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A NEW METHOD FOR HEMISPHERICAL RADIATION HEAT FLUX MEASUREMENT

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ABSTRACT

In a number of combustion chambers differentiation between radiation and convective heat transfer on the surface is a problem of substantial interest. Hemispherical radiation heat flux meter proposed by Afgan and Leontiev [1] and patented by Afgan, Carvalho and Leontiev [2] has potential possibility to be used as an instrument with sufficient accuracy to measure difference between hemispherical radiation heat flux and convective heat flux in the respective environment.

The hemispherical radiation flux meter is numerically analyzed with the aim to define the optimal design parameters to be used for experimental verification. With a proper selection of the design parameters corresponding to the conditions encountered in the boiler furnace, it will be possible to measure with the same instrument the radiation heat flux and convective heat flux.

Particular attention was focused on the discussion of the respective parameters of the flux meter in order to meet corresponding requirements in different environment. Attention was focused on the effects of differences in main mass flow rate and blow of gas mass flow rate , heat conductivity of the holder and porous fillament and difference in temperature between solid structure and fluid flow in the fillament.

For the selected parameters of the main flow and radiation heat flux range, the radiation heat flux meter was designed.

1. INTRODUCTION

Thermal radiation measurement is an important parameter for the diagnosis of a number of systems. Boiler, furnaces, combustion chambers are among those systems, where the most important parameter to be determined is the thermal radiation flux at the respective walls. Number of attempts have been made to develop the instrument for heat flux measurement in the enclosures[3] to [6].

With different success most of the methods have been used in the control and diagnostics of the systems. There are different limitations observed for each of the specific instrument design. For this reason the development of the new heat flux measurement method is a challenging incentive. In particular, the thermal radiation flux measurement in hostile environment is needed to meet requirement of the respective diagnostic of the system.

The new instrument for the thermal hemispherical radiation flux measurement [1], is based on the determination of the temperature difference of the gas flowing through the porous fillament exposed to the respective heat flux to be measured, Fig. 1. When the critical blow of gas mass flow rate is reached the boundary layer is blown of from the porous surface exposed to the hot gas environment. Heat transfer and fluid flow in the porous fillament has to be respectively selected in order to meet requirements posed by the instrument to reach corresponding accuracy and material limitations.

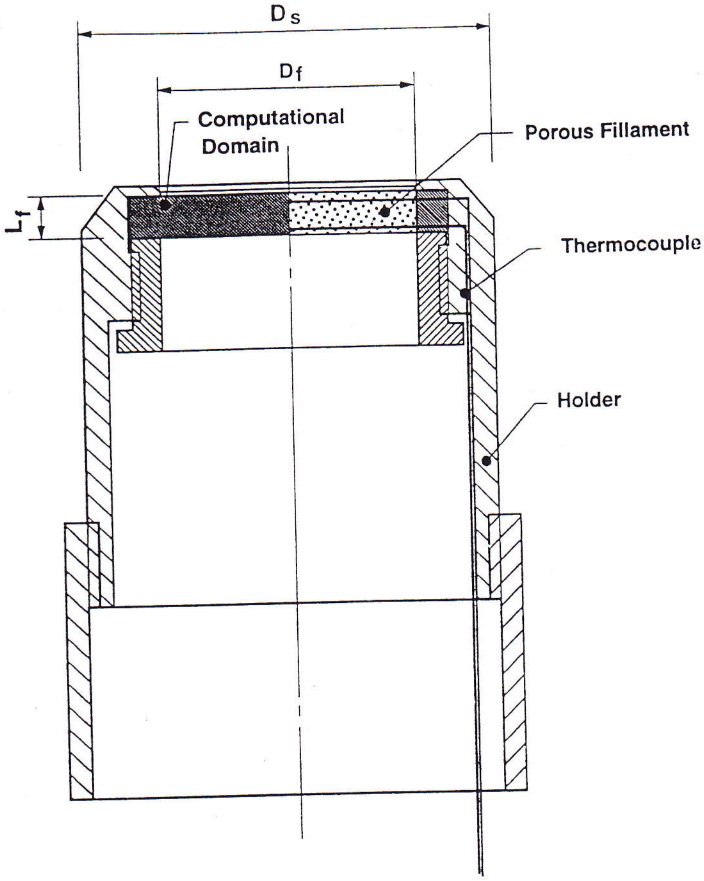


Figure 1 - The flux meter head

For this reason, this study is devoted to the numerical analysis of the parameters effecting the imposed limitations of the instrument. In this respect special attention is devoted to the analysis of the global parameters of the instrument and also to the analysis of the gas velocity and temperature distribution in the porous fillament. In order to determine physical dimensions, gas and porous material parameters analysis is focused to the specific limitations imposed by the hostile environment where the instrument is suppose to work. The selection of the geometrical and physical parameters of the instrument is based on the analysis of the presented numerical study of the problem.

