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Johansson, Nils

Published in:
Proceedings 11th Conference on Performance-based Codes and Fire Safety Design Methods

2016

Document Version:
Early version, also known as pre-print

Link to publication

Citation for published version (APA):
Johansson, N. (2016). The pre-flashover compartment fire and fire safety engineering – a review of hand-calculation methods. In *Proceedings 11th Conference on Performance-based Codes and Fire Safety Design Methods* (pp. 84-95). Society of Fire Protection Engineers.

Total number of authors:
1

The pre-flashover compartment fire and fire safety engineering – a review of hand-calculation methods

Nils Johansson
Division of Fire Safety Engineering
Lund University, Sweden

INTRODUCTION

Computer modelling software for fire safety engineering has evolved rapidly during the last decades. Such software is generally good for fire engineering purposes; however, there is still a need for simple engineering methods and there are several reasons for this.

Firstly, hand-calculation methods are time-efficient compared to advanced methods and the result from a rather rough and conservative hand-calculation can help an engineer to determine if it is necessary to perform more detailed calculations e.g. with computer modelling software. Secondly, simple methods can be used to increase the knowledge and understanding of different fire phenomena and relationships between different parameters. In the area of structural engineering [1], it has been argued that the conceptual understanding of a problem can be negatively affected by use of advanced computer models. Such models might include "black box effects", i.e. concealed processes that restricts the user information and control of the calculation process. This might result in that the user's understanding of the studied problem is inhibited. Lamb [2] states that the understanding of the structural behaviour of a single element is an essential part of structural modelling, and this can be translated to the field of fire safety engineering by stressing the importance of understanding fundamental fire dynamics in order to be able model smoke spread in a building. Therefore, simple transparent methods are considered to be valuable in order to understand the fundamentals of complex fire dynamics problems, because such methods include the most important variables that govern the studied phenomenon. Finally, simple hand-calculations methods can easily be used in probabilistic analysis when thousands of calculations might be needed.

Consequently, there are several reasons why to use hand-calculation methods in fire safety engineering. However, the engineer needs to be aware of the underlying assumptions, limitations and uncertainties with these methods before applying them. The purpose of this paper is therefore to review hand-calculation methods for pre-flashover compartment fires in regard to these aspects. Subsequently, before focusing on individual methods it is considered necessary to characterize what a compartment fire is.

The compartment fire

There are currently no methods or models available for fire safety engineering that can be applied for the range of problems and tasks that a fire safety engineer can face. The methods that can be applied when studying the consequences of fires in buildings depend very much on the purpose of the analysis. For instance, if life safety is of interest methods applicable for the pre-flashover fires are applied, while methods for post-flashover fires can be used when looking at the temperatures that a structure is subjected to. The characteristics of the building itself will also influence the hazardous conditions created and determine the type of methods to use.

Fires in buildings can be divided into three different categories depending on the characteristics of enclosure in which the fire is contained (se Figure 1). The first category is “Fires in structural elements” and it involves fires that start in, or spread to, a structural element, e.g. inside walls, attic space, facade or roof. The second category is the “Compartment fire”, which include fires in small- and medium-sized enclosures, e.g. residential rooms, cellular offices, or small industrial units. The principal feature of the compartment fire is that the hot gas layer can be regarded as rather homogenous, with regard to temperature and composition, due to the stirring of the hot gas by the fire. However, if the fire is small compared to the size of the enclosure the temperature differences within in the hot gas layer cannot be regarded as homogenous and this is the case in the early stages of enclosure fires. However, the enclosure can also be that large that it is not reasonable to assume the hot gas layer properties to be homogenous, and this is the main characteristic of the last category of fires, which here is termed as: “Fires in large enclosures”.

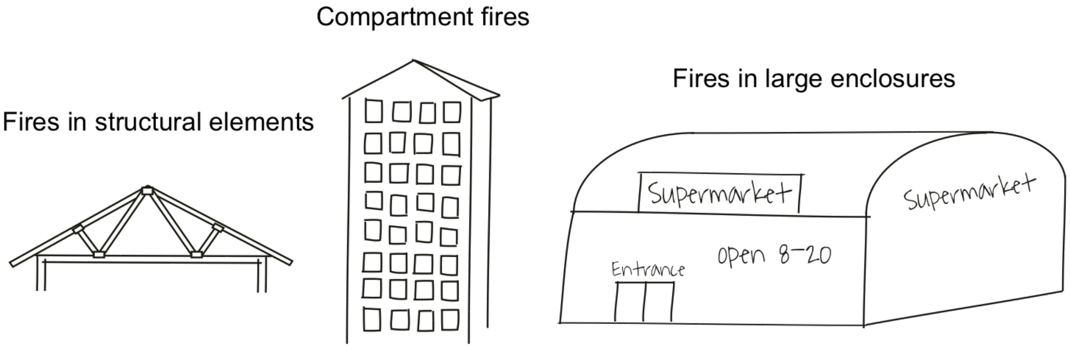

Figure 1: Different categories of fires in buildings. Based on an illustration in Johansson [3].

