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Influence of the built environment on design fires

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ABSTRACT

Design fires are often used to the evaluate performance based designs by fire protection engineers all over the world and can be an invaluable tool if used properly. One potential big issue however is the fact that the exact same design fire is recommended by authorities in similar building types despite the fact that some building characteristics, such as building material, can differ greatly. This paper focused on investigating several key characteristics of a building (building material, openings, room floor area size and ceiling height) and its effect on the design fire using computational fluid dynamics. When well to moderately insulating materials was used the design fire growth rate and maximum heat release rate was in many cases significantly increased, especially if the room was well ventilated, the ceiling height was relatively low and the room floor area was moderate. However, using thermally thin materials (steel sheet) or materials with large heat storing capacity (concrete) very little change was seen on the growth rate or maximum heat release rate. In conclusion it was recommended that one should take precaution when using recommended design fires in buildings with certain characteristics since it potentially can overestimate the safety in such case.

1. Introduction

The simple design fire concept has been used extensively to evaluate performance based designs all over the world and is an invaluable tool for many fire protection engineers. However, the design fire is a rough simplification of the real world and using it in applications outside the boundaries of its original intent might result in erroneous conclusions in regard to fire safety. E.g., the Swedish National Board of Housing, Building and Planning (Boverket in Swedish) recommends different fire growth rates depending on the type of activity in a building [1], but one problem that can arise from directly using proposed growth rates is that the characteristics of the fire compartment is never accounted for; e.g. will a heavily insulated building behave the same as a steel sheet building or does the radiative feedback increase the fire growth and maximum heat release rate? Does a smaller room behave different from a big room? How much does the amount of openings (both normal openings and those caused by evacuating people, as in doors being opened) to the fire room affect the development of a fire? Some studies has been made on this topic, e.g. an experimental study done by Evegren et al. that indicates that the effects of using highly insulated compartments will influence the mass loss rate [2] to some degree, but the scope of different scenarios was rather limited in that work. This work focuses on investigating typical building materials, the amount of door openings supplying air to the fire room, fire room floor area and ceiling height and how they affect the fire growth and maximum heat release rate using the computer software Fire Dynamics Simulator [3] doing so called numerical experiments [4].

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2. The design fire

Design fires are often used when doing performance based design of the fire safety in buildings. The time to critical conditions (for example visibility, toxicity, temperature and radiative heat flux levels) inside the building or compartment in case of a fire is compared to the time it takes for the occupancies to safely egress; if occupants are not exposed to critical conditions prior to leaving the building it is often presumed to be as safe as needed. The approach to design fires is divided into three parts; the growth phase, the steady phase and the decay phase. In this work the primary phase of interest is the growth phase, but some discussion is also focusing on the steady phase, specifically the maximum heat release rate.

2.1. The growth phase

The most common way to describe the growth phase is to use the following mathematical formulation:

$$\dot{Q} = \alpha \cdot t^2 \tag{1}$$

what this means is that the heat release rate $\dot{Q}$ at a certain moment determined by a number α and the time t since the fire started. A larger α value would mean that the heat release rate would increase more quickly than a smaller number, and a common classification of this number has been done by the National Fire Protection Association (NFPA), which can be seen in Table 1. This standard classification will be used throughout this paper by using references to both the name of the growth rate classification as well as the given α-value. A visual representation (with a given maximum heat release rate of 5 MW) of the different classifications can be seen in Fig. 1.

When selecting the growth rate for a design fire it is most often depending on the building type and building content (e.g. office, school, shopping mall) and sometimes the national authorities give recommendations on which value to use, as the example from Sweden seen in Table 2. The heat release rate is then allowed to increase over time up until a pre-set maximum value, which initiates the steady phase. As can be seen in the Swedish example in Table 2, all buildings within the same activity group will be treated exactly the same even though their building construction and building materials can differ greatly.

2.2. The steady phase

If oxygen depletion does not occur during the growth phase a maximum prescribed heat release value is reached and sustained until the decay phase (unless oxygen depletion once again interferes). This phase is called the steady phase. The magnitude of the maximum heat release value and the duration of the steady phase is often determined by the building type and building content, similar to the growth phase. And as with the growth phase, the national authorities often give recommendations on which value to use (see Table 2 for example), and once again all buildings within the same activity group will be treated the same even though their building construction and building materials can differ greatly.

3. Specification of the numerical experiments

To investigate the influence of the building material and opening factor on the design fire a simple room was created with the following dimensions; $10 \times 10 \times 3$ m (width $\times$ length $\times$ height), see Fig. 2. The $10 \times 10 \times 3$ m compartment was selected as the “default” room to represent a reasonable “normal” case, but also adapted to be able to see a clear distinction for each material. If the ceiling would have been very high the radiation from the ceiling and hot gasses might potentially be relatively low which in turn would mean that the growth rate probably would never be changed. The same thing would probably happen if the room floor area was relatively large, since there would be very little build-up of a hot gas layer and there would probably be very little radiative heat flux feedback from the walls. To further analyze these assumptions additional simulations were done to investigate the influence of the room floor area size and the room ceiling height.

3.1. Wall materials

The main goal was to investigate the influence of the building materials used in the walls, ceiling and floor. Four different materials were selected, each having different properties and responses (thermal properties and thickness/heat storing

Table 1
Standard classification of different growth rates according to NFPA 204M [5].

Growth rate	$\alpha\,[kW/s^2]$	Time to reach 1055 kW
Ultra fast	0.19	75
Fast	0.047	150
Medium	0.012	300
Slow	0.003	600

