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On equivalent fire exposure

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ABSTRACT

The ability to accurately determine fire resistance requirements is one of the most important aspects of fire safety science. Since fire resistance depends on fire severity, which is a rather ambiguous term, there have been continuous efforts to develop a method for quantifying the term fire severity itself as well as converting it into fire resistance requirements. This paper evaluates two approaches – equivalent temperature and normalised heat load methods, by employing computer fire simulation. It is shown that the latter is a more appropriate quantifier, as it does not rely on an arbitrarily selected reference point and allows for a comparison in an unlike enclosures.

Keywords: Fire severity · Fire resistance · Equivalent fire exposure · Enclosure thermal properties · Heat load

1. Introduction

Fire resistance is the basic property of any fire resisting construction. As straightforward as this requirement may seem, there is ambiguity in the way of translating real-world fire severity into a fire-resistance requirement. Even the term *fire severity* itself is somewhat ambiguous; is it the temperature history of a fire, its overall heat output, or the heat absorbed by the enclosure boundaries?

At the moment, standardised fire-resistance tests, such as those referenced in [1], are used to determine the fire resistance of a construction product or building element. These tests methods simulate a fire by following one of standardized time-temperature curves. Such an approach controls the temperature within the test furnace and allows for comparison under reference conditions.

On the other hand, there are real-world fires in buildings, the construction elements of which must withstand the exposure. These fires vary greatly with the nature and layout of the fuel and geometry and construction materials of the building. Therefore, the open question that needs close attention is: *"Which real-world fire severity descriptor should be selected and how to translate it into the standardised test conditions?"*

2. Fire resistance and standardised fire resistance testing

Fire resistance is the ability of a construction member to withstand fire exposure for a given time period, maintaining the required fire-resistance criteria. These criteria are most often load-bearing ability, integrity and insulation, but there are other criteria available.

In order to be able to undertake such testing, there are reference time-temperature curves available, which describe the development of a fire. Most often the standard time-temperature curve is employed in fire resistance testing, the development of which follows the equation (1) [1-2]:

$$T = \log_{10}(8t + 1) + 20 \qquad (1)$$

where T is average furnace temperature (°C) and t is time (min).

The actual development of the temperature during a 60 fire exposure is shown in Fig. 1.

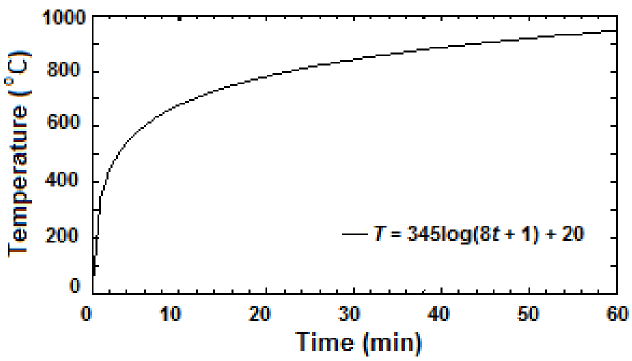

Figure 1 Standard time-temperature curve

From the above, it is obvious that, when testing to this, but also other (C-H, exterior fire, tunnel fire, etc) standard-

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ised time-temperature curves, the furnace temperature conditions change only with time, following the course of the selected curve.

The advantage of this system is that fire resistance is determined on a reference basis and it is therefore possible to compare tested construction members with each other. However, the disadvantage of this approach is that the development and intensity of heat loading in real fires is not identical with the standardised time-temperature curves. Hence, there is a need for a method which would allow conversion of the intensity or development of a fire in a building to the intensity or development of the fire achieved by a standardised time-temperature curve, to specify sufficient resistance levels of the construction elements for a given fire.

3. Fire severity

As mentioned earlier, fire severity is not a standardised term with fixed meaning. It is, however, generally accepted that is should represent the detrimental effect of a fire on the construction element(s) in question. There are a number of methods which, utilizing various input parameters, convert the calculated intensity of a fire, expressed by various means, to the equal duration of exposure in a test furnace under one of the standardised time-temperature conditions. Some of these methods are evaluated in this paper.

