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Performance of Different Temperature Sensors in Standard Fire Resistance Test Furnaces

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ABSTRACT

Defining a methodology for measuring temperature in fire resistance furnaces is a challenge. This paper presents and discusses the performance of six different types of temperature sensors in wall and floor fire resistance furnaces namely: the ASTM E119 shielded thermocouples, ISO 834 plate thermometers, directional flame thermometers, bare-bead thermocouples, Inconel grounded and ungrounded sheathed thermocouples. The Inconel grounded and ungrounded sheathed thermocouples provided comparable results to those of the bare-bead thermocouples and are most suitable when a fast response time is desirable. Because of the fast response time and good durability, grounded and ungrounded junction thermocouples are well-suited for use in controlling the temperature in fire resistance standard test furnaces. The predicted and measured incident heat flux in furnaces controlled by either the bare-bead or grounded and ungrounded sheathed thermocouples are in good agreement.

Keywords: furnace, shielded thermocouple probes, plate thermometers, directional flame thermometers, bare bead thermocouples, grounded thermocouples, ungrounded thermocouples, fire resistance, time constant, incident heat flux

INTRODUCTION

Fire-rated building systems such as walls, floors, beams and columns formed with new materials and designs have been increasingly used in residential and non-residential buildings alike. To determine the fire resistance performance of these systems, standard full-scale furnace tests are required. The fire resistance performance of building systems tested in a standard furnace is mostly controlled by the furnace thermal exposure and applied structural load on test specimen. With the absence of the complete design furnace specifications in the ASTM E119¹ standard, defining thermal exposure in fire resistance test furnaces is a challenge. Thermal exposure in furnaces is mainly controlled by heat radiation and also by heat convection especially in the early part of the test. The standard time-temperature curves in ASTM E119, ISO 834² and CAN/ULC S101³ consist of a rapid temperature rise in the first 10 minutes and followed by a less rapid temperature further on. As the temperature rises rapidly in the first 10 minutes, the furnace response time of the furnace temperature measuring device greatly affects the thermal exposure conditions. Currently, different types of temperature measuring sensors are being used in the ASTM E119 and ISO 834 fire standards: shielded thermocouples and plate thermometers, respectively.

The ASTM E119¹ Standard requires the time constant for thermocouples used in measuring the furnace temperature in the range from 5 to 7.2 minutes. The ASTM standard also provided a note that described the thermocouple design that can achieve the required time constant as “A typical thermocouple assembly that meets the time constant requirements may be fabricated by fusion-welding the twisted ends of No. 18 gauge Chromel-Alumel wires, mounting the leads in a porcelain insulator and inserting the assembly so that the thermocouple bead is ½ in from the sealed end of a standard weight nominal ½ in. iron or steel or Inconel pipe”.

The ISO 834² “Fire-Resistance Tests – Elements of Building Construction – Part 1: General requirements” specifies the furnace temperature to be measured by the plate thermometers. The standard specifies the design detail of the thermometers in Section 5.5.1.1; unlike the ASTM E119 Standard where the time constant for thermocouples was specified, the laboratories that conduct the ISO 834 test are obliged to use plate thermometers designed as specified in the standard. The time constant for the plate thermometer was reported as 40 seconds⁴. The plate thermometer was developed by the SP Technical Research Institute of Sweden and was adapted in 1999 for use in the ISO 834² and EN 1363-1⁵ fire resistance standards. As the time constant of the ISO plate thermometers is much smaller than that of ASTM shielded thermocouples, the earlier is expected to respond faster to the thermal changes within the furnace than the latter especially in the first 10 minutes of the test where the temperature rises more rapidly.

A recent study⁶, conducted using a floor and a wall furnaces controlled by either the ASTM shielded thermocouples or by the ISO plate thermometers indicated that during the initial period (8 minutes) of fire exposure, the difference in furnace temperature measured by shielded and by plate thermometers is significant. However, after 8 minutes, the difference is insignificant. In another similar study⁷, conducted using a floor furnace where furnace temperature was controlled by four temperature sensors: shielded thermocouples, plate thermometers, directional flame thermometers and bare-bead thermocouples, significant differences were found between the temperatures measured with different sensors in the initial 10 minutes of fire exposure, however, after 10 minutes, the differences are insignificant. These results are consistent with the results reported in Reference 6.