The terminology can create confusion because “Fires in large enclosures” are also fires in compartments, but the “Compartment fire“ is considered to be an established concept of enclosures fires where homogenous proprieties of the hot layer are assumed. The concept of the compartment fire dates back to the 1950s when Kawagoe [4] preformed studies on enclosure fires. However, today many modern building have large open floor plans, which means that the fire engineering methods for the compartment fire may not always be applicable.

Torero et al [5] revisited the compartment fire concept and its applicability in regard to the interaction between the fire and building structure. Even though there are limitations in how the compartment fire concept should be used, it still provides a robust and simple way of describing fire conditions for certain fire and enclosure characteristics; consequently, it is important to know when these models are applicable. The available compartment fire methods are based on general mass and energy balances that have been solved with the help of empirical data and Torero et al states that the limitations of the compartment fire methods for the ventilation controlled post flashover fire situation (labelled *Regime I* by Torero et al) are related to the conditions and setup of the experiments that they are based on.

Unlike the ventilation-controlled post-flashover fire the heat released in the fuel-controlled pre-flashover fire is not dependent on the supply of air through the opening. Besides that the assumptions in fuel-controlled pre-flashover fire methods are rather consistent with the compartment fire methods available for the ventilation-controlled scenario. Even so, it is considered important to highlight the limitations of the fuel-controlled pre-flashover fire.

It has been seen in experiments that the horizontal temperature distribution in compartments will be non-uniform when the ratio between the compartment depth (L) and height (H) is high [5]. This means that the validity of the homogenous temperature (or zone model) assumption decreases with increasing enclosures size. Such limitations have previously been explicitly expressed for two-zone models in ISO 13390 (see Table 1). A condition of the heat release rate (HRR), $\dot{Q}$, in regard to the enclosure area, $A = L \times W$, and height is also expressed in ISO 13390 (see Equation 1).

Table 1: Acceptable ratios between enclosure depth (L), width (W) and height (H).

Acceptable value	Special consideration required
L/W ≤ 3	3 < L/W < 5
L/H ≤ 3	3 < L/H < 6

$$\dot{Q} \geq 5 \cdot A\sqrt{H} \qquad \text{Equation 1}$$

Similar acceptable ratios, as in Table 1, are described in the technical reference guide for CFAST [6]. Table 1 and equation 1 indicates the limitations of the zone model approach when it comes to aspect ratios and HRR in relation to room size. Similar limitations are reasonable to expect for other methods where the homogenous temperature assumption is used.

The so-called MQH correlation [7] is considered to be the most established hand-calculation method to predict hot gas layer temperatures. This method and other similar methods are presented and described in the SFPE handbook [8], and have also been subjected to previous reviews [9]. However, during the last years there has been an increase of available calculation methods, which means that there are more methods available for the practitioners that needs to be evaluated. Therefore, the objective of this paper is to review the most established and the most recently developed hand-calculation methods that can be used to calculate properties important for fire safety engineering.

DESCRIPTION OF METHODS

Different life safety criteria, with regard to hazards that can arise in a pre-flashover fire, are used in fire safety analyses around the world. Visibility and exposure of heat and toxic gases are hazards that will determine the tenability for occupants in a building [10, 11]. Hazardous gases and heat produced by the pre-flashover fire will be accumulated in the hot gas layer, and it is the composition of the hot gas layer that will determine visibility for occupants. The hot gas layer interface height and temperature are therefore considered to be the most important criteria in pre-flashover fire safety engineering analyses; consequently, are methods that can be used to calculate these properties in focus in this paper.

Methods for single-rooms compartments

Two methods to calculate hot gas layer interface height and temperature in a single-room enclosure are reviewed and evaluated in this paper.

