, it may be used with advantages when compared with the first approach presented.

2.3. Transient mode

The above-described methods require that a steady condition be achieved for the instrument outputs, in particular for temperature at the outlet surface of porous disc. This requirement may not be acceptable if a short response time is necessary. An alternative method to determine the radiation flux, without the need to establish a time independent output will be discussed in this paragraph. This method has the advantage to shorten the response time of the instrument, what may be a valuable characteristic under certain applications.

Taking as valid the assumptions discussed in the steady-state mode operation, the energy balance equation under unsteady conditions may be written as follows:

$$\alpha \cdot Q_R = \rho_D \cdot c_{p_D} \cdot \frac{d\overline{T}_D}{dt} \cdot V + j_G \cdot c_{p_G} \cdot (T_{G,o} - T_{G,i}) \cdot A_F, \tag{13}$$

where

$$\overline{T}_D = \frac{1}{V} \int_V T_D \, dV = C_1 \cdot T_{D,o} = C_1 \cdot T_{G,o}. \tag{14}$$

making the following variable substitution $\theta = T_{G,o} - T_{G,i}$ and considering that the difference between the TG and the solid matrix is negligible and the TG inlet temperature is constant, Eq. (5) can be written as follows:

$$\frac{d\theta}{dt} + \xi \cdot \theta = \beta \tag{15}$$

with

$$\xi = \frac{j \cdot c_{p_G}}{C_1 \cdot \rho_D \cdot c_{p_D} \cdot L}, \quad \beta = \frac{\alpha \cdot q_R}{C_1 \cdot \rho_D \cdot c_{p_D} \cdot L}. \tag{16}$$

The solution of Eq. (7) with $t = 0 \Rightarrow \theta = 0$, i.e., $T_{D,o} = T_{D,i} = T_{G,i}$ as initial condition is

$$\theta = e^{-\xi \cdot t} \cdot \left(\frac{\beta}{\xi} \cdot e^{\xi \cdot t} + C_2 \right) \tag{17}$$

with

$$C_2 = -\frac{\beta}{\xi}. \tag{18}$$

Substituting (10) in (9) and recovering the original variables, the following solution is found

$$\theta = \frac{\alpha \cdot q_R}{j \cdot c_{p_G}} \cdot (1 - e^{-\xi \cdot t}). \tag{19}$$

As expected, if $t \to \infty$, i.e., under steady-state conditions, Eq. (19) is equivalent to Eq. (8). However, the interesting result here is that if θ is plotted as a function of the parameter $(1 - e^{-\xi \cdot t})$ a straight line is obtained and its slope is proportional to the incident to the incident radiation flux. It should be noticed that $(1 - e^{-\xi \cdot t})$ is a measure of the elapsed time, weight by a factor ξ, that is only a function of the instrument design parameters.

It may be concluded that it is not necessary to wait for a steady-state response of the instrument output to determine the incident radiation flux. Actually, it may be obtained during the transient response of the instrument considering the results of the above-discussed analysis.

2.4. Time response

The time-dependent analysis made in the previous paragraph is useful to discuss the time response of the instrument.

Eq. (19) is the central expression to the instrument transient analysis. Actually, the instrument time constant, τ is given by

$$\tau = \frac{1}{\xi} = C_1 \cdot \frac{\rho_D \cdot c_{p_D} \cdot L}{j \cdot c_{p_G}} \tag{20}$$

and it only depends on design and operation parameters. The constant C_1 was introduced in Eq. (6) to associate the volume-averaged temperature of the porous disc and its temperature on the outlet surface. It will be shown in the next chapter that it also is only a function of design and operation parameters, i.e, $C_1 = f(k, p, j, L, c_{p_D})$.

From Eq. (20) it may be concluded that for a given instrument, i.e., for fixed design parameters, the response time can be adjusted by tuning the TG mass flow rate or by using TGs with different specific heats.

2.5. Evaluation of critical mass rate

Independently of the operation mode, i.e., of the way the incident flux is determined, it is clear that the gas stream is an essential feature of the method since it has the purpose:
- To cut the convection component of the total hemispherical heat flux.
- To avoid the possibility of fouling on the sensible surface.
- To cool the instrument's sensible surface.
- To adjust the instrument range to the heat flux level to be measured.
- To control the radial heat losses, thus the instrument's accuracy.
- To adjust the instrument time constant.