Babrauskas and Williamson⁸ provided a detailed analysis on the time response of thermocouples and showed that the errors associated with temperature measurement in fire resistance test furnaces are large in the first 20 minutes of test.

In fire test furnaces, where radiation is the dominant heat transfer mechanism, the time response constant of a temperature sensor “ τ ” can be determined from the following equation⁸:

$$\tau = (T_f - T_t) (\Delta t) / \Delta T_t$$

where:

T_f , furnace measured by bare-bead thermocouple

T_t , measured temperature by a sensor

The shielded thermocouples and directional flame thermometers have a larger time constant than the plate thermometers and bare-bead thermocouples. Also, the plate thermometers and bare-bead thermocouples have a shorter life span than the shielded and directional flame thermometers. Currently, the North American fire resistance standards (a century old) such as ASTM E119 and CAN/ULC S101 use shielded thermocouples to control fire resistance furnace

temperature and this type of thermocouples has a slow temperature response time (5 to 7 minutes) in the first 10 minutes. This makes the test more severe in that period, which is a major issue for a shorter duration fire resistance test such as the 15 minute test for floor systems of passenger railcars. Recently, ISO and CEN have adopted the use of plate thermometers in their ISO 834 and EN 1361-1 standards. Although, plate thermometers have much faster response time (40 seconds), they have a relatively short life span. The latter results in frequent sensor replacements, that increases operating cost for testing laboratories. To obtain a faster response time and increase durability two temperature sensors, in addition to the four sensors considered in a previous study⁷, were included in this study: Inconel-sheathed thermocouples with grounded and ungrounded junction. The objective of this paper is to evaluate the performance and provide comparisons of furnace temperature measurements by six different temperature sensors for consideration by the standard writing organization in their fire resistance standards. This paper also provides comparisons of measured and predicted incident heat flux in two furnaces of different size and orientation.

EXPERIMENTAL STUDY

Descriptions of the six different temperature sensors, heat flux sensor, furnace cover specimens, full-scale wall and floor furnaces and experimental procedure are given below.

Temperature Sensors

The temperature sensors used in this study consists 5 shielded thermocouples, 5 plate thermometers, 5 directional flame thermometers, 5 bare-bead thermocouples, 5 grounded sheathed thermocouples and 5 ungrounded sheathed thermocouples. Only the shielded and bare-bead thermocouples were fabricated in-house while all other sensors were bought commercially. Descriptions of the temperature sensors used in this study are given below.

ASTM E119 Shielded Thermocouples – The shielded thermocouple was fabricated in accordance with the ASTM E119 standard by fusing the twisted ends of No. 18 gauge Chromel-Alumel wires, and mounting the leads inside a porcelain insulator. The thermocouple with the porcelain insulator was inserted inside a 12.7 mm diameter Inconel 600 tube so that the thermocouple bead was 12.7 mm away from a sealed end steel cap. The shielded thermocouple is schematically shown in Figure 1.

ISO 834 Standard Plate Thermometers – The plate thermometer consists of a 100 mm by 100 mm Inconel 600 plate, 0.7 mm thick, with a surface emissivity greater than 0.7. A Type K, 1 mm diameter sheathed thermocouple is held against the centre of the back side of the plate. This side faces the test specimen and is insulated with 10 mm thick ceramic fibreboard. The other front side of the plate faces the furnace. A schematic of the plate thermometer is shown in Figure 2. These thermocouples were made by Thermo-Electra based on the description in Reference⁴. The plate thermometer temperature reading can be used to estimate the total incident heat flux based on the adiabatic surface temperature methodology described in Reference 9.