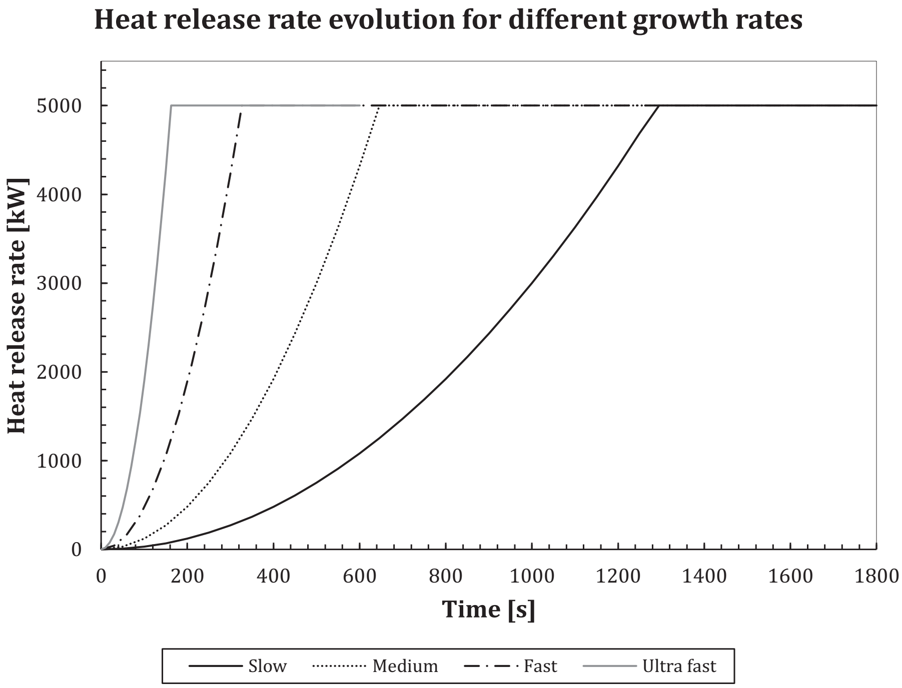

Fig. 1. Visual representation of the different standard growth rates according to NFPA 204M [5].

capacity); a drywall construction (13 mm gypsum, 70 mm insulation 13 mm gypsum), 200 mm concrete, 2 mm sheet steel and finally 100 mm insulation (to represent a modern light sandwich construction). The thermal data for each material used in the different wall constructions can be found Table 3 (the insulation thermal properties was set to be temperature dependent as they could vary significantly within the expected temperature span).

3.2. Compartment openings

Since it was likely that the supply of oxygen would also influenced the burning behavior two different setups of door openings was used; one setup using one door opening and a second setup using four door openings, with each door having the dimensions of 0.8×2.2 m ($W \times H$). The openings was initially assumed to mostly affect the maximum heat release rate but was suspected to affect the growth rate too at least some degree since the potential initial strong peak in radiative

Table 2
Recommendations on design fire growth rates and maximum heat release rates given by the Swedish national board of housing, building and planning [1].

Activity	Growth rate [kW/s^2]	Maximum heat release rate [MW]	Heat of combustion, [MJ/kg]
Offices and schools	0.012	5	16
Dwellings, hotels, nursing homes etc.	0.047	5	20
Shopping centers, entertainment centers etc.	0.047	10	20

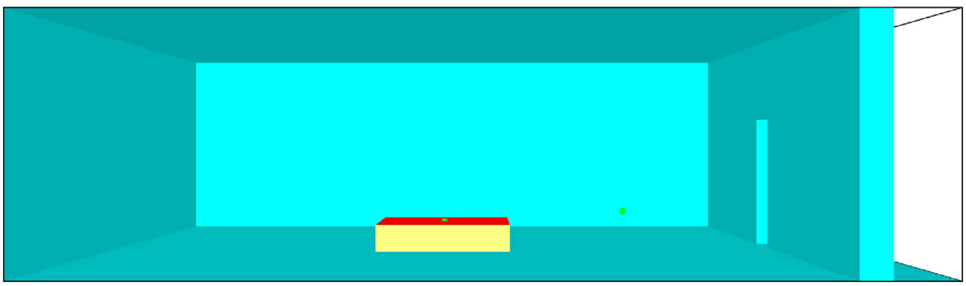

Fig. 2. The $10 \times 10 \times 3$ m room that was used in the simulations with one door opening and the fire source placed in the middle of the room.

Table 3
Thermal properties of the different building materials that were used in the simulations.

Material ID	'GYPSUM'	'CONCRETE'	'STEEL'	'INSULATION'
Emissivity [–]	0.9	0.9	0.95	0.9
Specific heat capacity [kJ/(kg*K)]	1.09	1.04	0.46	$T = 20.0$, $c_p = 0.8$ $T = 677.0$, $c_p = 2.0$
Conductivity [(W/(m*K)]	0.17	1.8	45.8	$T = 20.0$, $k = 0.05$ $T = 377.0$, $k = 0.1$ $T = 677.0$, $k = 0.2$
Density [kg/m^3]	930.0	2280.0	7850.0	200.0

feedback to the fuel source could be dampened (or rather never happen) if not enough oxygen was supplied during the initial stage of the fire. Since the room was only $10 \times 10 \times 3$ m it did not seem reasonable to further increase the amount of open doors, but if a very open structure was of interest to this type of analysis it would be important to further increase the opening area and look at the effects.

3.3. Compartment floor area size and ceiling height

Besides the “standard” 10×10 m floor area two different floor areas were tested (5×5 m and 20×20 m), as well as two additional ceiling heights apart from the “standard” 3 m (5 and 7 m). To reduce the number of simulations and resulting data, only the wall material and growth rate that had given the largest relative increase in growth rate in previous simulations were tested with changed floor area size and ceiling height. As seen in the results section this turned out to be the insulating walls in conjunction with the slow growth rate.

3.4. Fire source

In most cases where design fires are used it is assumed that solid objects are combusted. However, since simulation of solid combustion is often considered relatively complicated and unreliable, a more simple approach was desired. Using the approach described in the next section, a liquid with well-known thermal and chemical properties can be relatively well modeled; hence this approach was taken in this paper. The burning behavior of heptane (C_7H_{16}) has been rather well-studied [2,6,7,8] and the needed thermal and chemical properties are well-known which made it a perfect candidate to use in this work. The following data for heptane was used in the simulations; boiling temperature 98 °C, heat of vaporization 318.0 kJ/kg, heat of combustion 44 566 kJ/kg and soot yield 0.015.

The fire source area was set to 4 m^2 in all cases and the surface was placed 0.4 m above the floor in the very center of the room. The maximum specified heat release rate was set to 5000 kW in all cases, resulting in a heat release per unit area to be 1250 kW/m^2.

4. Accounting for the effect of oxygen depletion and radiative feedback

To be able to predict the changes in heat release rate and growth rate two things are essential; a model for radiative feedback to the fuel and a model for taking into account oxygen depletion. A simple model used to dynamically change the heat release rate in Fire Dynamics Simulator (FDS) [3] has been validated and explained more in detail in [9] but a short description is included here for the sake of convenience. The implemented model consists of two distinct parts; lowered mass loss rate due to lowered oxygen levels close to the fire source and increased mass loss rate due to radiation from external sources, such as walls and smoke layer.

Peatross and Beyler correlated a range of experiments to determine a linear dependency between the oxygen fraction close to the flame base and the normalized mass loss rate compared to a free burning value [10]. The correlation provides fuel mass loss rate against oxygen concentration measured at the flame base for large-scale fire compartments. The data was taken for several different tests with different fuels. The resulting correlation can be seen in Eq. (2):

$$\dot{m}''_{O_2} = \dot{m}''_{\infty} \cdot (0.1 \cdot O_2[\%] - 1.1) \quad (2)$$

where $\dot{m}''_{O_2}$ is the predicted mass loss is rate, $\dot{m}''_{\infty}$ is the steady-state free burning value of a specific fire source and $O_2[\%]$ is the oxygen volume percentage close to the flame base.