The critical blow-off gas (TG) mass flow rate required to promote the destruction of the boundary layer over the porous disc is a basic parameter to be defined for the proposed heat flux sensor. In the definition of the critical TG mass flow rate, it is necessary to consider the laminar or turbulent nature of the mainstream flow, its velocity and temperature, the density ratio between the TG and the main stream gas and the local geometry.

For the small diameter of the gauge head (10 mm) it is not possible to prove that the local boundary layer on the porous disc surface is always laminar. Actually, the three-dimensional nature of the local boundary layer, the possibility of separation and the high turbulence intensity of the main stream, are good reasons to consider the possibility of a transition to a turbulent boundary layer at relatively low Reynolds number. For that reason, critical TG mass fluxes have to be determined under different flow conditions in order to estimate a limiting critical TG flux.

For the *laminar* boundary layer blow-off, [14] proposed the following relation, valid for $Pr = 0.7$ and 1.0:

$$\frac{Nu}{\sqrt{Re_x}} = 0 \quad \text{if} \quad \frac{u_w}{u_0}\sqrt{Re_x} = C \tag{21}$$

with C is equal to 0.62 and 2.35, respectively, for laminar flow over a flat plate and for laminar stagnation plane flow. These equations can be re-written in a more useful form as follows:

$$j_{w,cr} = C \cdot \rho_o \cdot u_o \cdot Re_x^{-1/2}, \tag{22}$$

where C is the above-referred constant.

In the definition of the critical TG mass flux for a *turbulent* boundary layer the blowing parameter b, correlating the TG stream and the main stream, was introduced, [15,16]:

$$b = \frac{j_w}{\rho_o \cdot u_0} \cdot \frac{2}{C_f}. \tag{23}$$

Thus, the critical TG mass flux $j_{w,cr}$ is given by

$$j_{w,cr} = b_{cr} \cdot \rho_o \cdot u_o \cdot \frac{C_f}{2}. \tag{24}$$

To determine the critical blowing parameter, the following equations were derived for the limiting condition of $Re^{**} = \infty$:

$$b_{cr,o} = \frac{1}{1-\psi} \cdot \left[\ln \frac{1 + (1-\psi)^{1/2}}{1 - (1-\psi)^{1/2}}\right]^2 \quad \text{for } \psi < 1, \tag{25}$$

$$b_{cr,o} = \frac{1}{\psi - 1} \cdot \left(\arccos \frac{2-\psi}{\psi}\right)^2 \quad \text{for } \psi > 1, \tag{26}$$

where ψ is given by

$$\psi = \frac{\rho_o}{\rho_w} = \frac{M_o}{M_w} \cdot \frac{T_w}{T_o}. \tag{27}$$

To obtain b_{cr}, a correction has to be made for finite values of Re^{**}. The proposed correction is

$$\frac{b_{cr}}{b_{cr,o}} = 1 + 0.83 \cdot (Re^{**})^{-0.14}, \tag{28}$$

which can be written as a function of Re_x if a velocity profile is assumed. For $u/u_\infty = (y/\delta)^{1/7}$, valid in the range $5 \times 10^5 < Re_x < 10^7$, Eq. (27) can be re-written as

$$\frac{b_{cr}}{b_{cr,o}} = 1 + 1.32 \cdot (Re_x)^{-0.112}. \tag{29}$$

Assuming the following friction law:

$$C_f = 0.0576 \cdot (Re_x)^{-1/5} \quad \text{for } 5 \times 10^5 < Re_x < 10^7 \tag{30}$$

and considering that for the present application, $\psi \leqslant 1$, since the TG is always at a lower temperature than the main stream gas, Eqs. (25), (29) and (30) can be substituted in Eq. (24) leading to

$$j_{w,cr} = 0.0288 \cdot \frac{1}{1-\psi} \cdot \left[\ln \frac{1 + (1-\psi)^{1/2}}{1 - (1-\psi)^{1/2}}\right]^2 \cdot \left(1 + 1.32 \cdot Re_x^{-0.112}\right) \cdot \rho_o \cdot u_o \cdot Re_x^{-1/5} \tag{31}$$

valid for $5 \times 10^5 < Re_x < 10^7$. The insensitivity of the friction and heat transfer laws to changes in the main stream velocity makes Eq. (31) valid both for flat plate and stagnation flow.