2. MATHEMATICAL MODEL

2.1 Introduction

To assist the development of the heat flux sensor, two mathematical models were implemented. The first model is based on integral energy and mass balances, assuming the porous fillament as a set of aligned capillary ducts with a laminar air flow through them. This model was used to define the limits within the most important design parameters should be for a certain set of working conditions.

The second model is based on the numerical solution of the energy, momentum and continuity differential equations in their 2D-axissimetric, steady state form for an homogeneous porous media crossed by a laminar air flow. 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 term.

2.2 Critical Blow Of Gas Mass Flow Rate

The critical blow of gas mass flow rate required to promote the destruction of the boundary layer over the porous fillament is a basic parameter to be defined for this heat flux sensor.

Under the influence of the blow of gas on the boundary layer at the vicinity of the wall, a momentum transfer from the blow of gas to the main stream will take place leading to the decrease of the main stream gas velocity in the vicinity of the wall. This will result in the decrease of the velocity gradient $\left(\frac{\partial u}{\partial y}\right)_w$. 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 blow of gas mass flow rate, the velocity profile on the boundary layer will present an inflection point characterized by $\left(\frac{\partial u}{\partial y}\right)_w = 0$. In the definition of this point the critical blow of gas mass flow rate is introduced by Leontiev [7] as:

$$J_{cr} = C\frac{\rho_o u_o}{\sqrt{Re_o}} \tag{1}$$

$$Re_o = \frac{\rho_o u_o D}{\mu_o} \tag{2}$$

where C is a constant dependent on the geometry.

These equations relate the gas mass flux through the porous fillament with the conditions at the vicinity of its wall surface.

Figure 2 shows the critical blow of gas mass flow rate for different porous fillament diameters as a function of the external flow velocity, considering C = 0.62 and assuming a main stream flow temperature of 1200 K.

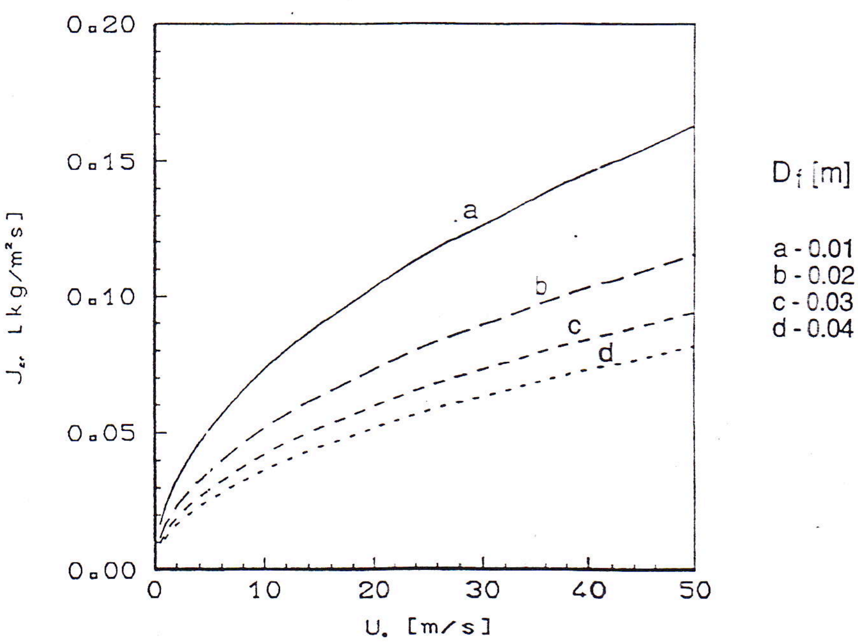


Figure 2 - Critical blow of gas flow rate for an infinite slab

2.3 Integral balance model

A simple model based on integral balances of energy and mass and considering the porous fillament as a set of capillary ducts was developed. The model considers a Darcean laminar flow through the ducts and constant fluid properties. Due to it importance, the critical blow of mass flow rate range was considered (from the *blowing of* point of view). The studied parameters are:

- temperature difference of the air flow between the inlet and outlet surfaces of the porous fillament.
- pressure drop in the porous fillament.
- temperature difference between gas and solid phases.