The method by McCaffrey, Quintiere and Harkleroad (MQH)
The *MQH method* is based on experimental observations and gives the temperature increase (ΔT) in a cubical room as a function of the HRR, size of a rectangular opening, room geometry and thermal properties of the boundaries. The correlation is based on over 100 experimental observations and it is valid for well-ventilated pre-flashover fires [7].

$$\Delta T = 6.85\left(\frac{\dot{Q}^2}{A_0\sqrt{H_0}h_k A_T}\right)^{1/3} \qquad \text{Equation 2}$$

Where $\dot{Q}$ is the HRR, A_0 is the area of the opening, H_0 is the height of the opening, h_k is an overall heat transfer coefficient and A_T is the total surface area, minus area of openings, in the room. h_k represents several different modes of heat transfer and is not easy to determine. However, the following simplified expressions can be used to get an estimate of h_k.

$$h_k = \sqrt{\frac{k\rho c}{t}} \qquad \text{[Semi-infinite construction]} \qquad \text{Equation 3}$$

$$h = \frac{k}{d} \qquad \text{[Thermally thin construction]} \qquad \text{Equation 4}$$

The Mass and energy balance method
The *Mass and energy balance method* is based on a simple mass and energy mass and energy balance for a compartment (see equation 5). Johansson and van Hees [12] have previously described the method.

$$\dot{Q} = \dot{Q}_W + \dot{Q}_L \qquad \text{Equation 5}$$

Where $\dot{Q}_{W,i}$ is the heat loss due to conduction through the exterior boundaries in the room and $\dot{Q}_L$ is the convective losses through the openings. Equation 5 can also be expressed as in equation 6.

$$\dot{Q} = hA_w\left(T_g - T_a\right) + \dot{m}_g c_p\left(T_g - T_a\right) \qquad \text{Equation 6}$$

Where h is an overall heat transfer coefficient, A_w is the surface area in contact with hot gases, T_g is the hot gas layer temperature, T_a is the ambient air temperature, $\dot{m}_g$ is the mass flow rate of hot gases through openings and c_p is the specific heat of the hot gas. h is determined in the same way as h_k for the thermally thin case (see equation 4); however, equation 7 for the thermally thick case.

$$h = \sqrt{\frac{k\rho c}{\pi t}} \qquad \text{[Semi-infinite construction]} \qquad \text{Equation 7}$$

Equation 6 can be rearrange and ΔT can be expressed as in equation 8.

$$\Delta T = \frac{\dot{Q}}{\dot{m}_g c_p + h A_w} \quad \text{Equation 8}$$

The mass flow rate of hot gases can be calculated with the help of a mass balance where the height to the hot gas layer interface, z_{int}, is found by using the following three equations.

$$\dot{m}_p = \dot{m}_g \quad \text{Equation 9}$$

$$\dot{m}_g = 0.684 A_o H_o^{1/2} (1 - z_{int}/H_o) \quad \text{Equation 10}$$

$$\dot{m}_p = 0.0058 \dot{Q}_c (z/L) \quad \text{Equation 11}$$

Where $\dot{Q}_c$ is the convective part of the HRR and $\dot{m}_p$ is the plume mass flow at the height z above the fuel. Equation 11 is a plume correlation that is considered appropriate for a compartment fire. L is the flame height which is calculated with Heskestads flame height correlation [13].

When z_{int} is calculated it is possible to calculate $\dot{m}_g$ using equation 10 and A_w. It is also possible to solve the energy balance and calculate ΔT with equation 8.

Methods for multi-room compartments

Adjacent room temperature correlation

Johansson and van Hees [14] have presented a correlation similar to the MQH correlation that can be used to estimate the hot gas layer temperature for a given HRR in an adjacent room connected to the room of fire origin. The method is based on a numerical experiment including approximately 90 FDS simulations with different room configurations and heat release rates. The hot gas layer temperature increase in the adjacent room was considered as a dependent variable and a correlation to several independent variables was found with the help of a multiple regression analysis.

$$\Delta T_2 = 10.4 \frac{\dot{Q}^{0.73} (A_{o,1}\sqrt{H_{o,1}})^{0.24}}{A_{T,1}^{0.45} A_{T,2}^{0.33} (A_{o,2}\sqrt{H_{o,2}})^{0.19} {h_k}^{0.34}} \quad \text{Equation 12}$$

$A_{o,1}\sqrt{H_{o,1}}$ is the ventilation factor between the fire room and adjacent room and $A_{o,2}\sqrt{H_{o,2}}$ is the ventilation factor between the adjacent room and the outside. The heat transfer coefficient, h_k, can be calculated with equation 3 or 4 for semi-infinite and thermally thin boundaries, respectively.

The Mass and energy balance method

The *Mass and energy balance method* can also be applied for a multi-room compartment. A general energy balance, similar to equation 5, can be formulated for a multi-room compartment where each room is connected to the next room by an opening and the last room is connected to the outside by a final opening (see Figure 2).