Eqs. (22) and (31) relate the critical TG mass flux through the porous wall with the conditions at the vicinity of its surface, respectively, for a laminar and a turbulent boundary layer. Fig. 2 shows the critical TG mass flux as a function of Re_x and ψ.

As it is not possible to predict the Re_x when transition occurs, the relations for the turbulent boundary layer were plotted for an extended Reynolds range.

Other parameters have to be considered for the definition of the TG mass flux, e.g., the temperature control of porous sensing element. However, the above equations are required to define the minimum (critical) TG

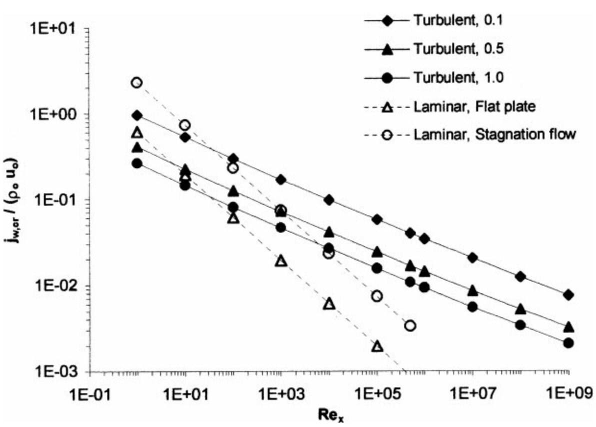

Fig. 2. Critical TG mass flux as a function of Re_x and ψ.

mass flux to cut-off the convective heat flux to the sensing element. An important aspect resulting from the transpiration cooling theory is the possibility to extend the proposed heat fluxmeter concept in order to measure convection fluxes in high temperature environments. The above analysis explored the possibility of destroying the boundary layers with the purpose of eliminating the possibility of convection fluxes. However, if a sub-critical TG mass flow rate is applied the boundary layer will not be destroyed and a fraction of the *original convection flux* will be transferred to the sensing element. The *original convection flux* is that one the sensing element would receive in the absence of any TG flow.

The existing theories for the transpiration cooling mechanism are able to provide the relationship between the acutal convection heat flux and the original convection flux as a function of the blowing parameter. Consequently the total heat flux (convection and radiation) of the sensing element can be determined by using a sub-critical TG mass flow rate. Considering that the radiative component can be determined using a critical or over-critical TG mass flow rate, two consecutive measurements at different TG mass flow rates are enough to determine the convective and radiative components of the total heat flux since $q_{tot} = q_{rad} + q_{conv}$. This is an important aspect of the new concept for heat flux measurement.

3. Mathematical model

A detailed mathematical model of heat and mass transfers in a porous media crossed by airflow was developed. The model is based on the solution of differential conservation equations for energy in each phase in addition to the momentum and continuity equations in the gas-phase. The equations are considered in their two-dimensional, steady-state form and are solved in cylindrical co-ordinates by a finite difference technique [17]. A detailed analysis with the differential balance model is performed with selected parameters as shown in Table 1.

Table 1
Considered parameters for numerical evaluation

Parameter	Values	Units
TG mass flow rate, j	2 and 8	kg m^{-2} s^{-1}
Disc diameter, D_f	10, 30, 40	mm
Disc thickness, L_f	5, 15, 20	mm
Heat Flux, Q	50, 100, 200	kW m^{-2}
Material	Stainless steel	–
Porosity, π	0.3 and 0.5	–
Size of the pores, D_p	50 and 100	μm

Table 2
Selected parameters after numerical evaluation

D_f (mm)	L_f (mm)	D_p μm	π
10	2	100	0.5

Fig. 3. Instrument prototype.

