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Development of an analytical model to quantify downward smoke displacement caused by a water spray for zone model simulations

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ABSTRACT

A stand-alone analytical model for downward smoke layer displacement caused by a water spray is developed. The model can be implemented into two-zone model calculations. Smoke flow into and out of the water spray envelope is incorporated, as well as a model for the heat exchange between the smoke and the water droplets. The model input quantities are water flow rate, orifice diameter, droplet diameter, spray angle, initial smoke layer thickness and temperature, and ambient air temperature. The quality of the model predictions is illustrated for a range of experimental conditions. Results are shown to be sensitive to the mean droplet diameter and the spray angle. Then, the combinations of values of these parameters are suggested for the sprinkler considered. A practically important phenomenon of abrupt strong downward smoke layer displacement is explained in that the upward buoyancy flow diminishes due to the entrainment of cool air into the water spray envelope. This only occurs for high enough water flow rates and as long as the smoke layer thickness is below a critical value. Therefore, this is particularly dangerous during the smoke layer build-up phase. Finally, the accuracy of the model for the heat transfer rate from the hot smoke layer to the droplets and the smoke temperature inside the spray region are evaluated by comparison to experimental data.

1. Introduction

Downward displacement of fire smoke, caused by sprinkler/spray systems, has been noticed in experiments for decades [1–5,17]. Tests in the large-scale experimental mall at the Fire Research Station showed that, under certain conditions, the smoke layer could be brought down by a manually operated sprinkler spray [4]. Bullen [4] described a theory to indicate a criterion for the downward smoke displacement, based upon the ratio of the drag force of the water droplets (D) to the buoyancy of the smoke layer in the spray region (B). Zhang [5] and Li et al. [1] further presented a new criterion respectively by considering the smoke layer temperature gradient and the spatial distribution of the drag force inside the spray region. Furthermore, a simplified equation to calculate the smoke penetration depth (smoke downward displacement distance) was proposed by Li and Spearpoint [7]. However, the experiments carried out by Williams [2], Li [1], and Chow et al. [17], show that the downward smoke displacement can happen when ratio of D to B is less than 1 in some tests. The reason has been explained in our previous work [8], taking into account 'downward buoyancy' by the cooling effect of the water droplets inside the hot smoke layer. In addition, Cooper [6] developed the LAVENTS sub-model to simulate the interaction between a smoke layer and water droplets involving six possible flow conditions. The cooling effect and entrainment are considered in the model. The smoke penetration depth can also be calculated by the model. The above introduced models rely upon many assumptions to simplify phenomena and solutions. Consequently, simple input quantities and short calculation times are advantages and it is appealing to investigate implementation into existing two-zone fire model simulations.

There are many more studies only concerning the interactions between water droplets and a hot layer, e.g. heat transfer and entrainment phenomenon [9–14,19–21,26,28]. Chow et al. [10] developed a one-dimensional model for calculating spray characteristics, shape of the spray envelope, gas temperature, and flow rate inside the spray envelope with heat and mass transfer to the induced air flow. Furthermore, Li and Chow [18] studied the evaporation of water droplets while travelling in hot air layer. Jackman [20], improved the original model established by Gardiner [19], and presented a more complex model, called 'SPLASH'. The input data of 'SPLASH' include the dimensions of the building, details of the fire smoke layer and characteristics of water droplets from several commercial available sprinklers, while the output

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Nomenclature

C_D	drag coefficient
C_p	specific heat (J kg^{-1} K^{-1})
D_d	diameter of an individual water droplet (m)
d_n	orifice diameter of the nozzle (m)
F_d	drag force on an individual water droplet (N)
F_D	total drag force (N)
F_B	total buoyancy (N)
g	gravity acceleration (m s^{-2})
h	depth of the smoke layer below the nozzle (m)
h_c	heat transfer coefficient between water and gas (W m^{-2} K^{-1})
Δh	depth of the downward smoke displacement (m)
L_v	latent heat of vaporisation of water ($J \cdot kg^{-1}$)
m	mass (kg)
$\dot{m}$	mass flow rate (kg s^{-1})
$\dot{V}_w$	water volume flow rate (m^3 s^{-1})
$\dot{N}_d$	water droplet number rate (number/s)
Nu	Nusselt number
P	water operating pressure (MPa)
Pr	Prandtl number
$\dot{Q}_c$	convection heat exchange rate (W)
r	radial coordinate (m)
Re	Reynolds number
t	water droplet travelling time (s)
T	temperature (K)
$\vec{v}$	velocity (m s^{-1})
z	vertical coordinate (m)

