Thermal Exposure in Fire Resistance Furnaces

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ABSTRACT

Over the last six years, CEN TC 127 and more in particular its working groups ad hoc 14 and ad hoc 7 have been active in evaluating and improving the reproducibility of fire resistance testing. Ad hoc 14 developed a draft procedure for the evaluation of the performance of fire resistance furnaces in 1994. The two working groups were subsequently responsible for an extensive series of proving tests aimed at evaluating the procedure, but also at investigating the possible role of the Plate Thermometer in harmonising thermal exposure.

The results of the work are that, when furnaces are controlled using small diameter sheathed thermocouples, the thermal exposure of a test specimen differs greatly over the various furnaces. Controlling the furnaces on Plate Thermometer readings brings thermal exposures much closer together. This paper gives an overview and a quantitative explanation of the findings.

KEY WORDS: Fire resistance, Furnace Calibration, Furnace Performance, Plate thermometer.

INTRODUCTION

It is commonly known that the test methods for fire resistance have a rather low reproducibility. This is true even when the furnaces are operated within the limits set by current test standards. Up to recently however, very little reliable quantitative information was available to corroborate the doubts and to support actions to solve the problem.

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The problem of unsatisfactory reproducibility of the fire resistance test methods is perhaps the single most important technical issue standing in the way of (European) harmonisation of fire resistance testing and thereby of the CE marking of construction products. The development of requirements to the equipment, i.e. the furnaces and installations, has been taken up in 1993 by working group ad hoc 14 of CEN TC 127, later also by ad hoc 7.

This paper aims to report to the wider fire community the work of ad hoc 14 and ad hoc 7 of CEN TC 127, and to explain the major features of the solutions they have proposed.

CONTROL OF THERMAL EXPOSURE

The discussion in this paper will focus on thermal aspects within the furnace. In current national and international standards, the thermal exposure to a specimen is controlled by prescribing that the average temperature in the furnace must follow the Standard Fire Curve within well defined bounds. The average temperature is determined from the reading of small (diameter up to 3 mm) bare or sheathed thermocouples (TC's), distributed over the surface of the specimen at 100 mm distance from the specimen. Requirements to the furnace are limited to the properties of the wall linings (density or thermal inertia).

WORK WITHIN ISO AND CEN

From the known reproducibility problems it is clear that the above requirements do not control the thermal exposure to a specimen to a sufficient degree. SP in Sweden have suggested the development of two pieces of equipment in CIB W14 [1]:

The Plate Thermometer (PT, see fig. 1). This instrument was developed to replace the standard small thermocouples (TC) for controlling furnaces [2]. When furnaces heat up, different designs will lead to different convective (gas) and radiation temperatures experienced at the standard distance of 100 mm from the specimen. If either one or both heat transfer coefficients at the specimen differs from those at the sensor, differences between radiation and convection temperature will lead to differences in heat flux to the test specimen and the sensor.

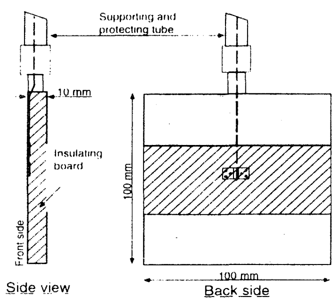


FIGURE 1 The Plate Thermometer

The radiative heat transfer coefficient does not depend on the size of the heated object. The convective heat transfer coefficient does: a very small object such as a sheathed 1 or 3 mm thermocouple experiences a high heat transfer coefficient, whereas an object of 10 cm square experiences a much lower heat transfer coefficient due to the development of a boundary layer next to it. Due to its large size, the PT is much more representative for the heat transfer to a real test specimen than the small TC.

For a theoretical treatment of the advantages of using the PT rather than the TC to control the furnace, refer to Annex 1.

CALIBRATION ELEMENT (CE, see fig. 2)

This was designed in the 80's as a reference test specimen for calibrating furnaces [3]. It is essentially a sandwich construction made up from two steel plates with a ceramic insulation board in between. The sandwich is mounted in a recessed opening in a concrete wall. Temperatures are measured on both steel plates. Thermal exposure in different furnaces is assumed to be the same if the temperature response of the exposed steel plate is the same during a fire resistance test.