The integral energy balance assumes that all the energy received by the fillament is transferred to the fluid and that lateral walls of the fillament are adiabatic The temperature difference of the gas between inlet and outlet surfaces is given by

$$\Delta T = \frac{Q}{c_p\, J} \qquad (3)$$

The pressure drop through the porous fillament for a laminar, fully developed flow in a duct was considered, and the Hagen-Poiseuille equation was used in the form of a Darcy law as a function of the mass flow rate as follows:

$$\Delta p = \frac{32\, \mu_g\, L_f}{\varepsilon\, D_p^2\, \rho_g}\, J \qquad (4)$$

The temperature difference between the gas and solid phases was determined under the same assumption of the previous paragraph, i.e., considering a Hagen-Poiseuille flow inside each pore. The heat flux received by the porous skeleton is transferred to the gas by convection, so that :

$$\Delta T_{ln} = \frac{Q}{n\, \pi\, k_g\, L_f\, Nu} \qquad (5)$$

where the Nusselt number is determined by correlation's valid for laminar forced convection through cylindrical tubes.

2.4 Differential Balance Model

A more detailed mathematical model of the heat and mass transfer in a porous media crossed by a air flow was developed. The model is based on the solution of the 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 coordinates by a finite difference (control volume) technique. The set of equations constituting the mathematical model are as follows:

<u>Continuity:</u>

$$\frac{\partial}{\partial x}(\rho\, u_x) + \frac{1}{r}\frac{\partial}{\partial r}(r\, \rho\, u_r) = 0 \qquad (6)$$

Momentum
$$\rho\, u_x \frac{\partial u_x}{\partial x} + \rho\, u_r \frac{\partial u_x}{\partial r} + \frac{\partial p}{\partial x} - \frac{\partial}{\partial x}\left(\mu \frac{\partial u_x}{\partial x}\right) - \frac{1}{r}\frac{\partial}{\partial r}\left(\mu\, r \frac{\partial u_x}{\partial r}\right) - S_x = 0 \qquad (7)$$

$$\rho\, u_x \frac{\partial u_r}{\partial x} + \rho\, u_r \frac{\partial u_r}{\partial r} + \frac{\partial p}{\partial r} - \frac{\partial}{\partial x}\left(\mu \frac{\partial u_r}{\partial x}\right) - \frac{\partial}{\partial r}\left(\mu \frac{1}{r}\frac{\partial}{\partial r}(r\, u_r)\right) - S_r = 0 \qquad (8)$$

Energy (gas)
$$\rho\, u_x \frac{\partial h}{\partial x} + \rho\, u_r \frac{\partial h}{\partial r} - \frac{\partial}{\partial x}\left(\frac{\mu}{Pr}\frac{\partial h}{\partial x}\right) - \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\mu}{Pr}\, r \frac{\partial h}{\partial r}\right) - S_h = 0 \qquad (9)$$

Energy (solid)
$$\frac{\partial}{\partial x}\left(k_{eff}\frac{\partial T_s}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(k_{eff}\, r \frac{\partial T_s}{\partial r}\right) - S_h = 0 \qquad (10)$$

Momentum equation source terms, S_x, S_r. An additional source term appears on the momentum equation because the porous structure is treated as a continuos. Several attempts are being made in order to arrive at an equation equivalent to the Navier-Stokes, for the description of the fluid flow through porous media, [8]. A *semiheuristic volume-averaged* treatment of the flow field was made adding to the standard momentum equations a source term with two components. The first accounts for the microscopic shear stress (Darcy term) the second component describes the microscopic inertial force (Ergun inertial term):

$$S_i = \frac{\mu}{K} u_i + \frac{1.8\,(1-\varepsilon)}{D_p\,\varepsilon^3}\,\rho\, u_i^2 \qquad (i=x,r) \qquad (11)$$

where

$$K = \frac{\varepsilon^3 D_p^{\,2}}{180\,(1-\varepsilon)^2} \qquad (12)$$

Energy equation source term, S_h. The coupling of the solid matrix and the gas flow energy equation is made through a source term representing the energy transfer between the phases,

$$S_h = A_{spc}\, h_{sg}\, (T_s - T_g) \qquad (13)$$

The interstitial convection heat transfer coefficient used, h_{sg} was experimentally evaluated by Wakao and Kaguey for packed beds of spherical particles, [9]. The simple cubic arrangement geometry was considered to determine the specific surface area, A_{spc}.

