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AN APPARATUS FOR APPLYING FIRE-LIKE HEAT FLUX TO BENCH-SCALE SAMPLES

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ABSTRACT

The research study presented in this paper concerns an experimental electricity-powered apparatus for applying fire-like heat flux to bench-scale samples. It consists of various elements, of which the most important are ceramic heating pads used to impose a defined heat flux on the exposed side of the sample mounted in a steel holder. The test method allows to control the heating pads' temperature as well as to adjust the distance between the heating pads and the specimen to obtain heat fluxes up to 150 kW/m^2. The thickness of the convective boundary layer at the heating pads' surface is estimated to be around 3 cm, significantly lower than in case of gas-fired radiant panels. The performance of the apparatus was analysed in a case study on soda-lime-silica glass specimen. Experimental results were compared to numerical modelling. This analysis showed that a thermal exposure compared to the ISO 834 fire curve can be imposed on the exposed side of the specimen. There are many research possibilities for future applications of the presented experimental methodology: among others, tests with bigger specimens with heating pads surface up to 1.34 m^2, and tests in controlled atmosphere.

Keywords: H-TRIS; radiant panels; fire testing; heat transfer; glass; heat flux

1 INTRODUCTION

Spread of fire in a building is highly driven by materials which can be found inside and by their reaction to fire. Many researchers have been working to understand the performance in high temperatures of various, sometimes very complex, materials. This is usually analysed through material testing. In this case, a preference is shown for bench-scale tests compared to large-scale furnace tests because of their multiple advantages, for instance lower temporal and economic costs and better-defined thermal boundary conditions.

There are various methods to impose a heat flux on bench-scale samples to study the behaviour of insulating or structural materials at elevated temperatures. Some of them aim at locally imposing a high heat flux, for example with a blowtorch [1]. However, the majority of them aims at imposing a uniform radiative heat flux on the whole specimen surface. The most common methods include the cone calorimeter allowing to test samples of 10x10 cm² [2] as well as the Heat-Transfer Rate Inducing System (H-TRIS) apparatus [3-7] used for bench-scale samples. The first one, cone calorimeter, is limited to imposing constant incident heat flux during a test and its response time is low due to the high thermal inertia of the electrical resistance. On the other hand, H-TRIS is a gas-fired radiant panel that allows to impose constant or varying time-

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histories of incident heat flux by changing the distance between the radiant panel and the specimen surface. Thanks to its important advantage of well-defined thermal boundary conditions, it has been widely used in research and development studies which included, among others, behaviour analysis of concrete spalling, intumescent coatings, timber structures and glass structures [6-12].

Nevertheless, its relatively high costs and safety concerns due to the presence of gas burners make it an unsuitable solution for some laboratories and researchers. For these reasons, a similar apparatus to H-TRIS but powered by electricity has been designed, easy to maintain and budget-friendly, at the same time providing repeatable and relatively accurate results.

2 APPARATUS AND TEST METHOD

2.1 Apparatus

The first prototype of the apparatus is shown in Figure 1. It has been built with basic and economically available resources to validate the concept before relying on more sophisticated components for a permanent and long-term utilisation.

a) b)

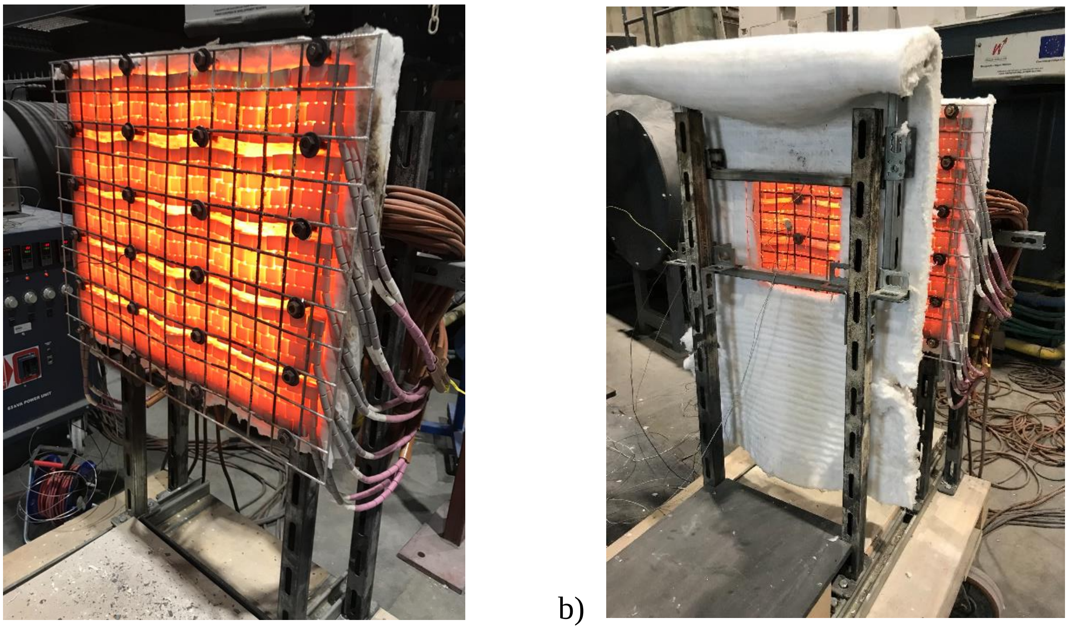

Figure 1. The apparatus a) without the specimen holder, b) with the specimen holder

The apparatus consists of:

1) A 70 x 55 cm² vertical steel plate on which two layers of 5 ceramic heating pads each (Mannings, CP24, 61 x 8.5 cm² each) are fixed. Ceramic fibres insulation is placed between the pads and the steel plate. A steel grid is mounted with screws to support the heating pad strips. The heating surface is 61 x 46 cm². A thermocouple is placed in a special hole very close to the surface of the heating pads and connected to a measuring device.
2) A steel frame serving as a specimen holder.
3) A Mannings 65kVA transformer unit that has the capability to control the temperature of the heating pads in six different zones independently, although in this application only three of them are used (two to four heating pads are connected to each zone) and all of them have the same settings.
4) A wooden base with wheels.

