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DESIGN AND SENSITIVITY ANALYSIS OF A NEW GAUGE FOR RADIATION HEAT FLUX ASSESSMENT

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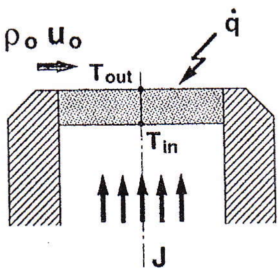
ABSTRACT

The need of sensors for the measurement of radiation and convection heat flux in high temperature industrial equipment such as furnaces, kilns and boilers showing a reliable, flexible, accurate and fouling-free behaviour, is a strong motivation for the research effort on this topic. In the present paper, a new instrument for the measurement of the heat flux in industrial thermal equipment is presented. Due to it constructive and functional characteristics, the developed gauge is particularly adequate to be used in industrial harsh environments. The new instrument consists on an intrumented porous disc, crossed by a transpiration gas (TG); wich is exposed to the radiation heat flux to be measureed. The temperature difference between the two faces of the porous disc for a fixed TG mass flow rate is a measure of the incident heat flux. The distinction between the convection and radiation heat fluxes can made based on the theory of the *boundary layer blow-off*. For a TG mass flow rate higher than a critical value, required to blow the boundary layer, the convection heat flux is driven to zero. Therefore, only the radiation component of the total heat flux is collected by the porous surface. For sub-critical values of the TG mass flow rate, the porous disc is exposed to the total heat flux (radiation and convection). With two independent masurements it may be possible to determine the twocomponents of the total heat flux. The present paper reports the approach considered for the thermal design of the porous filament as well as a sensitivity analysis of the relevant design and calibration parameter

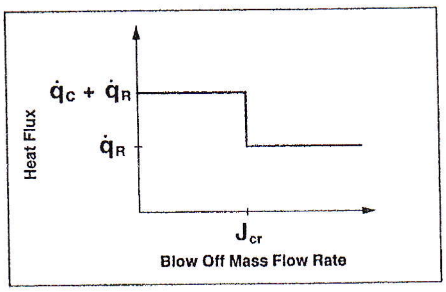
1. INTRODUCTION

Thermal radiation is an important parameter for the diagnosis of a number of systems. Boilers, furnaces, combustion chambers are among those systems, where one of the most important parameters to be determined is the thermal flux at the respective walls or charge.

A number of attempts have been made to develop instruments able to perform heat flux measurements in thermal equipment [1] to [4]. An extensive review of recent developments in this area was published by Diller [5]. With different success, most of the methods have been used in the control and diagnostic of those systems, however there are different limitations observed for each of the specific instrument designs. For this reason the development of a new heat flux measurement method is a challenging incentive. In particular, the thermal radiation flux measurement in hostile environment is needed to meet the requirements of the respective diagnostic systems. The new instrument for the thermal hemispherical radiation flux measurement [6] and [7], is based on the determination of the temperature difference of the gas flowing through the porous disc exposed to the particular heat flux to be measured.



$$J > J_{cr} \Rightarrow q_c = 0$$



A first attempt to develop a heat flux sensor based on the same principle is due to Moffat et al. [8]. The referred authors developed a so called *transpiration radiometer* that takes advantage of the possibility of to destroy the boundary layer on the sensible surface to avoid convection heat fluxes as a source of error. However, due to the early development of the reanpiration boundary layer theory, the possibility of to measure the convection heat lfux was not antecipated. In addition, non-acceptable relationships between the required blow-off mass flow rate and the external flow were proposed [9].

