Available online at www.sciencedirect.com

ScienceDirect

Fire Safety Journal 43 (2008) 495–511

FIRE SAFETY JOURNAL

www.elsevier.com/locate/firesaf

Numerical simulations of full-scale enclosure fires in a small compartment with natural roof ventilation

Bart Merci[a,b,*], Karim Van Maele[b]

[a] *Fund of Scientific Research—Flanders (FWO-Vlaanderen), Belgium*

[b] *Department of Flow, Heat and Combustion Mechanics, Ghent University—UGent, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium*

Received 29 May 2006; received in revised form 12 January 2007; accepted 6 December 2007
Available online 28 January 2008

Abstract

Numerical simulation results are presented of full-scale fire tests in a small compartment ($3 \times 3.6 \times 2.3$ m). A range of total fire heat release rates (330, 440 and 550 kW), fire source areas (0.3×0.3 m and 0.6×0.6 m) and ventilation roof opening areas (1.45×1, 0.75×1 and 0.5×1 m), is covered. Both two-zone model calculations and field model simulations are considered. For the different configurations, profiles of mean temperatures and temperature fluctuations are reported. Furthermore, the mean flow field and temperature field in the compartment are extensively discussed, providing insight in the entrainment and mixing phenomena in the plume in the compartment. The smoke layer depth is determined for all configurations. The computational fluid dynamics (CFD) simulations agree well with experimental observations. The total fire heat release rate value has the strongest influence on the hot smoke layer average temperature rise, while the influence of the fire source area and the roof opening is smaller. The hot smoke layer depth, determined from the mean temperatures, is hardly influenced by the total fire heat release rate. The roof opening also only has a moderate influence in the range considered. The largest impact on the layer depth is due to the fire source area with an increase of the depth as the fire source area increases. Correlations are given for the average hot smoke layer temperature rise and the total smoke mass flow rate out of the compartment, as a function of the different parameters mentioned. A study of the buoyancy reference velocity leads to the verification of a formula to estimate the total smoke mass flow rate out of the compartment. The performance of different entrainment models in zone model calculations is discussed in relation to the obtained CFD results.

Keywords: CFD simulations; Compartment fire; Natural ventilation; Zone modeling

1. Introduction

In [1], an analysis of an experimental study of full-scale fire tests in a small compartment with a roof opening for natural ventilation is presented. Correlations are presented in [1] of the hot smoke layer thickness and average temperature rise as a function of the total fire heat release rate, roof opening area and fire source area. Three manual calculation methods [2–4], widely used in the design of smoke and heat exhaust ventilation systems, were evaluated. To that purpose, an estimate had to be made of the total smoke mass flow rate out of the compartment.

The major aim of the present study is to provide insight in the flow phenomena inside the compartment, by means of computational fluid dynamics (CFD) simulations. Therefore, numerical simulation results are presented for all the configurations experimentally studied in [1]. These simulations contain by far more detailed information than the experimental temperature measurements. They provide insight into the entrainment mechanism in the plume, so that the entrainment models of the manual calculation methods [2–4] can be evaluated.

The NIST code fire dynamics simulator (FDS) [5] is applied. First, it is verified that the mean temperatures and hot smoke layer thickness values, obtained from the CFD simulations, agree well with the experimental data, indicating that the simulation results are reliable. Next, the influence of the thermal wall boundary conditions and the grid sensitivity of the results are investigated.

*Corresponding author at: Department of Flow, Heat and Combustion Mechanics, Ghent University—UGent, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium. Tel.: +32 9 264 33 14; fax: +32 9 265 35 75.

E-mail address: Bart.Merci@UGent.be (B. Merci).