In the present arrangement as shown in Figure 2, the distance between the heating pads and the specimen holder can only be modified from test to test. Limited modifications of the support of the specimen holder could make it possible to vary this distance also during a test.

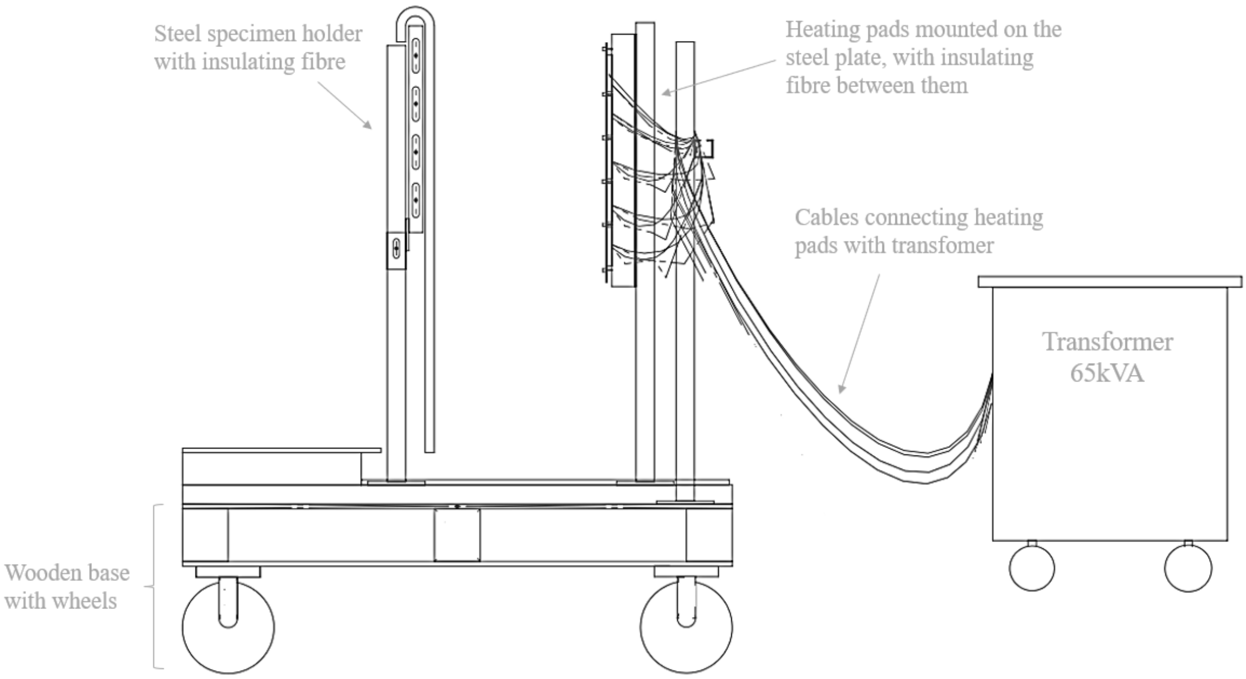

Figure 2. Schematic drawing of the apparatus

2.2 Test method

Two different parameters which can be adjusted to reproduce specific heating regimes.

1. Temperature of the heating pads

The controller allows to impose a predefined temporal evolution of the temperature of the heating pads, for example following a linear or curvilinear evolution; the maximum heating rate that can be achieved on the heating pads is 50°C/min. The temperature can also be maintained at a given constant level up to around 800°C. This temperature is controlled with a thermocouple placed in a special hole in the heating pads, very close to the heating surface, in the central area.

The settings can be assigned separately for six different zones, but it has been observed that, with the dimensions of the radiant panel and of the specimen described here, a sufficiently uniform heating on the specimen's surface is obtained when all zones are set to follow the same evolution. Figure 3 shows the temperature is uniform over the whole surface of the heating pads excluding the area around 3 cm from the edges.

For the tests reported in this paper, the transformer was set to work at full power from the beginning of the test, which leads to temperatures of the heating pads up to 1300°C when a steady state situation has been established.

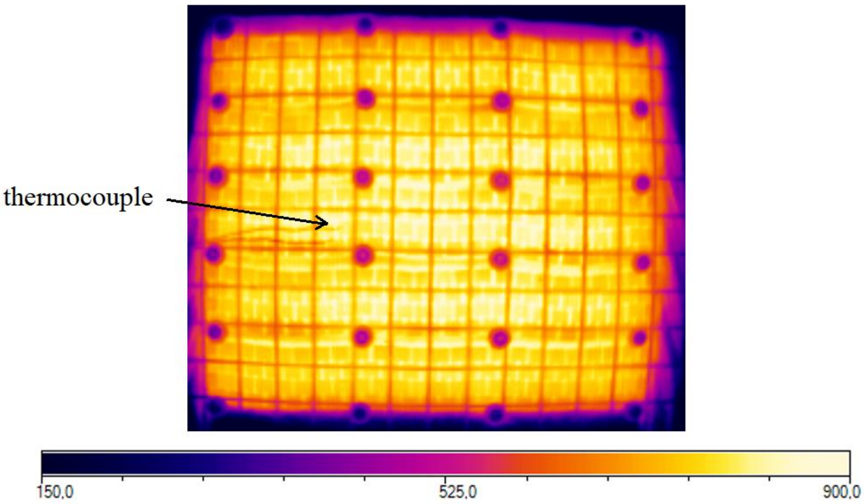

Figure 3. Temperature distribution on the heating pads, captured by infrared camera for temperature 800°C measured by the thermocouple in the centre of the heating pads

Two sets of different heating pads (Mannings CP24) were used until now. The first ones are made of nickel-chrome alloy, allowing a maximum temperature of 1050°C according to the producer. This limitation in temperature, plus the fact that they tend to break after a few utilizations close to the maximum allowed temperature, was the reason to change to the *high temperature* heating pads with the heating wire made of canthal alloy. These heating pads have the maximum temperature of 1300°C, can provide a faster heating rate and they are more robust with no failure observed so far. Their higher price (60 € versus 25 € per heating pad at the time of writing) is easily compensated by the higher durability.