The gas stream is an essential aspect of the method in reference since it has the purpose of to cool the instrument sensible surface, to avoid the possibility of fouling on it and to make possible to distinguish between the radiation and convection components of the total hemispherical heat flux, which is a problem of substantial interest for many industrial processes. This is made taking advantage of the possibility of to *blow off* the boundary layer from the sensor surface by the referred gas stream. The boundary layer on the sensor surface is blown off over a critical gas stream. If an over-critical *blow off* mass flow rate is imposed, the convection component of the total heat flux is zero. If a sub-critical blow off mass flow rate is considered, the incident heat flux presents the two components, see Figure 1. A sequence of two measurements is enough to gather the required data to determine the radiation and convection components of the total heat flux. The heat transfer characteristic of the porous matrix and the associated fluid flow has to be selected to meet the requirements posed to the instrument in what concerns to accuracy and material limitations. A scheme of the proposed instrument head is shown in Figure 2.

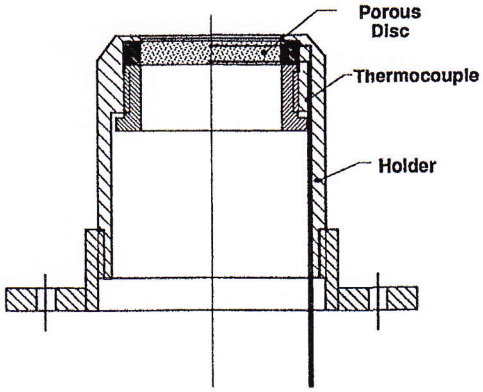


Figure 2 - Scheme of the instrument

2. CRITICAL BLOW OFF GAS MASS FLOW RATE

The critical *Blow Off Gas (BOG)* mass flow rate, required to promote the destruction of the boundary layer over the porous disc is a basic parameter to be defined for this heat flux sensor.

Under the influence of the BOG on the boundary layer at the vicinity of the wall, a momentum transfer from the tangential to the normal direction will take place in the main stream in the vicinity of the wall. This will result in the decrease of the velocity gradient $|\partial u_t/\partial y|_w$. As a consequence of the velocity profile deformation and increase of the boundary layer thickness the decrease of the friction force is obtained under other constant conditions. With the increase of the BOG mass flow rate, the velocity profile on the boundary layer will present an inflection point characterised by $(\partial u_t/\partial y)_w = 0$. Leontiev [9] introduced the definition of the critical BOG mass flow rate as follows:

$$j_{crit} = C \cdot \rho_\infty^{-1} \cdot Sc \cdot Re_\infty^{1/2} \qquad (1)$$

where C is a geometric constant. These equations relate the gas mass flux through the porous disc with the main stream conditions at the vicinity of its wall surface. Figure 3 shows the critical BOG mass flow rate for different porous disc diameters as a function of the external flow Reynolds number. (Assuming C = 0.62 (flow on a flat wall) and a main stream flow temperature of 900 K.)

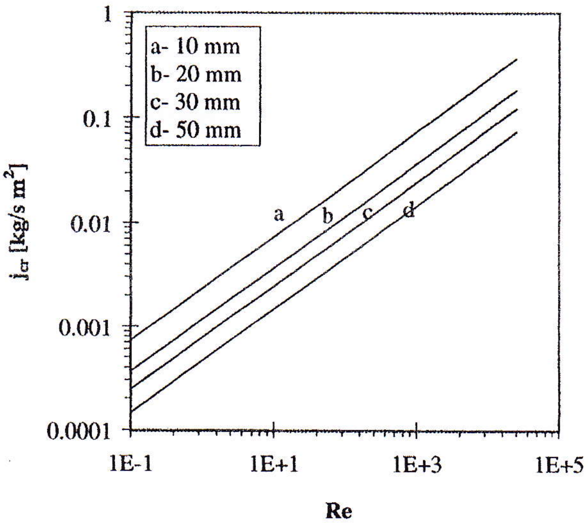


Figure 3 - Critical BOG mass flow rate as a function of the sensor diameter and main stream flow conditions.

3. NUMERICAL ANALYSIS

Two mathematical models were implemented to assist the study of the heat transfer phenomena occurring in the porous disc crossed by the BOG and subjected to a known heat flux. An integral model was used to define broad limits within the most important design parameters should be for extreme working conditions. A differential model was used for a more detailed study of the heat and mass transfer characteristics of the porous disc.