The mathematical model allowed the simulation of different sensor designs and working conditions. Taking into consideration a set of selection criteria [17] and the respective sensitivity analysis [19,20] the instrument performance was evaluated. The following design parameters for the radiation heat fluxmeter were defined as shown in Table 2 and a prototype was built, see Fig. 3.

4. Experimental verification

In order to simplify experimental set-up the verification of the sensor was performed only for the over-critical gas flow operation. Also, the radiation heat transfer calibration requires a specially designed environment in order to obtain respective accuracy.

The experimental set-up, Fig. 4, consists of a black body furnace acting as radiation source, a heat fluxme-

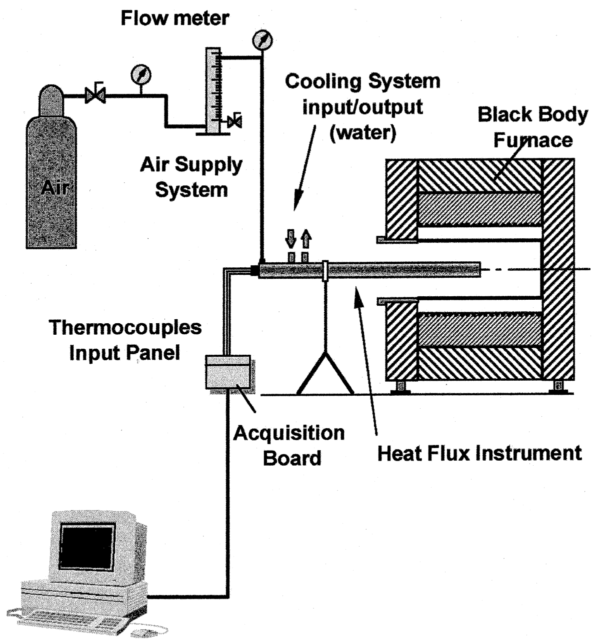

Fig. 4. Experimental set-up.

ter prototype with the respective cooling system, an air supply system and a data acquisition system.

A description of the experimental set-up components can be found in [19,20].

4.1. Experimental procedure

The radiation heat source was heated up to the first set point and staged at that temperature until a stable temperature level was attained. The blow-off air mass flow rate was set to the appropriate level. The heat fluxmeter was then introduced into the radiating cavity at a depth such that the heat flux stabilises at the highest level in order to avoid edge effects from the furnace cavity.

The temperature evolution was continuously monitored via the acquisition system and when transient effects were not present, the temperature readings from the thermocouple were taken. For each temperature level in the furnace, different TG mass flow rates were considered and the corresponding temperatures of the thermocouples read. The considered range for the calibration furnace temperature and for the respective TG mass flow rates are summarised in Table 3.

Table 3
Experimental ranges considered for calibration

Set-point (°C)	Heat flux ($kW\ m^{-2}$)	TG mass flow rate (slpm)
650–1000	41.2–149.0	1.2–16.0

5. Results and discussion

5.1. Calibration curve and accuracy

For the tested design, the incident hemispherical radiation flux can be determined by Eq. (10). The heat flux can be directly calculated by measuring the temperature difference and the corresponding TG mass flow rate

$$q = \vartheta \cdot \dot{m} \cdot (T_{\text{out}} - T_{\text{in}}) \tag{32}$$

with

$$\vartheta = 682.76 \left[\frac{W}{\text{slpm} \cdot m^2 \cdot {}^\circ\text{C}} \right].$$

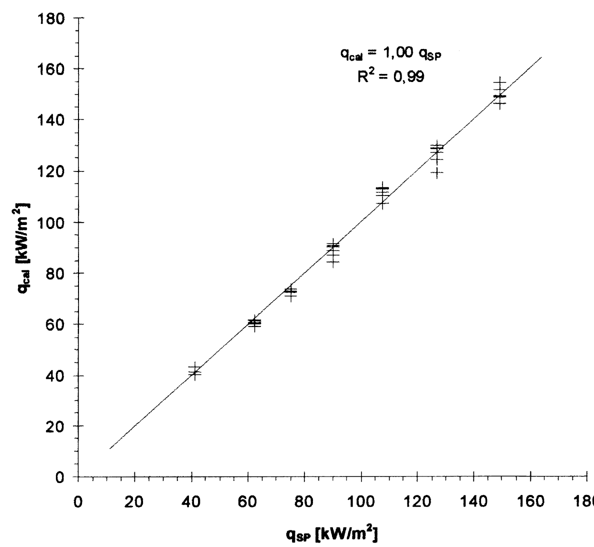

Fig. 5. Measured radiation heat flux vs. set-point flux.