Heating pads can be mounted as one layer or two layers, as shown in Figure 4, or even more. To impose heat fluxes in the range of those corresponding to the ISO 834 curve, it was found that two layers of heating pads were necessary. In this case, the inner layer reaches higher temperatures than the outer layer due to differences in heat losses at the pads surface, for example when the temperature of the outer layer is 1180°C, the inner layer reaches around 1250°C.

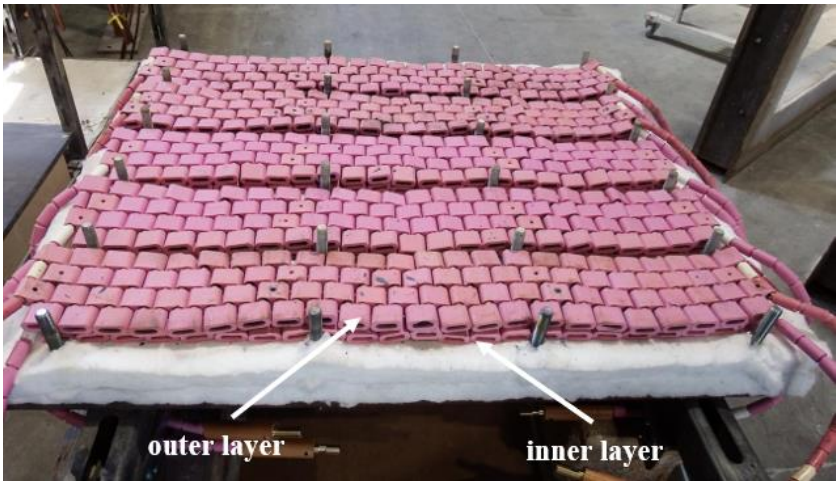

Figure 4. Positioning of two heating pads layers: outer layer and inner layer

2. Distance between heating pads and specimen

Similarly to H-TRIS, the distance between the heating pads and the specimen is crucial to determine the level of heat flux reaching the exposed side of the specimen. Figure 5 shows the evolution of the incident heat flux measured by the Gardon heat flux gauge placed in the specimen holder, positioned in front of the centre of the heating pads, at two different distanced when the full power is applied. The heat flux gauge was surrounded by insulating fibre to recreate conditions used in tests. Due to the limits specified by the producer of the heat flux gauge, the measurements were held until 150 kW/m^2.

It is important to mention that when the transformer is set on full power, the temperature on the heating pads surface (and therefore the heat flux) depends on various factors and might change if one of these factors is changed, for example the presence or not and the type of insulating fibre mats located around the specimen as seen in Figure 1 (providing feedback to the heating pads which increases temperature of the heating pads) and their distance from the heating pads. This means the temperature on the heating pads in this case is not automatically regulated.

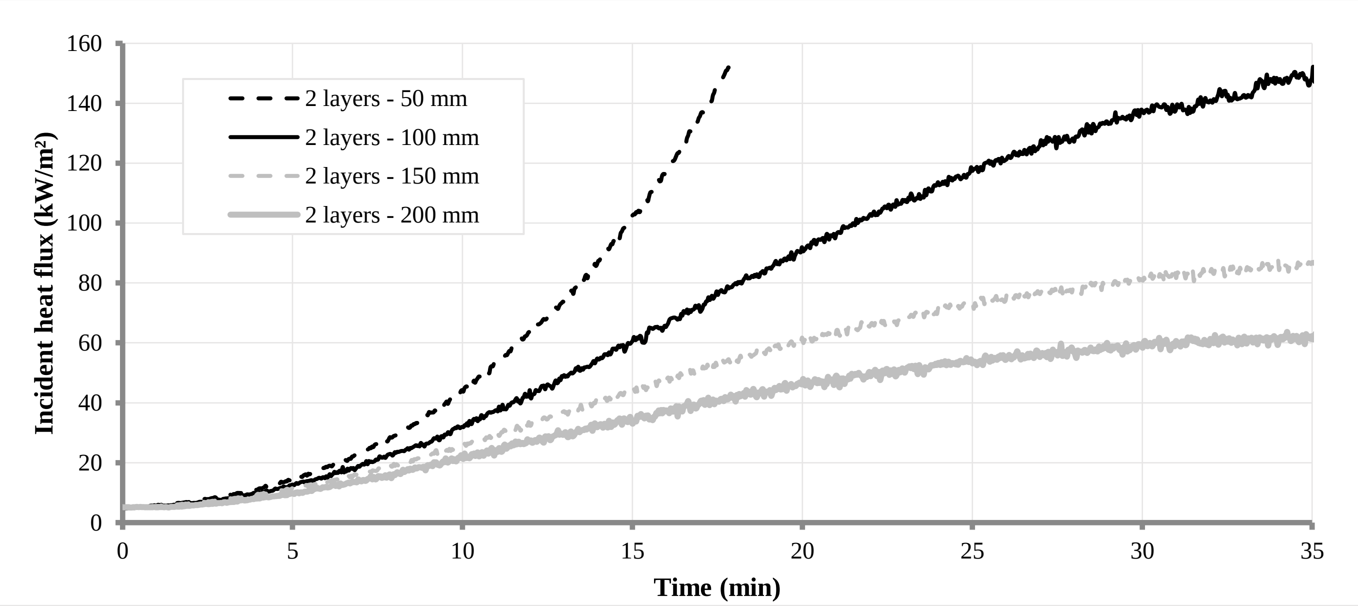

Figure 5. Incident heat flux obtained with two layers of heating pads, and for the distance of 50mm, 100mm, 150mm and 200mm between the heating pads and the specimen, with full power of the transformer