Directional Flame Thermometers – The directional flame thermometer consists of two 120 mm by 120 mm Inconel plates, 3 mm thick. Ceramic fibre insulation 19 mm thick is sandwiched between the two plates. Two sheathed Type K thermocouples with ungrounded junction are attached to the unexposed faces of the Inconel plates with a thin Nichrome foil spot-welded over the tip of the thermocouples. The exposed surfaces of the Inconel plates are coated with Pyromark 2500 black¹⁰ or are heavily oxidized¹¹ to provide consistent radiation properties. The time constant for the directional flame thermometers is estimated at approximately 89 seconds

at the start of the test¹². A schematic of the directional flame thermometer is shown in Figure 3. The directional flame thermometer temperature readings of both sides can be used to estimate the total incident heat flux using the inverse heat conduction code reported in reference 11.

Bare-Bead Thermocouples – The bare-bead thermocouple was fabricated by fusing the twisted ends of 20 gauge Chromel-Alumel wires. Bare-bead thermocouples are generally used when an extremely fast response time is required. In fire resistance testing, where the hot gas temperature exceeds 1000 °C, the bare-bead thermocouples do not last for many tests.

Grounded Sheathed Thermocouples – The grounded sheathed thermocouple¹³, shown in Figures 4 and 5, consists of a closed-end Inconel tube sheathing, 6.5 mm O.D., with Type K (20 gauge) Chromel-Alumel wires. The wires were inserted inside the inconel sheath tube and the junction of the thermocouple was welded to the protective sheath tube end as shown in Figure 5. As the thermocouple sheath is made from Inconel, it provides stiffness and durability in harsh environments such as in fire resistance tests.

Ungrounded Sheathed Thermocouples – The ungrounded sheathed thermocouples¹³ of Inconel tube 6.5 mm O.D. are similar to the grounded sheathed thermocouples, except that the thermocouple wire junction is not connected to the protective sheath tube end as shown in Figure 6. As this type of thermocouple is not in contact with the sheath, it is generally used where fast response time is required and in an environment where electrical noise exists.

The sensors were placed in 5 clusters in both the wall and the floor furnaces: one cluster was placed at the centre of furnace and each of the remaining 4 clusters was placed at the centre of the quarter section of the furnace. Each cluster has 6 different sensors and they were placed as close as possible to each other as shown in Figures 7 and 8. All temperature sensor clusters were located 100 mm away from the furnace cover specimen in both wall and floor furnaces except the shielded thermocouples that were placed at 300 mm for the floor tests and 155 mm for the wall tests in accordance to ASTM E119 standard.

Heat Flux Sensor

Five heat flux sensors, water-cooled Gardon Gauge heat flux meter shown in Figure 9, were used to measure the incident heat flux to a test specimen in the full-scale wall and floor furnace tests. These gauges are of 25 mm in diameter and 25 mm long copper cylinders and have a stated accuracy of $\pm 3\%$. The cooling water flow temperature was maintained at 25 °C during the entire test which is within the temperature range specified by the manufacturer for the sensors.

Furnace Cover Specimens

In the floor furnace, the furnace cover specimen used was a castable refractory slab, marketed as KS-4, composed of 20 rectangular elements, 800 mm wide by 1200 mm long by 1500 mm thick, suspended on a steel beam. The elements were tightly butted with a ceramic fibre sheet along their perimeters to form a 3.9 m by 4.8 m unit. To measure the heat flux received by the test specimen, 5 heat flux sensors were installed flush with the specimen surface: one at the centre of the furnace and one at the centre of each quarter section of the furnace as shown in Figure 7 to measure the receiving heat exposure to the specimen surface.

For the wall furnace, the cover specimen was composed of five slabs of KS-4 castable refractory brick, 600 mm square by 150 mm thick. The slabs were inserted in a block brick wall covered with ceramic fibre insulation on the fire-exposed side. One slab was placed at the centre and four at the centre of the quarter sections of the wall as shown in Figure 8. As in the floor furnace mentioned above, water-cooled Gardon gauge heat flux meters were installed

flush with the surface of measuring incident heat flux to the centre of each slab. The location of the heat flux sensors is shown in Figures 7 and 8. Each slab was sealed at the edges with ceramic fibre blanket.