$$A_{spc} = \frac{\pi}{D_p} \qquad (14)$$

$$h_{sg} = \frac{k_g}{d_p}\left(2 + 1.1\, Re^{0.6} Pr^{1/3}\right) \qquad (15)$$

Effective thermal conductivity, K_{eff}. A considerable revue of the many available studies for the determination of K_{eff} can be found at [8]. On this study as a first approach a geometric mean (between gas and solid thermal conductivity) was considered.

$$k_{eff} = k_g^{\varepsilon} \cdot k_s^{(1-\varepsilon)} \qquad (16)$$

Boundary conditions. The assumed boundary conditions are listed in table 1

Table 1 - Boundary conditions

	x = 0.0	x = L	r = 0.0	r = R_1
continuity	$u_r = 0.0$ $u_x = \frac{j}{\rho}$	$u_r = 0.0$ $\frac{\partial u_x}{\partial x} = 0.0$	$u_r = 0.0$ $u_x = 0.0$	$u_r = 0.0$ $u_x = 0.0$
x momentum	$u_x = \frac{j}{\rho}$	$\frac{\partial u_x}{\partial x} = 0.0$	$\frac{\partial u_x}{\partial r} = 0.0$	$u_x = 0.0$
r momentum	$u_r = 0$	$u_r = 0$	$\frac{\partial u_r}{\partial r} = 0.0$	$u_r = 0.0$
energy (gas)	$T_g = T_g^i$	$\frac{\partial T_g}{\partial x} = 0.0$	$\frac{\partial T_g}{\partial r} = 0.0$	$\frac{\partial T_g}{\partial r} = 0.0$
energy (solid)	$\frac{\partial T_s}{\partial x} = 0.0$	$k_{eff}\frac{\partial T_s}{\partial r} = Q$	$\frac{\partial T_s}{\partial r} = 0.0$	$k_{eff}\frac{\partial T_s}{\partial r} = Q$

2.5 Numerical Procedure

Method of solution. In the present work a finite difference approach was used to solve the equations of the above described model The hybrid central/upwind method was used to discretise the convection terms [10], and the pressure coupling is performed with the SIMPLE algorithm, [11]. After each iteration, the thermo-physical properties of solid and gas phases are updated as well as the source terms of the energy and momentum equations.

Some computational details. The presented model was applied to the prediction of the mean flow and heat transfer between the gas and the solid matrix in the instrument *holder*. The *holder* is considered as the part of the instrument where the porous fillament is accommodated as is shown in Fig. 1.

The computational domain is represented at Fig. 1, both the porous fillament and part of the holder are considered. Due to symmetry reasons a single slice of the sensor was studied. The thickness of the holder was the same for all the tests we made (5.0 mm). A staggered grid with 20 x 20 nodes was used. As convergence criterion we considered that the dimensionless residual sources of all equations should be smaller than 0.005 and the integral energy balance should be satisfied.

Based on the results of the integral balance model a first selection of parameters was made in order to perform a more detailed analysis with the differential balance model. The studied parameters are listed in table 2.

Table 2 - Studied parameters

Parameter	Considered Values	Units
Blow of gas mass flow rate, J	2 and 8	kg m^{-2} s^{-1}
Fillament Diameter, D_f	10, 30 and 40	mm
Fillament Thickness, L_f	5, 15 and 20	mm
Heat Flux, Q	50, 100 and 200	kW m^{-2}
Material	Stainless Steel	-
Porosity, ε	0.3 and 0.5	-
Size of the Pores, D_p	50 and 100	µm

3. DISCUSSION OF THE RESULTS

The results obtained with 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.

3.1 Selection Criterion's

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

Accuracy to be obtained by the instrument. The accuracy of the instrument is defined by the ratio of the temperature distribution in the fillament to the uniform temperature, as a measure of the heat loss due to the temperature distribution in the fillament.

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

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

3.2 Selection of the principal characteristics of the porous fillament.

For the heat flux levels found in industrial boilers (> 100 kW/m^2) the blow of gas mass flow rate must be some order of magnitude higher than it critical value to avoid high temperatures in the porous fillament, as shown in Fig. 3. Actually, for the considered porous fillament diameters, the critical blow of gas mass flow rate never exceeds 0.15 kg/m^2s(Fig. 2) but to avoid porous fillament temperature higher than 700 K, the blow of gas mass flow rate has to be between 1 and 10 kg/m^2s.

The pressure drop in the porous fillament is not a critical parameter if the porosity is equal or higher than 0.5, as can be seen on Fig. 4.