The first model is based on integral energy and mass balances, assuming the porous disc as a set of aligned capillary ducts. The model considers a fully developed, Darcean laminar flow with constant fluid properties through the ducts, which is an acceptable assumption since we are dealing with ducts with extremely small diameters (0.1 mm).

The second model is based on the numerical solution of the differential conservation equations for energy 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 (control volume) technique. Local thermal equilibrium between gas and solid phases is not valid so, the model considers separated energy equations for each present phase coupled by a source terms. An additional source term appears on the momentum equation due to the continuos treatment of the porous structure. A detailed description of the mathematical formulation is presented in [10].

4. PARAMETER SELECTION

The thermodynamic behaviour of the porous disc is controlled by a set of parameters that have to be quantified in order to fit operational requirements such as temperature level, pressure drop and cooling needs, as a function of the heat flux range.

The selection and quantification of the relevant parameters controlling the gauge thermal behaviour in the presence of different heat flux levels was assisted by the mathematical models above referred. From the analysis of the ruling equations it can be identified design parameters and operation parameters that must be adjusted in order to adapt the sensor to the operation needs, in particular in what respect to the pressure drop and temperature distribution in the porous disc, see [10].

As relevant design parameters, we may list the dimensional and morphological characteristics of the porous disc, such as the disc diameter and thickness, the porosity, pores size and material. Important operation parameters are the heat flux level and BOG mass flow rate. In addition, a non-dimensional coefficient, called *flat coefficient* was introduced and analysed. The flat coefficient, F, is given by (2) and (3) and is a measure of the radial temperature profile uniformity, i.e., how well the temperature on the centre of the disc represents the averaged forth power of the temperature on the disc surface. If the temperature is constant, F=1.

$$F = \frac{\overline{T}^4}{T_c^4} \qquad (2)$$

$$F = \frac{2}{T_c^4 \cdot R^2} \int_0^R T^4(r) \cdot r \cdot dr \qquad (3)$$

4.1 Selection Criteria

Independently of the incident heat flux level, the temperature level must be within an upper limit, imposed by the material resistance limitations and a lower limit due to sensitivity reasons, the radial temperature profile should also be as flat as possible in order to provide a low deviation of the temperature at the centre of disc and the averaged top surface temperature. At the same time, the pressure drop level must be lower than a pre-defined value in order to keep the pumping effort and gas leakage negligible

Fixing the heat flux as an input parameter, it is important to analyse which is the effect of the listed parameters on the pressure drop, temperature level and. it distribution on the top of the disc. In order to systematise the effect of the above-referred parameters on the performance indicators; a parametric study involving the above-referred variables was made.

The developed models have been used to select the required characteristics of the heat flux meter and to define the range of parameters, under which it can meet limitations imposed by its design, working conditions and material. Attention was also devoted to determine the limitation imposed by the requirement of use the same instrument for radiation heat transfer and convection heat transfer in the hot gas environment.

The selection of geometric and operating design characteristics for the heat flux meter was based on the following criteria :

<u>Accuracy to be obtained by the instrument</u>. The accuracy of the instrument is given by combination of the bias error and the accuracy of each one of the apparatus involved in direct measurements to determine the heat flux, such as thermocouples and flow meters. The first is related to the ratio of the temperature distribution in the disc to the uniform temperature, as a measure of the heat gain due to the temperature distribution in the disc. The flat coefficient, F, is a measure of the bias error. Although there is the theoretical possibility of to extract the bias error from the readings, it should be kept as low as possible in order to minimise it side effects such as higher temperature for a given heat flux. The second is related to the accuracy of the sensors involved in the flux determination as well as the range of the variable to be measure and it relationship with the corresponding instrument range. The design of the porous disc is an important step to minimise this effect. Actually, acting on geometric and operation variables it is possible to adjust the quantities to measured and the corresponding gauges in order to reduce the combined error.