Full-scale Floor and Wall Furnaces

A full-scale fire resistance floor furnace is approximately 3.9 m wide by 4.8 m long by 2.4 m deep. The wall furnace is 3.6 m wide by 3 m high by 0.5 m deep (see Figure 9). The walls of the floor furnace were made of insulated firebrick while the walls of the wall furnace were covered with a ceramic fibre blanket. Details on these furnaces can be found in Reference 14.

Experimental Procedure

The furnace temperature and incident heat exposure were measured in 12 furnace experiments. The duration of the experiment was 1 hour and the data was recorded every 10 seconds. Six experiments were conducted using the floor furnace and the other six experiments were conducted using the wall furnace. In each experiment, the furnace temperature was controlled by the average of five sensors of the same kind while incident heat flux and other temperature sensor readings were recorded for comparison. The wall and floor furnaces were controlled electronically in such a way that the furnace temperature followed the ASTM E119 time-temperature curve as closely as possible.

RESULTS AND DISCUSSION

The main mechanisms of heat transfer in a fire resistance test furnace are by radiation and to a certain extent by convection. The radiation heat transfer depends on the furnace hot gas temperature and emissivity as well as on the thermal conductivity and emissivity of furnace wall lining material. The use of a lining material with very low thermal conductivity results in the furnace lining surface temperature being close to the hot gas temperature. This helps the harmonization among different furnaces¹⁵. The convective heat transfer depends in part on the furnace size and location of furnace burners and hot gas exit ports. In a larger furnace, convective heat transfer is primarily by natural convection where the burners are away from test specimen; however, in a shallow furnace such as a wall furnace, the convective heat transfer could be dominated by forced convection due to proximity with the burners. It is important to use a temperature-measuring device that senses both convective and radiation with a small response time constant.

Furnace Temperature Measurements

Furnaces Controlled by Shielded Thermocouple Probes – Two experiments were conducted: one using the floor furnace with a 2.4 m depth and other using a wall furnace with a 0.5 m depth.

In the floor furnace experiments, the furnace temperature was controlled by an average of five-shielded thermocouple probes to follow the ASTM E119 time – temperature curve. In the ASTM E119 standard time-temperature curve, the rate of temperature increases rapidly in the first 10 minutes than the remainder part of the curve. A comparison of the average furnace temperatures measured with the six different types of sensors is presented in Figure 11. The results are consistent with the response time characteristics of the sensors. The furnace temperature rises rapidly at the start to follow the steep part of the standard temperature curve. During this initial period, approximately 8 minutes, the bare-bead thermocouples reading increases at the fastest rate followed by the grounded and ungrounded sheathed thermocouples and by the plate thermometers. This is in part due to a small time constant of less than 1 minute

for these temperature sensors. The reading of the shielded thermocouple probe with the largest time constant increased at the slowest rate. The response of the directional flame thermometers was somewhat faster than the shielded thermocouples. This is also related to the time constant of the directional flame thermometers, which was the second largest of all sensors. After approximately 8 to 10 minutes, the temperature for all sensors starts to level off and converge. This is consistent with the fact that as the furnace temperature rise starts to level off, the temperature sensor response time becomes unimportant and all measurements converge. This is consistent with the ASTM E119 standard time-temperature curve, the rate of temperature increases rapidly in the first 10 minutes than the remainder part of the curve. However, the bare-bead thermocouple readings continue to be higher for the remainder of the test. This is due to the fact that the ratio of convective vs. radiative heat transfer is higher for the bare-bead thermocouples compared to the other sensors.

In the wall furnace experiment, the furnace temperature was controlled by an average of 5 shielded thermocouple probes. A comparison of temperature measured by different sensors is shown in Figure 12. Unlike the temperature measured in the floor furnace in the first 10 minutes, all sensor readings were erratic except the shielded thermocouples, due to the automatic turn off of the furnace following the ASTM E119 curve when temperature measured by the shielded thermocouples started to exceed the standard curve. This is due to the furnace design characteristics, i.e. a shorter depth and burner flames that are closer to the sensors than the floor furnace. However, there are similar trends for temperature measured by different sensors as in the floor furnace. The bare-bead thermocouple also measured the highest temperature and this, once again, is due to the time constant of the sensors. After approximately 10 minutes, all sensors start to level off, as the standard temperature starts to level off, and then converge similarly to the response in the floor furnace. The results measured by different sensors indicate that the temperature measurements in fire resistance test furnaces, even with different depths, depend on the time constant of the temperature sensor particularly in the first 10 minutes.