The oxygen volume fraction at the flame base is used to describe the change of radiative feedback to the fuel caused by cooling of the flame, extension of the flame or detachment of the flame from the pool surface. The reduction in radiative heat flux feedback in turn results in lowered mass loss rate. Since simulating the radiation feedback from the flame can be a very challenging, using the oxygen fraction at the flame base can potentially represent this behavior in a simplified model.

In many general cases the temperature of the fire room walls and smoke layer does not heat up enough to re-radiate any significant amount of energy to the fire source; this could either be due to well-ventilated conditions with a lot of air exchange or due to large heat losses through the compartment boundaries. But in some cases, such as sealed compartments or well insulated compartments as used in this study, this re-radiation can amount to a significant portion of the total mass loss rate and in some cases even be the dominating contributor. Since the aim of the model is to be relatively simple a very basic approach was taken; the net radiative heat flux to the fire source that does not originate from the flame, as in radiation form heated walls and smoke layer divided by the heat of vaporization of the fuel will result in a linear addition of mass loss, see Eq. (3). The outgoing term is approximated to be directly determined by the boiling temperature of the fuel [11].

$$\dot{m}''_{\mathrm{rad}} = \frac{\dot{q}''_{\mathrm{rad.in,enclosure}} + \dot{q}''_{\mathrm{rad.in,smoke}} - \dot{q}''_{\mathrm{rad.out,fuel}}}{\Delta h_{\mathrm{v,fuel}}} \tag{3}$$

where $\dot{m}''_{\mathrm{rad}}$ is the extra mass loss rate due to radiation, $\dot{q}''_{\mathrm{rad.in,enclosure}}$ is the radiative feedback from the walls, ceiling or other objects in the enclosure, $\dot{q}''_{\mathrm{rad.in,smoke}}$ is radiative feedback from the smoke layer, $\dot{q}''_{\mathrm{rad.out,fuel}}$ is the outgoing radiate heat flux based on the boiling temperature of the fuel and$\Delta h_{\mathrm{v,fuel}}$ is the heat of vaporization of the fuel.

Combining Eqs. (2) and (3) yields the following simple equation:

$$\dot{m}''_{\mathrm{tot}} = \dot{m}''_{\infty} \cdot (0.1 \cdot \mathrm{O_2}[\%] - 1.1) + \frac{\dot{q}''_{\mathrm{rad.in,enclosure}} + \dot{q}''_{\mathrm{rad.in,smoke}} - \dot{q}''_{\mathrm{rad.out,fuel}}}{\Delta h_{\mathrm{v,fuel}}} \tag{4}$$

The total mass loss rate is then related to the oxygen volume fraction close to the fuel base and the radiation from external sources; the complex radiation from the flame is altogether ignored in the formulation (although indirectly included due to the user being forced to specify the free burning mass loss rate value). This formulation is similar to the one presented by Utiskul et al. [12].

5. Results and discussion

This section presents and discusses the results from simulations done using a custom built version of FDS 6.1.1 which implements the previously described feedback model. Since the objective of the paper was to look at the effect on the growth rate, the maximum heat release rate and the fire source interaction with the environment affecting the growth rate (oxygen volume fraction and external radiation onto the fuel surface) the results focuses on this data.

The reported maximum heat release rate was the maximum value found during full 3600 s of simulation time for each case. The calculated growth rates were calculated using Eq. (5) to find the data point which yielded the highest value of α during each respective case.

$$\alpha = \frac{Q}{t^2} \tag{5}$$

5.1. Influence of building material and growth rate

As can be seen in Tables 4–7, as well as the example given in Fig. 3, there is minor changes in the growth rate depending on the building material (concrete 1–7%, drywall 8–35% and steel 0–20%) with the exception of the insulated walls where the difference in growth rate is at most almost 300% and the least about 115%. The actual growth rate when using the insulating walls and specifying a growth rate of 0.003 kW/s^2 is calculated to 0.012 kW/s^2; the same as the next standard classification "medium". The relative increase is not as great (114–213%) using the higher growth rates, but it could still be considered significant when used to assess the fire safety in a building.

It can also be noted that the maximum heat release is increased with increased growth rate for all building materials. But, as observed in the example given in Fig. 3 the peak heat release rate duration is rather short (similar for all growth rates) since the oxygen depletion starts to affect the mass loss rate rather quickly. It is evident that the growth rate was hampered by the lack of oxygen being supplied to the compartment. An example of what causes the heat release rate dynamics can be explained by looking at Figs. 4 and 5; the heat release rate initially increases according to the specified growth rate causing

Table 4
Resulting α-values for different growth rates when using concrete as building material and having one door opening present.

Concrete, 1 door open				
Input α [kW/s^2]	0.003	0.012	0.047	0.19
Output α [kW/s^2]	0.0031	0.0121	0.050	0.20
% Difference	3.9	1.1	7.4	6.2
Max HRR [kW]	2199	2692	3492	4186
Min O_2 vol. fraction [–]	0.13	0.13	0.13	0.13
Max rad. feedback [kW/m^2]	0.0	0.0	0.0	0.0

Table 5
Resulting α-values for different growth rates when using drywall as building material and having one door opening present.

Drywall, 1 door open				
Input α [kW/s^2]	0.003	0.012	0.047	0.19
Output α [kW/s^2]	0.0041	0.0159	0.061	0.21
% Difference	35.6	32.4	30.2	8.1
Max HRR [kW]	2469	3132	4107	5065
Min O_2 vol. fraction [–]	0.07	0.06	0.05	0.05
Max rad. feedback [kW/m^2]	4.2	4.3	4.4	4.3

Table 6
Resulting α-values for different growth rates when using insulation as building material and having one door opening present. *The maximum radiative heat flux value reported was the initial peak value, the value inside the parenthesis is the maximum value obtained in the later stages of the simulation which is more comparable to the other given values.

Insulation, 1 door open				
Input α [kW/s^2]	0.003	0.012	0.047	0.19
Output α [kW/s^2]	0.012	0.038	0.12	0.41
% Difference	294.9	213.4	159.3	113.7
Max HRR [kW]	4208	4794	5846	7293
Min O_2 vol. fraction [–]	0.04	0.04	0.04	0.04
Max rad. feedback [kW/m^2]	6.1	6.4	7.3 (6.5)*	8.0 (6.5)*

Table 7
Resulting α-values for different growth rates when using steel as building material and having one door opening present.