The plot in Figure 6 correlates the temperature at the surface of the heating pads and the incident heat flux measured at different distances from the heating pads. The incident heat flux decreases when the distance increases.

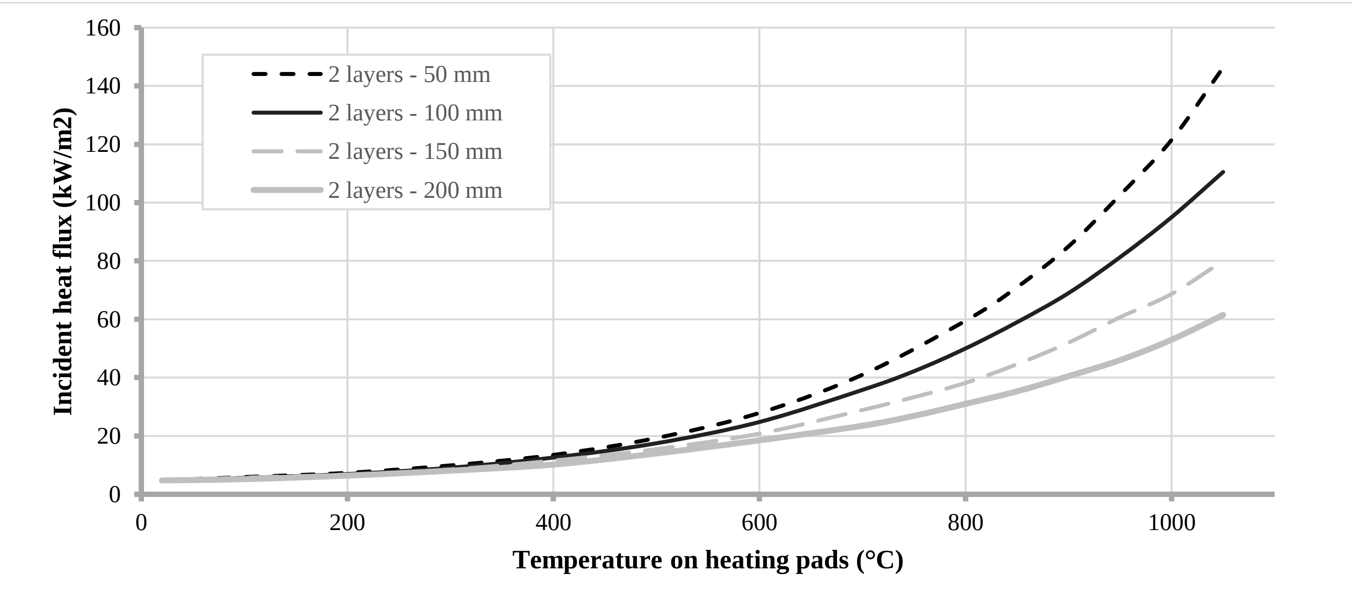

Figure 6. Incident heat flux dependence on temperature obtained on the heating pads for two layers of heating pads, and for the distance of 50mm, 100mm, 150mm and 200mm between the heating pads and the specimen, with full power of the transformer

In order to show the incident heat flux measured at different positions of the heat flux gauge as a function of the distance between the pads and the heat flux gauge, the heating pads were set to automatically regulated temperature of 750°C. It can be noticed that the incident heat flux with stable temperature of 750°C on the heating pads increases smoothly with the decrease of distance between the heat flux gauge and the heating pads (Figure 7). This is the highest temperature of the heating pads which can be obtained when no insulating fibre mat is located around the specimen.

