Influence of a misalignment of the cone or the sample holder on the view factor with a Monte Carlo approach

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ABSTRACT
The cone calorimeter is a fire test internationally standardized as ISO 5660-1 [1], developed at The National Institute of Standards and Technology in the 1980’s [2]. It allows to study different flammability and combustibility parameters, as the ignition time, mass loss, mass loss rate, gaseous emissions and the rate of heat released by materials exposed to radiant heat flux. However, the results obtained with this set-up are clearly dependent on several critical points, especially the aeraulic conditions around the material and the radiation thermal stress imposed to the material. It appears important to properly characterize this last one to ensure that the parameters obtained experimentally are correlated to the true experimental conditions.

Among the critical points, the incident flux received by the sample holder through the radiant spirals of the cone calorimeter is identified as being the most significant. This incident flux depends on the temperature and the radiative properties of the spirals, and on the view factor between the spirals and the sample. This work focuses on the latter, and most specifically on the sensitivity evaluation of the geometrical parameters on the incident radiative flux. In order to determine the view factor, two distinct strategies may be applied. The first one is the algebraic derivations of geometric view factor that may be fastidious when the geometrical configuration increase in complexity. The second one consists in a rigorous experimental study by measuring the incident flux at different locations of the sample holder using flux meter. However, this approach is time-consuming and concedes a lot of measurement uncertainties. This article presents an intermediate method, easy, precise and allowing a parametrical study (axiality, horizontality, radiation coefficient, dimensions etc.) by means of a numerical Monte Carlo method.

KEYWORDS
Suggested Keywords: cone calorimeter, numerical method of Monte Carlo, view factor, uncertainty, experimental error, homogeneity of the radiative flux.
INTRODUCTION

The Construction Products Regulation [3] requires the qualification of the fire reaction of building materials. This is why the cone calorimeter is very widely used. However, this type of device is also used in the field of research and development, in order to compare newly created materials, as well as for the development and validation of numerical models.

As stated by Guillaume et al. [4], it is essential during experimental investigations to determine test bench uncertainties. In fire safety science, at small scale, the experimental uncertainties depend both on the heterogeneity of materials (especially for polymers and natural materials) and the accuracy of the different measurement sensors (temperature, oxygen concentration, differential pressure...) [5, 6, 7, 8, 9]. Other parameters (i.e. the positioning of the igniter, the radiant spiral and finally the sample holder) that are difficult to model mathematically are taken into account in the calculation of uncertainty by repeatability and reproducibility [4]. However, it is interesting to know the numerical impact of these parameters.

This study can be conducted experimentally with a flow meter like Wilson et al. [10] and Kang et al. [11], but the experimental errors are too important and the measurement not fine enough. This observation motivated us to develop a numerical method in order to study the biases with regard to the positioning of the different devices. To reach this aim, a radiation transport model based on a Monte Carlo approach is developed following the concept described in the reference book of Modest [12].

The interest of this paper thus relies in an explorative research of the uncertainties associated with the relative positioning of the sample holder and the radiant spiral. Indeed, the sources of errors related to the positioning of these two devices consist of (as illustrated on Fig. 1): i) the axiality of the sample holder with respect to the radiant spiral; ii) the horizontality of the sample holder and the radiant spiral; and iii) the distance between the sample holder and the radiant spiral. To determine the effect of the three parameters considered, we compare the results obtained with the ideal configuration (according to ISO 5660-1 [1]).

![Schematic diagram of the main errors of implementation and dimensions of the cone.](image)

It should be noticed that the ISO 5660-1 [1] requires the control of axiality and horizontality in the context of regulatory tests. Therefore, this study is only relevant for fundamental and applied research trials, especially when specific sample holders are used.

MONTE CARLO RADIATIVE APPROACH TO DETERMINE THE VIEW FACTOR

The Monte Carlo method is a probabilistic numerical approach that consists in simulating the trajectory of quanta (i.e. bundles of energy), in a ballistic way, from an emitting sub-surface to a receiving one. For more information on this method you may refer to Modest [12].

