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B. Yao and W.K. Chow, “Smoke venting effect when discharging a solid-cone water spray”, Journal of Applied Fire Science, Vol. 20, No. 3, p. 201-209 (2010-2011).

Smoke Venting Effect When Discharging a Solid-cone Water Spray

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June, 2011

Abstract

Possible venting of smoke in a room fire while discharging a solid-cone water spray was studied. The water spray would act at the smoke layer at positions away from the burning object. In this way, water droplets would not reach the fire plume and affect the combustion directly. The spray dimension was assumed to be relatively small in comparing with the compartment. It is observed that operating the solid-cone water spray would give smoke venting effect. The compartment can be divided into three quasi-steady regions: an upper smoke layer, a lower air layer and a one-dimensional spray. Fire environment under different spray characteristics was investigated by applying a two-layer zone model developed earlier with some modifications. Results indicated that the fire environment would be affected significantly by the solid-cone water spray through hot gas entrainment and water evaporation. The smoke layer interface height would move up with the smoke layer temperature and the flow rate to adjacent space decreased. Predicted results agree with experimental observations in the small burning test.

Keywords: fire engineering, computational mechanics, mathematical modeling, water spray

1. Introduction

A good understanding of the effect of fire protection systems on a compartment fire is important for providing adequate safety. Poorly designed systems would cause damages instead of controlling the fire. One of the important areas is the effect of water spray on the smoke layer. There are concerns on whether discharging water into a hot smoke layer would disturb its stability. Smoke might then be pulled down to lower level to give adverse effects to the occupants [1-4]. Variables including smoke layer interface height, smoke temperature and outgoing flow rate through the opening to adjacent space should be studied carefully.

Works were reported on the effect of hollow-cone spray with large droplets such as those discharged from a sprinkler system [3,5-9] on a fire. Others were reported on solid-cone water sprays with small droplets discharged from water mist fire suppression systems [10-18]. Surrounding gas would have more influence on the motion and heat transfer for smaller droplets than for larger droplets. Water spray in hot gas should be considered carefully to investigate the entrainment effect on the smoke.

Upon discharging water spray, the smoke layer would not be stable [e.g. 1-4] if the drag force due to the spray is greater than the buoyancy of the smoke layer. Action of a solid-cone water spray of relatively small droplets in a compartment fire is more complicated. The interaction area would be relatively small for spray dimension smaller than that of the room geometry. Smoke layer under the spray nozzle is affected by the discharged water spray. However, smoke layer outside the spray envelope might not be dragged by the droplet directly, and so remains stable. This small solid-cone spray would perform like a ‘vent’ in entraining the hot gas inside the spray envelope without affecting the stability of the smoke layer significantly. Therefore, two-layer zone models [e.g. 19,20] can be applied for the part of smoke layer other than the spray envelope to predict the fire environment. This case is different from that with the entire compartment covered by sprinkler sprays, water mists or gas agents from total flooding systems [e.g. 13].

In this paper, a small-scale experiment was carried out first to demonstrate the ‘vent’ effect of the solid-cone spray on the smoke layer. The change of smoke layer height was obviously observed. Then, physics of the vent effect for real-scale scenario would be investigated by modifying a one-dimensional model developed earlier [10,18] for studying the interaction of a water spray with smoke layer. In this model [18], the hot smoke and cool air are taken as two layers under quasi-steady state. Water droplets of the solid cone spray can be described by four distribution functions for four sizes. The hot gas would be entrained inside the spray envelope. The spray pattern is modeled using a Lagrangian approach on balancing heat, mass and momentum of single droplets. The system of equations is solved using a space marching Runge-Kutta scheme of the fourth order. Spray characteristics such as droplet diameter and velocity, shape of the spray envelope, gas temperature and flow rate inside the spray envelope can be calculated for various smoke layer conditions. This modified model would be applied to study the vent effect of a solid-cone water spray. The results would help to better understand the effect of fire protection systems on a compartment fire, and select and design suitable water spray for safety purpose.

