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An evaluation of two methods to predict temperatures in multi-room compartment fires

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ABSTRACT

The objective of this paper is to compare predictions with two hand-calculation methods with data from a small-scale two-room compartment fire experiment including 52 individual tests. The first method is based on two previously presented empirical models, and the second method consists of several calculation steps in order to solve a simple energy balance. The second method is based on the conservation of energy and mass and it performs as a simple two-zone model that can be used to get an estimate of the gas mass flow, hot-gas-layer temperature and interface height in the fire room and adjacent rooms.

An experimental setup consisting of two small rooms connected with an opening has been used to gather experimental data. The size of the rooms, openings and fire source were varied in the experiment, which resulted in 16 unique experimental tests and each test was repeated at least three times.

A majority of the temperature predictions in the fire room with the two hand-calculations methods were within the bounds of the experimental uncertainty, and the predictions in the adjacent room had a similar accuracy. The hot-gas-layer interface height predictions, which were calculated with second method, were overall within the experimental uncertainty.

1. Introduction

Advanced computer-modeling software that can predict smoke spread and hot-gas-layer (HGL) temperatures have evolved significantly in the last decays. With two-zone and computational fluid dynamics (CFD) models it is possible to calculate smoke layer heights, species and temperatures etcetera in a multi-room geometry. There are several models available [1] and some, like e.g. the Fire Dynamics Simulator (FDS) [2], are continuously developed and improved. These types of software are generally good tools for fire engineering purposes, but there is even still a need for simple engineering methods. The motivation is that simple hand-calculations methods can be used in order to get an estimate before any more advanced and time consuming analyses are conducted. Hand-calculation methods are inexpensive and the result form a hand-calculation can help an engineer to determine if it is necessary to perform a detailed calculation. Simple methods can also be used to increase the knowledge and understanding of different fire phenomena and relationships between different parameters. This is important because it is considered to be necessary to have a general understanding of the fire phenomenon of interest when using more advanced and less transparent fire models.

The HGL temperature is one of the most important parameters a fire model can predict because it is the temperature in the room that will determine the impact of a fire [3], in terms of e.g. its influence on the heat release rate (HRR) and fire spread in the room. Furthermore, performance criteria in regard to the HGL temperature are often applied in fire safety analysis [4]. The so-called MQH correlation [5] (Eq. (1)) is an example of a hand-calculation method that can be used to predict HGL temperatures and it is described in several handbooks used by practitioners [6,7]. The correlation gives the temperature increase (ΔT) in a cubical room as a function of the HRR, size of a rectangular opening, enclosure geometry and thermal properties of the enclosure. The correlation is based on 112 experimental observations in conventional sized rooms and it is valid for well-ventilated pre-flashover fires, i.e. for temperatures below 600 °C.

$$\Delta T = 6.85\left(\frac{\dot{Q}^2}{A_0\sqrt{H_0}h_kA_T}\right)^{1/3} \tag{1}$$

There are other methods available that can be used to predict single-room temperatures [7–9]. These methods along with the MQH correlation are generally rough and less accurate compared with simulations, but they have the benefit of being simple and cost-effective, and still give a good description of the physical problem [10]. In a study by Deal and Beyler [11] several different methods for predicting room fire temperatures were compared

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Nomenclature

A_o	area of opening (m^2)
A_t	surface area in contact with hot gases (m^2)
A_T	surface area, minus area of openings, in the room (m^2)
c_p	Specific heat at constant pressure (kJ/(kg K))
d	thickness (m)
E	experimental data
g	gravitational constant (m/s^2)
H_o	opening height (m)
h	heat transfer coefficient (W/m^2k)
h_k	heat transfer coefficient (W/m^2k)
k	thermal conductivity (W/m K)
L_f	flame height (m)
l	length (m)
M	model data
$\dot{m}_a$	mass flow rate of ambient air (kg/s)
$\dot{m}_g$	mass flow rate of hot gases (kg/s)
$\dot{m}_p$	plume mass flow (kg/s)
$\dot{Q}$	heat release rate (kW)
$\dot{Q}_c$	convective part of heat release rate (kW)
$\dot{q}_{loss}$	heat loss to boundaries (kW)
T	Temperature (K)
t	time (s)
U	expanded uncertainty
$\tilde{U}$	relative expanded uncertainty (dimensionless)
W	opening width (m)
z	height above floor (m)
z_{int}	height to HGL interface (m)
z_0	height of virtual origin of fire plume (m)