For an application requiring a shorter fire resistance test such as a 15 minute test, thermal exposure is more severe in a test controlled by shielded thermocouple probes than those controlled by other sensors. These results could be of interest for standard writing organizations that develop short-duration fire resistance tests.

Furnaces Controlled by Plate Thermometers – Two experiments were conducted where the floor and wall furnaces were controlled by the plate thermometers to follow the ASTM E119 standard time-temperature curve. The first experiment was carried out using the floor furnace. A comparison of the average furnace temperatures measured with six different sensors is presented in Figure 13. In the first 10 minutes, as in the case where the furnace is controlled by shielded thermocouples, the bare-bead thermocouples and grounded and ungrounded sheathed thermocouples, due to their shorter time constant, are higher than other sensors. However, the shielded thermocouple probes and the directional flame thermometer temperatures are lower than the plate thermometers and this is due to the larger time constant for those sensors compared to the plate thermometer time constant. After 10 minutes, all sensors start to level off as the standard temperature starts to level off and then converge. This is similar to the response in the floor furnace when the furnace is controlled by the shielded thermocouples. The results are consistent with the response time characteristics of the six sensors and their sensitivity to convective vs. radiative heat transfer as discussed in the previous section. A comparison of the average furnace temperatures measured with the six different sensors in the wall furnace test is presented in Figure 14. A similar temperature trend was shown for all six sensors as in the case above for floor furnace during the entire experiment. The temperatures measured by the grounded and ungrounded sheathed

thermocouples are similar and their differences, with respect to the bare-bead thermocouple temperature, were the smallest. The furnace size did not create erratic temperature distributions in the first 10 minutes as seen above when the furnace was controlled by the shielded thermocouple and this is due to a shorter time constant for the plate thermometer.

Furnaces Controlled by Directional Flame Thermometers – Two experiments were also conducted with furnaces controlled by the directional flame thermometers: one with a floor furnace and the other with a wall furnace. In these experiments, the average of five directional flame thermometers were used to control the furnace in such a way that the furnace temperature is following the ASTM E119 time – temperature curve. Comparisons of the furnace average temperatures measured with six types of sensors are presented in Figures 15 (floor furnace) and 16 (wall furnace). The results showed that in the first 10 minutes, all temperature sensors except the shielded thermocouples measured higher temperatures than the directional flame thermometer. This is due to the time constant as explained before. The temperatures measured by the grounded and ungrounded sheathed thermocouples are similar and their differences, with respect to the bare-bead thermocouple temperature, were the smallest. The results are also consistent with the response time characteristics of the sensors and their sensitivity to convective vs. radiative heat transfer as discussed in previous sections. After 10 minutes, all sensors start to level off as the standard temperature starts to level off, and then converge. This is similar to the response in the floor furnace when the furnace is controlled by the shielded thermocouples and by the plate thermometers.

Furnaces Controlled by Bare-Bead Thermocouples – Two experiments were conducted using the floor and wall furnaces. The furnaces were controlled by five bare-bead thermocouples to follow the ASTM E119 time – temperature curve. Comparisons of the furnaces average temperature, measured with six types of sensors is presented in Figures 17 (floor) and 18 (wall). Since the bare-bead thermocouples have a fastest response time, using them to control the furnace, especially in the first 10 minutes of experiment, was a challenge. During the first 10 minutes of the test, only the grounded and ungrounded sheathed thermocouples measured approximately similar temperature to the bare-bead thermocouples. The shielded thermocouple probes, directional flame thermometers, and plate thermometers are all measuring lower temperature than the bare-bead thermocouple by as much as 75%, 65% and 50%, respectively. This is because the time constant for these three sensors are larger than those of the bare-bead thermocouples. After 10 minutes of fire exposure, the three sensors measured the same temperature; however, these were lower by 8% than the bare-bead thermocouples. After 10 minutes, all sensors started to level off as the standard temperature started to level off, and then converge.