2. Smoke Venting Effect

The small-scale experiments on a chamber of size 1.0 m by 0.6 m and 0.6 m high as in Figure 1a were carried out. There was an opening of height 0.25 m and width 0.1 m at one end with a sill. A small diesel pool fire of diameter 0.05 m was placed on the floor at a distance 0.25 m away from the other end. The water mist nozzle was placed 0.25 m away from the opening, and 0.02 m below the ceiling. The solid-cone spray discharged is of maximum dimension 0.2 m. Water was discharged manually from the nozzle after getting a stable smoke layer. A digital video camera was used to record the transient changes of the smoke layer.

Before discharging the water spray, a rather stable smoke layer was formed in the upper part of the test chamber as shown in Figure 1b. Hot smoke flowed out through the opening. When water was discharged, the smoke near the spray was brought down, while the other part of the smoke layer away from the spray rose up as shown in Figure 1c. The smoke layer was observed to be stable. The smoke layer thickness was thinner than that before discharging water spray, if the spray velocity was not too large. For this small-scale test demonstration, the effect of discharging water spray is similar to operating a 'vent' to reduce the smoke layer thickness.

Note that for a vent, the smoke would be removed out of the compartment. But for such a 'vent' induced by the solid spray, smoke would be brought down to the lower air layer, then mixed with air in the lower layer. The lower layer characteristics would be changed significantly and water vapor produced would affect the intermediate combustion chemical reactions. In general, heat release rate under some spray characteristics would be decreased due to physical, thermal and chemical effects. But the combustion might be enhanced if the reactions are accelerated by radicals such as H· and ·OH produced from water vapor; or when the soot formed within the flame is reduced by water vapor to give incomplete combustion [21,22]. Under the conditions in this experiment, the flame size was observed to become larger when water mists were discharged as shown in Figure 1c. Further detailed investigation should be carried out to describe the complicated phenomena.

3. Fire Scenarios

A scenario with a water spray acting at the fire-induced smoke layer in a compartment as shown in Figure 2 is considered. The solid-cone spray is discharged at some distance away from both the burning object and the opening. The gas flow through the opening and the fire plume would not be affected directly by the water spray. Therefore, three regions can be divided:

- Region 1: An upper hot smoke layer,
- Region 2: A lower cool air layer and,
- Region 3: A solid-cone water spray.

The fire environment under various spray characteristics can be studied by a two-layer zone model. Interactions among the three regions can be deduced by conservation of mass, momentum and heat. The one-dimensional model for solid-cone spray developed by Chow and Yao [10] was further developed by Yao and Chow [18] by considering the 'quasi-steady' smoke layer during each time step in calculating the smoke layer characteristics. Note that the characteristic changing time of the smoke layer is much longer than that of the water spray. Main assumptions made in the model are:

- Pre-flashover fire is assumed with the pressure in the compartment taken as very close to the ambient pressure.
- All gases are assumed to obey the ideal gas law.

- Smoke is entrained into the spray envelope in a perpendicular direction and then mixed with the gas inside the spray thoroughly. If the water spray travels through the interface of two layers, or even reaches the floor, the gas inside the spray would mix well with the lower layer; or with the upper layer and almost all water droplets would be evaporated.
- The heat release rate of the fire is kept at the design value without affected by reduction in oxygen concentration in the air layer due to water evaporation. Effect of oxygen on the heat release would be discussed later.

All the key equations in the three regions had been described by Yao and Chow [18].

4. Numerical Simulations

A compartment of 8.0 m long, 5.0 m wide and 3.5 m high with an opening of 2.0 m high and 2.0 m wide was considered. The nozzle was located at 10 cm below the ceiling which was away from both the opening and the fire. The spray radius was much smaller than the compartment dimensions.