In this study, the radiative scene is composed of the elements described previously, namely: the cone calorimeter and the sample holder, each of them being discretized into squared cells.

The sum of energy (proportional to the number of quanta) received by an elementary cell of the target, divided by the incident heat flux emitted from the radiative source, allows to calculate, thanks to Eq. 1, the view factor of the element.

\[
F_{\text{ve}} = \frac{\hat{q}_{e}}{\hat{q}_{e}} = \frac{N_{r}/S_{r}}{N_{t}/S_{t}}
\]

Where

- \( F_{\text{ve}} \): View factor of each discretized element
\( \dot{q}_c \): Received heat flux (sum of specific energy of a quanta) (kW.m\(^{-2}\))

\( \dot{q}_e \): Incident heat flux from cone calorimeter (kW.m\(^{-2}\))

\( N_r, N_e \): Respectively the number of received and emitted quanta (kW)

\( S_r, S_e \): Respectively the surface of reception and emission (m\(^2\))

It is well-known that stochastic methods need a certain amount of quanta in order to produce an accurate resolution, in this case a view factor spatial distribution. The higher the number of photons shot, the better the result. One can notice that the calculation time is directly proportional to the number of quanta used. There is no specific rule to estimate the number of quanta needed to solve a radiative problem. In our case, we choose to perform 10 simulations with a number of quanta between \(10^{10}\) and \(10^{12}\) to determine when the standard deviation stabilizes.

To illustrate this point, Fig. 2 presents the evolution of the convergences with respect to the number of quanta simulated. When \(10^{10}\) quanta are drawn (1.25e\(^6\) quanta shot per surface), the CPU time with a single Intel Core I7-5500 U processor (2.4 GHz) and 8 Go RAM is about 4.5 min. It is 43.9 min and 475.5 min respectively for \(10^{11}\) and \(10^{12}\) quanta shot (1.25e\(^6\) and 1.25e\(^7\) quanta shot per surface).

![Simulation results of Monte Carlo radiative evaluation of the impact of the cone calorimeter on a plate plane using different number of quanta.](image)

Fig. 2. Simulation results of Monte Carlo radiative evaluation of the impact of the cone calorimeter on a plate plane using different number of quanta.

With a fine mesh of the sample holder (0.5 mm by 0.5 mm), Fig. 2b shows that a short calculation time (45 min equivalent to \(10^{11}\) quanta shot) is enough to obtain a relative standard deviation that starts to stabilize at 6.94%. Below this value, the quantity of quanta is insufficient to obtain a satisfactory solution (considering homogeneity) especially when the number of quanta is about \(10^{10}\) (Fig. 2a). To obtain a precise result (net outline of the different zones), it is necessary to shot at least \(10^{12}\) quanta above which the value of the relative standard deviation is constant at 6.93% (Fig. 2c).

**VALIDATION OF THE MONTE CARLO RADIATIVE APPROACH**

In order to validate the present model, the view factor obtained, using \(10^{12}\) quanta, are compared with values from literature [11] in Table 1. The comparison is performed with values at the centre of a horizontal plane for different altitude of the cone.

| Z (mm) | Present study | Ref. [11] | Relative error (%) |
|-------|---------------|-----------|--------------------|
| 15    | 0.7650        | 0.7660    | 0.13               |
| 20    | 0.7586        | 0.7599    | 0.17               |
| 25    | 0.7452        | 0.7461    | 0.12               |
| 30    | 0.7255        | 0.7261    | 0.08               |
| 35    | 0.7008        | 0.7014    | 0.08               |

Table 1 shows that the results obtained are in perfect agreement with other studies. The relative errors calculated for all values are very low and the maximum error is reached for the height of 20 mm with only 0.17 %. This analysis confirms the feasibility to determine the view factor using the present Monte Carlo approach.