$\dot{Q} = \sum_{i=1}^{n} \dot{Q}_{W,i} + \dot{Q}_L$ Equation 13

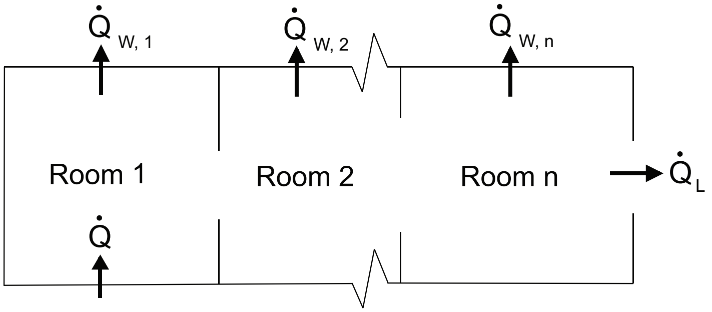

Figure 2: Energy balance in a simple multi-room geometry

The energy balance for the adjacent room in a two-room compartment can be expressed as in equation 14 with the help of the excess temperature in the room of fire origin (ΔT_1).

$\Delta T_2 = \frac{\dot{m}_g c_p \Delta T_1}{\dot{m}_g c_p + h A_{w,2}}$ Equation 14

The hot gas layer interface height in the adjacent room, $z_{int,2}$, can be calculated using equation 10 because the mass flow exciting the second room is equal to the mass flow entering the second room. $A_{w,2}$ is the surface area in contact with hot gases in the adjacent room.

Using the methods for transient fire conditions

The presented methods are entirely (equation 2 and 12) or partly (equation 11) based on data from experiments with constant heat release rates. However, these methods may still be used with an appropriate time-dependent HRR. By doing this, the quasi-steady state assumption is used. The assumption implies that when a change in HRR occurs at the fire source, full effects of the change occur immediately, i.e. the temperature of the hot gas layer increases directly to the corresponding value.

EVALUATION OF METHODS

The evaluation of the presented methods is based on the work previously presented by Johansson et al [15] and Karlsson and Kjellberg [16]. Johansson et al [15] looked at steady conditions (constant HRR) for a two-room compartment setup where the experimental uncertainties as well as the model uncertainties where quantified. Karlsson and Kjellberg [16] preformed a set of tests with transient fires (time dependent HRR) and studied the applicability of the presented methods for transient fires.

In a study by Deal and Beyler [9] several different methods for predicting room fire temperatures were compared and it was found that the *MQH method* gave good estimates of single room fire temperatures. The National Institute of Standards and Technology have also evaluated several hand-calculations methods [17] and it was found that *MQH method* in general over-predicted the hot gas layer temperature with 17% compared to experimental data.

Steady fire conditions

The four methods presented have been evaluated for steady fire conditions. The experimental setup is described by Johansson et al [15] and a brief description of the setup is given here.

The experimental setup consisted of two rooms (one small and one larger). The small room corresponded to a 1/4th-scale ISO 9705 room, and the large room was 1.2 × 1.2 × 0.8 m. Both rooms were made of 12 mm thick fibre silicate board. The two rooms were connected with an opening and an opening was also provided from the adjacent room to the outside (see Figure 16). The size of the openings could be varied between a small (0.2 × 0.5 m) and a larger opening (0.3 × 0.5 m). Two different fuels, heptane and methane, with two different heat release rates each, were used in the tests. The fire was placed in the centre of the inner room. The two room configurations and the two opening sizes were combined into five different geometrical scenarios and by varying the fire source, a total of 16 unique fire test setups were created. These tests were performed 3 or 4 times, a total of 52 tests were executed in the experiment.

Thermocouple trees were placed in both rooms that were used to approximate the hot gas layer interface height and temperature with the help of a data reduction method. The experimental uncertainties for the hot gas layer interface height and temperature were estimated. The relative combined experimental uncertainties for the hot gas layer interface height and temperature were concluded to be 13% and 12%, respectively. Further details of the experimental setup and uncertainties are presented in the paper.