0379-7112/$ - see front matter
doi:10.1016/j.firesaf.2007.12.003

Nomenclature

A_f	fire source area (m^2)
A_i	ventilation inlet area (m^2)
A_{roof}	roof ventilation area (m^2)
A_v	ventilation outlet area (m^2)
C_i	discharge coefficient of inlet ventilation area (dimensionless)
C_v	discharge coefficient of outlet ventilation area (dimensionless)
c_p	specific heat capacity (kJ/(kg K))
d	hot smoke layer thickness (m)
D	fire source hydraulic diameter (m)
D_{tc}	thermocouple diameter (m)
h	convection coefficient (W/(m^2 K))
H	compartment height (m)
ΔH_c	total heat of combustion (J/kg)
HRR	heat release rate (kW)
k	conduction coefficient (W/(m K))
L_{fl}	flame height (m)
$\dot{m}_f$	fuel mass flow rate (kg/s)
$\dot{m}_s$	total smoke mass flow rate (kg/s)
Nu	Nusselt number (dimensionless)
P	fire source perimeter (m)
Pr	Prandtl number (dimensionless)
$\dot{Q}_f$	total fire heat release rate (kW)
$\dot{q}_f$	total fire heat release rate per unit area (kW/m^2)
$\dot{Q}_s$	convective heat per time unit in the hot smoke layer (kW)
T	temperature (K)
T'	temperature fluctuations rms value (K)
T_{amb}	ambient absolute temperature (K)
T_o	absolute reference temperature (K)
$T_{s,av}$	average hot smoke layer temperature (K)
$T_{s,max}$	maximum hot smoke layer temperature (K)
T_∞	effective ambient temperature for radiation correction (K)
Y	smoke-free height (m)
z_o	virtual origin height (m)
ε	emissivity (dimensionless)
χ	factor of incompleteness of combustion (dimensionless)
ρ_{amb}	ambient density (kg/m^3)
ρ_s	smoke density (kg/m^3)

Finally, two-zone model calculation results are also discussed, by means of the program OZONE [6].

2. Simulation set up

2.1. Description of the configurations

Fig. 1 shows the compartment geometry as a 'Smokeview' picture. A complete description is provided in [1]. The dimensions are $3.6 \times 3.0 \times 2.3$ m with a door opening (0.9×2.0 m) in the middle of the front wall. The two openings in the roof are of size 0.75×1 m each (one opening is covered in Fig. 1). They are centrally positioned around $x = 1.8$ m. The distance between the roof opening centers and the front wall is 1 m. The fire source is positioned in the center of the compartment at 0.3 m height. Two fire source areas are considered: $A_f = 0.3 \times 0.3$ and 0.6×0.6 m. Three fire heat release rate values are applied: $\dot{Q}_f = 330$, 440 and 550 kW. Three values of the roof opening area are used: $A_{roof} = 2(0.725 \times 1.0\,\text{m}) = 1.45\,\text{m}^2$, $A_{roof} = 1(0.75 \times 1.0\,\text{m}) = 0.75\,\text{m}^2$ and $A_{roof} = 0.5 \times 1.0\,\text{m} = 0.5\,\text{m}^2$.

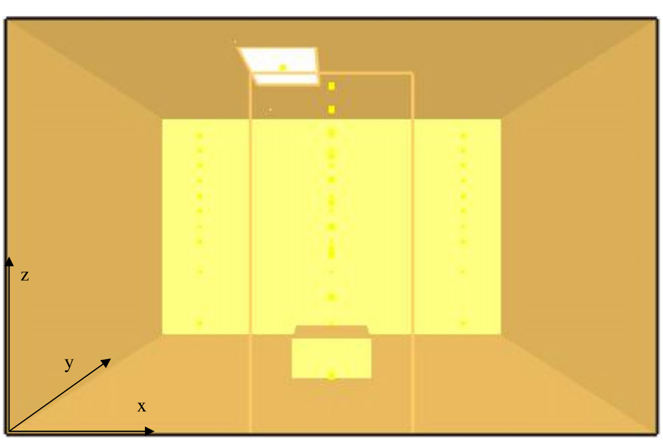

Fig. 1. Geometry of the compartment in the numerical simulations (Smokeview).

2.2. Zone model simulations

The configurations, mentioned in Section 2.1, are computed with the zone model package OZONE [6]. In general, the OZONE default values are used. This means, e.g. for the internal convection coefficient in the hot layer $h_i = 25\,\text{W/(m}^2\,\text{K)}$ and in the cold layer $h_i = 9\,\text{W/(m}^2\,\text{K)}$. Radiation is accounted for, with all emission coefficients equal to 0.8. Altering these values affects the absolute values, but not the observed trends. As in [1], complete combustion is assumed: $\chi = 1$. The discharge coefficients are set equal to $C_i = C_v = 0.6$. The two-zone model is used. The fire source is assumed steady, with area equal to the experimental value.

An important aspect in OZONE is the possibility to choose between four entrainment models:

- '*Heskestad*' [7]: this is the entrainment model, implicitly used in the manual calculation method [4]. This model distinguishes between entrainment in the flame region and in the plume region. The flame height is defined as $L_{fl} = 0.235(0.7\dot{Q}_f)^{2/5} - 1.02D$, with $\dot{Q}_f$ expressed in kW. For the cases considered, L_{fl} varies between 1.5 and 2.2 m, which is high, compared to the compartment