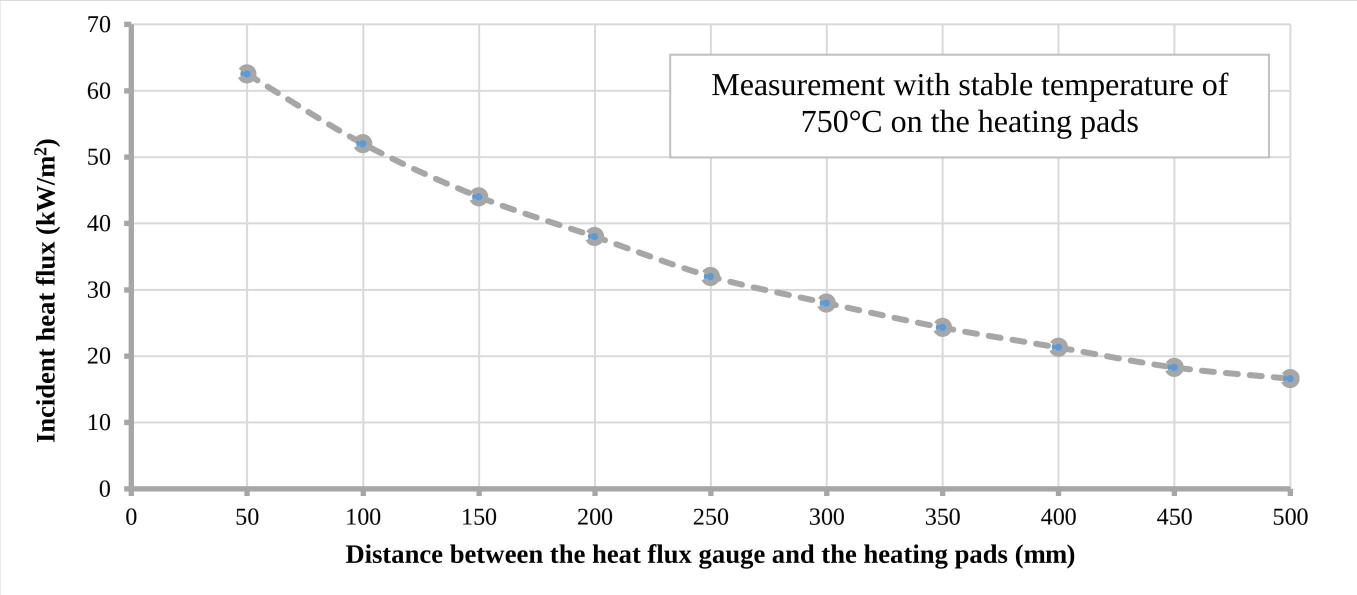

Figure 7. Incident heat flux obtained for different distance between the heating pads and the specimen, with two layers of heating pads, for stabilized temperature on the heating pads of 750°C

The first utilisation of the current apparatus has been for testing the performance of construction products subjected to heat flux comparable to the one pertaining to the ISO 834 curve. Because of the too slow heating rate observed at the start of the heating, an insulating plate is placed between the heating pads and the specimen, and the transformer is set to work at full power. The plate is removed when the temperature of the heating pads reaches 500°C (around 6 minutes from the start of the heating) which creates the thermal shock characteristic of the ISO 834 curve. The same effect could be obtained by a rapid variation of the distance between the specimen and the heating pads, provided a rather simple displacement system is given on the specimen holder.

It may be possible to recreate in a similar way other heating regimes, such as external fire curve or hydrocarbon curve (only for specific materials), however this still has to be investigated.

2.3 Boundary conditions

The heat transfer on test samples is considered unidimensional, following the main direction of the heat flow: from the heated pads to the exposed sample surface and through the sample thickness. The incident heat flux $\dot{q}''_{inc}$ imposed by experimental apparatus at the exposed surface of the test specimen is considered as radiant incident heat flux, therefore the sample receives a surface heat flux due to electromagnetic waves. The surrounding environment is considered at ambient conditions; hence the sample surface has convective and radiative heat loses with this environment. According to this assumption, the thermal boundary conditions in equation (1) are obtained.

In case of stable and homogenous temperature on the heating pads (up to 750°C) and open environment around the test specimen (free convection), the thermal boundary conditions imposed on the exposed surface of test samples can be described as in the following [5, 13]:

$$\dot{q}''_{net} = \alpha \cdot \dot{q}''_{inc} - h_c\left(T_{surf} - T_{\infty}\right) - F\varepsilon\sigma\left(T_{surf}^4 - T_{\infty}^4\right) \qquad (1)$$

Where $\dot{q}''_{inc}$ is the incident heat flux imposed by experimental apparatus at the exposed surface of the test same and $\dot{q}''_{net}$ is net heat flux absorbed by the sample at the exposed surface, which has a surface temperature equal to T_{surf} and it is surrounded by a gas temperature equal to T_{∞}. The absorptivity and the emissivity of the exposed surface are α and ε, respectively. The convective heat losses are described by the convective heat transfer coefficient h_c, while the radiative heat losses are considered by the Stefan-Boltzmann constant σ and the view factor F.

By modifying the relative distance between the heating pads and the sample surface and/or the electric power fed to the experimental apparatus (therefore the heating pads temperature), the incident radiant heat flux $\dot{q}''_{inc}$ can be controlled and quantified through the calibration process (see Figure 7).

However, if the transformer is set at full power, the temperature on the heating pads is not automatically regulated and it might change depending on various factors, for instance the distance between the specimen holder and the heating pads or insulation material used around the specimen. This is the consequence of feedback from the specimen and convection flow caused by the surrounding insulation material and, as a result, the definition of the thermal boundary condition becomes more complex.

2.4 Convective boundary layer

To verify that the main mode of heat transfer is radiation, it is important to understand the convective heat transfer in proximity to the experimental apparatus. In particular, to avoid convective heat transfer between the test sample and the convective boundary layer of the heated pads, a sufficient spatial separation between the heating pads and the exposed surface of the test sample must be ensured [13]. This distance should be at least higher than the thickness of the boundary layer of the radiant panel and the test sample. The test sample one's depends on the sample characteristics, while the boundary layer thickness of the radiant panel composed of heating pads can be estimated following conventional calculations considering it as a vertical hot plate subjected to natural free convection [14]. Assuming the panel surface temperature equal to 900-1000°C, an ambient temperature of 20°C and the panel vertical characteristic dimension equal to 46 cm, the thickness of convective boundary layer of the heating pads panel can be estimated equal to 3.2-3.3 cm. This result was also confirmed by a qualitative measurement using a flag made of several aluminium thin foils, as shown in Figure 8. This outcome highlights that the convective boundary layer of this experimental apparatus is much smaller than the ones for gas-fired radiant panels, typically in the range of 150-200 cm [13, 15].