<u>Sensitivity to be obtained by the instrument</u>. The sensitivity of the instrument is defined by an axial temperature difference in the porous material or the

temperature difference between a well-defined location in the porous disc and the BOG temperature. It is important to optimise the design and operation parameters in order to achieve measurable temperature differences for heat fluxes levels as lower as possible.

Physical limitation of the materials. For the selected range of working conditions, the disc material as well as the thermocouples may not exceed it temperature limitations. The selected design parameters have to met this requirements under prescribed conditions.

Pressure drop in the disc. In order to prevent strong effect of the BOG to its surrounding and limit excess use of the BOG, the pressure constrain is introduced as one of the criterion's for the design parameters selection

4.2. Selection of the principal characteristics of the porous disc.

The selection of the principal parameters controlling the instrument performance was made take in account the selection criteria above described and the developed mathematical models as designing tools. Two relevant working regimes were identified. For both it is possible to verify the enunciated selection criteria, in particular $F \cong 1$.

The first regime is achieved when a small diameter (10 mm) and thick (15 mm) porous disc is used. Under this regime the outlet temperature profile is uniform if a low BOG mass flow rate is supplied. The outlet BOG temperature will be dictated by the incident radiation flux, so this regime is specially adequate for low radiation fluxes otherwise the maximum temperature may exceed the physical limitation of the used materials. This is an appropriate design for low flux application such as solar radiation measurement and convection measurements. Due to the low heat fluxes involved, the BOG mass flow rate may be in the critical range without cooling problems.

The second regime is achieved when larger porous disc (30-40 mm) with low thickness (5 mm) is considered. Under this conditions a flat temperature profile is also possible, but now the outlet temperature is fixed mainly by the inlet temperature of the BOG. This regime is adequate for high heat flux measurement since for low heat flux levels the temperature difference to be measure is not acceptable due to the limitation imposed by the sensitivity criteria and thermocouples errors. If the heat flux is extremely high, additional cooling may be required.

In the first regime, the porous disc acts as a high efficiency heat exchanger, and is adequate for low heat flux levels. In the second regime the disc acts as a low efficiency heat exchanger, it is more convenient for high heat fluxes. Figure 4a and Figure 4b shows representative temperature distributions in the porous disc predicted for each one of the discussed regimes

The pressure drop in the porous disc is not a critical parameter if the porosity is equal or higher than 0.5, see [10].

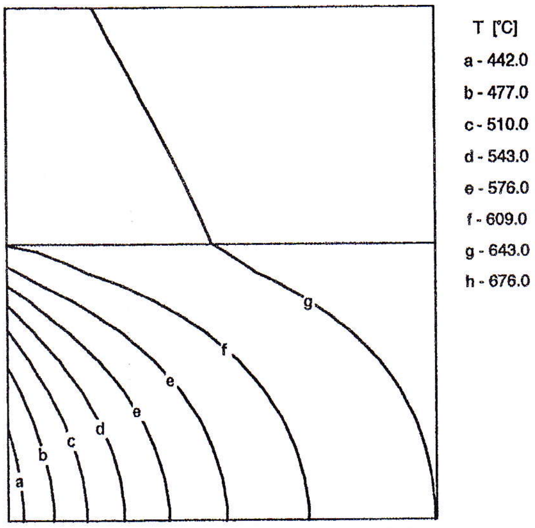


Figure 4a- Representative temperature distribution in the porous disc for the low heat flux regime