The fire was taken as an ultra-fast growth t-square fire with peak heat release rates of 0.5 MW or 1.0 MW. The heat loss fraction L_c due to radiation and conduction to the compartment was assumed to be 0.3, and the radiation loss fraction of the total heat release rate λ_r was assumed to be 0.35.

The initial velocity and spray angle at the nozzle were 20 ms^{-1} and 35^o respectively. The volume mean diameter (VMD) of the water spray was selected as 600 μm and 300 μm. For the spray of VMD 600 μm, the diameters of the four classes were 965, 697, 400 and 132 μm respectively. For the spray of VMD 300 μm, the four typical classes were 480, 350, 200 and 65 μm respectively. The water flow rate varied from 0.1 ls^{-1} to 1.0 ls^{-1}. The water spray was activated at 20 s after the ignition of the fire, and the total calculating time is 300 s.

5. Results and Discussions

The model developed earlier was modified [10,18] to study the spray characteristics such as droplet velocity, diameter, spray envelope radius, and gas flow rate while traveling through the stable hot smoke layer. As the smoke layer itself changes with time, these spray characteristics would be affected. Heat and mass transfer among the two layers and spray envelope would then be affected significantly by the gas flow rate inside the spray envelope.

Transient smoke interface heights for a water application rate of 0.5 ls^{-1} were measured [18]. Before discharging water spray, the smoke interface height fell down to 1.3 m for a 0.5 MW fire. Upon discharging water spray, the smoke layer interface height up to 1.7 m for VMD of 600 μm. Gas flow entrained rate increased by the water spray. This entrainment effect due to water spray is similar to a vent in removing heat and mass. The smoke flow rate through the opening decreased when water spray was applied.

In contrast to a vent, the lower air layer would be affected by the water spray significantly. The hot gas including water vapor would be brought to the lower layer by the spray-induced flow.

The water application rate would affect the mass, momentum and heat transfer between the water droplets and hot gas. This would give different spray envelopes and smoke layer development.

6. Conclusions

The compartment fire environment under the action of a solid-cone water spray was studied. There might be vent effect if the water spray is relatively small and located away from the burning object. A simple small-scale experiment was performed to demonstrate the vent effect. In fact, the compartment can be divided into three quasi-steady regions, an upper smoke layer, a lower air layer and a one-dimensional spray. Characteristics of the water spray such as droplet size distribution, velocity distribution and water application rate would affect the vent effect. Suitable water spray can be used to reduce the smoke damage to adjacent space through decreasing the smoke temperature and outgoing flow rate of gases.

7. Additional Comments

The paper was published as a journal paper [23]. With the practice of publisher, preprint is allowed to upload at a website. There are further studies on this topic [24-52].

Acknowledgement

This project is supported by The Croucher Foundation with title “Active Fire Protection in Supertall Buildings” and account number 5-ZH46.