3.1. Equality of time-temperature areas

The earliest concept, proposed by Ingberg [3], bases the equivalence of fire severity on the equality of the areas under the time-temperature curves of the real fire and test furnace fire. The proposed equation (2) for determining the equivalent fire duration was:

$$\tau_{\mathrm{e}} = 0.0205 \cdot L \qquad (2)$$

where τ_{e} is equivalent fire duration (time-temperature curve) (hours) and L is fire load (kg.m^{-2}). This approach is completely insensitive to the effect of ventilation and the thermal properties of enclosing construction.

Czechoslovakian standard CSN 73 0802 [4] utilized a similar approach adjusted for the nature of fuel and effect of ventilation.

3.2. Equality of temperature in reference points

The second group of methods involves the equality of temperatures achieved in selected parts or depths of a construction element. The basis of this approach is that two fires (real and test) are of an equal severity if the temperature achieved in the selected reference point is identical. A number of methods working on this principle have been developed including those of Law [5], Petterson [6], DIN [7] and Reichel [8-9].

The calculation methods employed for determining the critical temperature vary, but all of them are based on the equation of energy balance. Although of they provide a higher level of accuracy, a great care must be taken when selecting the point of reference, as it cannot be generalised. For reinforced concrete members it is usually the temperature at the reinforcing steel, however, the selection of a reference point for masonry walls may not be as straightforward.

3.3. Normalized heat concept

The basis of the normalized heat concept, developed by Harmathy [10-11], is that the severity of the fire can be expressed as the overall heat penetrating into the enclosure boundaries with the normalization being done through their thermal properties. This way the fire severities of fires in unlike enclosures may be compared. The mathematical equation (3) of normalised heat load is:

$$H = \frac{1}{(\lambda \cdot \rho \cdot c)^{1/2}} \cdot \int_0^{\tau} q \, \mathrm{d}t \qquad (2)$$

where H is normalised heat load (s$^{1/2}$.K), $(\lambda.\rho.c)^{1/2}$ is thermal absorptivity and τ is time duration of exposure (s).

4. Computer modelling evaluation

In order to evaluate the capabilities and suitability of the methods described in Section 3 of this paper a number of computer simulations were carried out. The results from the simulations are then compared, utilizing both concepts – equal temperature and normalized heat load.

Fire Dynamics Simulator version 6 [12-13] was selected for the simulation. It is a freely available software package by NIST that allows simulation of combustion, heat generation and its transfer in an enclosure. Fire Dynamics Simulator is a suitable tool for both the prescribed time-temperature and free-burning fire (heat generation) scenarios.

4.1. Computer model scenarios

4.1.1. Computer model scenarios

There were three alternative material configuration with different thermal properties simulated. These included – mineral wool as thermal insulator, normal weight concrete as thermal conductor and a layered combination of the above. In the layered alternative the mineral wool was on the exposed side followed by concrete. The thermal properties of the materials are described in Tab. 1.

4.1.1. Simulated scenarios

There were two types of scenarios simulated – test furnace and room fire. In the test furnace simulation, a reduced scale test furnace was created. In both cases the simulation time was 3600s (one hour).

Grid resolution was set to 10 cm in each direction, which provides a good compromise between accuracy and computational times. The thickness of the simulated walls was 20 cm. In the case of the layered configuration the first 10 cm represented mineral wool and second 10 cm concrete.

The furnace was simulated as a cubic enclosure with a side of 1 m in each direction. Five of the walls were specified as heaters, in order to heat the interior of the enclosure as per the standard time-temperature curve. The sixth wall represented the test specimen. The layout of the test furnace model is shown in Fig. 2.

The room fire scenario (Fig. 3) involved a cubic room with a side of 2 m in each direction. Each wall (20 cm thick) was prescribed the same boundary condition, corresponding with the material alternative modelled. The computational domain was extended 1m from the front wall to allow free air circulation into the room. There was a single opening, 1 x 1m (1m^2) in the front wall providing access for fresh air. Given the size of the enclosure, this approximately equals to a ventilation parameter of 0.04 which is the same as that of the standardised time-temperature curve [8]. Therefore the ventilation conditions should not cause deviation from the test furnace results.