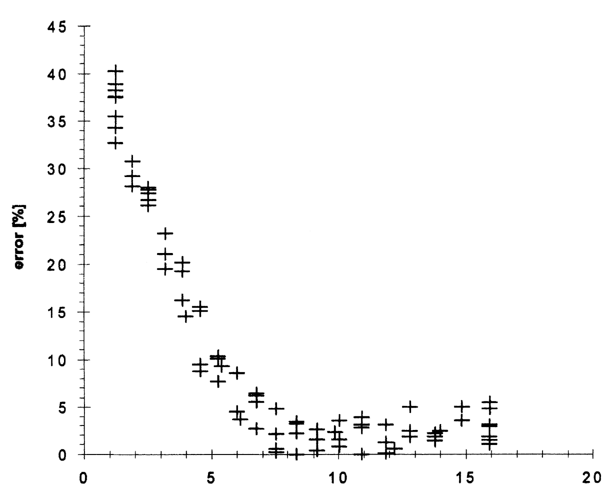

Fig. 6. TG mass flow rate and instrument accuracy.

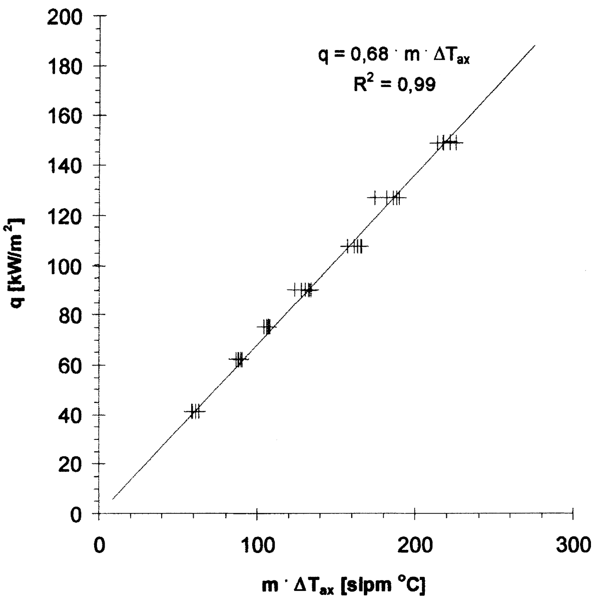

Fig. 7. Calibration curve.

In Fig. 5 the heat flux determined using Eq. (10) is plotted against the corresponding calibration heat flux from the calibration furnace (reference value).

The agreement between the data is good with respect to linearity and shift at zero, presenting an error always less than ±5% for the studied range. The respective linear regression line shows a good agreement between the calculated and the reference heat fluxes. The accuracy of the instrument is defined by the error equation. Fig. 6 shows the calculated error for all the tested operating conditions as a function of the blow-off mass flow rate. Nevertheless, the large errors obtained for low TG mass flow rates due to radial loss effects, are lower than 5% for mass flows rates higher than 7.5 slpm.

Fig. 7 shows a practical calibration curve to be used when operating the instrument relating the measured quantities and the required heat flux.

6. Conclusions

A new method heat flux measurement is developed with porous media sensor element. The gas stream flow through porous element is used to measure heat received by the sensor surface exposed to the hot gas environment.

The numerical model of sensor with appropriate boundary condition is used to perform analysis of possible options in the design of the sensor. The analysis includes geometry of element, physical parameters of gas and solid and gas flow rate through the porous element.

For the optimal selection of parameters the experimental set-up was designed, including sensor element with corresponding cooling and monitoring systems and high temperature radiation source. The linear dependency of the heat flux and respective temperature difference of the gas were verified. The accuracy analysis of the sensor reading has proved high linearity of the calibration curve and accuracy of ±5%.

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