Greek alphabet

θ	spray angle (deg)
λ	thermal conductivity (W m^{-1} K^{-1})
υ	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})

Subscript

a	air
aih	average value inside the smoke hood
d	an individual water droplet
en	entrainment
i	inside the spray envelope (in the spray region)
in	initial conditions
o	outside the spray envelope
s	smoke
r	radial direction, resultant, reference
z	vertical direction

data involves many variables, including heat and mass transfer effects in the fire smoke and the physical and thermal histories of droplets as they travel through the smoke layer. Morgan [21] developed a theory for calculating the heat transferred from a fire smoke layer to a sprinkler spray. The theory involves calculating the heat transfer to a single water drop as it describes its trajectory, and uses experimentally derived information on the nature and structure of such sprays to calculate heat transfer to the whole spray. The accuracy of this model is illustrated by the experiments in mall conducted by Morgan and Baines [20]. Although the aim of these models is not to simulate the scenario that the smoke from upper hot layer moving into lower cool layer, they indeed provide the fundamental mechanism for the interaction between water droplets and their surrounding gas. Based on the model in [8] and the basic heat transfer and entrainment principles, this paper is to introduce a model not only could simulate the thermal interaction between droplets and hot gas, but also could predict the hot gas motion deduced by spray in a two-layer environment (hot upper layer and cool bottom layer).

In our previous work [8], we have already described an analytical model to quantify the downward smoke displacement caused by a water spray. The model has been developed from first principles, expressing a balance between (Fig. 1, left): the downward drag force (Zone III in Fig. 1); the possible downward buoyancy due to a cooling effect within the water spray envelope inside the smoke layer (the upper part of Zone III); and the upward buoyancy in the ambient air below the smoke layer (the lower part of Zone III). The rationale and accuracy of the model has been illustrated in [8]. However, no heat transfer model was incorporated and the temperature inside the spray region was prescribed. According to the findings of the experimental study as reported in [3], the smoke temperatures in the spray region are related to heat transfer from smoke to water droplets and to entrainment phenomena. Therefore, simplified heat transfer equations and flow motion equations are now incorporated into the model in order to calculate the smoke temperature distribution inside the spray region. As such, the model requires fewer input quantities and has more output quantities. The most important new outputs are the smoke temperature and velocity inside spray region, the heat transfer from smoke layer to droplets and the smoke/air mass entrainment. Moreover, the model in its present form, as a useful tool to simulate the interaction between droplets and smoke layer, can be implemented into two-zone model simulations (noting that the possible interaction of the water with the fire source is not considered at present).

The structure of this paper is as follows. The basic assumptions for the model are introduced first, after which the model is presented completely. Next, the accuracy of the model for predicting downward smoke layer distance and heat transfer rate is tested by means of experimental data. Some combinations of model parameters for the water spray angle and the mean droplet diameter are suggested for the sprinkler considered. Next, the model is applied to a range of

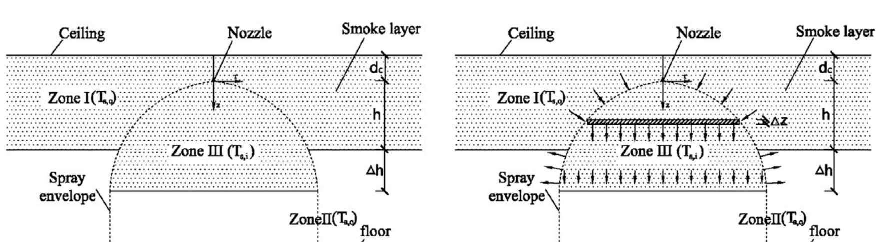

Fig. 1. Schematic sketch of the configuration and the model ingredients. Left: previous model formulation [8]; Right: present model formulation.