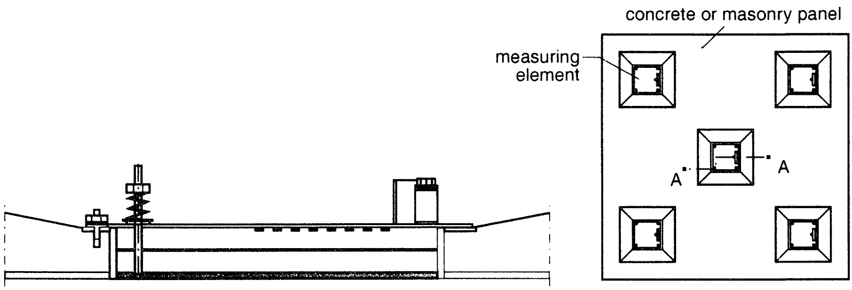


FIGURE 2 Calibration element and assembly wall

PROVING TEST SERIES BY AD HOC 14

A total number of 14 laboratories participated in the proving test series carried out under the auspices of ad hoc 14 after completion of a draft calibration procedure in 1994 [4]. Main features of the proving test programme included:

- emphasis on the performance of well insulated separating elements
- inclusion of both vertical and horizontal furnaces.

With the aim to improve the significance of comparisons of results obtained in different furnaces, details of the test protocols have been strictly defined. Amongst these: all TC and PT for furnace control were supplied from one source and the same batch. Four sets of calibration elements were circulated among the participating laboratories. Control tolerances were reduced.

During the tests, both the thermal exposure inside the furnace and the thermal response at the unexposed side of the insulation element have been investigated. The proving tests were organised in five phases according to the following table:

TABLE 1. Overview of Ad hoc 14 tests

Phase no.	Furnace control	Orientation	Curve	No. of labs	Ref.	Subject
1	TC	Vertical	Standard	14	[5]	TC control
2	PT	Vertical	Standard	3	[6]	Confirmation under PT control
3	PT	Vertical	Slow, Hydro Carbon	3	[7]	Other fire curves
4	PT	Horizontal	Standard	8	[8]	Horizontal furnaces
5	PT	Vertical	Standard	3	[9]	Poorly insulated specimens

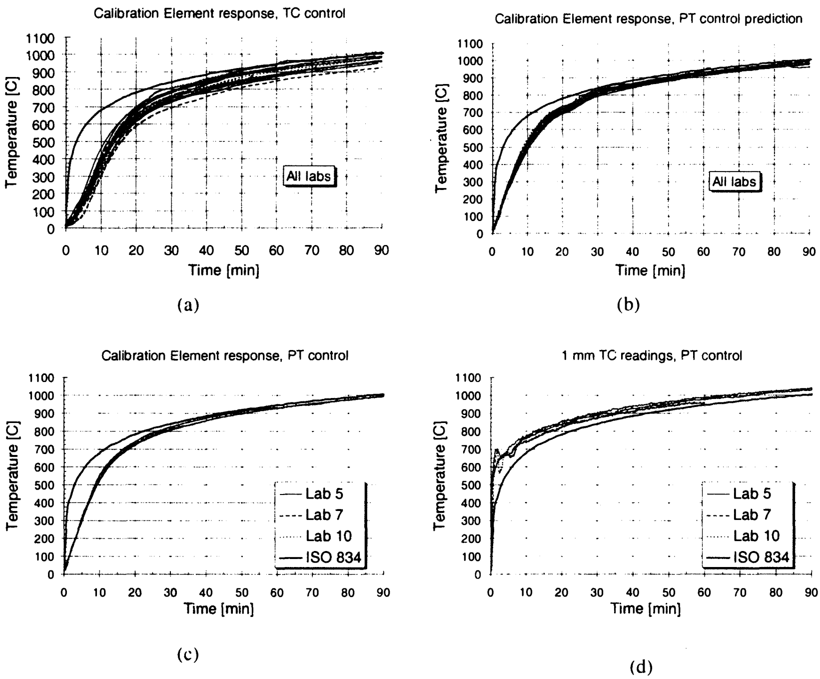


FIGURE 3 Results of adhoc 14 tests.