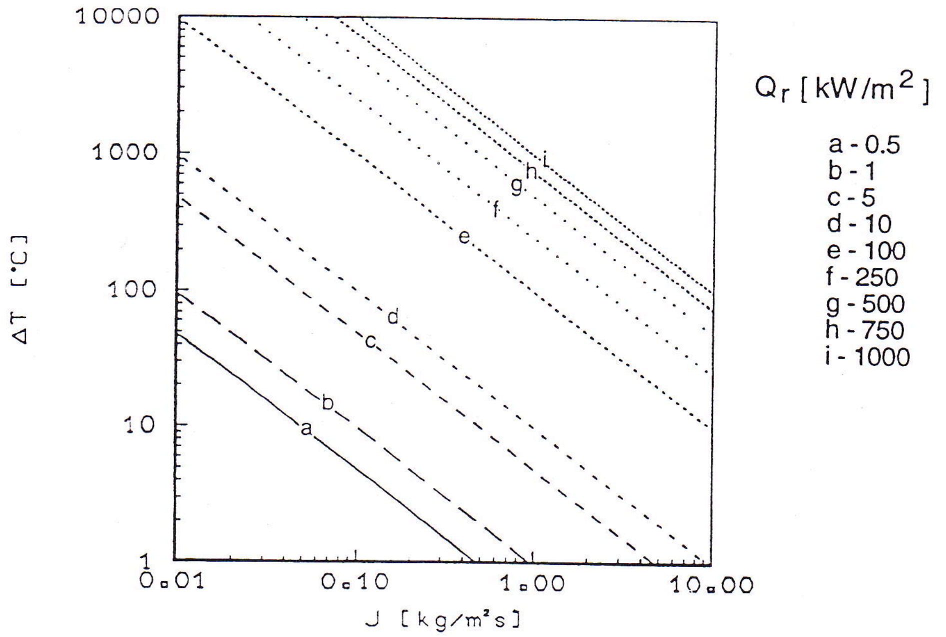


Figure 3 - Predicted temperature difference between the inlet and outlet of the porous fillament

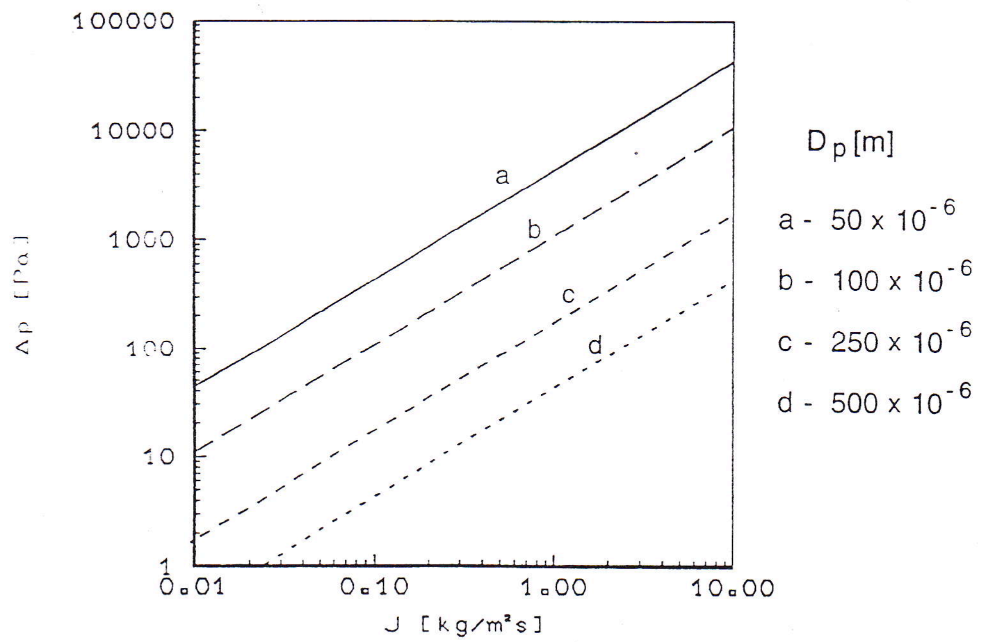
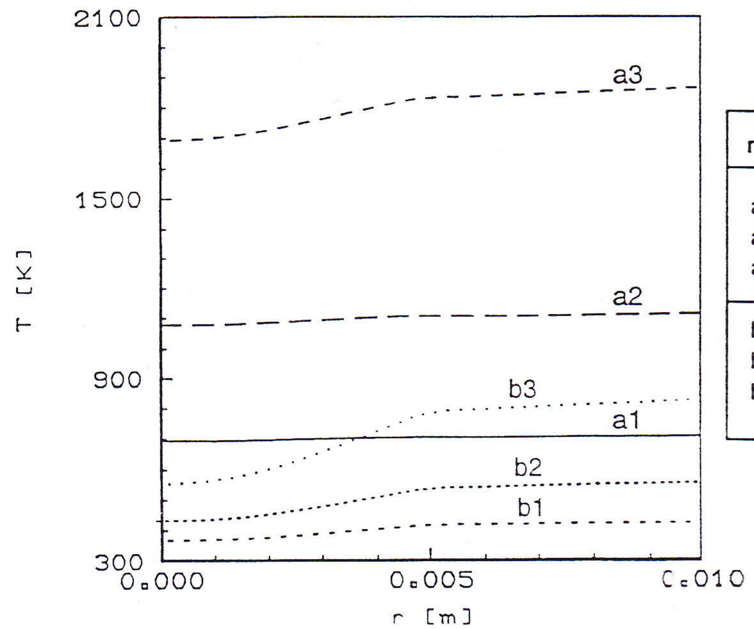