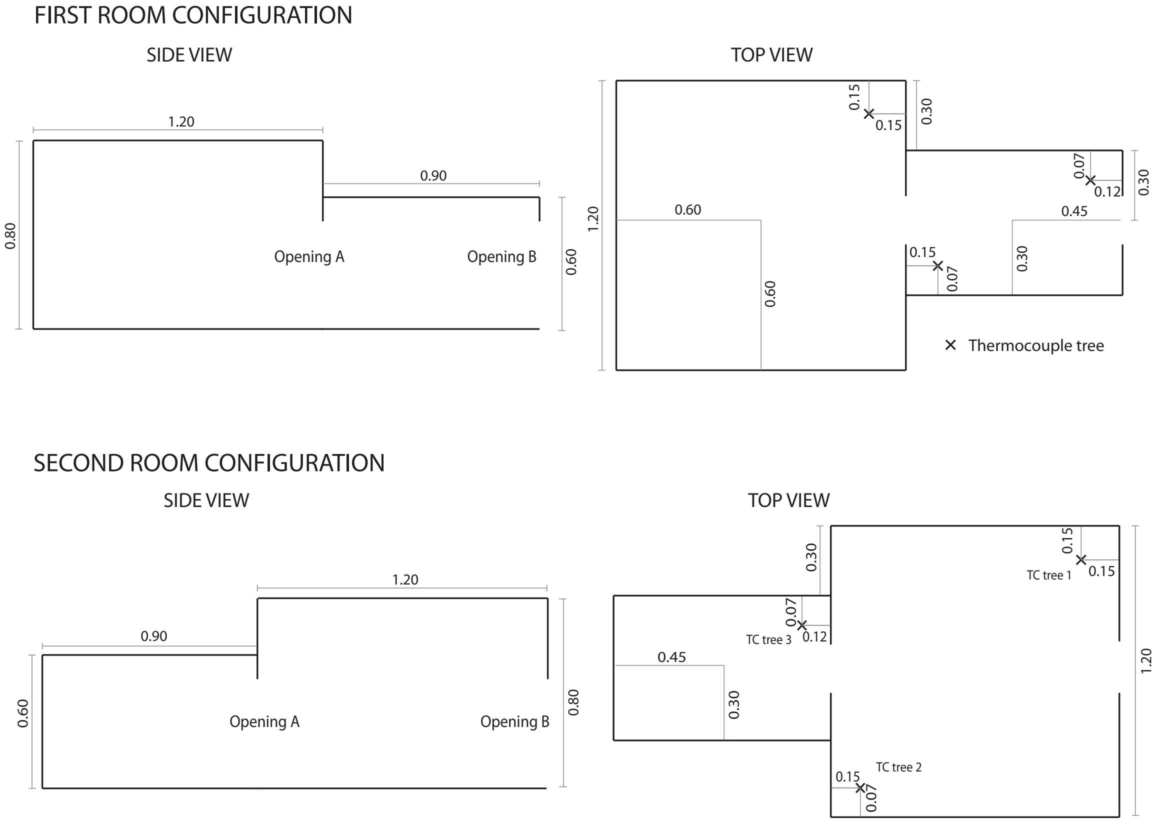

Figure 3: Schematic layout of the two room configurations in the small-scale setup.

The model uncertainty for each method was estimated based on the difference between the experimental measurements and model predictions that could not be explained by the experimental uncertainty. The model uncertainty was expressed by the precision ($\tilde{\sigma}_M$) and bias (β) of the predictions. A bias of 1 indicates that the model on average predicts the experimental values and the precision is a standard deviation (scatter) of the predictions around the average.

The *MQH method* (equation 2) and the *Adjacent room temperature correlation* (equation 12) were used to estimate the temperature in the room of fire origin and adjacent room respectively. The *Mass and energy balance method* (equation 8, 9, 10 and 14) was used to estimate the hot gas layer temperature and height.

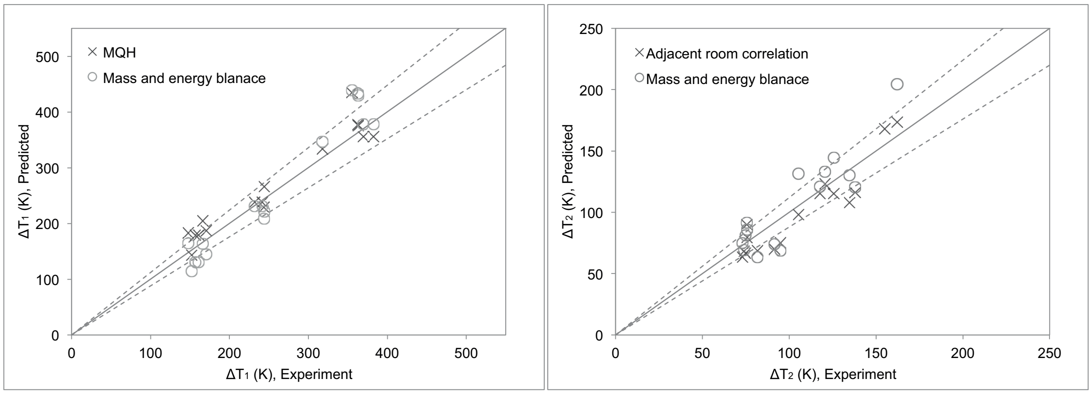

Figure 4: Predicted values plotted against experimental values of the hot gas layer temperature for the fire room (left) and adjacent room (right).