Steel, 1 door open				
Input α [kW/s^2]	0.003	0.012	0.047	0.19
Output α [kW/s^2]	0.0032	0.013	0.057	0.19
% Difference	7.1	9.6	20.6	−0.6
Max HRR [kW]	2109	2771	3832	4249
Min O_2 vol. fraction [–]	0.14	0.14	0.14	0.14
Max rad. feedback [kW/m^2]	0.0	0.1	0.1	0.2

the oxygen volume fraction to decrease inside the compartment. As the walls heat up and compartments is filled with hot gasses the radiation to the fuel source is increased which in turn increases the mass loss rate, which in turn further decreases the oxygen volume fraction but also further heat up the walls and hot gasses. Once the oxygen volume fraction is very low (around 11%) most combustion will happen detached from the fuel base and the local heating of the walls and hot gases decreases (and therefore also the radiative heat feedback to the fuel source) will start to decrease. This loss of radiative feedback in combination with the already oxygen depleted environment then causes a rapid decrease in the mass loss rate until the room once again starts to heat up which again increases the radiative feedback, this time in a slower more controlled pace. The fact that the maximum heat release is increased with increased growth rate is simply due to the fact that a faster growth rate reaches a higher heat release rate before the effects of oxygen depletion sets in.

5.2. Influence of door openings

As can be seen in Tables 8–11 , as well as in the example given in Fig. 6, the effect on the growth rate is larger in all cases compared to when only one open door was present. For example, the growth rate when using the insulating walls and specifying a growth rate of 0.012 kW/s^2 now exceeds the next standard classification (fast, 0.047 kW/s^2) with a calculated growth rate of 0.057 kW/s^2. In fact, all specified growth rates are higher or close to the next standard classification (when available), even the specified “fast” growth rate (0.047 kW/s^2) closes in on the “ultra fast” growth rate (0.19 kW/s^2) with a value of 0.016 kW/s^2. Looking at recommendations from the Swedish National Board of Housing, Building and Planning in Table 2, this would mean that the time available to perform safe egress from a building would probably be overestimated in such a case.

Looking at example given in Fig. 6 the heat release rate is not abruptly cut off due to oxygen depletion as in the case when only one door was present. Looking at Tables 8–11, the maximum heat release rate is also no longer always increasing with increased growth rate, and the heat release rate increases as time progresses due to radiation from the ceiling and the hot gas layer. Since more air is supplied a larger portion of the combustion can occur inside the compartment and closer to the fire source and this increases the temperature of the walls and hot gasses, hence intensifying the radiative feedback. This can

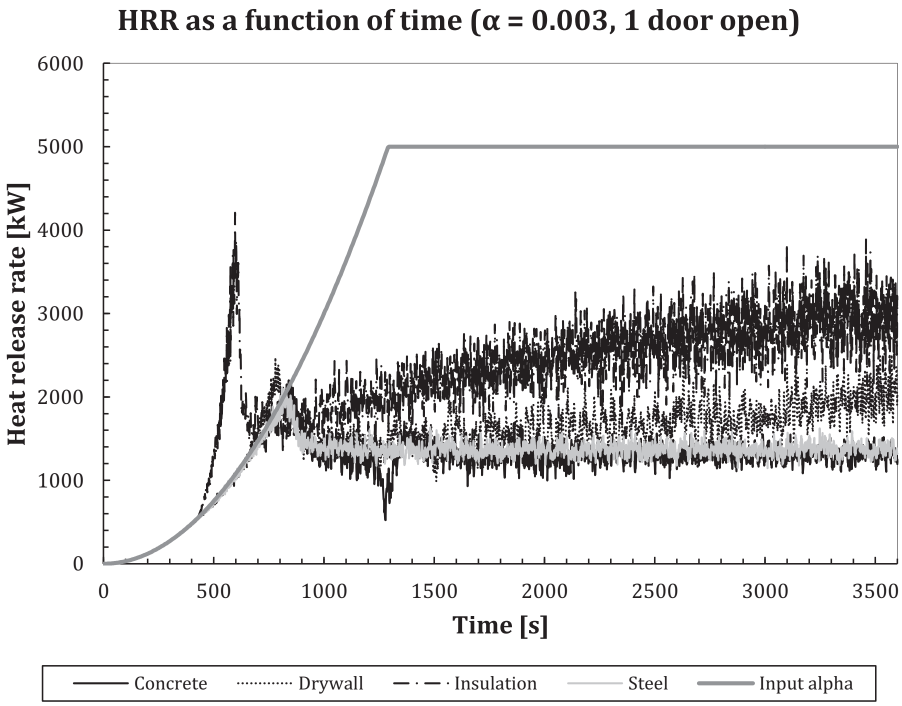

Fig. 3. Heat release rate as a function of time using different building materials, one door opening and a growth rate of 0.003 kW/s^2.

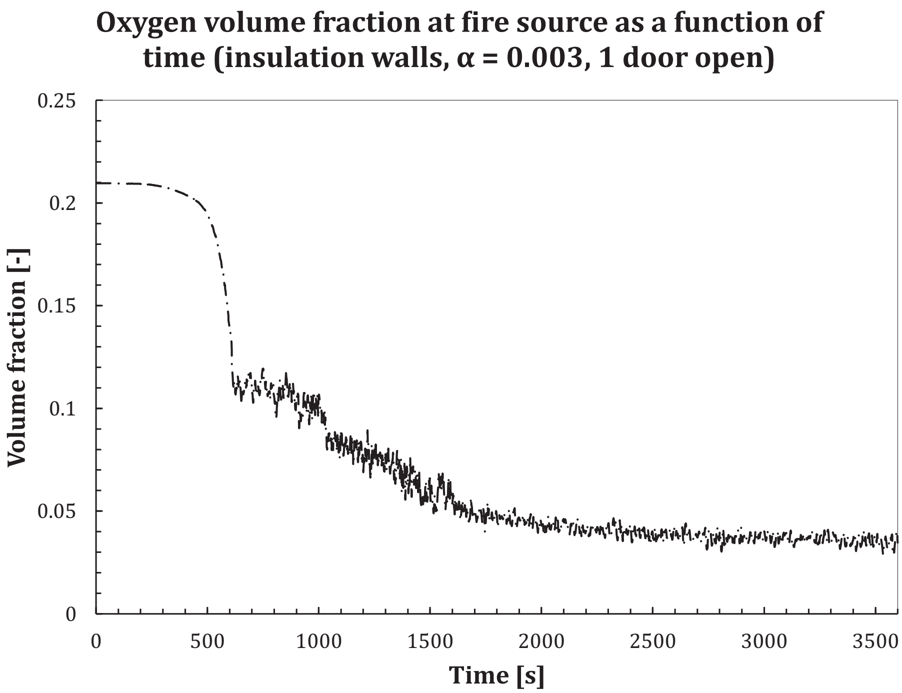

Fig. 4. Oxygen volume fraction close to the fire source as a function of time using insulated walls, one door opening and a growth rate of 0.003 kW/s^2.