Greek

β	bias of model predictions
σ	standard deviation
σ_E	experimental uncertainty
σ_M	model uncertainty

subscripts

1	property in fire room
2	property in adjacent room
a	ambient gas property
c	combined uncertainty
g	hot gas property
F	full-scale
M	model scale
Me	Measurement uncertainty
MI	propagated input uncertainty
o	opening
u	upper layer property

and it was found that the MQH correlation gave good estimates of single room fire temperatures. The U.S. Nuclear Regulatory Commission (NRC) and National Institute of Standards and Technology (NIST) have also evaluated several hand-calculations methods [3,12], and it was found that MQH correlation captured the appropriate physics but in general over-predicted the HGL temperature with 17% compared to the experimental data.

Efforts were made during the 1980s to derive analytical models for predicting different fire conditions, but there are also examples of work conducted lately [13,14]. Nevertheless, most of the work has been done on single room compartments, and few have studied the conditions outside the room of fire origin. This is probably due to the increased complexity of the problem with an increased amount of influencing variables. Even so, it can be quite useful for practitioners to extend their toolbox of simple engineering methods in order to study a wider spectrum of compartment fire scenarios than a single room. It could be to get an estimate of the conditions for evacuees in an escape way adjacent to the room of fire origin or the heat exposure to components (e.g. cables and electronics) in an adjacent room [10].

In this paper two different methods to evaluate conditions in a two-room compartment are presented. Predictions with the two methods are evaluated with a set of tests in a small-scale experimental setup and the focus is primarily on predicting the HGL temperature in a room adjacent to the room of fire origin.

2. Theory

Two different hand-calculation methods are presented in this section. The two methods are based on the same underlying assumptions but have been developed in different ways. The main assumption is that the temperature distribution in the compartment can be approximated into a two-zone model, e.g. a well-mixed upper layer with a homogenous temperature and a well-mixed cooler lower layer with homogenous temperature. Additionally, it is assumed that the following energy balance (Eq. (2)) can be applied for a room adjacent to the room of fire origin in a two-room compartment.

$$\dot{Q} = \dot{m}_g c_p (T_{g,2} - T_a) + \dot{q}_{\text{loss},1} + \dot{q}_{\text{loss},2} \quad (2)$$

This energy balance is similar to the simple energy balance that often is applied for a single-room compartment [6]. The energy flux flowing out through an opening from the adjacent room is described with the first term on the right-hand side. The second and third term describes the heat loss to boundaries in the fire room and adjacent room respectively (see Fig. 1). Eq. (2) can be solved numerically for a specific case, but it cannot be solved directly because it contains temperature dependent variables that govern the temperature in the two rooms.

2.1. Method 1 – empirical models

The first method that is evaluated in this paper is constituted of two empirical models for calculating HGL temperatures in the fire room and in the adjacent room. As previously mentioned can the HGL temperature in the room of fire origin be estimated with the MQH correlation (Eq. (1)). The MQH correlation is based on a simple energy balance, an analysis of dimensionless variables and empirical data.

An empirical model (Eq. (3)) similar to the MQH correlation, developed by Johansson and van Hees [10], makes it possible to estimate the HGL temperature for a given HRR in a adjacent room connected to the room of fire origin as illustrated in Fig. 1. The method is based on a numerical experiment, a research method that Johansson [15] has elaborated on. The numerical experiment included approximately 90 FDS simulations with different room configurations and heat release rates. The HGL temperature increase in the adjacent room was considered as a dependent variable and a correlation to several independent variables, identified with the help of Eq. (2), was found with the help of a multiple regression analysis.