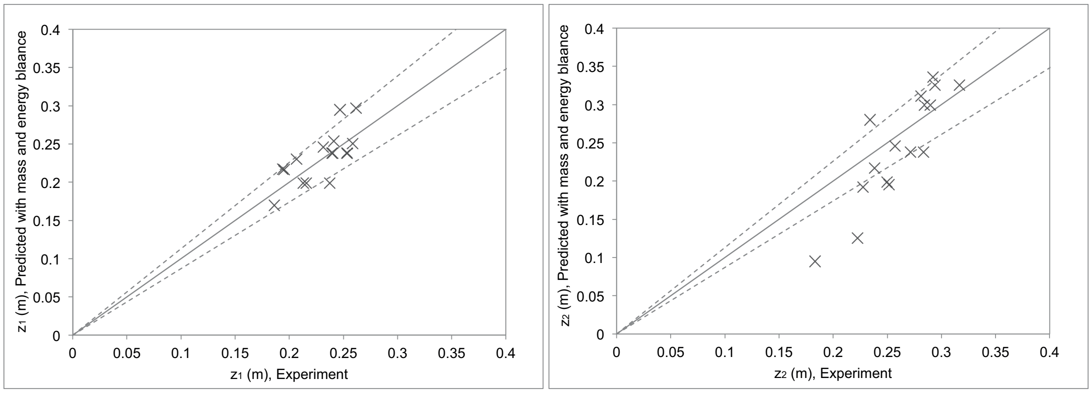

Figure 5: Predicted values plotted against experimental values of the hot gas layer interface height for the *Mass and energy balance method* in the fire room (left) and adjacent room (right).

Table 2: Model bias ($\boldsymbol{\beta}$) and precision ($\boldsymbol{\tilde{\sigma}_M}$) in calculations of hot gas layer temperature.

Method	Location	β	$\tilde{\sigma}_M$
MQH	Fire room	1.03	0.08
Adjacent room correlation	Adjacent room	0.89	0.13
Mass and energy balance	Fire room	0.96	0.15
Mass and energy balance	Adjacent room	0.99 (0.99*)	0.23 (0.22*)

* Outliers excluded

In the room of fire origin the *MQH method* has a bias is closer to 1 compared to the *Mass and energy balance method*. The *Mass and energy balance method* includes several simplifications while the *MQH method* and the *Adjacent room temperature correlation* provides a best-fit to empirical data within a certain range. The constants provided by the best-fit analysis will compensate for the simplifications inherent in the simplified energy balance (equation 13), and this is probably the reason why the correlations gives better agreement.

The precision is slightly poorer in the adjacent room methods. This is reasonable because the complexity increases when the conditions in adjacent rooms are studied. The temperature in the adjacent room is dependent on factors both in the adjacent room in the first room.

Table 3: Model bias (β) and precision ($\tilde{\sigma}_M$) in the calculation of height to the hot gas layer with the *Mass and energy balance method*.

Location	β	$\tilde{\sigma}_M$
Fire room	1.03	0.08
Adjacent room	0.93 (0.99*)	0.23 (0.12*)

* Outliers excluded

The model bias and precision in the hot gas layer interface height calculations with the *Mass and energy balance method* (see Table 3) will be better than the temperature predictions. This is reasonable because the hot gas layer interface height is calculated as a step when the temperature is calculated. The precision will be poorer in the adjacent room; a reason for this is that equation 10 was developed for a single room with an opening to the outside and not for calculating the gas flow between two rooms. Additionally, equation 10 is optimized for temperatures above 200°C [12] and the temperatures in the adjacent room were lower.

Transient fire conditions

The two methods for a single room compartment presented previously (*MQH method* and the *Mass and energy balance method*) have been evaluated for transient fire conditions. The experimental setup is described by Karlsson and Kjellberg [16]. A brief description of the setup is given here.