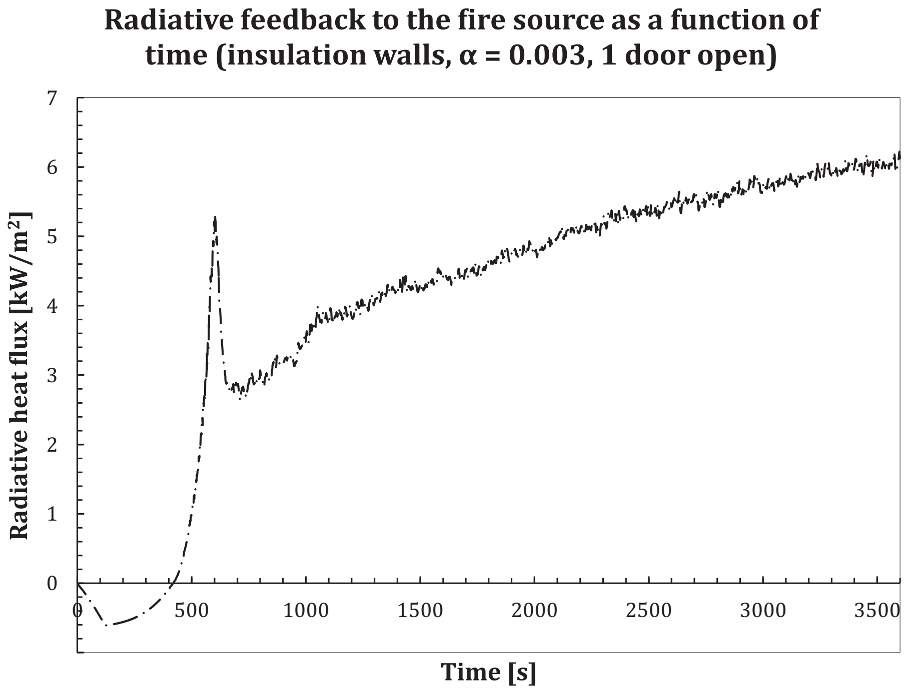

Fig. 5. Radiative feedback to the fuel surface as a function of time using insulated walls, one door opening and a growth rate of 0.003 kW/s^2.

Table 8
Resulting α-values for different growth rates when using concrete as building material and having four door openings present.

Concrete, 4 doors open				
Input α [kW/s^2]	0.003	0.012	0.047	0.19
Output α [kW/s^2]	0.0033	0.013	0.055	0.18
% Difference	10.4	7.7	16.4	−7.2
Max HRR [kW]	7318	7667	7622	8416
Min O_2 vol. fraction [−]	0.17	0.17	0.17	0.17
Max rad. feedback [kW/m^2]	6.0	6.7	6.7	6.8

Table 9
Resulting α-values for different growth rates when using drywall as building material and having four door openings present.

Drywall, 4 doors open				
Input α [kW/s^2]	0.003	0.012	0.047	0.19
Output α [kW/s^2]	0.0078	0.025	0.070	0.20
% Difference	161.1	109.3	48.6	7.0
Max HRR [kW]	14974	15510	15459	15811
Min O_2 vol. fraction [−]	0.04	0.04	0.04	0.04
Max rad. feedback [kW/m^2]	27.3	27.8	28.5	28.6

Table 10
Resulting α-values for different growth rates when using insulation as building material and having four door openings present.

Insulation, 4 doors open				
Input α [kW/s^2]	0.003	0.012	0.047	0.19
Output α [kW/s^2]	0.018	0.057	0.16	0.47
% Difference	509.4	372.6	241.0	146.3
Max HRR [kW]	16164	16415	16288	16047
Min O_2 vol. fraction [−]	0.04	0.04	0.04	0.04
Max rad. feedback [kW/m^2]	30.8	30.9	31.0	30.9

Table 11
Resulting α-values for different growth rates when using steel as building material and having four door openings present.

Steel, 4 doors open				
Input α [kW/s^2]	0.003	0.012	0.047	0.19
Output α [kW/s^2]	0.0050	0.015	0.047	0.21
% Difference	67.0	23.0	0.3	8.6
Max HRR [kW]	7058	6814	7450	7006
Min O_2 vol. fraction [–]	0.18	0.18	0.18	0.18
Max rad. feedback [kW/m^2]	4.0	4.0	4.0	4.0

clearly be seen since the radiative heat flux to the fuel source with four doors reaches approximately 30 kW/m^2, compared to 6 kW/m^2 when only one door opening was present. It can however be noted that each building material seem to have a allowed maximum heat release rate controlled by the radiative feedback; the insulated walls having the highest heat release recorded and the steel walls having the lowest due to relatively large heat losses.

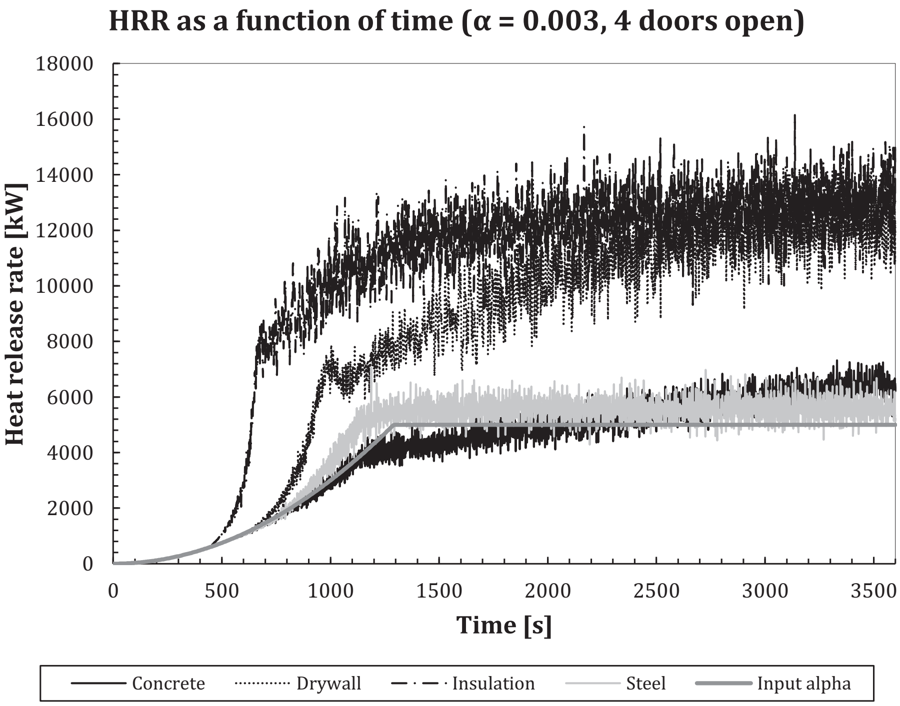

Fig. 6. Heat release rate as a function of time using different building materials, four door openings and a growth rate of 0.003 kW/s^2.

