Experimental Study on Cross-ventilation Compartment Fire in the Wind Environment

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ABSTRACT

When fire occurs in the rooms of high-rise buildings, the strong ambient wind will play an important role in fire spread and smoke movement behavior. However, wind effect on compartment fire in cross ventilation condition has not been fully studied so far. In the present study, an effort has been made to study cross-ventilation compartment fire in the wind environment through experimental investigations. The experimental fire was generated by 250ml (10cm×10cm tray burner) or 500ml (20cm×20cm tray burner) n-heptane on the floor of a cube enclosure with two opposite vents on the walls. The inside and outside gas temperature profiles at different vertical and horizontal locations were recorded by two thermocouple matrixes. The ambient wind velocity was set to zero, 1.5m/s and 3m/s. It is observed that the ambient wind has two contradictory effects on the compartment fire: promoting fire severity by more oxygen supplying and cooling the fire by heat removing and combustible gases diluting. The spilled-out flame/plume extends horizontally farther with the increase of wind speed. It is found that the compartment fire with 500ml fuel reaches post-flashover stage while that with 250ml doesn't. The wind effect is obviously observed in larger fires while not significant in smaller fires.

KEYWORDS: compartment fire; wind; cross ventilation; external flame

NOMENCLATURE LISTING

A	opening area (m^2)	**Greek**	
C_p	wind pressure coefficient	ρ	gas density
g	gravity acceleration ($9.8 m/s^2$)	Λ	wind pressure
H	opening height (m)	**subscripts**	
H_N	height of the neutral plane (m)	$_W$	windward
P_i	pressure inside the compartment	$_L$	leeward
P_o	ambient pressure	$_{cr}$	critical
T	temperature	$_a$	ambient
V	ambient wind speed (m/s)	$_g$	hot gas

INTRODUCTION

Many skyscrapers have been constructed everywhere in the Far East. Fire safety provisions for these high-rise buildings have been a concern as the number of fires due to accidents, arson, etc., has been increasing in recent years. As for the fire scenarios in these buildings, the strong ambient wind plays an important role because wind velocity increases from zero at the ground to higher values at some elevations. Strong wind may influence fire spread and smoke movement behavior in the buildings remarkably, for example, mechanical ventilation routines might not extract smoke efficiently under the action of wind. The research on compartment fire phenomena in high-rise buildings under wind effect is an essential step to provide a guideline for fire safety design of these buildings.

Generally, an uncontrolled compartment fire, with or without ambient wind action, usually follows the same typical sequence. After ignition the fire goes through a growth phase followed by a transition known as flashover to a fully developed fire in the burning phase which may continue for some time, and lastly a decay phase occurs as the fire burns itself out [1]. Numerous studies on the experimental compartment fires or theoretical modeling are available in literature since the pioneering work of Kawagoe [2]. Most of these researches were conducted for the compartment with single ventilation opening. In this configuration, outside air will be drawn into and hot gases/smoke will escape from the compartment through the same opening, driven by buoyancy forces. The air inflow rate of fully developed compartment fire has been

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shown to be weakly dependent on the room temperature but strongly dependent on the geometry of the opening, which is characterized by the ventilation factor, $A\sqrt{H}$, with A (m^2) being the opening area and H (m) the opening height [3]. For compartment fires with two or more openings, some experimental studies are available for the enclosure with one wall vent and one roof vent [4-6], however, very few studies have been reported on the effect of two or more openings located on the walls. A compartment with openings on two opposite walls may have cross ventilation, especially if there is a wind blowing, producing increase of burning rate [7]. Recently, Kumar et al. [8] reported the experimental study on the effect of two same-size openings located on opposite walls i.e., in cross-ventilation condition, on the development of fire in a compartment. Their study observed that the temperatures in cross ventilation condition are higher than those in single ventilation condition for larger fire size. Later, they proposed a simple mathematical zone model to predict the experimental temperature profiles [9]. Their work seems to be the first one studying the compartment fire with two opposite vents, however, the wind effect is not considered. Some discussions of wind effect on the motion of buoyant smoke motion and control in buildings can be found in the article of Porch et al. [10]. The analyzed fire compartment in their work is an enclosure with dual openings on the opposite walls—the windward one at lower elevation near to floor and the leeward one at upper elevation near to ceiling. The opening heights are negligible so that the pressure difference distributions along the openings can be neglected and the flow is undoubtedly unidirectional. This configuration is suitable for theoretical analysis of the smoke movement under wind effect, however, it seems simple in real fire scenario because the buoyancy pressure difference usually varies along the door-like or window-like openings. It appears that the compartment fires with two opposite openings under wind action need more comprehensive investigation, experimentally and theoretically.

