Numerical Study on Fire characteristics in Force-Ventilated Compartment with different air inlet locations

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Abstract. The effects of air inlet locations on fire characteristics in force-ventilated compartment were investigated by computational fluid dynamics (CFD) simulations. The flame behaviour, the oxygen concentration above fire, the distribution of soot concentration and velocity of smoke in the closed compartment were discussed. The results show that the flame behaviour was mainly affected by the inflow air flow, and the flame inclined to the opened inlet in one-inlet scenario. The flame was found inclined to the exhaust vent in two-inlet scenarios. The difference between the soot concentrations in upper and lower space of the compartment was smaller in one-inlet scenarios compared with that in two-inlet scenarios, and the soot concentration was more uniform in the scenarios with higher air inlet elevation. The velocity of smoke on the side of inlet was larger than the other side in one-inlet scenario, which might cause stronger entrainment on the side with air inlet. In the two-inlet scenarios, the velocities of smoke on the sides of two air inlets were almost the same.

1. Introduction

For the compartments in ships, nuclear power stations and underground spaces, it is hard to acquire the natural ventilation, so the forced ventilation is usually used. The forced ventilation may still operate when the fire happens in these compartments. The fire characteristics in force-ventilated compartment are different from those in closed compartment and compartment with natural ventilation, and it deserves attentions.

There were already many studies focused on the forced ventilation enclosure fires [1-3]. Twenty seven experiments were conducted by Alvares et al. [4], and the results showed that the complete combustion could be achieved in forced ventilation enclosure fires with the oxygen concentration more than two times of the concentration with the stoichiometric ratio. Foote et al. [5] established a method for predicting the average temperature rise in forced ventilation enclosure fires, and the critical ventilation rate for avoiding flashover was also provided. Coutin et al [6] explored the electrical cabinet fires in closed and mechanically ventilated compartments, and established a method for achieving the heat release rate of fires with complex combustibles. To sum up, the effects of inlet locations on fire characteristics in force-ventilated compartment has not received sufficient attentions.
We have investigated the effects of air inlet configurations on forced ventilation enclosure fires experimentally [7]. The mass loss rate, the gas temperature rise and the oxygen concentrations in compartment have been presented. In this study, more parameters were provided to clarify this kind of enclosure fire by numerical simulation. The flame behaviours in different viewpoints, the oxygen concentration above fire source, the distribution of soot concentration and the vector velocity field of smoke in force-ventilated compartment with different air inlet locations were discussed in this study.

2. Numerical Simulations and Scenarios
The fire characteristics in forced ventilation compartment fires were investigated by using computational fluid dynamics (CFD) modelling. The software used in this study was Fire Dynamics Simulator (FDS), which was established by the National Institute of Standards and Technology. The FDS had been widely used for exploring many problems on fire science, and the results have been showed acceptable [8-10].

The dimensions of the closed compartment were 3.6 m (L) ×3.4 m (W) ×2.05 m (H). There were two air inlets and one exhaust vent in the compartment. The elevations of air inlet were changed in the simulations, and only one air inlet opened in the one-inlet scenarios. In all simulations, the elevation of the exhaust vent was 2.0m above the floor. The ventilation rates for both the air inlet system and the smoke exhaust system were 1500m$^3$/h, which is about 60 air change rates per hour. The ventilation rates of supply and exhaust ventilation systems were balanced in the simulation.

The fire source was located in the center of the force-ventilated compartment. The height of the fire source was 0.25 m above floor, and the area of fire source was 0.04 m$^2$. The HRR of fire was about 130 kW in all simulations. There were two viewpoints in the simulation model used for investigating the fire characteristic in the closed compartment. The viewpoint 1 was set from the exhaust vent to the air inlets, and the viewpoint 2 was set from one inlet to the other one.

There were four simulations conducted in this study. The scenario 1 and 3 was one-inlet scenario with the air inlet elevations of 0.25 m and 1.65 m, respectively. In scenario 2 and 4, both the two inlets were opened, and the above two air inlet elevations were considered.

3. Results and Discussions
3.1. Flame behaviours
The flame behaviors of the forced ventilation enclosure fires with different inlet locations were investigated first. The flame behaviors from viewpoint 1 and 2 in force-ventilated compartment with the inlet elevation of 0.25 m are shown in Figure 1 to Figure 4. In one-inlet scenario, the left inlet was opened as shown in Figure 1 and 2. From Figure 1, the flame inclined to the opened air inlet from viewpoint 1 in the experiments with one air inlet, especially at the middle and late stages of fire. It might due to the effect of inlet airflow on entrainment of the fire plume. The incline of flame was also found in scenario 3, in which there was also one air inlet opened and the air inlet was located at 1.65 m. In the one-inlet scenarios, the entrainment of fire plume on the side of air inlet was stronger than that on the other side, which might cause flame inclining to the air inlet. This hypothesis is also supported by the vector velocity field in the force-ventilated compartment, which discussed in below. The same phenomenon was also found in the previous experimental study [7]. In the scenarios with two opened air inlets, the incline of flame to air inlet was not observed, as shown in Figure 3. From viewpoint 1, the flame was almost in the middle of the two inlets during the whole simulation.