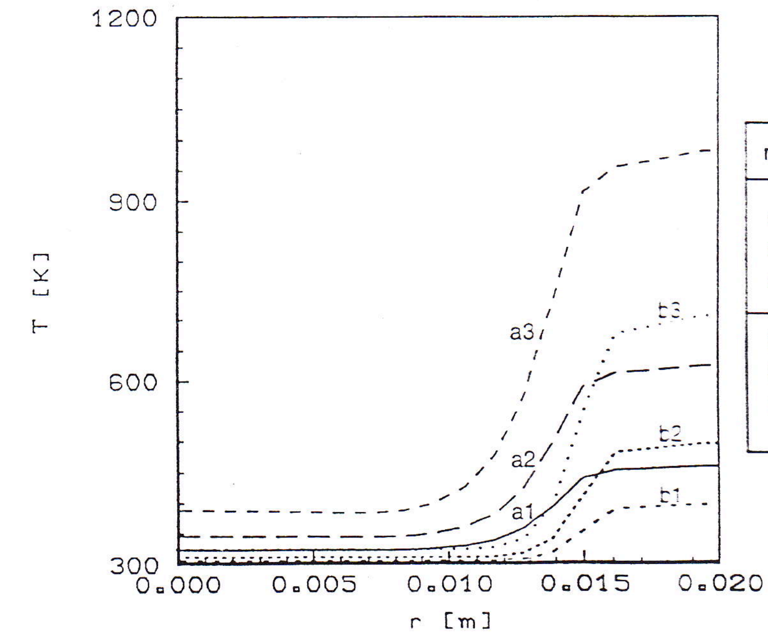
Figure 4 - Pressure drop in the porous fillament

The analysis of the results obtained by the differential balance model shows that the heat transfer between the gas phase and the solid matrix is controlled by the specific surface area.The temperature difference between the phases is almost zero in all the domain except near the boundary of the porous matrix and solid holder where a temperature difference can be found.



ref.	J[kg / m²s]	Q_r[kW / m²]
a1		50
a2	2	100
a3		200
b1		50
b2	8	100
b3		200

Figure 5 - Predicted radial temperaturre profiles at the porous fillament outlet surface (option 1)



ref.	J[kg / m²s]	Q_r[kW/m²]
a1		50
a2	2	100
a3		200
b1		50
b2	8	100
b3		200

Figure 6 - Predicted radial temperaturre profiles at the porous fillament outlet surface (option 2)

It can be shown that the first criterion can be satisfied by two options of porous fillament:

option 1- a small diameter (10 mm), large thickness (> 15 mm) and low porosity (0.3).

option 2 - a large diameter (30 mm), small thickness (5 mm) and high porosity (0.5).

With the first option the blow of gas is heated with an high efficiency, resulting in a very homogeneous temperature distribution on the gas fillament. This high heat transfer efficiency is due to the low porosity, large heat exchange surface and high thermal conductivity of the porous matrix. The low porosity is responsible for the high pressure drop.

The second option is characterized by a low heat exchange efficiency between gas and solid phases, mainly due to the high porosity, low thermal conductivity of the porous matrix and small thickness of the fillament. As a consequence of the low heat exchange efficiency between the phases the temperature profile shows a strong influence of the inlet gas temperature that prevails over most of the porous fillament surface with a pronounced change at the vicinity of the boundary between the porous matrix and the solid holder.

Figures 5 and 6 shows radial temperature profiles at the gas outlet for different heat flux and blow of gas mass flow rate, respectively for the first and second solutions.