Table 12
Resulting α-values for different room floor areas when using insulation as building material, 3 m ceiling height and having one door opening present. *The maximum radiative heat flux value reported was the initial peak value, the value inside the parenthesis is the maximum value obtained in the later stages of the simulation which is more comparable to the other given values.

Ceiling height 3 m, 1 door opening			
Floor area [m^2]	5 × 5	10 × 10	20 × 20
Input α [kW/s^2]	0.003	0.003	0.003
Output α [kW/s^2]	0.018	0.012	0.011
% Difference	501.2	294.9	257.9
Max HRR [kW]	6160	4208	6630
Min O_2 vol. fraction [–]	0.04	0.04	0.11
Max rad. feedback [kW/m^2]	11.4	6.1	7.2 (2.7)*

Table 13
Resulting α-values for different room floor areas when using insulation as building material, 3 m ceiling height and having four door openings present.

Ceiling height 3 m, 4 door openings			
Floor area [m^2]	5×5	10×10	20×20
Input α [kW/s^2]	0.003	0.003	0.003
Output α [kW/s^2]	0.048	0.018	0.011
% Difference	1485.0	509.4	259.1
Max HRR [kW]	17818	16164	10434
Min O_2 vol. fraction [–]	0.04	0.04	0.07
Max rad. feedback [kW/m^2]	48.0	30.8	16.2

5.3. Influence of the room floor area

As can be seen in Tables 12 and 13, as well as Figs. 7 and 8, the room floor area can have a significant influence on the growth rate and maximum heat release rate. In almost all cases the main driving force is the radiative feedback since the oxygen volume fraction close to the fire source reduces to a value close to or below the limit for extinction (around 11 volume-% without external radiation).

The external radiation heat flux does get significantly larger in the cases with 4 door openings due to the same reasons given before; since more air is supplied more combustion can occur inside the compartment and closer to the fire source and this increases the temperature of the walls and hot gasses; hence the radiative feedback intensifies. It is also important to note that the radiative feedback increases as the room floor area decreases independent of how many door openings are present (although to a larger extent when four door openings are present). The reasons for this are two-fold; firstly it takes longer time to heat up the walls and ceiling the larger the floor area is. Secondly, even if the walls and ceiling would be of the same temperature in all cases only the ceiling would consistently contribute the same amount of radiative feedback, the walls would not simply due to the fact that they are further away from the fire source. This could have implications when the fire is placed in a corner or when other nearby objects heat up and can contribute with radiative feedback.

Another interesting observation is on the maximum heat release; when only one door opening is present the highest recorded heat release rate is in the largest floor are but only for a very brief time. When four door openings are present the smallest floor area reaches the highest heat release rate and over a much longer period of time. The reason that the maximum heat release rate is in found in conjunction with the largest floor area when only one door opening is present is due to the

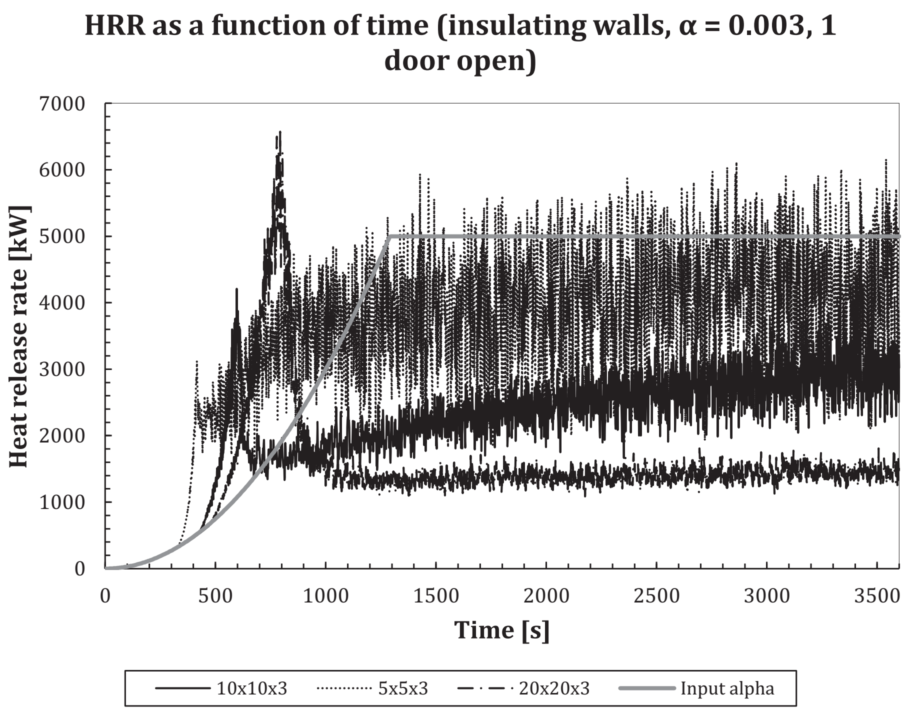

Fig. 7. Heat release rate as a function of time using different room floor areas, one door opening and a growth rate of 0.003 kW/s^2.