Fig. 3(a) shows the "raw" results of all 14 tests of Phase 1: the temperature development at the exposed side of the calibration elements, averaged over the 5 elements in the assembly wall. The highest curve represents the standard fire curve. It is seen that the scatter between all 14 responses is substantial: a bandwidth of about 100 °C.

Fig. 3(b) shows curves that represent the expected response if the tests of Phase 1 would have been run under PT instead of TC control. The expected response was determined from a perturbation calculation using a thermal model of the heat transfer through the Calibration Element [5]. The bandwidth is reduced dramatically w.r.t. fig. 3(a).

Fig. 3(c) gives response curves for Phase 2, consisting of 3 tests under PT control in furnaces that had had results far apart in fig. 3(a). The results confirmed the expectations from Phase 1, in that the measured bandwidth is within the limits set up by the predictions of 3(b)

Fig.3(d) presents information relevant to the influence of PT control on the "severity" of the tests. It shows that in all three furnaces involved, small thermocouples read consistently higher temperatures than the PT. In other words, compared with TC control, the test under PT control leads to a higher temperature in the furnaces (as measured with the TC) and therefore to higher thermal exposure of the specimen.

PROVING TEST SERIES BY AD HOC 7

Aim of this programme was to assess the performance of the Plate Thermometers under practical test conditions, including their contribution to harmonisation of testing, repeatability and the severity of thermal exposure. The work was divided in two phases A and B:

TABLE 2. Overview of Ad hoc 7 tests

Phase	Furnace control	Orientation	No. of tests/labs	Ref.	Test specimens
A	PT	Vertical	28/14	[10]	Partitions: CaSi, timber, glazing
	PT/TC	Vertical	6/3	[10,11]	Unprotected structural steel
B	PT	Vertical	8	[12]	2-D elements: protected steel beam, penetration seals, fire dampers

Key figures from the Phase A test results are presented in fig. 4(a) through 4(f).

Fig. 4(a) and 4(b) show furnace temperature measurements taken with different sensors in two tests on uninsulated glazing elements. In fig. 4(a) (test 24), the PT readings are only very little below the readings of 3 mm and 6 mm sheathed thermocouples located in the close vicinity of the PT. In fig. 4(b) (test 29), the PT read significantly higher (50 °C) than the TC, indicating that for this combination of furnace and specimen, a test under PT control is actually less severe than under TC control.