It may be concluded that the first option may be appropriated for situations where convection heat fluxes must be considered. With a smaller diameter it is easier to reach a critical blow of gas mass flow rate (Fig. 2), which is essential for this kind of measurements. Due to the low heat fluxes and low blow of gas mass flow rate, this solution will not present the problems with the high temperatures and high pressure drop.

The second option is in good accordance with the selection criterion's namely with respect to the required homogeneity of the temperature field in the porous fillament, the temperature level (always below 900 K) and the pressure drop (less than 7 kPa for $j = 2$ kg/m^{2}s and 30 kPa for $j = 8$ kg/m^{2}s), for the studied range of blow of gas mass flow rate, pores diameter and heat flux.

The select design parameters for the radiation heat flux meter were:

Table 3 - Selected design parameters

D_f	L_f	D_p	ε
30 mm	5 mm	100 µm	0.5

3.2 Analysis of the selected Sensor

A more detailed analysis of the selected set of design parameters (table 3) was performed using the differential balance model.

The investigated parameters are the radial and axial temperature profiles, Fig. 7 and 8, and the temperature difference between the inlet and outlet surfaces, Fig 9, for different heat flux levels.

From Fig. 7 it may be concluded that for heat fluxes higher than 500 kW/m2, external cooling of the flux meter will be required. Figure 7 and Fig. 8 show that for all the heat flux levels considered, there is a core where the influence of the inlet gas temperature is dominant. It should be stressed that the considered range of heat flux levels covers most of the known engineering applications with high heat fluxes.

Figure 9 shows the predicted calibration curve for the selected porous fillament. It shows that the sensor has to be calibrated accordingly to the heat flux levels to be measure in order to increase its sensibility. The calibration can be made adjusting the blow of gas mass flow rate.The presented curve (Fig. 9) can be used to measure heat fluxes between 250 and 750 kW/m2. For the lower heat fluxes to be considered, the blow of gas mass flow rate can be decreased.

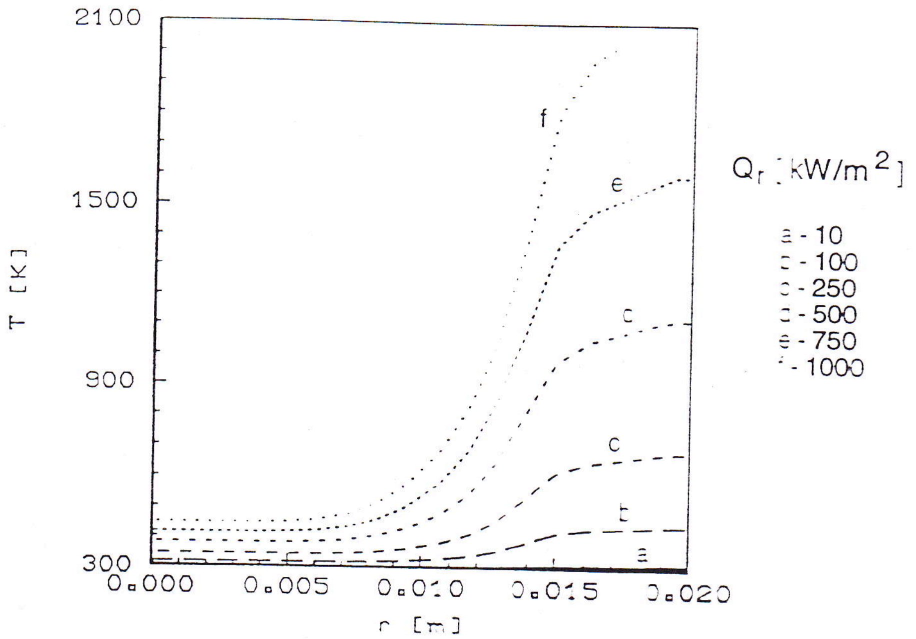


Figure 7 - Predicted radial temperature profiles at the porous filament outlet surface (selected opt.)