The experimental setup consisted of a single room. The room had the dimensions of a 1/4th-scale ISO 9705 room (see Figure 6). The size of the openings could be varied between a high (0.3 × 0.5 m) and a low opening (0.3 × 0.25 m). The fuel consisted of two differently constructed wood cribs in order to represent two differently growing fires (low and high). The actual growth rate for the different wood cribs varied depending on the size of the opening, examples of the fire growth rate are given in Figure 7. The fire was placed in the centre of the room. The room was made of 12 mm thick fibre silicate boards. The two opening sizes and the two fire growth rates were combined into four unique fire test setups. Each test was repeated three times, and a total of 12 tests were executed in the experiment. Furthermore, the test series was duplicated with extra insulation (50 mm stone wool) attached on the unexposed side of the fibre silicate board, these results are however not presented in this paper but are available in a master thesis [16].

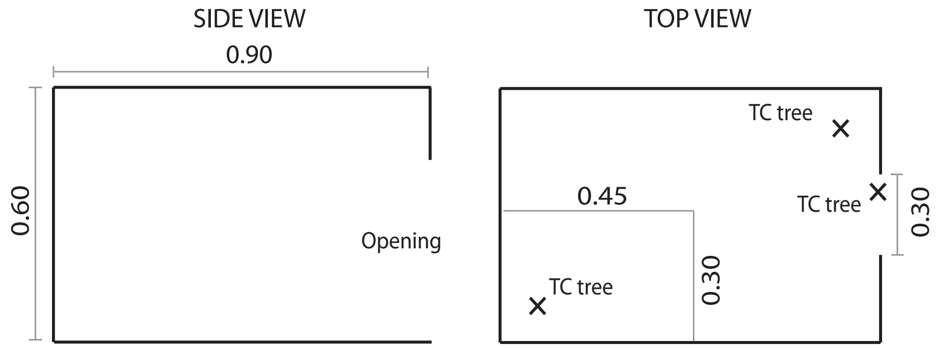

Figure 6: Schematic layout of the room in the small-scale setup.

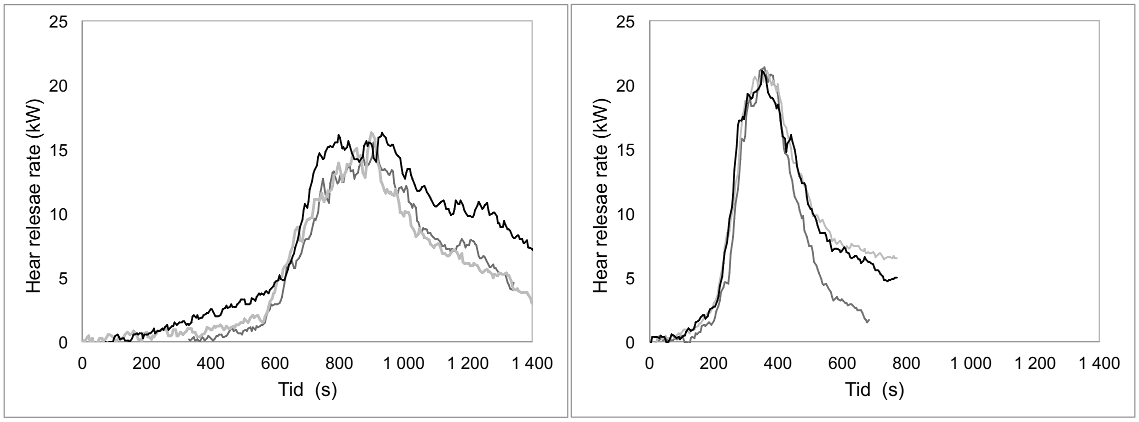

Figure 7: Heat release rate in three repeated tests for the low (left) and high (right) growth rate when the room opening was high.

Two thermocouple trees were placed in the room and these were used to approximate the hot gas layer interface height and temperature with the help of a data reduction method.

The conditions in the four fire tests were predicted with hand-calculation methods and FDS. The *MQH method* (equation 2) was used to estimate the temperature in the room, while the *Mass and energy balance method* (equation 8, 9, 10 and 14) was used to estimate both the hot gas layer temperature and height. Results from two of the tests are given in Figure 8 and Figure 9.