Furnaces Controlled by Grounded Sheathed Thermocouples – Two experiments were conducted where the floor and wall furnaces were controlled by the grounded sheathed thermocouples to follow the ASTM E119 standard time-temperature curve. The first experiment was carried out using the floor furnace. A comparison of the average furnace temperatures measured with six different sensors is presented in Figure 19. In the first 10 minutes, as in the cases above for other controlled sensors, the bare-bead thermocouples are slightly higher than the grounded sheathed thermocouples. All other sensors except the ungrounded sheathed thermocouples measured lower temperatures; however, there is not much difference in the temperature measured by either the grounded and ungrounded sheathed thermocouples. This is due to their shorter time constant compared to the plate thermometer, shielded thermocouples and directional plate thermometers. After 10 minutes, all sensors start to level off as the standard temperature starts to level off, and then converge and this is similar to the response in the floor furnace when the furnace was controlled by the shielded thermocouples.

The results are consistent with the response time characteristics of the six sensors and their sensitivity to convective vs. radiative heat transfer as discussed in the previous section. In the second experiment, the wall furnace was controlled by the grounded sheathed thermocouples. A comparison of the average furnace temperatures measured with six different sensors is presented in Figure 20. Similar temperature trend was shown for all six sensors as in the case above for floor furnace during the entire experiment. The temperatures measured by the grounded and by ungrounded sheathed thermocouples are similar, and their differences with respect to the bare-bead thermocouple temperature were the smallest, therefore, they provided faster response than the plate thermometers.

Furnaces Controlled by Ungrounded Sheathed Thermocouples – Two experiments were conducted where the floor and wall furnaces were controlled by the ungrounded sheathed thermocouples to follow the ASTM E119 standard time-temperature curve. The first experiment was carried out using the floor furnace. Comparisons of the average furnace temperatures measured with six different sensors are presented in Figure 21 for the floor furnace and Figure 22 for the wall furnace. The temperature results are similar to those measured in furnaces controlled by grounded sheathed thermocouples. The temperature measured by either the bare-bead, grounded and ungrounded sheathed thermocouples are more or less similar.

Temperature Lag with Respect to Bare-Bead Thermocouples Measurements

The Bare-bead thermocouples have the smallest time response among the other temperature sensors. To quantify temperature lag between the bare-bead thermocouples measurements and all other temperature sensors, the temperature measurements of the ASTM shielded thermocouples, ISO plate thermometers, directional flame thermometers, grounded and ungrounded sheathed thermocouples were subtracted from the bare-bead thermocouples measurements in the tests where these sensors were used to control the floor and wall furnaces. The temperature lag is plotted in Figures 23 and 24 for the floor furnace and wall furnace, respectively. The results show that, in the first 10 minutes, the temperature lag is significant, but after 10 minutes, the temperature lag becomes insignificant. However, a relatively small temperature bias remains after 10 minutes due to differences of the sensors' sensitivity to convective versus radiative heat transfer. In both floor and wall furnaces, the temperature lag for the grounded and ungrounded thermocouples is the smallest followed by the plate thermometers, directional flame thermometers and the largest is the ASTM shielded thermocouples. The difference in the temperature lag is due in part to the difference in the temperature response time of these sensors compared to the bare-bead thermocouples.

Effect of Furnace Depth

The temperature difference between a bare-bead sensor and other sensors in furnaces with different depth, namely a floor furnace and a wall furnace, where the furnaces were controlled by each of the temperature sensors is shown in Figures 23 and 24. These figures show that there are a lot of temperature fluctuations in the first 8 minutes for the smaller depth furnace (wall furnace) than for the larger furnace (floor furnace). This was created by having the furnace burners designed closer to the temperature sensors in the wall furnace than in the floor furnace. However, the temperature trend was more or less similar. Therefore, a deeper furnace is easier to control its initial rapid temperature rise than a shallow furnace.

