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STUDY OF THE INFLUENCE OF CONVECTIVE EFFECTS IN INCIDENT RADIATIVE HEAT FLUX DENSITY MEASUREMENT UNCERTAINTY

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Abstract − This study describes the measurement uncertainty propagation of the incident radiative heat flux density quantity associated with different exposure conditions of the heat flux meter, taking into account the convective effects in reaction to fire tests.

To accomplish this aim, considering the complexity and non-linearity of the applied mathematical models to perform the indirect measurement of the mentioned quantity, the Monte Carlo method approach was selected.

The use of this numerical approach allows to determine the quality of the measurements within a high accuracy level and to overcome the main constrains found in other methods, specially the GUM method, which can only provide an approximate solution for this metrological problem.

The experimental examples studied concern the reaction to fire testing (the room-corner test and the flooring radiant panel test) with different exposure conditions of the heat flux meter used. For each case, the applied mathematical model is described and an analysis of the input uncertainty contributions is presented.

Keywords: incident radiative heat flux density; measurement uncertainty; Monte Carlo method.

1. INTRODUCTION

The measurand incident radiative heat flux density has an important role in reaction to fire testing being applied in the room-corner test [1] and the flooring radiant panel test [2], where it is the most significant heat transfer mode that occurs in a fire. In these tests, the knowledge of this physical quantity allows the evaluation and the characterisation of tested materials in terms of its contribution to fire deflagration and propagation.

In the mentioned reaction to fire tests, this thermal quantity is indirectly measured using an appropriate mathematical model derived from the energy balance performed at the surface of the heat flux meter used [3]. The focus of this study was on the Schmidt-Boelter heat flux meters, one of the most common used in reaction to fire laboratories, including the *Laboratório de Ensaios de Reacção ao Fogo* at the *Laboratório Nacional de Engenharia Civil* (LNEC/LERF) which supported the experimental work done.

The equipment used is unable to perform direct measurement of the incident radiative heat flux density component, due to the combined effects of radiation and convection, despite some attempts to reduce the convective effect. One of the attempts made was the use of glass windows connected to the heat flux meter, being this solution inconvenient because of the magnitude of additional uncertainties related with the optical properties of the glass [4].

The aim of the present study was to evaluate the propagation of the measurement uncertainty of the incident radiative heat flux density taking into account the convection effects, using the Monte Carlo Method (MCM) [5] specially adequate for complex, non-linear mathematical models in indirect measurement, as this is the case.

In order to discuss this approach, two experimental examples were studied: the room-corner fire test in which the heat flux meter sensor head (with a cylindrical shape) is totally exposed to the air flow (figure 1.a); and the radiant panel fire test in which only the top sensor surface is exposed to the air flow (figure 1.b). Since the air flow over the top surface of the sensor depends on the exposure condition, the convective heat transfer will also be different. This fact was considered to be significative and, therefore, should be accounted for in the applied mathematical model regarding the indirect measurement, as shown in section 2.

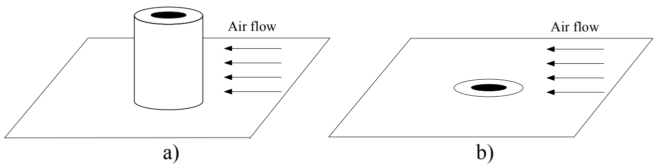

Figure 1. Different exposure conditions of the heat flux meter sensor head.

For both studied examples, the MCM method also allows a detailed analysis of the different input uncertainty contributions to the measurement uncertainty of the output quantity.

2. INCIDENT RADIATIVE HEAT FLUX DENSITY MEASUREMENT MODEL

The establishment of the incident radiative heat flux density measurement model implies performing an energy balance of the different heat transfer modes at the surface of the heat flux meter sensor head.

Figure 2 represents the surface and the control volume in which it is possible to identify the following heat transfer modes and corresponding heat flux densities:

- incident radiation, $\varphi_{\text{rad, inc}}$, originated by the high temperatures of the surrounding elements when performing a reaction to fire test;
- reflected and emitted radiation by the surface of the heat flux meter sensor head, $\varphi_{\text{rad, ref}}$ and $\varphi_{\text{rad, em}}$, respectively;
- convection, φ_{conv}, created by the air flow with temperature T_∞ and velocity u_∞ on the sensor surface;
- conduction, φ_{cond}, from the warm external surface to the cooled inner core.