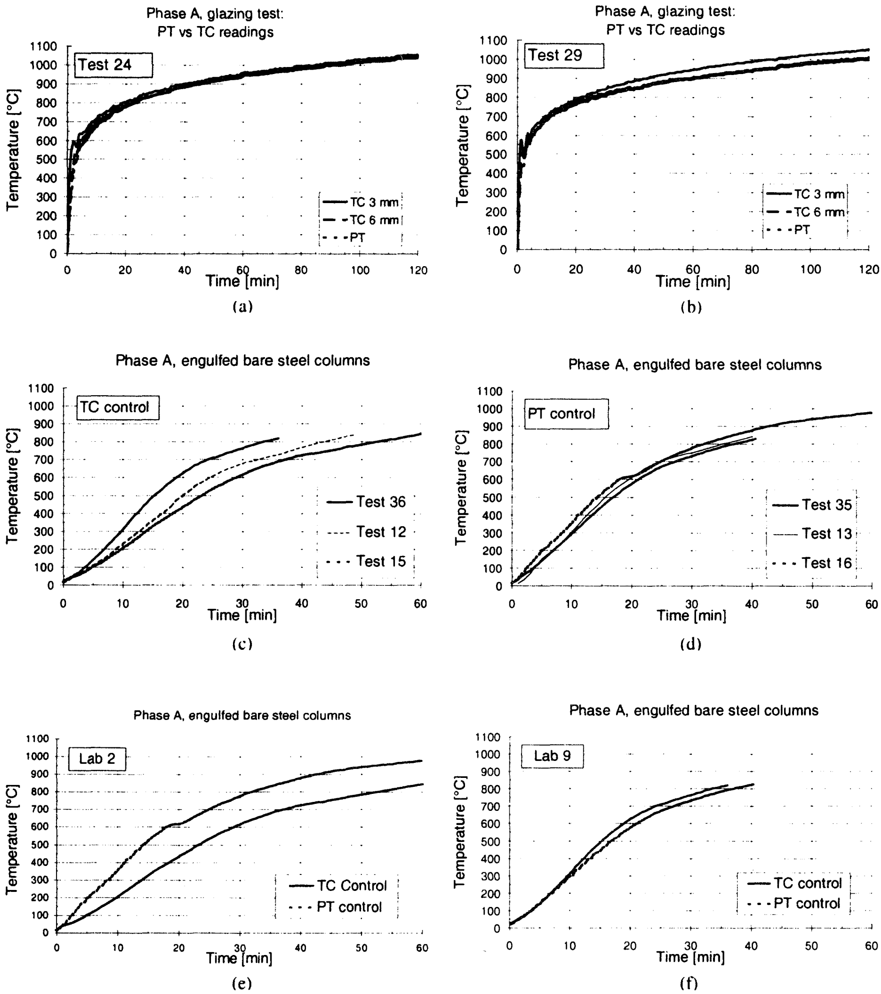


FIGURE 4 Ad hoc 7 test results

Figs. 4(c) and 4(d) show results of the 6 tests on bare steel sections. Three laboratories each carried out two tests, one under TC control and one under PT control. The large scatter of results under TC control is obvious in fig. 4(c), as is the harmonising effect of the PT in fig. 4(d).

The same data give information on the influence of control sensor on test severity. Fig. 4(e) shows that in lab no. 9 the test under PT control is substantially more severe than under PT control (a fire resistance time based on a critical temperature of 700 °C gives 37 minutes under TC control, 25 minutes under PT control). In lab 2, there is only a very small, but reverse, effect: 24 minutes under TC control, 27 minutes under PT control.

By and large the ad hoc 14 conclusions are confirmed by the ad hoc 7 test series. However, the harmonising effect of the PT on test results is partly overshadowed by the inherent scatter of the test results due to poorly defined test specimens and measuring techniques. The effect of PT control on severity of thermal exposure proved to be highly dependent on the type of element under test. The calibration element responding closer to a light structural steel element than to a highly insulating board partition.

THE INFLUENCE OF FURNACE CHARACTERISTICS ON THE RELATIVE BEHAVIOUR OF PT / TC

The use of fire curves in fire resistance tests and calculations suggests that the thermal environment within the furnace can be accurately represented by a single temperature, the furnace temperature. In reality, the thermal environment of a test specimen in a fire resistance furnace is much more complex. In a typical case, the test specimen receives heat flux contributions from a number of sources:

- convective heat flux from the furnace gas
- radiative heat flux emitted, reflected or transmitted by:
  - furnace gas
  - soot particles in the furnace gas
  - opposing furnace walls, floor, ceiling.

Since the furnace gases and walls are usually not perfectly uniform in temperature, the above contributions differ from place to place in the furnace. For the sake of argument we simplify the furnace to a gas body at uniform temperature surrounded by walls also at uniform -but different- temperature. Since the furnace gases constitute the primary heat source in the furnace, the gas temperature is always higher than the wall temperature.

