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b) Reference to a journal online first article: Martinka J, Kačíková D, Hroncová E, Ladomerský J. Experimental determination of the effect of temperature and oxygen concentration on the production of birch wood main fire emissions. *J Therm Anal Calorim*. Forthcoming 2012; doi: 10.1007/s10973-012-2261-2.

c) Reference to a book: Murphy JJ, Shadix CR. *Combustion Chemistry*. 2nd ed. Oxford: Blackwell Science; 2006. 400 p.

d) Reference to a book chapter: Pehrson R. Fire Behaviour. In: Cote AE, Pehrson R, editors. *Fundamentals of Fire Protection*. 2nd ed. Quincy: National Fire Protection Association; 2004. p. 101-133.

e) Reference to a conference proceedings paper: Osvald A, Fanfárová A. Fire retardants. In: Zachar M, Dúbravská K, editors. *Advances in Fire Engineering. 1st International Scientific Conference on Advances in Fire Engineering*; 2012 Nov 15-16; Zvolen, Slovakia. Zvolen: Technical University in Zvolen; 2012. p. 197-210.

f) Reference to a standard: British Standards Institution. BS 5950-8:2003. *Structural use of steelwork in building: code of practice for fire resistant design*. London: BSI; 2003.

g) Reference to a patent: Servatius J, Fehr RT, inventors; 3M Innovative properties Company, assignee. *Multidirectional single surface optically shaped film*. United States patent US 6,700,712. 2004 Mar 2.

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Smoke and heat emissions from boundaries of fire compartments and the impact of installation methods

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ABSTRACT

Fire resistance testing is intended to provide criteria and verification methods for stopping of fire spread between fire compartments. It has been used with success for this purpose for decades. The principle, testing schemes, and criteria do not provide information about tenability conditions in adjacent fire compartments however. This drawback has become increasingly obvious as fire safety engineering started to make it possible to evaluate tenability conditions using data on smoke emissions from construction materials and products, and as construction products with potency to emit significant amounts of opaque and toxic effluents found the way to building systems including those providing fire resistance. Findings of fire resistance testing of six non-loadbearing walls made of commonly used composite metal faced sandwich panels, two filled with mineral stone wool as core insulation (MW), and four filled with polymer polyisocyanurate (PIR) insulation material, demonstrated these effects. The project has been recently expanded by additional measurements of gas and particle effluents. This paper deals with new information reflecting back on original test results.

Keywords: Fire resistance testing • PIR • Polymer insulation • Flammable insulation • Smoke production • Heat release

1. Introduction

Fire resistance tests are to guarantee certain criteria of fire compartmentation, commonly expressed in minutes, where building elements are supposed to stop the fire spread exposed to a standard 'reference' fire exposure. The assumption is that the fire barrier itself is not a contributing element to fire and smoke spread to the safe side, as the definition of compartmentation is: "The subdivision of a building into relatively small areas so that fire or smoke can be confined to the room or section in which it originates" [1].

The tests simulate post-flashover fire conditions using the standard temperature/time curve, as expressed by the European standard fire resistance testing, according to EN 1363-1[2]. Non-loadbearing walls are tested to EN 1364-1[3]. As an indicator of fitness of such a wall to its use as a boundary of fire compartments, a combination of criteria described in EN 13501-2[4] are used; typically they comprise integrity (E), insulation (I), and radiation (W) from the unexposed surface.

Performed to EN 1364-1[3], the published test results[4] were analysed to determine possible interaction between the furnace and the tested building elements containing combustible and non-combustible core, using the elements with non-combustible core as a reference. To get a better insight on this behaviour, six specimens of non-loadbearing walls made of two different types of composite metal faced sandwich panels have been tested to investigate their performance when used as fire compartments. These products are harmonised in EU and subjected to CE-marking[6].

The insulation material in two of the six test specimen was non-combustible mineral stone wool (MW), to set a benchmark when investigating heat supply in the test furnace; in the other four the insulation material was polymer polyisocyanurate (PIR). Both types are commonly used as part of the building envelope, attached to the load-bearing (typically steel) structure, and as fire separating walls within buildings.

Two identical specimens in each configuration, with fire exposure from the same side have been tested. In addition to measurements required by the common fire resistance test method, heat input inside the test furnace was measured to evaluate the heat produced by the tested elements, and smoke/vapour emission outside the test furnace was registered (Fig.1). However no chemical or toxicological anal-

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yses of smoke/vapour were carried out at that time; it was the subject of subsequent test programme and analysis [7].