The fire was located across the entire floor prescribing it a uniform fixed burning rate of 0.025 kg.m^{-2}, which corresponds to a heat release rate of 471.5 kW.m^{-2} at the heat of combustion of 16.7 MJ.kg^{-1}. The burning rate is an average of values calculated by various methods [8, 15-16] and is a function of the ventilation parameter. It is the maximum burning rate achievable under the ventilation conditions. The fuel used in the model was wood. Research [17] confirms a strong dependence of burning rate on the radiant flux within the compartment which is reflected by the value used in the simulation. Further discussion on thermal degradation of wood under fire conditions may be found in [18].

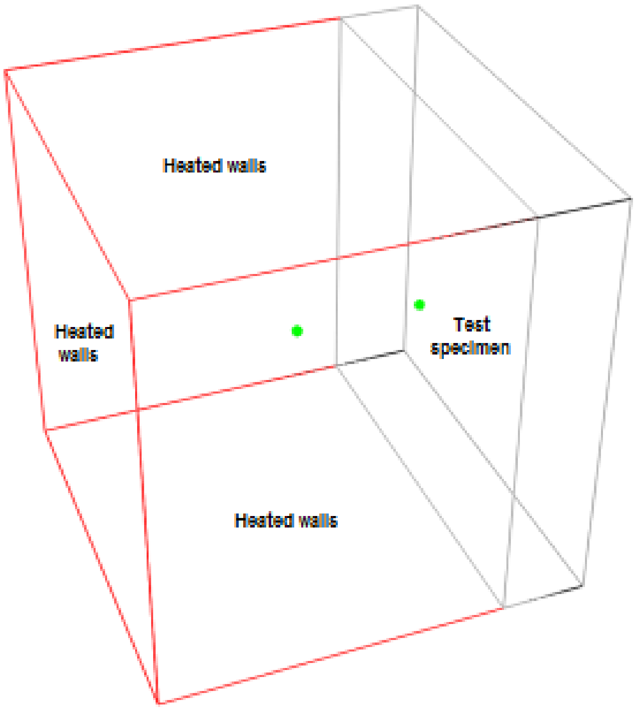

Figure 2 Wireframe visualisation of test furnace model

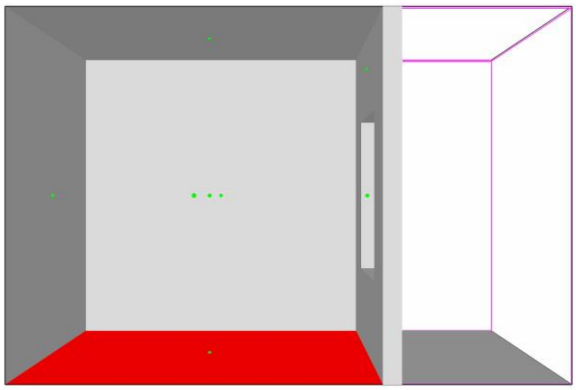

Figure 3 Visualisation of room fire model

Table 1 Thermal properties of construction materials used in model

Material	ρ (kg.m^{-3})	c (J.g^{-1}.K^{-1})	λ (J.m^{-1}.s^{-1}.K^{-1})	$(\lambda\,\rho\,c)^{1/2}$ (J.m^{-2}.s$^{-1/2}$.K^{-1})
Normal weight concrete	2400	837	1.67	1832
Mineral wool	60	880	0.072	62

5. Results and discussion

The results of the simulations were compared in order to evaluate the equivalent exposure using both the equal temperature and normalized heat load methods. The development of temperature in the test furnace was identical to the standard time-temperature curve shown in Fig. 2, regardless of the material simulated. On the contrary, in the room fire simulations, the development of the temperature showed a strong dependence on the thermal properties of the enclosing construction, refer to Fig 4. The scenarios with mineral wool lining reached much higher average temperatures inside the enclosure compared with concrete due to the amount of heat absorbed by the walls.