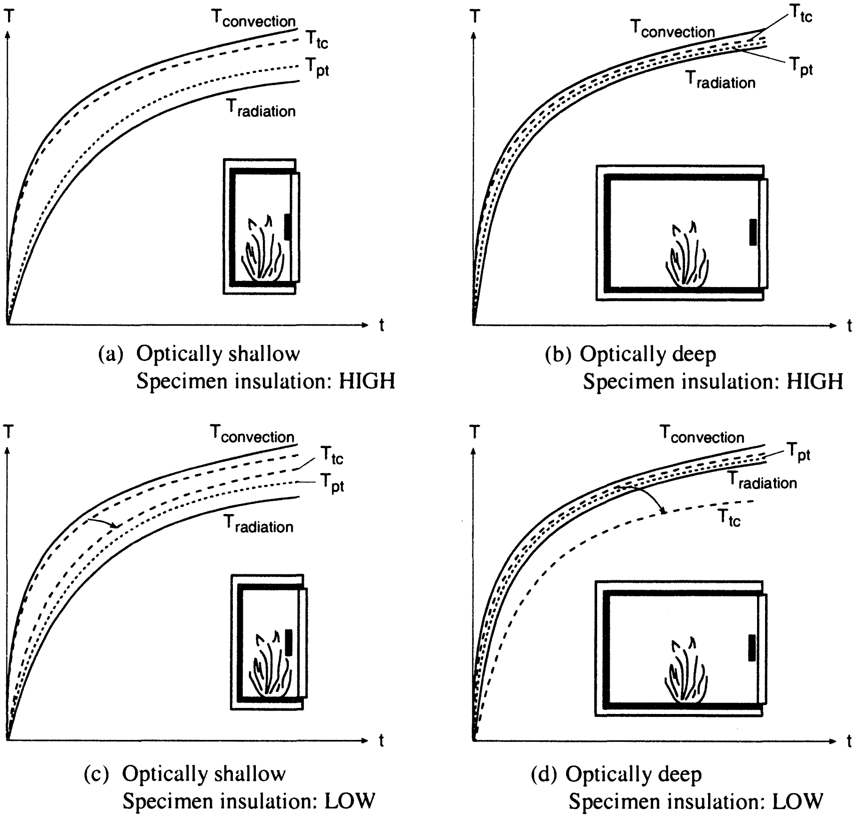
We can now distinguish between two cases:

a. The furnace is "optically shallow". The gas body is transparent to thermal radiation and/or the distance between specimen and opposing wall is small. In this case, the radiative heat flux incident on the specimen is dominated by the contribution from the opposing wall. The equivalent "radiation" temperature is lower than the gas or "convection" temperature.
b. The furnace is "optically deep". The gas body is opaque to thermal radiation and/or the distance between specimen and opposing wall is large. In this case, the radiative heat flux incident on the specimen is dominated by the contribution from the furnace gas and soot. The equivalent "radiation" temperature is equal to the gas or "convection" temperature.

Note that at the high temperature levels observed in fire resistance tests after the first few minutes, the radiative heat flux component strongly dominates the convective component. It is then easy to see that in the case of an optically shallow furnace the specimen experiences a "radiation" temperature equal to the relatively low temperature of the opposing walls. In a deep furnace, the "radiation" temperature experienced by the specimen equals the higher temperature of the furnace gas

In the light of the above, the differences between TC and PT reading can be illustrated in figure 5. The figures show sketched developments of the radiation and convection

temperatures experienced by a test specimen, as well as expected readings of a TC and a PT mounted in the usual fashion. These will both register a temperature between the radiation and convection temperature. Since a PT has a low convective heat transfer coefficient, its temperature will remain close to the lower radiation temperature. The TC with its high convective heat transfer coefficient stays close to the gas temperature.
Fig. 5(a) and 5(b) show the curves for a relatively well insulated test specimen.



(a) Optically shallow
Specimen insulation: HIGH

(b) Optically deep
Specimen insulation: HIGH

(c) Optically shallow
Specimen insulation: LOW

(d) Optically deep
Specimen insulation: LOW

FIGURE 5 Effect of furnace characteristics and specimen insulation.

In the optically shallow furnace of fig. 5(a), there is a substantial difference between the high convection temperature (= the gas temperature) and the low radiation temperature (= the wall temperature). Under these circumstances, the TC reads substantially higher than the PT.

In the optically deep furnace of fig. 5(b), the difference between the convection temperature and the radiation temperature is negligible, since they are both equal to the gas temperature. Under these circumstances, the TC and the PT give identical readings.