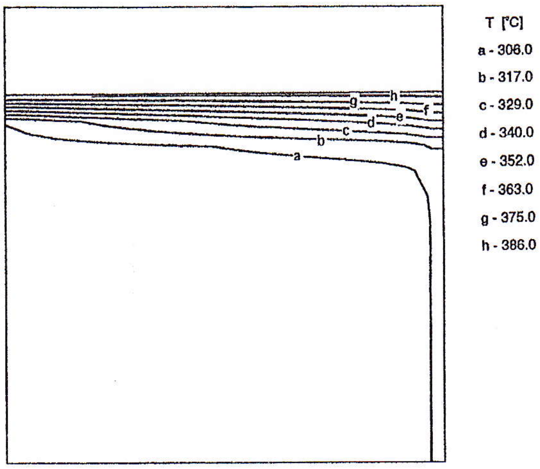


Figure 4b - Representative temperature distribution in the porous disc predicted for the high heat flux working regime

5. SENSITIVITY ANALYSIS

The present paragraph is devoted to the analysis of the parameters controlling the instrument accuracy, identifying its individual contribution. Accuracy may be defined as closeness to the true value, including the effect of precision and bias error. Assuming that the bias error can be compensated correcting the readings, the accuracy of the instrument will only be a function of it precision, i.e., of the precision of each sensor involved on the main quantity determination. For the gauge under analysis, to determine the incident heat flux it is necessary to measure the BOG mass flow rate, the inlet and outlet BOG temperature and dimension of the disc. The dependency among these variables can be derived from a energy balance to the porous disc, that assuming a steady state condition and neglecting minor terms as gas expansion or heat generation by friction forces, yields:

$$q = \chi \cdot \frac{\hat{j}}{D^2} \cdot Cp \cdot \left(T_{go} - T_{gi}\right) - q_L \cdot \frac{4 \cdot L}{D} \qquad (4)$$

where q_L is the lateral heat gain that can be associated to the bias error, so Eq. (4) can be simplified to:

$$q = \chi \cdot \frac{\hat{j}}{D^2} \cdot Cp \cdot \left(T_{go} - T_{gi}\right) \qquad (5)$$

Equation (5) establishes the dependency of the incident heat flux from the measured variable T_{go}, T_{gi}, j and D and it total differential can be used to determined the effect of each individual variable on the final result [11]. The total differential of (5), assuming the specific heat a known constant, is:

$$dq = \frac{\partial q}{\partial j} dj + \frac{\partial q}{\partial D} dD + \frac{\partial q}{\partial T_{go}} dT_{go} + \frac{\partial q}{\partial T_{gi}} dT_{gi} \qquad (6)$$

Equation (6) may be rearranged to yield:

$$\frac{dq}{q} = X_{\hat{j}} \frac{d\hat{j}}{\hat{j}} + X_D \frac{dD}{D} + X_{T_{go}} \frac{dT_{go}}{T_{go}} + X_{T_{gi}} \frac{dT_{gi}}{T_{gi}} \qquad (7)$$

where $X_{\hat{j}}, X_D, X_{T_{go}}$ and $X_{T_{gi}}$ are the sensitivity coefficients of each variable under analysis, that can be written for a generic function f, and a generic variable ξ as:

$$X_\xi = \frac{\xi}{f} \cdot \frac{\partial f}{\partial \xi} \qquad (8)$$

The sensitivity coefficients are weighting factors useful to stress the relative importance of a variation on each measured variable on the calculation of the main quantity, namely in what respects to the associated error to each individual measurement, [11]. Particularly, assuming that each individual measurement was previously corrected in what respect to it bias error, the accuracy associated to the main quantity is given by the root-sum-square of the product of each instrument accuracy and the respective sensitivity coefficient. For the present heat flux sensor it is as follows:

$$q_{Acc}^2 = \left(X_{\hat{j}} \cdot \hat{j}_{Acc}\right)^2 + \left(X_D \cdot D_{Acc}\right)^2 + \left(X_{T_{go}} \cdot T_{go\,Acc}\right)^2 + \left(X_{T_{gi}} \cdot T_{gi\,Acc}\right)^2 \qquad (10)$$