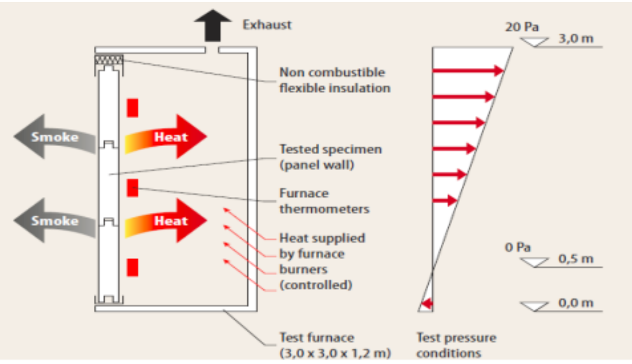

Figure 1 Vertical test furnace for fire resistance testing and investigation of smoke/heat emission from the tested specimens

The fire resistance tests [5] used the standard temperature/time curve which was achieved by supplying a relatively constant heat input of approx. 600 kW from gas-fed controlled burners. However, part of the energy input in the furnace might have been generated by the tested specimens themselves. In order to keep the heat build-up conforming to EN 1363-1[2] curve specification, gas supply from burners had to be reduced accordingly.

The test situation is oxygen controlled, especially if there is an oversupply of fuel coming from combustible test specimens: "For test specimens which burn rapidly, a deviation in excess of 100 K above the specified temperature/time curve may be exceeded for a period not in excess of 10 minutes provided that such excess deviation is clearly identified as being associated with the sudden ignition of significant quantities of combustible materials increasing the gas temperature in the furnace." [2]

The energy input into the furnace supplied by the burning test elements was identified as a reduction of energy input from the furnace burners during these periods ('missing' energy). These could clearly be identified as the time intervals during which reduced amount of gas was supplied to the burners.

Fire resistance tests do not contain smoke emission measurements. Smoke emission can be part of the general observations of the unexposed side of the tested specimen, but it is not reported as a test result, and does not make part of the fire resistance class achieved. The only information about smoke provided in the European system of reaction to fire [8] is the supplementary criterion -*s*1, -*s*2, -*s*3. This criterion is based on the optical density of smoke, obtained using thermal attack on the specimen surface by a relatively small source (30.75 kW) [9].

The smoke emissions from the unexposed side [5], [7] are the result of fire exposure of the entire exposed tested wall surface (9 m^2) to a source of heat of approx. 600 kW, where the standard temperature/time curve is employed, simulating a post-flashover fire.

2. Material and methods

Four composite metal-faced sandwich panel walls with PIR core, and two stone mineral wool core panel walls were tested [5]. The second part of the project examined a series of three PIR-core panel walls, supplemented by one MW-core panel wall and an inert brick wall as a reference [7].

Two installation methods were used, showing two different responses of the tested structures to the standard fire exposure.

In the first part of the project, the panels were fixed to hot-rolled steel beams using the screws specified by the producers (Fig. 2), in full accordance with the test method [3]. The fixing method used in these tests was chosen to be representative of practice where panels are mounted on a load-bearing steel structure of a building. Two parallel U-shaped hot-rolled steel profiles were used to simulate the load-bearing building structure. These profiles were welded on one side, and laid in brackets to allow for thermal expansion on the other side (Fig 2).

In the second series of fire resistance tests incorporating smoke analysis measurements, the primary goal of the project was to establish the quantities of gas species and particles released from the unexposed side of the tested walls. It was therefore agreed to attach the tested specimens around all their edges, leaving no provisions for a free-edge; as it turned out later, this difference from the original installation which deviates from the test method[3] resulted in a more uniform and possibly also reduced amounts of smoke emissions.

Top profile - fixed end   Bottom profile - free end for thermal expansion

Figure 2 Panels were fixed to load-bearing steel profiles

3. Results and discussion

When the free-edge installation was used and the panel walls were attached on three sides only, the behaviour of the tested elements showed that:

- Two of four PIR-cored panels displayed heavy smoke emission on the 'cold', unexposed side, changing over time erratically.
- Heat released from the specimens differed; the difference not only being between MW-cored and PIR-cored panel walls, but also among the PIR-cored panel walls themselves.
- Heat input from the burners seemed inversely proportional to smoke emissions on the unexposed side outside the furnace, comparing different test specimens, as well as comparing different test periods of individual test specimens.

The amount of smoke coming from some PIR-core panel walls during the fire resistance testing was significant (Fig. 3). The smoke emission outside the furnace from the cold unexposed side of the element started early in the test and continued for a prolonged time. Heavy smoke clearly emitted far within the declared fire resistance period of particular elements. In some cases, heavy smoke emissions started already in the 1st minute of the test. Smoke emissions were not always steady but changed over time in an erratic manner.

Two of four PIR-cored panel walls released enough heat during the fire resistance test that the furnace burners had to be switched off at certain periods during the test (Fig.4). The other two PIR-cored panel walls showed about the same pattern of gas consumption as the two mineral wool MW-cored panel walls; a linear trend pointing to a constant heat input in the furnace at the rate of 600 kW. However, during these latter tests heavy smoke emission out of the panel joints outside the furnace was observed (Fig.4).