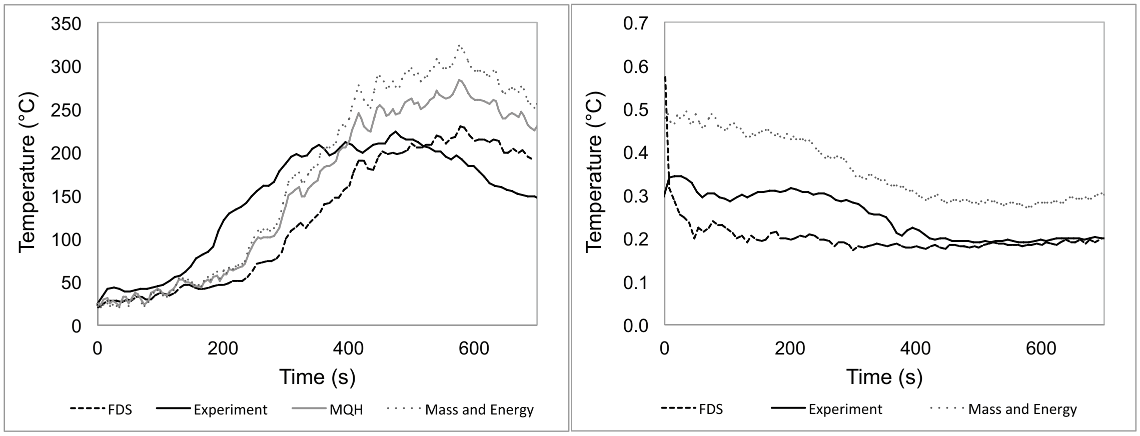

Figure 8: Hot gas layer temperature (left) and height (right) for low growth rate and high opening.

It is obvious that there is a delay in the experimental temperature measurement that is not accounted for in Figure 8. If this would be accounted for the calculated temperature rise is rather consistent with the experimental values. Nevertheless, there is a 25-50% difference in maximum temperature between the hand-calculation methods and the experimental data. FDS predicts the maximum temperature rather well. The *Mass and energy balance method* underestimates the hot gas layer height with 0.1m.

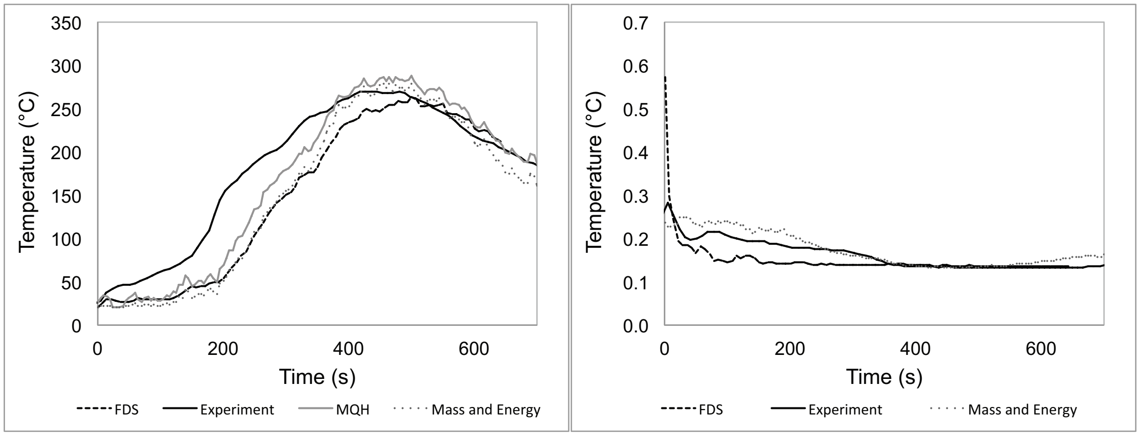

Figure 9: Hot gas layer temperature (left) and height (right) for low growth rate and low opening.

The model predictions are in general much better for the low opening than the high opening (see Figure 9). In this case it also seems there is a delay in the experimental temperature measurement that is not accounted for. The difference in maximum temperature between the hand-calculation methods and the experimental data in Figure 9 is less than 5%. The hot gas layer height is calculated to be within 10% of the experimental values.

The heat transfer greatly affects the results, and the methods available for determining it (equation 3, 4 and 7) includes simplifications that contribute to the large deviations from the experimental values that were seen in some of the cases.

CONCLUSION

Simple hand-calculation methods can be very useful for fire safety engineers. Two different methods that can be used to estimate the hot gas layer temperature and height in pre-flashover compartment fires have been evaluated in this paper. Data from two different small-scale compartment fire experiments have been used in this paper and the results indicate that the methods can make predictions within 5-20% of the experimental values. The studied correlations and the *Mass and energy balance method* can be used to perform estimate calculations in fire safety engineering. The *Mass and energy balance method* is especially suitable to use in order to comprehend and understand fundamental compartment fire dynamics because it is a transparent and flexible method that performs like a simple two-zone model.

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