5.1 Accuracy Analysis

In the present study the described methodology was followed to preview the accuracy to be required to each individual measurement device in order to impose an overall accuracy on the heat flux measurement lower than a pre-defined value of 5%. It was also used to verify some limitations of the gauge under development as well as the need of establish different gauges to be used under different heat flux ranges maintaining the accuracy under acceptable limits. The application of Eq. (8) to Eq. (5), allows to determine the sensitivity coefficients for each one of the variables to be measure in order to calculate the incident heat flux. Assuming that the BOG is Nitrogen, with a constant specific heat of 1100 J/kgK and typical accuracy values for mass flow meters, K-type thermocouples and dimensional measuring devices, given in Table 1, it is possible to predict the heat flux gauge accuracy as a function of the read heat flux.

As can be stated by figures 6a, 6b and 6c it is necessary to consider 3 different working conditions to cover completely the range 0-1000 kW/m^2 with an accuracy better than 5%. The adjusted parameter was the BOG flow rate and correspondent measuring device scale and the considered levels were 0.3, 3.0 and 30.0 $(dm^3/min)_{std}$ respectively for the 0-10, 10-100 and 100-1000 kW/m^2 heat flux ranges.

Table 1 - Sensitivity Coefficients

Variable	Sensitivity Coefficient	Individual Accuracy
$\hat{j}$	1.0	1.5 % of Full Scale
D	-2.0	0.05 mm
T_{go}	$\frac{T_{go}}{T_{go} - T_{gi}}$	max (1.1 °C,0.4%)
T_{gi}	$-\frac{T_{gi}}{T_{go} - T_{gi}}$	max (1.1 °C,0.4%)

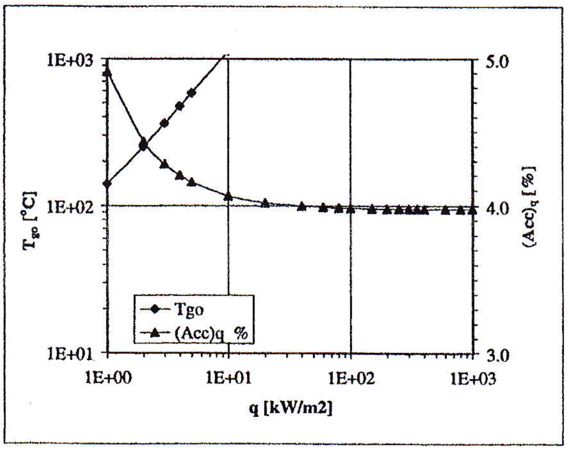


Figure 5a - Calibration and accuracy curves for a 30 mm diameter gauge and j = 0.3 $[dm^3/min]_{std}$.

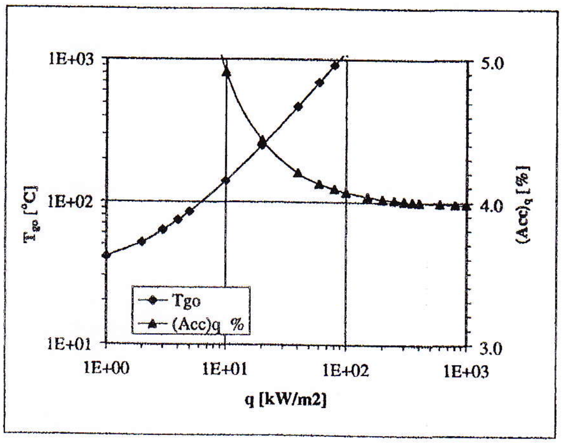


Figure 5b - Calibration and accuracy curves for a 30 mm diameter gauge and j = 3.0 $[dm^3/min]_{std}$.