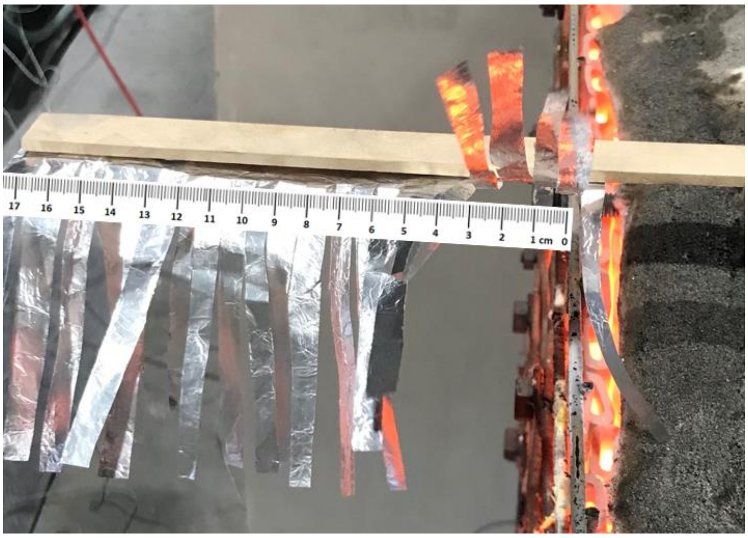

Figure 8. The zone of convective influence coming from the heating pads - qualitative measurement using a flag made of aluminium thin foil

2.5 Advantages and limitations

In addition to easily achieved safety conditions and relatively low cost, the apparatus showed several advantages compared to a gas-fired radiant panel. First, the power and the heating pads temperature can be controlled in a precise way, for most regimes, owing to the automatic regulation of the transformer. Secondly, no combustion and hazardous gases are produced, whereas these can disturb the heat transfer and influence chemical reactions at the surface of reactive materials when the specimen is located too close to a gas-fired panel. The thickness of the convective boundary layer on the panel surface is significantly lower than with gas-fired radiant panel.

The described apparatus is mobile and can be used in most circumstances, provided that there is enough electrical power available. If the tested specimen is non-combustible, it does not require a gas exhaust to collect combustion gases, a requirement which normally imposes a permanent positioning in the laboratory with gas-fired panels.

It is of course necessary to have a certain electrical power in the lab, although the power required to feed the surface of 0,28 m² is well below the 65 kVA capacity of the transformer. Due to thermal inertia of the heating pads, the cooling process is not instantaneous, and the apparatus must be left for 30 to 45 minutes to decrease the temperature back to 500°C. While the maintenance of the apparatus is quite limited, the heating pads may need replacement from time to time.

One of the main limitations of this apparatus is the fact that, when using full power of the transformer, the temperature on the heating pads, and therefore the incident heat flux, depends on the distance between the specimen together with the insulating fibre and the heating pads, as shown in Figure 9. The uniform character of the temperature distribution on the heating pads might also be lost if a specimen made of a material with thermal properties very different from those of the insulating fibre. Therefore, it is difficult to establish the thermal boundary conditions for this complex situation.

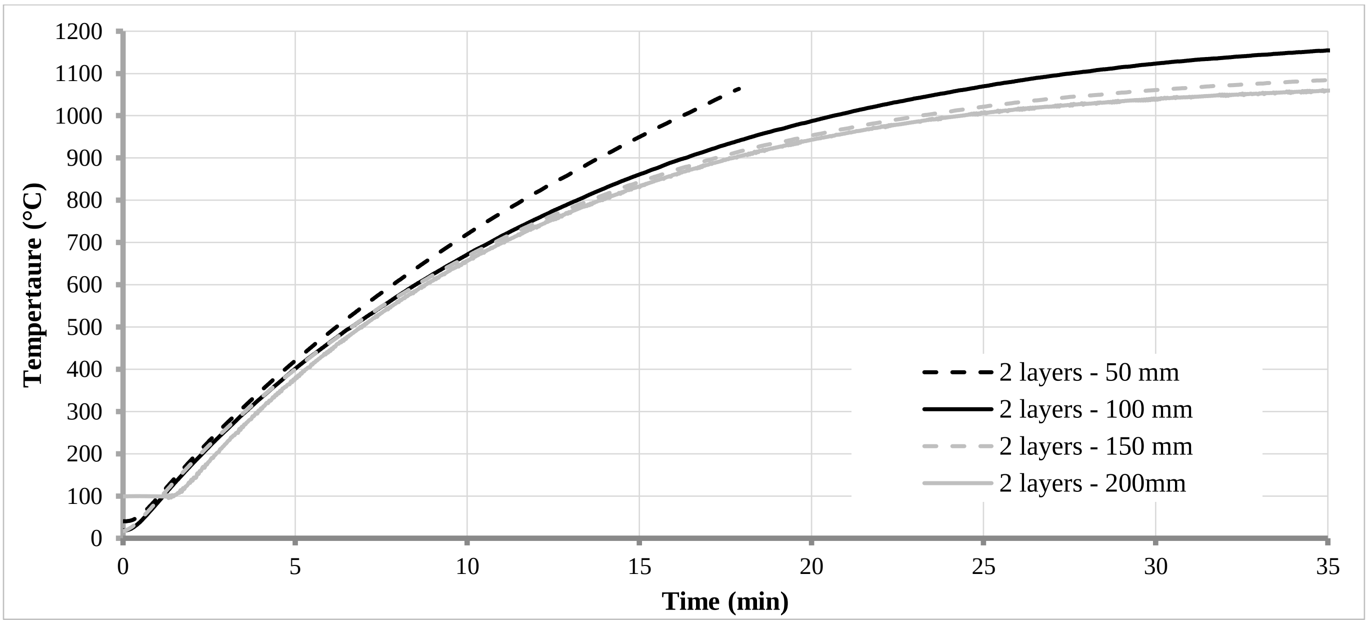

Figure 9. Temperature increase measured on the heating pads' surface for two layers of heating pads, and for the distance of 50mm, 100mm, 150mm and 200mm between the heating pads and the specimen, with full power of the transformer

2.6 Future possibilities

There are many future possibilities of research with use of the apparatus, among others:

- Tests with bigger specimens. It is easy to increase the panel size by increasing the number of heating pads from 10 up to 24 and, therefore, increasing the heating surface to 0.67 m^2 (two layers) or even up to 1.34 m^2 (one layer of heating pads);
- Tests with two different heating zones; the transformer allows to create up to six different temperature zones on the heating pads, for example to recreate specific glass breakage patterns which are caused by temperature gradient;

- Tests in different environments, for example in a controlled oxygen or nitrogen atmosphere, low pressure chamber etc. A special version of cone calorimeter has been already designed for this purpose [16], which could show a direction for future development of the apparatus.