![Figure 1. Flame behaviours in scenario 1 from the View Point 1](image-url)
Through the numerical simulation, it found that not only the air inlet, but also the exhaust vent might affect the flame behavior. The effects of exhaust flow on flame behavior were analyzed through the images from viewpoint 2. The flame behavior in scenario 1 was shown in Figure 3. It found that the effects of exhaust flow on flame behavior were not significant in the one air inlet scenario with the inlet elevation of 0.25 m. In scenario 1, the flame almost kept straightly from viewpoint 2 during the whole simulation duration. In scenario 2, in which both the two air inlets opened, the flame inclined to the exhaust vent obviously from the viewpoint 2, as shown in Figure 4. The incline of flame to the exhaust vent was due to the influences of the two air inlets and the exhaust vent on the entrainment of fire plume. Since the two opened air inlets were located at different sides of the fire source, the effects of the two air inlets might be counteracted, and the effect of exhaust vent was dominated. The inclining of flame to the exhaust vent was also appeared in the two-inlet scenario with the inlet elevation of 1.65 m, as shown in Figure 5.

3.2. Gas Concentrations
The oxygen concentrations above the fire source were measured in the numerical simulation. Due to the effects of combustion and ventilation, the oxygen concentration curves showed significant shock in all scenarios. The oxygen concentrations above the fire source in scenario 1 and scenario 2 are shown in Figure 5 to investigate the effects of air inlet number on oxygen concentration in forced ventilation enclosure fires. The oxygen concentration of two-inlet scenario was lower than that of the one-inlet scenario basically. The effects of air inlet elevation on oxygen concentration were illustrated in Figure 6 with the scenario 2 and scenario 4. It observed that the oxygen concentration of scenario 4 was slightly higher than that of scenario 2.
Figure 5. Oxygen concentrations above fire base: (a) effect of inlet number; (b) effect of inlet height

The distributions of soot concentrations in force-ventilated compartment at 150 s in scenarios 1-4 are shown in Figure 6. The soot concentration in the compartment was affected by the generation of soot due to combustion and the elimination of soot due to ventilation. Since the heat release rate of fire and the ventilation rate were accordant in all simulations, the maximum soot concentrations in the compartment were almost the same in different scenarios. The distributions of soot concentration were significant different in the scenarios with different air inlet numbers and elevations. Compared with Figure 6 (a) and (b), the difference between the soot concentrations in upper and lower spaces of the compartment was more obviously in one-inlet scenario than that in two-inlet scenario, and the similar result was found in scenario 3 and 4 as shown in Figure 6 (c) and (d). From Figure 8, it also observed that the soot concentration in the compartment was more homogeneous in the scenario with the inlet elevation of 1.65 m than that in the scenario with the inlet elevation of 0.25 m.

Figure 6. Soot concentration distribution in different scenarios at 150 s

3.3. Vector Velocity of Smoke
In the above discussion, the air inlet location showed obvious influence on the fire characteristic of the forced ventilation enclosure fires, which might relate to the entrainment of fire plume affected by the air flow. For further investigate the effect of air flow on the entrainment of fire plume, the vector velocity of smoke in the force-ventilated compartment are illustrated in Figure 7 and 8. From Figure 7,
the velocities of smoke in one-inlet scenarios were larger than those in two-inlet scenarios. This was because that the inflow air velocity in one-inlet scenario was twice larger than that in the two-inlet scenario. In scenario 1 and scenario 3, the velocity of smoke on the side of opened air inlet was obvious larger than the other side. It indicates that the entrainment of fire plume is stronger on the opened air inlet side than the other side in one-inlet scenarios, which may be the cause of inclining flame in these scenarios. In two-inlet scenarios, the velocities of smoke in the two sides of flame were almost the same from viewpoint 1. It means that the entrainments on the two sides were balanced, so the flame was stayed in the middle of the two inlets from viewpoint 1.

To sum up, some conclusions derived in the previous experimental research [7] were confirmed by numerical simulation, and the natural of the forced ventilation enclosure fire was further revealed through the simulations to some extent in the present study.
4. Conclusion

The fire characteristics in force-ventilated compartment with different air inlet locations were investigated by the CFD simulation. The fire behaviour, the oxygen concentration above the fire source, the distribution of soot concentration and vector velocity of smoke in the force-ventilated compartment were discussed. The results showed that both the inlet and exhaust vents affected the fire behaviour in the force-ventilated compartment. In the one-inlet scenarios, the flame inclined to the opened inlet and the effect of exhaust vent was not obvious. In the two-inlet scenarios, the effect of exhaust vent on flame behaviour was dominant, and the flames inclined to exhaust vent. The soot concentration distributions in one-inlet scenarios were more uniform than those in two-inlet scenarios, and difference between the soot concentrations in upper and lower spaces of compartment was smaller in the simulation with higher air inlet. The velocity of smoke in the side of opened air inlet was larger than that in the other side in one-inlet scenarios, and this might be the reason of the flame inclined to the air inlet under this condition. The velocities of smoke on the two side of flame from viewpoint 1 in the two-inlet scenarios were almost the same.

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