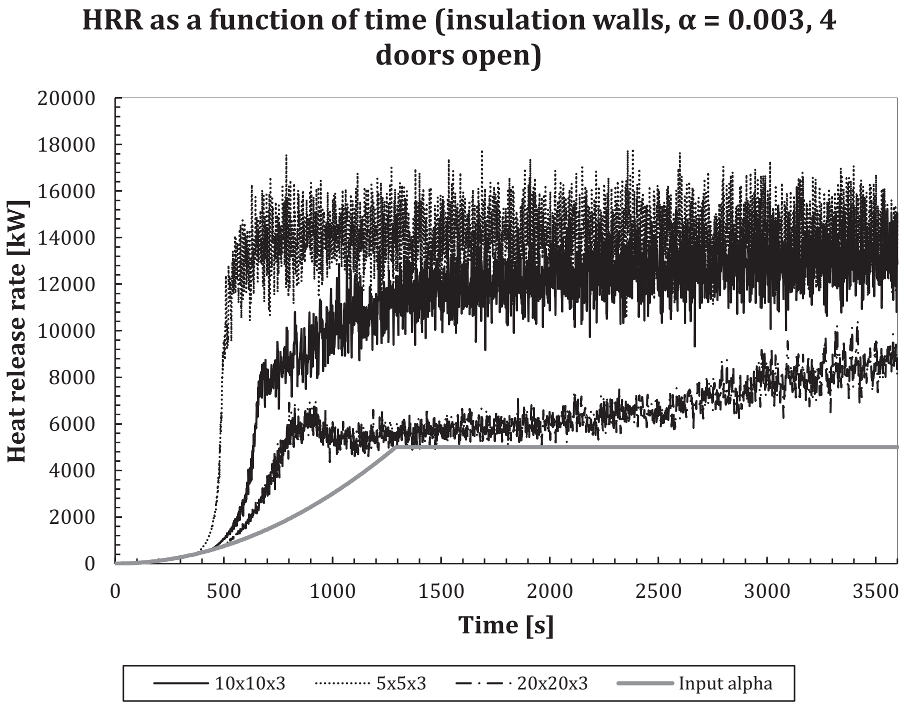

Fig. 8. Heat release rate as a function of time using different room floor areas, four door openings and a growth rate of 0.003 kW/s^2.

larger “oxygen reserve” stored inside the compartment. It takes longer time to reach lower oxygen levels with increased floor area, and when only one door opening is present the radiative feedback is not an as dominant contributor to the total heat release rate as when four door openings are present. This dynamics changes however once four door openings are present; the maximum heat release rate is decreased with increased floor area as seen in Fig. 8.

Table 14
Resulting α-values for different ceilings heights when using insulation as building material, 10 × 10 m floor area and having one door opening present.

Floor area 10 × 10, 1 door opening			
Ceiling height [m]	3	5	7
Input α [kW/s^2]	0.003	0.003	0.003
Output α [kW/s^2]	0.012	0.0042	0.0034
% Difference	294.9	39.3	13.9
Max HRR [kW]	4208	2690	2610
Min O_2 vol. fraction [–]	0.04	0.11	0.13
Max rad. feedback [kW/m^2]	6.1	2.3	1.0

Table 15
Resulting α-values for different ceilings heights when using insulation as building material, 10 × 10 m floor and having four door openings present.

Floor area 10 × 10, 4 door openings			
Ceiling height [m]	3	5	7
Input α [kW/s^2]	0.003	0.003	0.003
Output α [kW/s^2]	0.018	0.0064	0.0041
% Difference	509.4	112.9	37.4
Max HRR [kW]	16164	11179	6162
Min O_2 vol. fraction [–]	0.04	0.11	0.14
Max rad. feedback [kW/m^2]	30.8	14.9	6.8

Table 16
Resulting α-values for different ceiling heights when using insulation as building material, 5×5 m floor and having four door openings present.

Floor area 5 × 5, 4 door openings			
Ceiling height [m]	3	5	7
Input α [kW/s^2]	0.003	0.003	0.003
Output α [kW/s^2]	0.048	0.025	0.013
% Difference	1485.0	747.0	340.3
Max HRR [kW]	17818	18819	18398
Min O_2 vol. fraction [–]	0.04	0.06	0.07
Max rad. feedback [kW/m^2]	48.0	36.2	32.0

Table 17
Resulting α-values for different ceiling heights when using insulation as building material, 20×20 m floor and having four door openings present.

Floor area 20 × 20, 4 door openings			
Ceiling height [m]	3	5	7
Input α [kW/s^2]	0.003	0.003	0.003
Output α [kW/s^2]	0.011	0.004301145	0.003569
% Difference	259.1	43.4	19.0
Max HRR [kW]	10434	5908	5014
Min O_2 vol. fraction [–]	0.07	0.15	0.17
Max rad. feedback [kW/m^2]	16.1	0.6	0.6

5.4. Influence of the ceiling height

As seen in Tables 14–17 , as well as Figs. 9 and 10, the room height has a significant effect on the growth rate and maximum heat release. Having only one door opening, the growth rate drastically decreases as the ceiling height increases. This is due to the decrease of external radiative heat flux feedback with increasing ceiling heigh in combination with the fact that some degree of oxygen depletion occurs regardless of ceiling height. When four doors are present the effect is very similar although to a larger degree. However, the effect of the room height is not as significant if the room floor area is smaller since the walls seems contribute to a larger degree. A combination of a larger floor are and high ceiling height actually renders very

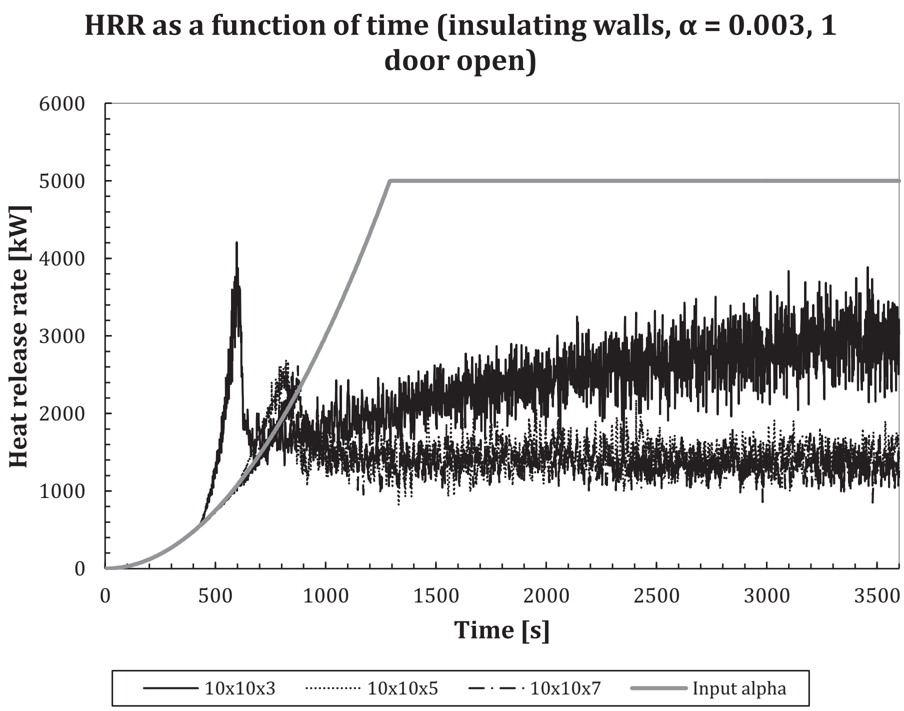

Fig. 9. Heat release rate as a function of time using different ceiling heights, one door opening and a growth rate of 0.003 kW/s^2.