The influence of a poorly insulating test specimen on the above relationships is illustrated in the remaining graphs of fig. 5. The main influence is that the TC now sees over half its surface the relatively cold test specimen and reads lower, whereas the PT, which is insulated on the back and therefore does not see the test specimen, remains unaffected. The extent of the temperature drop depends highly on the temperature of the specimen.

In the optically shallow furnace of fig. 5(c), with its substantial difference between convection temperature and radiation temperature, the TC comes closer to the PT. With an extremely poorly insulating specimen, the TC reading may even end up below the PT.
In the optically deep furnace of fig. 5(d), there was virtually no difference between PT and TC reading with the insulated specimen. Any temperature drop of the TC will bring the TC reading below that of the PT.

CONCLUSIONS

- The overall effect of the Plate Thermometer is to improve the reproducibility of a fire resistance test with respect to the separating function over that afforded by 1 mm and 3 mm diameter thermocouples.
- The effect of adopting the Plate Thermometer on the severity of the test will be to change the severity for fully enclosed test specimens such as structural steelwork, to a varying degree depending on the furnace. It will slightly reduce the severity for poorly insulated specimens such as uninsulated glazed walls. For combustible walls, calcium silicate walls, fire dampers and penetration seals there is no significant change in thermal exposure level.
- Furnace performance can only be evaluated on basis of specially designed, well-defined calibration elements. Even the best practical test specimens have been found to be unsuitable for this purpose.

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ANNEX 1: THEORETICAL MODEL

The discussion below is an attempt to theoretically prove the case of the Plate Thermometer as an appropriate instrument for controlling fire resistance furnaces. It will be shown that, under simplifying assumptions, the thermal exposure of a test specimen is almost independent of properties of the furnace if the furnace is controlled such that Plate Thermometers follow a standard curve, whereas the thermal exposure does depend on furnace properties if the furnace is controlled on basis of small thermocouple readings. The treatment is an extension of [2].

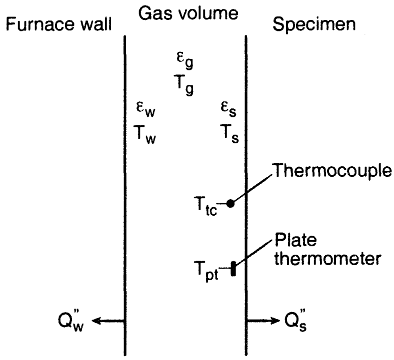

FIGURE 6 Thermal parameters

Figure 6 depicts the model representing a fire resistance furnace in this paper. In the notation, the subscripts refer to the following items: specimen (s), furnace wall (w), furnace gas (g), Plate Thermometer (pt).
The model distinguishes between convective heat transfer to the PT and to a specimen. The convective heat transfer coefficients are denoted as α.

If the furnace geometry approximates an ideal case of two infinite parallel plates, each having an emissivity equal to 1, the net heat flux entering the specimen is given by

$$Q_s'' = \alpha_s \cdot (T_g - T_s) + \varepsilon_g \cdot \sigma \cdot T_g^4 + (1 - \varepsilon_g) \cdot \sigma \cdot T_w^4 - \sigma \cdot T_s^4$$

Simplifying this expression by defining T_r through:

$$T_r^4 = \varepsilon_g \cdot T_g^4 + (1 - \varepsilon_g) \cdot T_w^4$$

and allowing for non-unity emissivity of the test specimen, the first equation reduces to

$$Q_s'' = \alpha_s \cdot (T_g - T_s) + \sigma \cdot (T_r^4 - \varepsilon_s \cdot T_s^4)$$

Notes :

- When non-unity values for the emissivity of furnace walls and specimen are allowed in the model, the net heat flux cannot be expressed in a simple form any longer (except for some ideal textbook cases). This is because heat emitted by the furnace walls is partly reflected by the specimen, then again partly by the furnace walls etc. This leads to a set of equations that can be solved by e.g. the Hottel zone method. The furnace gases absorbing and emitting make this behaviour more complicated.
- Similarly, the the equations are valid for an infinitely large furnace wall opposite an equally infinite specimen. With finite dimensions a more complex expression is needed.