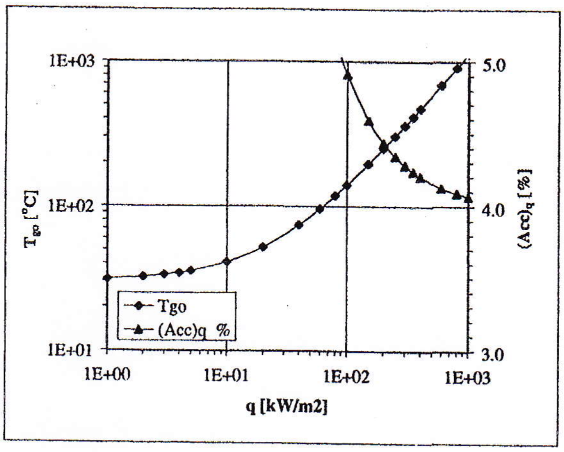


Figure 5c - Calibration and accuracy curves for a 30 mm diameter gauge and j = 30.0 $[dm^3/min]_{std}$.

This parameter has an important effect on the thermocouple contribution to the overall accuracy because it has a direct influence on the temperature level. Actually this is the principal mechanism controlling the instrument accuracy because the main contribution to the instrument error is due to the temperature measurement as can be verified at figures 9, 10 and 11 where the individual contribution of each measurement device is plot for each of the considered working conditions.

From the analysis of these plots it may be stated that it is favourable to keep the temperature level high to minimise the temperature reading error but there is a limitation on the 1000 °C from the thermocouple specification. These two mechanisms with contrary signs establish the heat flux range where measurements may be done with an accuracy equal or better than 5%. This range can be substantially enlarged following one of two different strategies to avoid the measurement of low temperature levels. The first one consists in to directly measure ΔT_{gio} using T_{gi} as cold junction instead of measure T_{go} and T_{gi} to determine Δt_{gio}, as can be stated from figure 7 that may be compared with figure 5c. The second one is based on to measure the temperature difference between two specific locations at the porous disc for two different BOG mass flows rates. Details of this strategy can be found at [6].

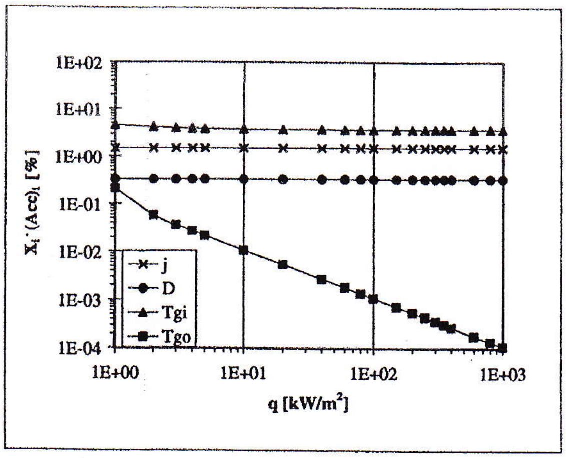


Figure 6a - Sensitivity coefficients for the range 0-10 kW/m², considering a 30 mm diameter gauge and j = 0.3 $[dm^3/min]_{std}$.

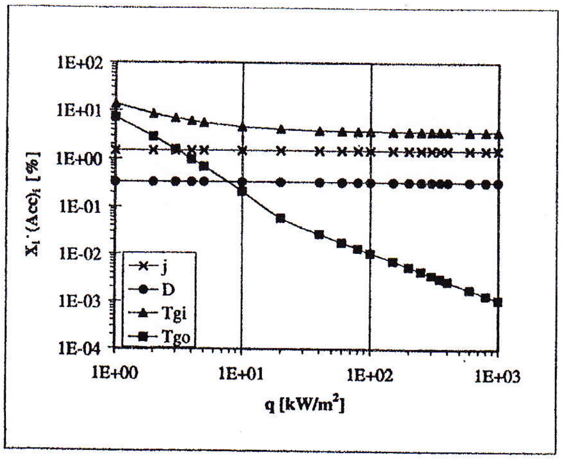


Figure 6b - Sensitivity coefficients for the range 10-100 kW/m², considering a 30 mm diameter gauge and j = 3.0 $[dm^3/min]_{std}$.