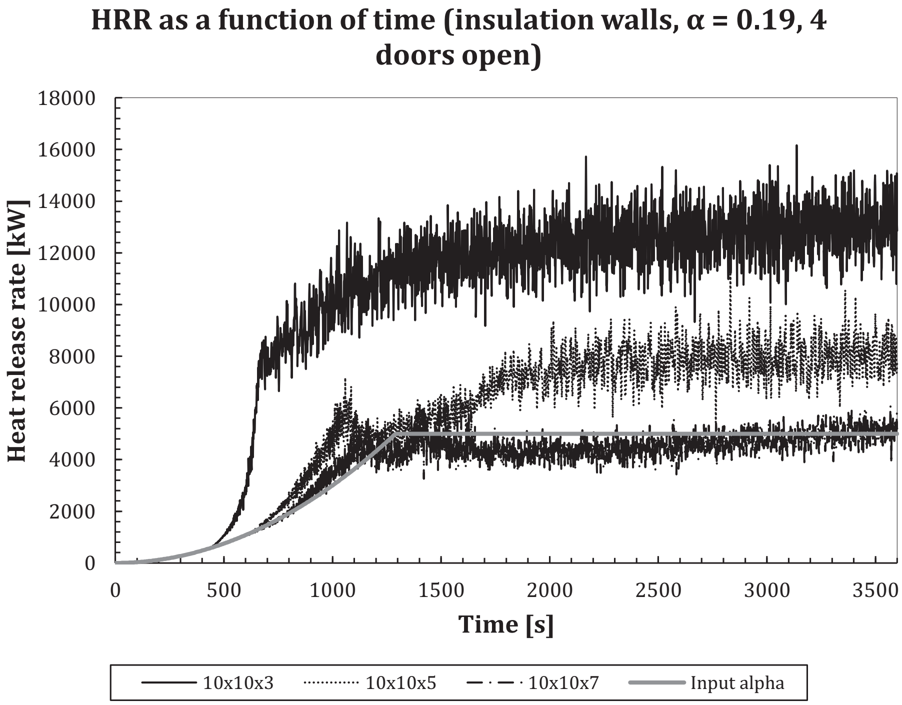

Fig. 10. Heat release rate as a function of time using different ceiling heights, four door openings and a growth rate of 0.003 kW/s^2.

little or almost no radiative feedback which might be "good news" for scenarios where performance based design often is applied (big open spaces). It should however be remembered that nearby objects or walls still can provide radiative feedback.

With room floor area sizes of 10×10 and 20×20 m the maximum heat release rate is decreased with increased ceiling height. This can yet again be attributed to the lack of radiative heat flux feedback, though the effect is somewhat lessened when the room floor area is smaller (10×10 m) since the walls can contribute more radiative feedback compared to when the walls are distant from the fire source. When the room floor size is 20×20 m there is very little difference between a ceiling height of 5 or 7 m and this difference seems to be sourced from lesser oxygen depletion since the radiative feedback is virtually non-existent for both ceiling heights. When the room floor area is 5×5 m the maximum heat release rate is the same regardless of the ceiling height; it is simply not possible to increase it further in that system even though the radiative feedback increases.

6. Conclusions

It has been shown that the building material used in a fire compartment might influence the growth rate of a design fire in a significant way; insulating wall/ceiling materials will probably increase the growth rate which in turn will mean that the time to critical conditions will be shorter compared to the expected result. However, if the building material used is thermally thin or has a large heat storing capacity the influence is rather negligible. The maximum heat release rate and transient behavior of the fire was shown to be very dependent on ventilation factor in combination with the building material; with only one door opening present the initial fire growth was rapid due to radiative feedback but was then hampered by the oxygen depletion which caused the heat release rate to decrease significantly during the course of the simulation duration. The heat release rate increased slowly over time but never reached above the preset maximum (5000 kW). This applied to all building materials. Using 4 door openings however allowed the initial peak heat release rate to become larger for the insulated and drywall compartments which meant an increase in calculated growth rate. Since more air was supplied more combustion could occur inside the compartment and this increased the temperature of the walls and hot gasses and hence the radiative feedback became more intense.

Further it was shown that the room floor area might have a significant effect on the growth rate and maximum heat release rate; with one door opening a larger room (floor area 20×20 m) would have a higher initial peak heat release rate than the smaller rooms, (5×5 and 10×10 m) but they would all get oxygen depleted soon thereafter and behave similarly for the rest of the simulation. If there were four door openings present the radiative feedback would overpower the oxygen depletion and the smaller the room the higher the maximum heat release rate and growth rate.

It was also shown that the ceiling height does have a significant effect on the growth rate and maximum heat release when coupled with four door openings. Having only one door opening present quickly decreases the oxygen volume fraction close to the fire source which decreases the heat release rate rapidly and this effect seem to happen with very little time delay independent of the room height. However, the effect of the room height was not as significant if the room floor area was smaller since the walls seems contribute to a larger degree in that case. Another important note was the fact that a combination of a larger floor area (20×20 m) and high ceiling height (above 5 m) actually rendered very little or almost no radiative feedback which might be "good news" for scenarios where performance based design often is applied (big open spaces).

It must be noted that the selected test case might not represent every possible scenario very well; objects close to the fire source might influence the radiative feedback, mechanical ventilation may influence the rate of oxygen depletion, complex flow patterns due to the location of inlets and outlets may also influence the rate of oxygen depletion etcetera. All of these factor and more must be taken into account and evaluated before application.

The fuel used in the simulations was a liquid (heptane) due to the relatively well known properties, fire behavior and the fact that the simple model used to take oxygen depletion and radiative feedback into account had previously been developed for pool fires. In a real case the fuel source would probably be solid objects which increases complexity and could very well yield different results than the ones observed. More experimental data would be beneficiary to investigate the differences between solid materials and liquids but unfortunately that was out of the scope for this paper. However, it is expected that the qualitative effects would be similar using solid fuels as on liquid fuels, though the magnitude would be very fuel dependent.

In conclusion it is recommended to investigate the applicability of design fires in compartments with highly or moderately insulating building materials as the environmental feedback will probably increase the growth rate significantly which in the end could affect the possibilities of obtaining satisfactory egress safety.

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