For the net heat flux entering the Plate Thermometer, a similar expression holds:

$$Q_{pt}'' = \alpha_{pt} \cdot (T_g - T_{pt}) + \sigma \cdot T_r^4 - \sigma \cdot \varepsilon_{pt} \cdot T_{pt}^4$$

But Q_{pt}'' is zero since a PT has a negligible heat capacity. Subtracting the last two equations and rearranging, we find:

$$Q_s'' = \alpha_{pt} \cdot (T_{pt} - T_s) - (\alpha_{pt} - \alpha_s) \cdot (T_g - T_s) + \sigma \cdot (\varepsilon_{pt} \cdot T_{pt}^4 - \varepsilon_s \cdot T_s^4)$$

This reduces to a simple expression under the following assumptions:

- The convective heat transfer coefficients α_s and α_{pt} are equal (=α). Typical values of convective heat transfer coefficients are: $\alpha_s = 10$, $\alpha_{pt} = 15$, $\alpha_{tc} = 150$ (W/m^{2}K).
- The surface emissivities ε_s and ε_{pt} are equal (=ε) (and close to 1, see discussion above). Typical values are : $\varepsilon_{pt} = 0.9$ (blackened steel), $\varepsilon_s = 0.7$-0.9 (concrete, ceramic fibre, oxidised metal).

The reduced expression reads:

$$Q_s'' = \alpha \cdot (T_{pt} - T_s) + \varepsilon \cdot \sigma \cdot (T_{pt}^4 - \cdot T_s^4)$$

Under these assumptions, the heat flux to a specimen depends only on:

- The properties of the specimen, determining its temperature response;
- The temperature reading of the Plate Thermometer T_{pt}
- The convective heat transfer coefficient α

Thus, the dependence of furnace properties is limited to the relatively unimportant convective heat flux. This effectively means harmonised thermal load. On the other hand, the derivation shows where, how and to what extent harmonisation breaks down when the assumptions made are not all met. It is easy to show that e.g. the furnace gas temperature T_g enters the expression for Q_s'' if the effective convective heat transfer coefficients for the specimen and for the PT are different.

The above treatment enables -at least in principle- a quantified estimation of the individual effects. For the convective part -for example- it can be shown that, under circumstances which are typical for a fire resistance test, the error in the heat flux entering the test specimen - by assuming $\alpha_s = \alpha_{pt}$ is less than 4%.

If the furnace is not controlled by PT but by TC, a similar argument can be made. However, since the thermocouple receives radiation almost equally from the test specimen and from the furnace environment, the equation for heat flux entering the TC reads:

$$Q_{tc}'' = \alpha_{tc} \cdot (T_g - T_{tc}) + 1/2 \cdot \sigma \cdot T_r^4 + 1/2 \cdot \varepsilon_s \cdot \sigma \cdot T_s^4 - \sigma \cdot \varepsilon_{pt} \cdot T_{tc}^4$$

and the equation for the heat flux entering the specimen, again after subtracting the above equation, reads (with $\varepsilon_{tc} = \varepsilon_s = \varepsilon$):

$$Q_s'' = \alpha_{tc} \cdot (T_{tc} - T_s) - (\alpha_{tc} - \alpha_s) \cdot (T_g - T_s) + \varepsilon \cdot \sigma \cdot (T_{tc}^4 - T_s^4) + 1/2 \cdot \sigma \cdot (T_r^4 - \varepsilon_s \cdot T_s^4)$$

We see that, due to the large difference between α_s and α_{tc}, the convective term involving (T_g-T_s) does not disappear; to the contrary, if α_{tc} may indeed be estimated at 150 W/m^2K, the term can be significant. The same goes for the radiative terms : the term involving furnace radiation is far from eliminated.

The above observations show that under TC control and the same simplifying assumptions, the heat flux to the specimen depends on furnace properties (T_g, α_{tc}).

The tests carried out within the proving test programme of CEN TC 127 ad hoc 14 can be seen as corroborating evidence to the theoretical analysis. Refer to the main text of this paper.