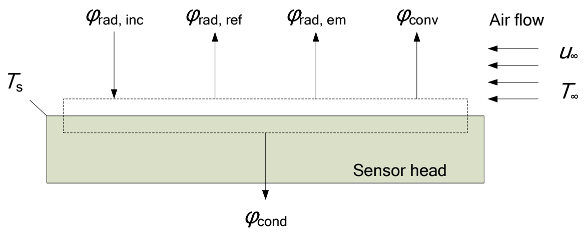

Figure 2. Energy flux transfer at the sensor head and influence quantities.

Assuming a steady-state condition, the energy balance can be expressed by the following model for incident radiative heat flux density quantity:

$$\varphi_{\text{rad, inc}} = \varphi_{\text{rad, ref}} + \varphi_{\text{rad, em}} + \varphi_{\text{cond}} + \varphi_{\text{conv}} \ . \tag{1}$$

In the determination of the other radiative terms, the surface of the sensor head is considered diffuse and grey, i.e, the surface's absorptivity and emissivity are taken as independent from the radiation direction and wavelength. With this assumption, the surface's emissivity, ε_{s}, is equivalent to its absorptivity, α_{s}, being the reflected radiation heat flux density given by

$$\varphi_{\text{rad, ref}} = \left(1 - \varepsilon_{\text{s}}\right) \varphi_{\text{rad, inc}} \ , \tag{2}$$

and the emitted radiation heat flux density

$$\varphi_{\text{rad, em}} = \varepsilon_{\text{s}} \ \sigma \ T_{\text{s}}^4 \ , \tag{3}$$

where σ is the Stefan-Boltzmann constant and T_{s} is the surface temperature of the heat flux meter sensor head.

The evaluation of the conduction heat flux density estimate is obtained using expression (1) being based on the heat flux meter calibration. The LNEC/LERF heat flux meter is calibrated by the spherical black-body cavity method, according with ISO 14934-2 (2006). This method implies the decrease of the convective effect on the heat flux meter to a minimum in such a way that it can be considered negligible. In this case, the energy balance is given by the following expression

$$\varphi_{\text{rad, inc}} = \varphi_{\text{rad, ref}} + \varphi_{\text{rad, em}} + \varphi_{\text{cond}} \ . \tag{4}$$

It is possible to establish a linear relation between the heat flux meter output voltage, V, and the incident radiative heat flux density based on the calibration results, i.e,

$$\varphi_{\text{rad, inc}} = C \ V \ , \tag{5}$$

where C is the calibration constant.

Applying the previous expression together with expressions (2) and (3) to the energy balance, expression (5) allows to write the conduction heat flux density as

$$\varphi_{\text{cond}} = \varepsilon_{\text{s}} \left(C \ V - \sigma \ T_{\text{s, cal}}^4 \right), \tag{6}$$

in which $T_{\text{s, cal}}$ corresponds to sensor head surface temperature during calibration.

The convective term presented in expression (1) can be expressed in general as

$$\varphi_{\text{conv}} = \bar{h}\left(T_s - T_\infty\right), \tag{7}$$

where $\bar{h}$ is the average convection heat transfer coefficient, being dependent on several parameters such as the surface geometry, the nature of the air flow (laminar or turbulent) and its thermophysical properties.

For both exposure conditions studied (displayed on figure 1), laminar air flow was considered and the thermophysical properties of the air flow refer to the film temperature (average temperature between the air flow temperature and the surface temperature of the heat flux meter sensor head). However, the surface geometry is different in each case, requiring the use of adequate convection coefficients.

According to [4], a reasonable coefficient estimate for the first exposure condition corresponds to

$$\bar{h} = \frac{0{,}24 \ u_\infty^{\frac{2}{3}} \ k}{\nu^{\frac{2}{3}} \ d^{\frac{1}{3}}} \ , \tag{8}$$

where k and ν are the air flow thermal conductivity and the cinematic viscosity at film temperature, respectively, and d is the sensor head diameter.

For the second exposure condition, the flat plate approach was considered and, according to [6], the average convection heat transfer coefficient in a laminar flow is given by

$$\bar{h} = \frac{0{,}664 \ Re^{\frac{1}{2}} \ Pr^{\frac{1}{3}} \ k}{d} \ , \tag{9}$$

being Re the Reynolds number and Pr the Prandtl number. This expression is valid only for $0{,}6 \le Pr \le 50$.