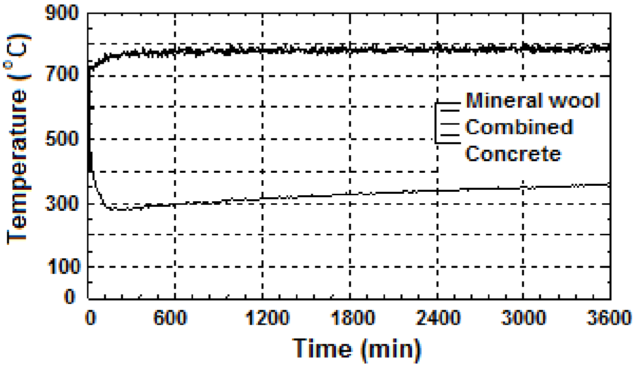

Figure 4 Development of temperatures in room fire simulations

For the evaluation of equal temperatures a number of reference points were monitored in the construction. These were as follows: exposed surface, within construction at 1 cm, 2 cm, 5 cm, 10 cm, 15 cm and rear surface. Fig. 5 - 7 show the temperatures attained in the reference points after 60 minutes of exposure for both scenarios – furnace and room fire.

It is apparent that there are differences in the maximum temperatures reached in the individual reference points, due to the different temperature profiles in the furnace and room scenarios. What is also very obvious, when comparing Fig 5 to Figs. 6 and 7, is the fact that the difference is considerably smaller for scenarios in which the walls were lined (formed) by mineral wool which is an insulator. The differences between the furnace and room fire scenarios also decrease with the increasing depth of the reference points.

The above confirms the importance of the correct selection of the equal-temperature reference point. For materials with higher thermal absobtivity $(\lambda\ \rho\ c)^{1/2}$, represented by normal weight concrete in this paper, the differences are significant. This is confirmed by the values shown in Fig. 8.

The time required to reach an equal temperature in the furnace decreases the closer is the reference point to the exposed side of the wall. For the concrete wall, it takes only 10 minutes to reach the same temperature in the furnace as is reached after 60 minutes in room fire scenario when the reference point is located 1cm beneath the exposed surface. When the reference point is located 5 cm beneath the exposed surfaces the time increases to 23 min and keeps increasing with the depth.

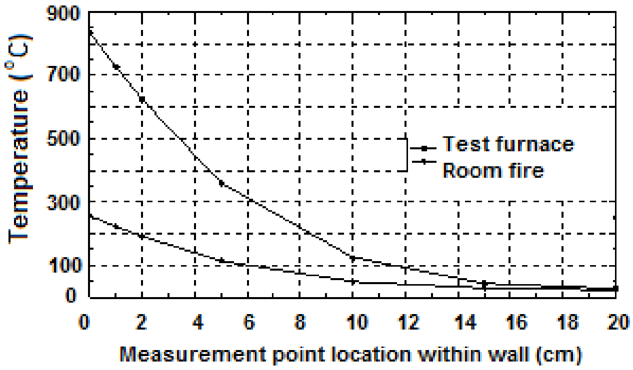

Figure 5 Temperatures achieved in construction after 3600s exposure – concrete

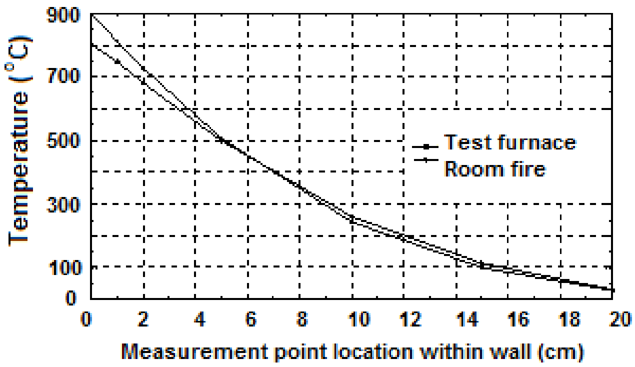

Figure 6 Temperatures achieved in construction after 3600s exposure – mineral wool