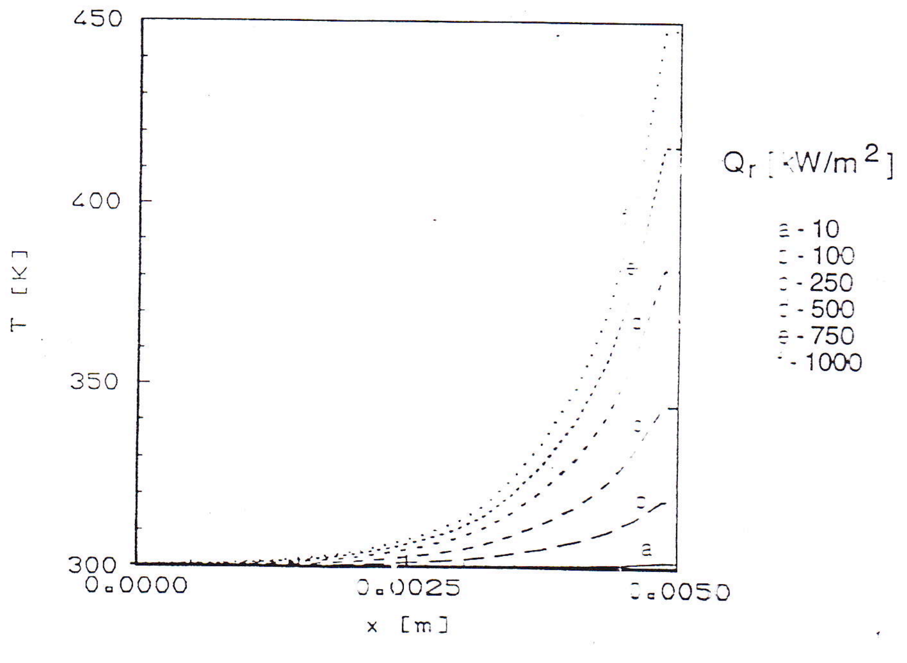


Figure 8 - Predicted longitudinal temperature profiles along the porous fillament axis (selected opt.)

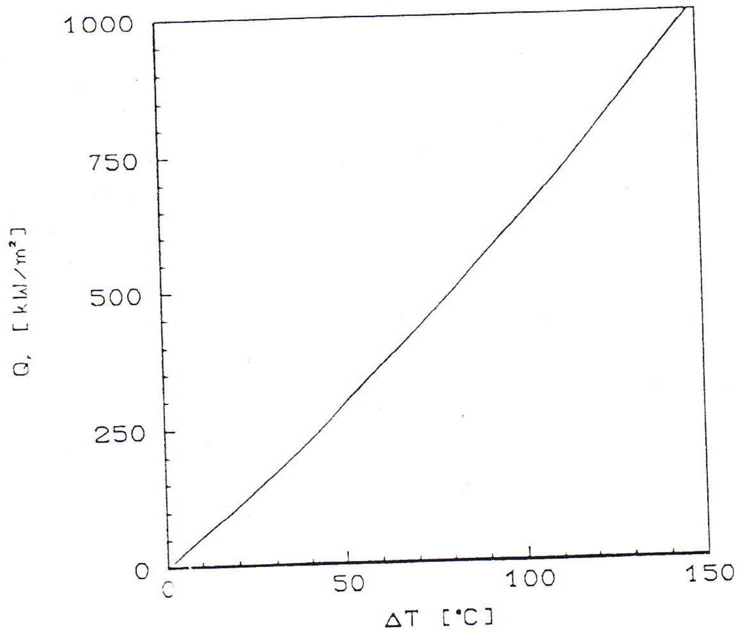


Figure 9 - Predicted calibration curve for the selected option

4 CONCLUSIONS

The numerical analysis of the instrument for the hemispherical radiation heat flux measurement presented in the paper, has shown that it is possible to obtain well defined design parameters under the selection criterion's applied. In this respect it was shown:

1. For the selected geometrical parameters of the instrument the required accuracy can be obtained not exceeding the physical limitation of the material. The range of the working parameters are specified to be Q_r = 250-500 kW/m^2.

2. Two options of the fillament are possible depending on the range of parameters to be considered. A so called low efficiency fillament and respective blow of gas mass flow rate is proposed for only radiation heat flux measurements. For working conditions where the convection heat flux has to be considered a high efficiency fillament is proposed.

3. It was proved that under specified working conditions it is possible to obtain a linear relation between the thermal radiation heat flux and the temperature difference between the inlet and outlet blow of gas, within the range of the thermophysical parameters of the working fluid (air) and of the porous fillament material (stainless steel) and geometrical parameters of the porous fillament.

NOMENCLATURE

Roman Symbols

Ao	-	Specific surface area
C	-	Blow of constant
Cp	-	Specific Heat
D	-	Diameter
h	-	Convection heat transfer coefficient
J	-	Blow of 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

Δ	-	Difference
ε	-	Porosity
μ	-	Viscosity
π	-	3.1415....
ρ	-	Density

Subscripts

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

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