Introducing the previous deducted expressions of the heat flux density terms into expression (1), the incident radiative heat flux density measurement model for the first exposure condition becomes

$$\phi_{\mathrm{rad,inc}} = \frac{1}{\varepsilon_{\mathrm{s}}}\left[\frac{0{,}24\, u_\infty^{\frac{2}{3}}\, k}{\nu^{\frac{2}{3}} d^{\frac{1}{3}}}\left(T_{\mathrm{s}} - T_\infty\right) + \varepsilon_{\mathrm{s}}\, \sigma \left(T_{\mathrm{s}}^4 - T_{\mathrm{s,cal}}^4\right) + \varepsilon_{\mathrm{s}}\, C V\right], \qquad (10)$$

and for the second exposure condition

$$\phi_{\mathrm{rad,inc}} = \frac{1}{\varepsilon_{\mathrm{s}}}\left[\frac{0{,}664 Re^{\frac{1}{2}} Pr^{\frac{1}{3}} k}{d}\left(T_{\mathrm{s}} - T_\infty\right) + \varepsilon_{\mathrm{s}}\, \sigma \left(T_{\mathrm{s}}^4 - T_{\mathrm{s,cal}}^4\right) + \varepsilon_{\mathrm{s}}\, C V\right]. \qquad (11)$$

3. MEASUREMENT UNCERTAINTY EVALUATION

According to expressions (10) and (11), both mathematical models share the same input quantities, with exception of the Prandtl number only used in the second model (the Reynolds number in the same expression can be written as a function of u_∞, d and ν), as illustrated by the functional diagram exhibited in figure 3.

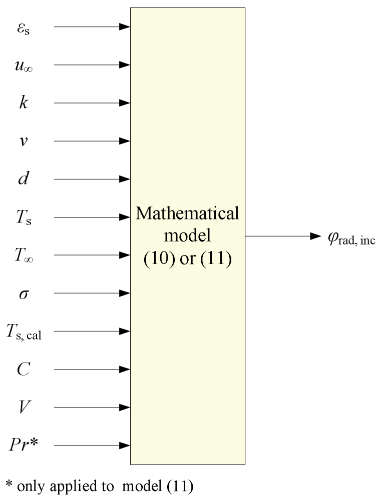

Figure 3. Functional diagram of the studied examples.

In the exposition condition related with the room-corner test (figure 1.a), the probabilistic formulation of the input quantities used in the MCM simulation is the same as the one presented in [4] which adopts the GUM approach. This allows a comparison between the measurement uncertainties obtained by both methods.

In the second case, associated with the radiant panel test (figure 1.b), the input data was based on the available information at LNEC/LERF regarding the heat flux meter used and the recorded test conditions, namely, the air flow temperature and velocity near the heat flux meter sensor head, both being determined experimentally.

MCM accuracy is strongly dependent on the quality of the tools used to perform the computational work. For the present studies the Mersenne Twister pseudo-random generator [7] was used, being able to generate numerical sequences with a dimension of 10^6 elements, and validated algorithms to perform the probability distributions conversions and the output sorting were used in accordance with [8]. The computational accuracy level of the numerical simulations was achieved using [9].

One of the aims of the study developed was to find out if any of the input quantities were dominant in what concerns the uncertainty budget. With this purpose, MCM simulations were carried out, considering each input quantity negligible at a time and doing a comparison of the measurement uncertainties.

4. CONCLUSIONS AND FINAL REMARKS

The present study allows the evaluation of measurement uncertainty estimates associated with the heat flux density quantity in reaction to fire tests, taking into account the convective effects originated by the exposure of heat flux sensor head to the surrounding environmental conditions.

The two main approaches to the exposure conditions of the heat flux meter sensor head were studied and from the results obtained it is possible to discuss which of them can lead to a higher accuracy level and, also, which of the input measurands should be considered dominant regarding the heat flux measurement uncertainty. This last comparison can be particularly useful in order to increase the overall measurement accuracy.

An important remark is the fact that the measurement uncertainties in this field are not very common and are usually obtained using the GUM method [4] which, due to the nature of the mathematical models involved, can lead to less accurate solutions. The use of MCM overcomes the models constrains, being able to provide appropriate convergent solutions for these metrological problems.

Despite considering that MCM provides a correct approach to the measurement uncertainty calculation stage, improvements are still possible in the formulation stage, since approximations are assumed in the probabilistic characterization of some input quantities. This is mentioned as a possible future trend of investigation.

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