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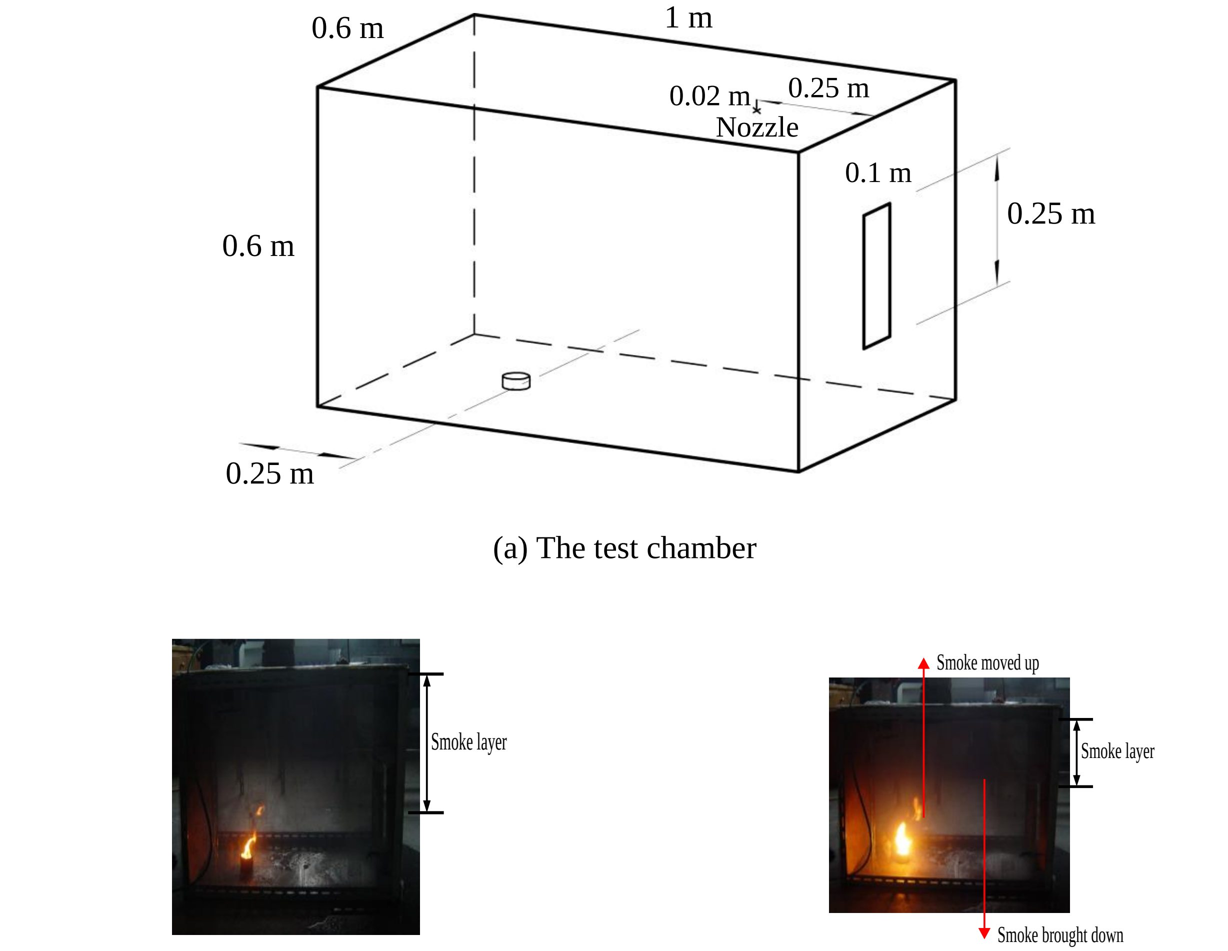

(a) The test chamber

(b) Before discharging solid-cone water spray (c) After discharging solid-cone water spray

Figure 1: Possible venting effect

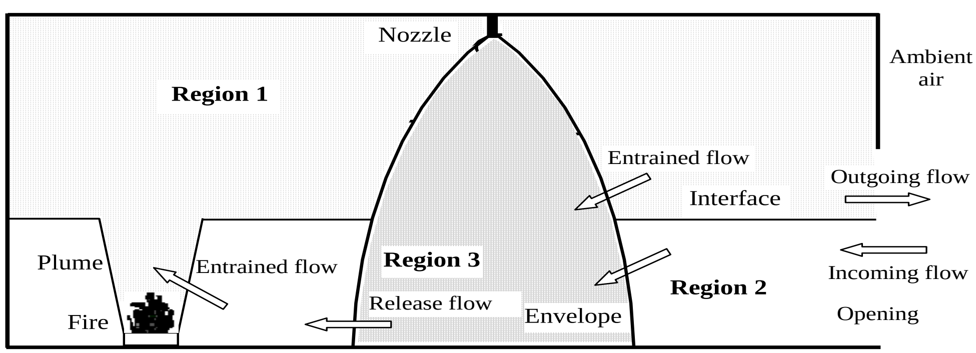

Figure 2: The identified scenario