An estimate of the heat release by the PIR-cored sandwich panel wall could be done using the calorific value of the fuel – as the equivalent of energy which would have otherwise been supplied into the furnace by the furnace burners. When the joints open inside the furnace, the (3 x 3) m wall segment made from PIR-cored sandwich panels containing 2 x 3 m of panel joints was found capable of a peak heat release rate of about 70 kW/m2 (compared to the available benchmark – MW-cored panel walls).

Two of the PIR-cored sandwich panel walls showed periods of significant increase in heat release rate (inside the furnace). One of them had vertically oriented panels, the other was placed horizontally. In the other two PIR-cored elements smoke emitted on the unexposed side through panel joints. Smoke discharge occurred within the first minutes, long before the panels failed any of the fire resistance criteria. These two PIR-cored sandwich panel walls, which showed no measurable contribution to heat release rate inside the furnace (compared to the MW-cored panels), displayed prolonged periods of intense smoke emission on the unexposed side. Thus these two phenomena seem to be inversely related.

When the free edge was NOT used and the panel walls were attached on all four sides, the behaviour of the tested elements showed that:

- All three PIR-cored tested walls displayed similar smoke emission patterns, with heavy smoke emission starting after 10th minute into the tests. Contributions of PIR-core panel walls to heat emission were uniform throughout the test as well as among the tested specimens.

The difference from the performance of specimens containing the free edge was probably caused by different strains imposed on the panel joints as a result of a more uniform stress over the wall surface. The absence of the free edge resulted in a more "neat" and predictable performance of panel walls installed in this special way. This way of installation is not foreseen by the test standard [4] unless the test result should be valid for the tested size (3 x 3) m only. Significant smoke emissions started after a 10-minute period of internal combustion and pressure build-up between the steel skins of the panels.

Panels installed vertically

Panels installed horizontally

Figure 3 Smoke generating from the unexposed side of PIR-cored sandwich panel wall