Incident Heat Flux Measurements

The incident heat flux measured for floor and wall furnaces where the furnaces are controlled by one of the six temperature sensors are presented in Figures 25 and 26, respectively. The

incident heat flux results showed that for the furnace controlled by the shielded thermocouples the heat flux are as much as 20% higher than the furnace controlled by bare-bead thermocouples. For furnaces controlled by the grounded and ungrounded thermocouples, the incident heat flux is approximately 5% higher than the furnaces controlled by the bare-bead thermopiles. These differences are due to differences in the time constant of different types of temperature sensors.

Comparison of Measured vs Predicted Incident Heat Flux

The incident heat flux in the furnace can be estimated from the following equation, assuming the convective heat transfer is small. As noted below, this assumption is not accurate during the first 5 to 10 minutes of the test.

$$Q = \sigma T^4 \quad (1)$$

Where T is the furnace temperature (controlled) measured by six sensors.

Comparisons of the estimated and measured incident heat flux based on the ASTM E119 time-temperature curve for a furnace controlled by shielded thermocouple probes, plate thermometers, directional flame thermometers, bare-bead thermocouples grounded sheathed thermocouples and ungrounded sheathed thermocouples is presented in Figures 27 to 38. The predicted heat flux in the first 10 minutes of fire exposure is much lower than the measured heat flux by Gardon gages. This could be due to the neglecting of the convective heat transfer, which is more predominant in the early stage in fire resistance test furnaces. After 10 minutes of exposure, the predicted heat flux is up to 10% lower than the measured value for a furnace controlled by plate thermometers or directional flame thermometers. The reason for the lower prediction is again due to the neglect of the convective heat transfer, which is less significant at high temperatures. The calculated incident heat flux by Equation (1) using the controlled temperatures in the case of bare-bead, grounded and ungrounded thermocouples provided best agreement with the measured heat flux among the six temperature sensors.

Summary

This paper discusses the performance of six different temperature sensors for controlling the furnace temperature in a floor furnace and a wall furnace as well as the temperature lag for ASTM shielded thermocouples, plate thermometers, directional flame thermometers and grounded and ungrounded sheathed thermocouples in comparison to the bare-bead thermocouples. It also discusses the incident heat flux and comparison of the predicted vs measured incident heat flux received by a specimen in a floor furnace and a wall furnace. The following are the key findings:

1. In fire resistance furnaces of different depths, the initial period of fire exposure (10 minutes), the difference in the temperature measured by six sensors is significant. However, after 10 minutes, the difference becomes insignificant. As a result, the furnace temperature measuring device response time is crucial in assessing building elements performance particularly in a short duration tests.
2. Because the ungrounded thermocouple has a fast response time and good durability, it could be a potential sensor for use in fire resistance standard test furnaces.
3. A deeper furnace is easier to control its initial rapid temperature rise than a shallow furnace.

4. Predicted incident heat flux by radiation based only on the fastest temperature response measured by either the bare-bead, grounded and ungrounded thermocouples provided the best agreement among the other sensors with measured heat flux.