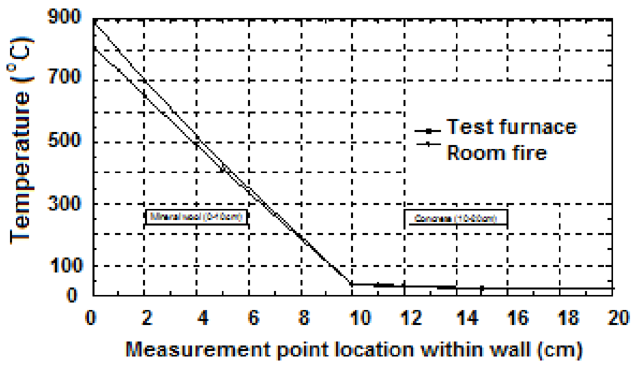

Figure 7 Temperatures achieved in construction after 3600s exposure – combined

A similar trend is observed in the scenario where mineral wool is used as lining material. There is also a difference between the furnace and room-fire scenarios in the individual temperature reference points, but it decreases sharply with increasing depth.

To provide a comparison with the equal-temperature method, the normalised heat load method results are also included. To determine the overall heat flux penetrating into the construction in question, trapezoidal integration of the individual data points in time was employed. The obtained values per square meter of wall surface area are listed in Tab. 2 together with the times required to achieve the same heat load in the furnace.

Again, the times required to reach the same heat load exposure on the concrete specimen is significantly shorter, that those of the insulating linings.

When the two approaches are compared it is obvious that for the non-insulating material with high thermal absorbtivity – normal weight concrete – the equal temperature method seems to yield similar results to the normalized heat load method in reference points closer to the exposed surface. On the other hand, the simulations where walls were lined with an insulator – mineral wool – seem to correspond at greater depths.

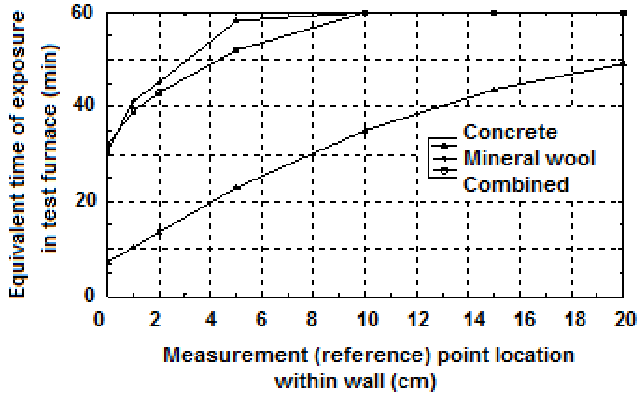

Figure 8 Test furnace equivalent exposure times – 60min room fire

Table 2 Heat loads and normalized heat loads construction evaluation after 60min exposure

Material	Heat load		Normalized heat load		Equivalent time
	Room fire	Furnace	Room fire	Furnace	
	(kW.m^{-2})	(kW.m^{-2})	(s$^{1/2}$.K)	(s$^{1/2}$.K)	(min)
Normal weight concrete	24963	83378	13.6	45.5	18.1
Mineral wool	3282	3315	53.2	53.77	58.4
Combined	3396	3402	55.1	55.18	58.2

6. Conclusion

A series of computer simulations were carried out in order to evaluate two different methods for determining equivalent fire exposure – equal temperature and normalized heat load concepts.

The results have confirmed that it is not possible to base the fire severity solely on the heat output of a fire. Even if ventilation does not change, as it was shown in the room fire simulations, the temperatures within the enclosure vary significantly, depending on the thermal properties of the boundary, which is in agreement a previous study [19].

The other issue highlighted in this paper is the importance of the selection of the equal-temperature reference point. For example, 2 cm beneath the exposed surface may be a crucial depth for prestressed concrete members, however, will not provide any relevant comparison for a brick wall. Furthermore, the differences decrease with the increasing depth of the construction.

In contrast to the equal temperature approach, the normalized heat method does not rely on a specific reference point and allows for comparison of unlike enclosures. This is achieved through the adjustment of the absorbed heat by the thermal properties of the boundary (thermal absorptivity).

Even a comparison of two very simple scenarios – thermal conductor vs thermal insulator – shows that the question of equivalent fire exposure is a complex issue. Given the above results, the amount of heat which a construction member is to withstand in a fire, appears to be a more suitable quantity for conversion into fire resistance requirements.

Acknowledgements

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