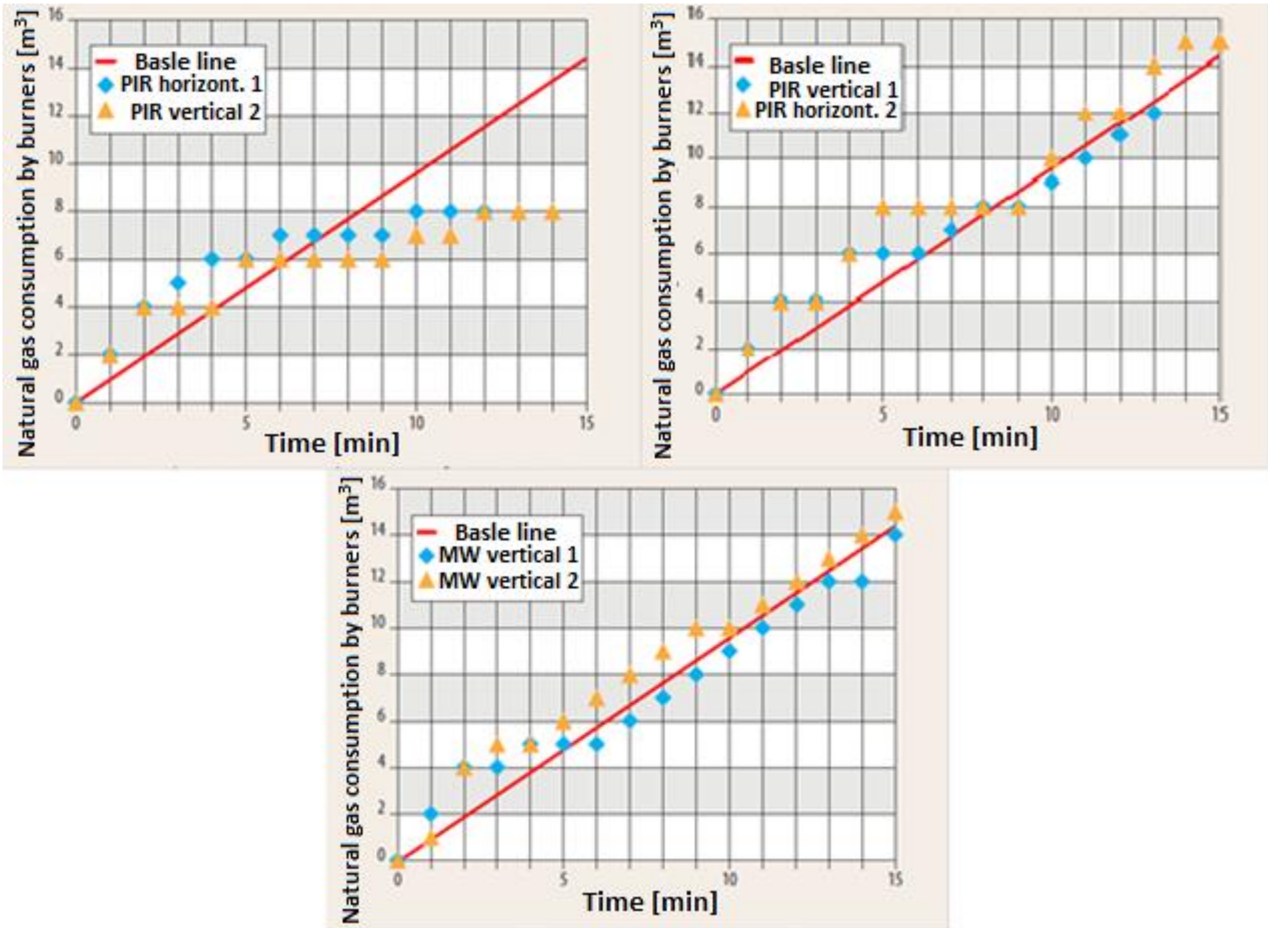

Figure 4 Fuel consumption of the furnace burners for all panel walls in the period 0 to 15 minutes

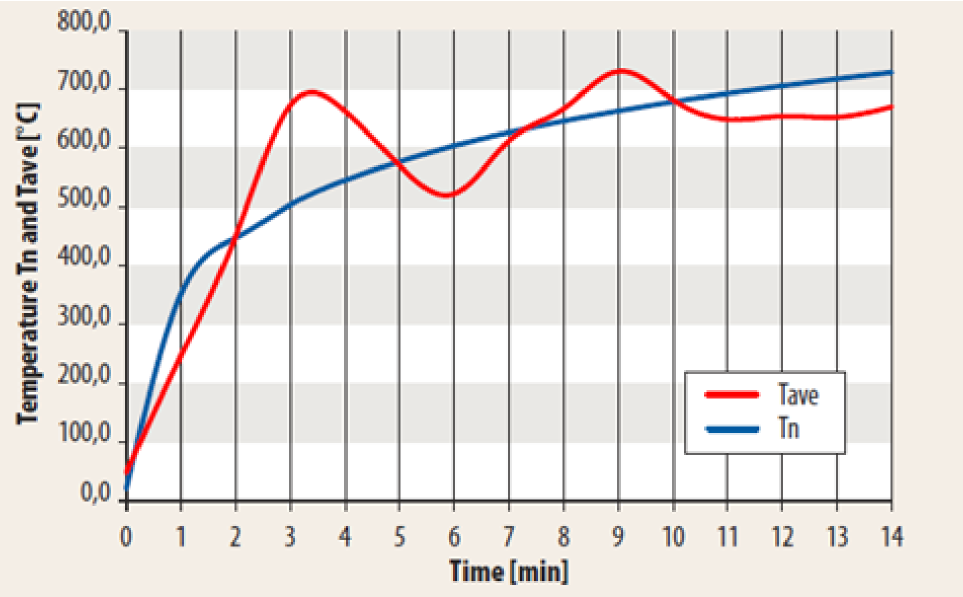

Figure 5 Temperature/time curve of a specimen releasing heat into the test furnace (PIR vertical 2). The fuel supply was effectively stopped after 2nd minute; this wall showed low smoke emission

3. Conclusion

Measurements and observations indicate that the two depicted phenomena – smoke and heat emissions – are just different effects of the same behavioural aspect of the tested specimens: pyrolysis and burning of the wall core. None of them makes part of fire resistance performance criteria. The observed performance is in apparent contradiction to the basic definition of fire compartment [1].

Composite metal faced sandwich panels with combustible core do not make inert boundaries of fire compartments. Polymer smoke and/or vapour emission may contribute to the heat on the exposed side on one hand, or, more importantly, may result in heavy smoke and/or vapour outpour on the unexposed side. These effects are not contained in, and cannot be derived from fire resistance classes which are part of the declared product properties available to the users of the product.

Based upon the data from the six tests it is not clear if it is possible to predict which mechanism will prevail during a test: smoke emission on the outside of the furnace, or contribution to heat release inside the furnace. These two mechanisms seem to be inversely related. Therefore, both mechanisms should be considered as the potential outcome during a real fire.

When assessing fire performance of composite structures like metal-faced sandwich panels used for fire partitioning applications, one should be aware of the importance of the mechanical responses of such structures to thermally induced loads and stresses. The amount of smoke and heat emitted may depend on panel deflections at joints, which may decide how much smoke is released to the "safe" unexposed side of the tested elements, how much these elements contribute to the fire side by releasing heat, and at what periods of time will either of these phenomena occur.

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