**SENSITIVITY ANALYSIS**

**Distance between the cone and the sample holder**

The positioning error between the cone and the sample holder, due to an incorrect installation of the sample holder for example, may affect the homogeneity of the incident flux. According to ISO 5660-1 [1], intumescent materials are positioned at 50 mm instead of 25 mm from the cone.

To study the effect of the distance on the incident radiative heat flux, simulations are performed with the distance between the cone and the sample holder ranging from 10 mm to 50 mm along the z axis. Firstly, the variation of the view factor along the z-axis is studied by generation the view factor distribution in the x-z plane at y=0. Then, the view factor distribution on the exposed surface (x-y plane) at different axis (z=23, 25, 27 and 50 mm) from the cone is interpreted.

Table 2 presents the average, the minimum and the maximum values of the view factor in the x-y plane at different heights. The standard deviation is calculated over the entire mesh of the exposed surface (200 × 200 values). The variation of the distance between the cone and the sample holder impacts particularly the maximum values and the homogeneity of the view factor on the exposed surface.

![View Factor Distribution](image)

**Table 2. Minimum, maximum and standard deviation of view factor of x-z plane of the sample holder.**

| Z (mm) | View factor |    |    |    |    |
|--------|-------------|----|----|----|----|
|        | Average | Min. | Max. | SD. | RSD. (%) |
| 10     | 0.7937 | 0.7675 | 0.8044 | 0.0093 | 1.2  |
| 20     | 0.6442 | 0.5931 | 0.6678 | 0.0216 | 3.3  |
| 25     | 0.5769 | 0.5196 | 0.6051 | 0.0248 | 4.3  |
| 30     | 0.5146 | 0.4528 | 0.5440 | 0.0263 | 5.1  |
| 40     | 0.4078 | 0.3503 | 0.4377 | 0.0255 | 6.2  |
| 50     | 0.3221 | 0.2723 | 0.3493 | 0.0221 | 6.8  |

Table 2 shows that the further the sample holder is from the cone, the more homogeneous and weak the factor of view is. Indeed, less than 10 mm below the cone, the standard deviation is very low. On the contrary, the standard deviation for distances between 20 and 50 mm below the cone is stable and at least twice as large as at 10 mm. The relative standard deviation continues to increase depending on the distance of the cone. Even if the incident flux is theoretically identical at the center of the sample at 25 and 50 mm, the thermal stress conditions of the exposed surface vary strongly between these two positions. Therefore, it is difficult to compare the fire behaviour of two materials at 25 and 50 mm (i.e. non-intumescent and intumescent materials). This observation is all the truer that the aerulic conditions are also different.

On the other hand, Table 3 shows that an incorrect installation of the sample holder of ±2 mm (25±2 mm from the cone) does not significantly impact the view factor and so the incident flux received by the exposed surface. Thus, the requirement of the standard on this point is relevant.

**Table 3. Minimum, maximum and standard deviation of view factor of x-y plane of the sample holder (exposed surface) as a function of the distance.**

| Z (mm) | Average view factor | Minimum view factor | Maximum view factor | SD. | RSD. (%) |
|--------|---------------------|---------------------|--------------------|-----|---------|
| 23     | 0.7360              | 0.5502              | 0.7576             | 0.0295 | 4.0     |
| 25     | 0.7221              | 0.5289              | 0.7452             | 0.0331 | 4.6     |
| 27     | 0.7078              | 0.5140              | 0.7382             | 0.0364 | 5.1     |
| 50     | 0.5430              | 0.3744              | 0.6129             | 0.0481 | 8.9     |

**Axiality of the sample holder**

A bad axiality is caused by a misalignment of the sample holder on the weighting device and/or the radiant spiral in the cone.
To study the impact of axially or eccentricity, it is chosen to center the sample holder from 0 mm (reference case) to 20 mm along one axis (x or y) and from 0 mm to 10 mm along two axes (x and y). The sample holder is positioned at 25 mm under the cone.