3 APPLICATION TO STUDIES ON A GLASS SPECIMEN

Until now, the apparatus has been used to analyse the behaviour of different materials and objects such as carbon steel tubular section, glass or insulating products subjected to an incident heat flux history similar to the one pertaining to the ISO 834 fire curve. One of these tests is described hereafter.

3.1 Bench-scale tests

The test was performed using two layers of heating pads and following the methodology described in Section 2.2.

Material analysed in the study was commercially available soda-lime-silica glass - a specimen of 20 x 20 cm^2 and thickness of 6 mm. A thermocouple (type K) was glued in the middle of the exposed side to measure the increase of temperature during the test. The glue itself contained a combination of silicate and kaolin and it was left to dry overnight.

The distance between the heating pads and the specimen was 8 cm. There was an insulating fibre placed around the specimen, as shown in Figure 1, and the transformer was set at full power. The specimen is exposed to heat flux when the heating pads reach the temperature of 500°C which compensates for the lack of rapid increase of the temperature present in a standard fire test. These conditions were previously identified for glass specimens through repetition of temperature measurements at different distances between the specimen and the heating pads. Due to lack of clearly defined boundary conditions for the full power set-up, it is not possible at the moment to quantify the net heat flux absorbed by a specimen.

The temperatures measured by the thermocouple on exposed side, as well as the temperature on the centre of the heating pads, are shown in Figure 10. The maximal temperature reached on the heating pads is lower than during the heat flux measurements presented in Figure 9 due to lower feedback provided by the glass specimen towards the heating pads compared to the insulating fibre mat that was used for heat flux measurements.

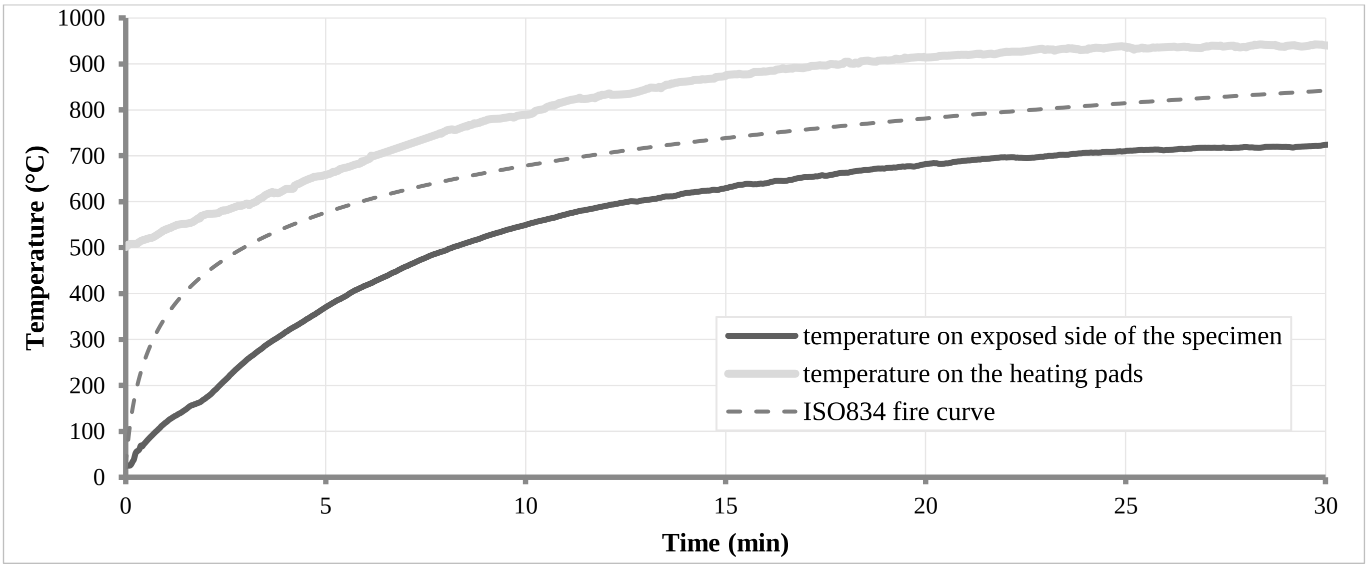

Figure 10. Temperature evolution on exposed side of the glass specimen, compared to temperature on the heating pads and the ISO834 fire curve

During this test, the temperature distribution on unexposed side of the specimen was checked using an infrared camera to control the influence of glass breakage on the temperature measurement. Except for the areas very close to the cracks in the glass and an area 1 cm wide from the edges, the temperature was uniform on the surface of the specimen, as shown in Figure 11. The cracks are not present in the vicinity of the thermocouple, so there was no influence of glass breakage on the temperature measured on the specimen.