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References

1. ASTM E119-08, "Standard Methods of Fire Tests of Building Constructions and Materials", ASTM, Philadelphia, PA.
2. ISO 834-1, "Fire Resistance Tests Elements of Building Construction – Part 1"
3. CAN/ULC-S101-07, "Standard Methods of Fire Endurance Tests of Building Construction and Materials" ULC, Toronto, Ontario Canada
4. Wickström, U., "The Plate Thermometer – Practical Aspects", SP- Report 1997:28, Swedish National Testing and Research Institute, 1997.
5. The European Standard EN 1363-1:1999, "Fire Resistance Tests – Part 1: General Requirements", European Committee for Standardization, rue de Stassart 36, B-1050 Brussels, 1999.
6. Sultan, M.A., "Fire Resistance Furnace Temperature Measurements: Plate Thermometers vs. Shielded Thermocouples", Fire Technology, 2008.
7. Sultan, M.A., "Comparisons of Temperature and Heat Flux in Furnaces Controlled by Different Types of Temperature Sensors" Published online, Journal of ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, 2009.
8. Babrauskas, V and Williamson, R.B., "Temperature Measurement in Fire Test Furnaces", Fire Technology, Vol.14, No. 3, 1978.
9. Wickström, U., "Adiabatic Surface Temperature and the Plate Thermometer for Calculating Heat Transfer and Controlling Fire Resistance Furnaces" Fire Safety Science Proceedings of Ninth International Symposium, 2008.
10. Longenbaugh, R.S. et al, Thermal Response of a Small Scale Cask-Like Test Article to Three Different High Temperature Environments", Sandia National Laboratories Report to Federal Rail Administration, DOT/FRA/ORD- 90/01, Feb. 1990.
11. Keltner, N.R., "Directional Flame Thermometers: A Tool for Measuring Thermal Exposure in Furnaces and improving Control" Interflam 2007, Proceedings of the Eleventh International Conference, Interscience Communications, 2007.
12. Keltner, Ned, private communication 2008.
13. The Temperature Handbook, OMEGA Engineering Inc., Vol. 20, Page A-7, P.O. Box 4047, Stamford, CT 06907-0047, USA
14. Shorter, G.W. and Harmathy, T.Z., "Fire Research Furnaces at the National Research Council, NRC 5732, National Research Council Canada, Ottawa, Ontario, Canada 1960.
15. Sultan, M.A. and Denham, M., "Harmonization of Fire Severity in Standard Fire Resistance Test Furnaces", Fire Safety Sciences – Proceedings of the Fifth International Symposium, 1997.

Figure 1 ASTM Shielded Thermocouple

Figure 2 ISO Plate Thermometer

Figure 3 Directional Flame Thermometer

Figure 4 Grounded and Ungrounded Thermocouples

Figure 5 Grounded Thermocouples

Figure 6 Ungrounded Thermocouples

Figure 7 Temperature Sensors in Floor Furnace

Figure 8 Temperature Sensors in Wall Furnace

Figure 9 Gardon Gauge Water Cooled Heat Flux Sensor

Figure 10 Floor and Wall Furnaces

Figure11 Floor Furnace Controlled by ASTM Shielded Thermocouples

Figure 12 Wall Furnace Controlled by ASTM Shielded Thermocouples

Figure 13 Floor Furnace Controlled by Plate Thermometers

Figure 14 Wall Furnace Controlled by Plate Thermometers

Figure 15 Floor Furnace Controlled by Directional Flame Thermometers

Figure 16 Wall Furnace Controlled by Directional Flame Thermometers

Figure 17 Floor Furnace Controlled by Bare-Bead Thermocouples

Figure 18 Wall Furnace Controlled by Bare-Bead Thermocouples

Figure 19 Floor Furnace Controlled by Grounded Sheathed Thermocouples

Figure 20 Wall Furnace Controlled by Grounded Sheathed Thermocouples

Figure 21 Floor Furnace Controlled by Ungrounded Sheathed Thermocouples

Figure 22 Wall Furnace Controlled by Ungrounded Sheathed Thermocouples

Figure 23 Temperature Difference between Bare-Bead Sensor and Other Sensors (Floor Furnace)

Figure 24 Temperature Difference between Bare-Bead Sensor and Other Sensors (Wall Furnace)

Figure 25 Incident Heat Flux (Floor Furnace)

Figure 26 Incident Heat Flux (Wall Furnace)

Figure 27 Floor Furnace Controlled by ASTM Shielded Thermocouples

Figure 28 Wall Furnace Controlled by ASTM Shielded Thermocouples

Figure 29 Floor Furnace Controlled by Plate Thermometers

Figure 30 Wall Furnace Controlled by Plate Thermometers

Figure 31 Floor Furnace Controlled by Directional Flame Thermometers

Figure 32 Floor Furnace Controlled by Directional Flame Thermometers

Figure 33 Floor Furnace Controlled by Bare-Bead Thermocouples

Figure 34 wall Furnace Controlled by Bare-Bead Thermocouples

Figure 35 Floor Furnace Controlled by Sheathed Grounded Thermocouples

Figure 36 Wall Furnace Controlled by Sheathed Grounded Thermocouples

Figure 37 Floor Furnace Controlled by Sheathed Ungrounded Thermocouples

Figure 38 Wall Furnace Controlled by Sheathed Ungrounded Thermocouples