Table 4. Minimum, maximum and standard deviation of view factor of x-y plane of the sample holder (exposed surface) as a function of the axially.

| Decentred value | View factor | Average | Minimum | Maximum | SD. | RSD. (%) |
|-----------------|-------------|---------|---------|---------|-----|---------|
| X (mm) | Y (mm) | | | |  |
| 0 | 0 | 0.7233 | 0.5480 | 0.7452 | 0.0311 | 4.3 |
| 1 | 0 | 0.7232 | 0.5386 | 0.7453 | 0.0312 | 4.3 |
| 5 | 0 | 0.7218 | 0.4949 | 0.7453 | 0.0347 | 4.8 |
| 10 | 0 | 0.7171 | 0.4301 | 0.7457 | 0.0444 | 6.2 |
| 20 | 0 | 0.6972 | 0.2877 | 0.7457 | 0.0779 | 11.2 |
| 1 | 1 | 0.7232 | 0.5292 | 0.7416 | 0.0314 | 4.3 |
| 5 | 5 | 0.7203 | 0.4365 | 0.7440 | 0.0380 | 5.3 |
| 10 | 10 | 0.7108 | 0.3106 | 0.7419 | 0.0562 | 7.9 |

Table 4 shows that a small centering error (up to 5 mm), when placing the sample holder or the radiant spiral, has a small impact on the exposed surface. It is necessary that the decentering must be strong to have a significant impact on the factor of view: at least 10 mm. This configuration never occurs when the sample holder is in position unless decentering is voluntary. On the other hand, the risk is higher when repositioning the spiral. However, a displacement less than 5 mm may be considered as inconsequential on view factor estimation.

Horizontality of the sample holder or the cone

A bad horizontality is caused by a misalignment of the sample holder or the cone. To study the influence of such defect, it is chosen to vary the tilt angle from the horizontal axis of the sample from 0° (reference case) to 6°. In other words, a 10 mm offset from one side to another when the dimensions of the sample holder are 100 x 100 mm² (length x width). The sample holder is positioned at 25 mm from the cone.

Table 5. Minimum, maximum and standard deviation of view factor of x-y plane of the sample holder (exposed surface) as a function of horizontality.

| Tilt angle (°) | Average view factor | Minimum view factor | Maximum view factor | SD. | RSD. (%) |
|---------------|---------------------|---------------------|---------------------|-----|---------|
| 0 | 0.7203 | 0.5416 | 0.7459 | 0.0301 | 4.2 |
| 1 | 0.7203 | 0.5333 | 0.7474 | 0.0304 | 4.2 |
| 2 | 0.7203 | 0.5248 | 0.7492 | 0.0313 | 4.3 |
| 3 | 0.7203 | 0.5163 | 0.7523 | 0.0327 | 4.5 |
| 4 | 0.7203 | 0.5077 | 0.7554 | 0.0345 | 4.8 |
| 5 | 0.7203 | 0.4992 | 0.7593 | 0.0368 | 5.1 |
| 6 | 0.7203 | 0.4906 | 0.7646 | 0.0393 | 5.5 |

An error of horizontality, as important as it may be, does not seem to affect the average view factor of the exposed surface. On the other hand, the distribution of the view factor at the surface is impacted. For a tilt angle value inferior to 2°, the relative standard deviation is not affected and is about 4.2%. For higher angle values, the relative standard deviation increases slightly until it reaches nearly 5.5% with a tilt angle of 6° (figure of Table 5). The difference between the maximum and minimum view factors increases more and more with angle, leading to an increase in heterogeneity of the radiation exposure.

CONCLUSION

The results of this numerical study show that:

- It is also shown that the positioning of the cone or the sample holder (distance or misalignment) strongly impact the homogeneity of the flux received by the sample. Therefore, depending on the physical parameter studied, not all materials can be compared with each other, especially with regard to intumescent materials. Moreover, a misalignment of a few millimeters is negligible on the distribution of the factor of view.
However, the incident flux becomes more and more homogeneous when the sample holder moves away from the cone.