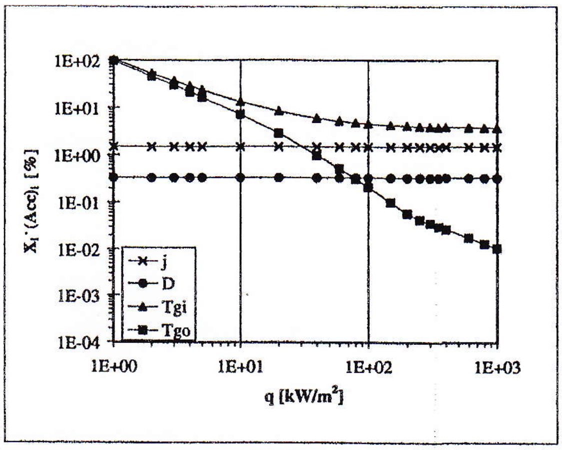


Figure 6c - Sensitivity coefficients for the range 100-1000 kW/m^2, considering a 30 mm diameter gauge and j = 3.0 [dm^3/min]$_{std}$.

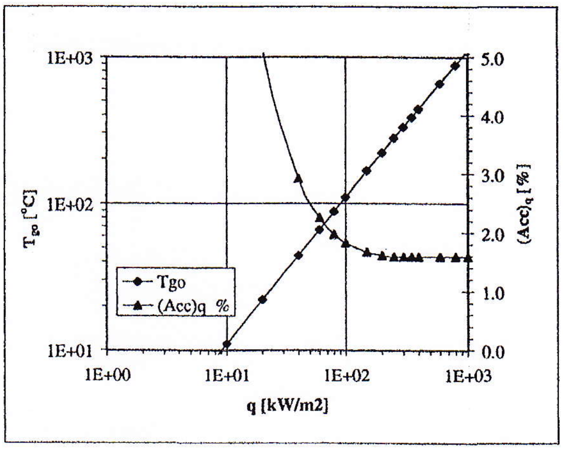


Figure 7- Calibration and accuracy curves for the range 100-1000 kW/m^2, considering a 30 mm diameter gauge and a differential thermocouple arrangement

6. CONCLUSIONS

The present paper describes a new gauge to assess radiation and convection heat fluxes. A parametric and a sensitivity analysis were made in order to establish the design and operational characteristics of the instrument that are most appropriated to different working conditions. From the analysis of the new gauge it was shown that:

a) It is possible to adjust the design and operational parameters in order to obtain a accuracy within ±5%.
b) The major contributor for the instrument error are the temperature sensors (thermocouples).
c) It is possible to minimize the thermocouples contribution for the overall instrument error by using a differential mounting of the termocouples, or by doing two sucessive measurements using different BOG mass flow rate.
d) Two different designs each one suitable for different heat flux levels are proposed.

NOMENCLATURE.

Roman Symbols

Ao	-	Specific surface area
C	-	Blow off constant
Cp	-	Specific Heat
D	-	Diameter
h	-	Convection heat transfer coefficient
J	-	Blow off mass flow rate
K	-	Permeability
k	-	Thermal conductivity
L	-	Thickness
n	-	Number of pores
Nu	-	Nusselt number
p	-	Pressure
Pr	-	Prandtl number
Q	-	Heat flux
r	-	Radial direction coordinate
Re	-	Reynolds number
S	-	Source term
T	-	Temperature
u	-	Velocity
x	-	Axial direction coordinate
y	-	transversal coordinate

Greek Symbols

D	-	Difference
e	-	Porosity
m	-	Viscosity
p	-	3.1415....
r	-	Density

Subscripts

cr	-	Critical
eff	-	Effective
p	-	Pores
r	-	Radial
s	-	Solid material
w	-	Wall
x	-	Axial
g	-	Gas
h	-	Energy
o	-	Main stream
f	-	Porous disc

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