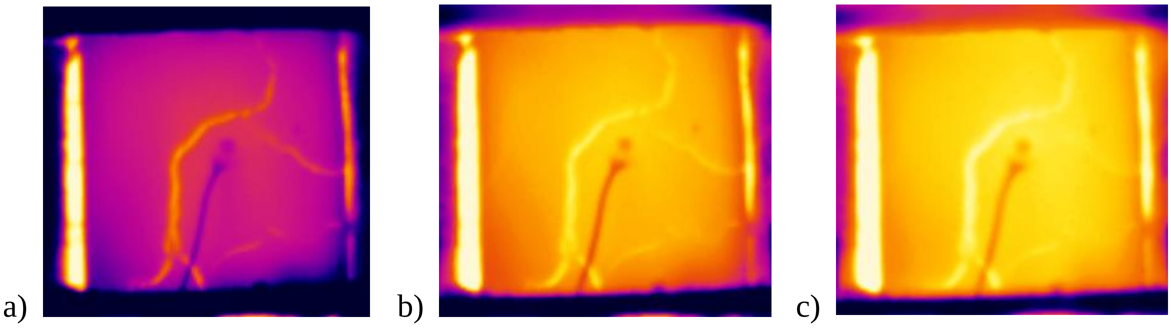

Figure 11. Temperature distribution on the unexposed side of the glass sample, captured by infrared camera for different temperatures on unexposed side: a) 350°C, b) 475°C, c) 550°C

3.2 Numerical modelling

A one-dimensional thermal analysis was performed for the glass specimen using ABAQUS 2019. The boundary conditions included:

- On exposed side heat transfer through radiation and convection with gas and radiation temperatures imposed following the ISO834 standard fire curve; the coefficient of convection was h = 25 W/m^2K [17]. and the glass emissivity ε=0.89 [18],
- On unexposed side heat transfer through radiation and convection with the far field at a constant temperature of 20°C; the coefficient of convection was h = 4 W/m^2K [17] and the glass emissivity ε=0.89 [18].

Thermal properties of soda-lime-silica glass were included as functions of temperature [19].

The temperature evolution on exposed side of the glass specimen obtained through numerical modelling is shown in Figure 12 and compared with the experimental results. The good fitting is visible with differences only up to approx. 35°C which proves that the apparatus and the methodology applied is suitable for applying ISO 834 fire-like heat flux to bench-scale specimens.

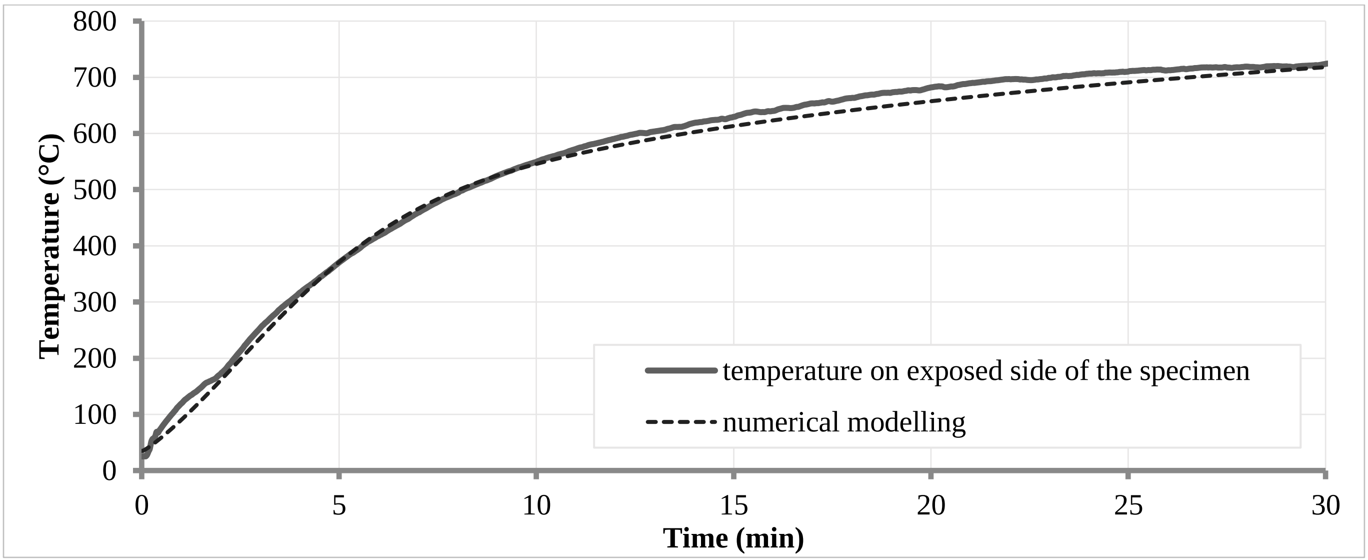

Figure 12. Temperature evolution on exposed side of the glass specimen obtained through numerical modelling and compared to experimental results

4 CONCLUSIONS

The paper presents an apparatus which allows to impose fire-like heat fluxes to bench-scale samples. It is a budget friendly, electricity-powered alternative to the well-known H-TRIS apparatus. However, there are some differences in the two methods for testing. For example, the incident heat flux is controlled by the temperature on the surface of the heating pads, while H-TRIS uses the variability of distance between the gas-fired panels and the specimen. The conditions which have been applied until now include heat flux present in full scale fire resistance test and it is possible to obtain relatively accurate results. It still needs to be verified which other regimes could be imposed.

There are many important advantages of the described apparatus, among others its relatively low cost, its possibility to extend the heating surface up to 1.34m^2 and the thin convective layer of hot gas close to the heating pads which is estimated as around 3.2 cm. On the other hand, the apparatus needs a certain power supply and the thermal inertia of the heating pads is a reason for slow cooling and heating rates. Additionally, more research should be done on the thermal boundary conditions, since they have been well-defined only until 750°C and they are more complex for the full power set-up. Therefore, it is crucial to consider all features of the apparatus when choosing as the testing equipment and method for a specific research program.

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