- The impact of axially on the distribution of the view factor on the exposed surface has little effect for an eccentricity inferior to 10 mm. Beyond, the impact is significantly large.
- The impact of axially by a few millimeters is negligible on the distribution of the factor of view.
- The impact of a horizontality error is negligible as long as the angle of inclination is lower than 3°. The minimum and maximum view factors are impacted.
- This study can be extended to other normative benches such as the IMO-LIFT, (ISO 5658 [13]).
- The Monte Carlo numerical approach makes it possible to propose an alternative method to experimental method which involves introducing new uncertainties due to the properties of the sensor and its positioning.

Knowing the view factor, the emissivity of the material, the temperature of the radiating spirals and the Stefan-Boltzmann constant, the incident flux on the exposed surface can be determined. Thus, it is possible to determine the energy loss or gain generated by these errors.

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REFERENCES

[1] International Standard Organisation, “ISO 5660-1 Reaction-to-fire tests -- Heat release, smoke production and mass loss rate - Part 1: Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement)”, Genève: ISO, 2002, p. 45. https://doi.org/10.3403/30255889.

[2] Babrauskas, V., “Development of the cone calorimeter – A bench-scale heat release rate apparatus based on oxygen,” Fire and Materials, vol. 8, pp. 81-95, 1984, https://doi.org/10.1002/nbm.82-261.1.

[3] The European Parliament, “Regulation (EU) No 305/2011 of the European Parliament and of the council of 9 March 2011,” Official Journal of European Union, vol. L 88, pp. 5-43, 2011.

[4] Guillaume, E., Marquis, D., Saragoza, L. and Yardin, C., “Uncertainty on heat release rate measurement with cone calorimeter during the combustion of a material,” Revue Française de Métrologie, Vols. 2012-3, no. 31, pp. 3-11, 2012.

[5] Enright, P. and Fleischmann, C., “Uncertainty of Heat Release Rate Calculation of the ISO5660-1 Cone Calorimeter Standard Test Method,” Fire Technology, vol. 35, no. 2, pp. 153-169, 1999.

[6] Zhao, L., “Bench scale apparatus measurement uncertainty and uncertainty effects on measurement of fire characteristics of material system,” Worcester polytechnic Institute, 2005.

[7] Zhao, L. and Dembsey, N., “Measurement uncertainty analysis for calorimetry apparatuses,” Fire and Materials, vol. 32, no. 1, pp. 1-26, 2008, https://doi.org/10.1002/fam.947.

[8] Brohez, S., “Comments to the paper uncertainty of heat release rate calculation of the ISO5660-1 cone calorimeter standard test method,” Fire Technology, vol. 45, no. 4, pp. 381-384, 2009, https://doi.org/10.1007/s10694-008-0050-z.

[9] Guillaume, E., Marquis, D. and Saragoza, L., “Calibration of flow rate in cone calorimeter tests,” Fire and Materials, vol. 38, no. 2, 2012, https://doi.org/10.1002/fam.2174.

[10] Wilson, M., Długogorski, B. and Kennedy, E., “Uniformity of radiant heat fluxes in cone calorimeter,” Fire Safety Science, vol. 7, pp. 815-827, 2003, https://doi.org/10.3801/iafss.fss.7-815.

[11] Kang, S., Choi, S. and Choi, J., “View factor in cone calorimeter testing,” International Journal of Heat and Mass Transfer, vol. 93, pp. 217-227, 2016, https://doi.org/10.1016/j.ijheatmasstransfer.2015.09.067.

[12] Modest, M. F., “Radiative Heat Transfer (Third Edition),” Academic Press, Amsterdam, 2013, p. 904, https://doi.org/10.1016/B978-0-12-386944-9.50026-1.

[13] International Organization for Standardization, “ISO 5658-2:2006+A1:2011 - Reaction to fire tests - Spread of flame - Part 2: Lateral spread on building and transport products in vertical configuration,” International Organization for Standardization, Genève, 2006, p. 35, https://doi.org/10.3403/30090264.