In this paper, a series of experiments are conducted to study wind effect on fire behavior in the compartment with two opposite openings i.e., in cross-ventilation condition. The wind velocity varies and the temperature profiles recorded at different locations inside and outside of the compartment, as well as mass loss rate of the fuel, are compared.

EXPERIMENTAL FACILITY AND PROCEDURE

The experimental facility (shown in Fig. 1) was composed of one wind tunnel, one compartment and measurement apparatuses. The wind tunnel with a 1.8m(width)×1.8m(height)×6m(length) experimental section can provide a steady air flow with the velocity varying from zero to 15m/s. In the experimental section of wind tunnel, an anemometer (Kanomax-KA12) with multi-sensors was placed to measure the wind speeds at the location numbered 3049-3051. Another sensor numbered 3052 was used to measure the wind speed in front of the fire compartment which was placed at the exit of the wind tunnel with the same floor level. In the windy experiments, the ambient wind velocity was calibrated by these sensors to be 1.5m/s or 3m/s.

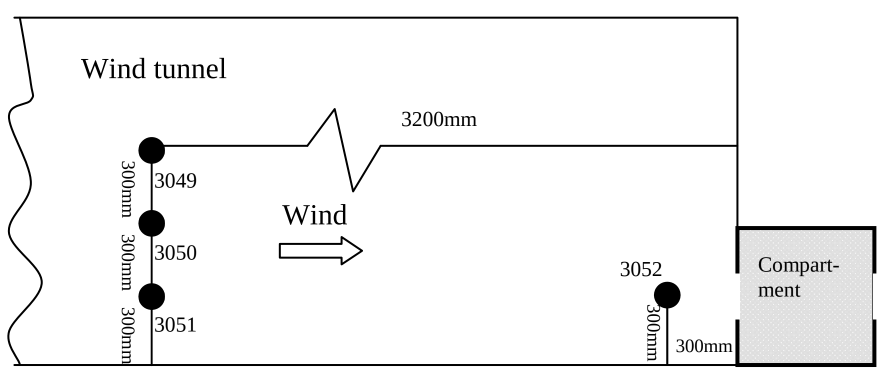


Fig. 1. Experimental layout with the measurement positions of wind velocity

Top: schematic layout; Bottom: full layout (left) and compartment layout (right)

The experimental compartment was a cube with inner size of 60cm×60cm×60cm. The ceiling and the floor were constructed by a two-layer structure. The inner layer was fire-resistant board (8mm thickness) to prevent heat loss and the outer was steel plate (2mm thickness) to maintain the structure stabilization. There were three layers in the sidewalls except the right one (see Fig.1 & 4). The inner layer was combustible fir board (25mm thickness), middle layer fire-resistant board (32mm thickness) and outer layer steel plate (2mm thickness). Two square windows (20cm×20cm) were opened in the center of the front and rear walls, respectively. The right sidewall was a fire-resistant glass for observation.

A tray burner (10cm×10cm, 4cm thickness) was placed on one steel platform ((16cm×16cm), supported by four posts. These posts penetrated the floor through four holes so that the outside electric balance can monitor the fuel mass variation. The platform was placed in three positions: the floor center, the upwind corner or the downwind corner. In the upwind case shown in Fig.1, there was a 2cm gap between the sidewalls and the platform, and the tray was placed at the platform corner nearest to the sidewalls. However, the tray was placed in the platform center if the platform was at the floor center. In some experiments, the tray was filled with 250ml n-heptane to generate fires. In other cases, a larger tray (20cm×20cm) was used to contain 500ml fuel.

Many thermocouples were planted inside and outside of the compartment to measure the temperature profiles at different locations. The 1mm-diameter inside thermocouples and 2mm-diameter outside thermocouples were placed and numbered as shown in Fig. 1-3. For discrimination, '10' is added as a prefix to the inside thermocouple number and '30' to the outside thermocouple number in this paper. For example, No 7 inside thermocouple is denoted as '1007' while No 7 outside thermocouple as '3007' in the following.

In each experiment, the wind velocity was firstly calibrated. After filling the fuel, the upwind window was blocked with a board and the torch was put in through the downwind window to ignite the fuel. Then the torch and the upwind blockage board were retreated sequentially. Besides the temperature and mass measurements, the fire was also recorded by several cameras from the side view and front view. The experimental details are presented in Table 1. For comparison, some free-burning fire experiments were conducted in open environment, still or windy.

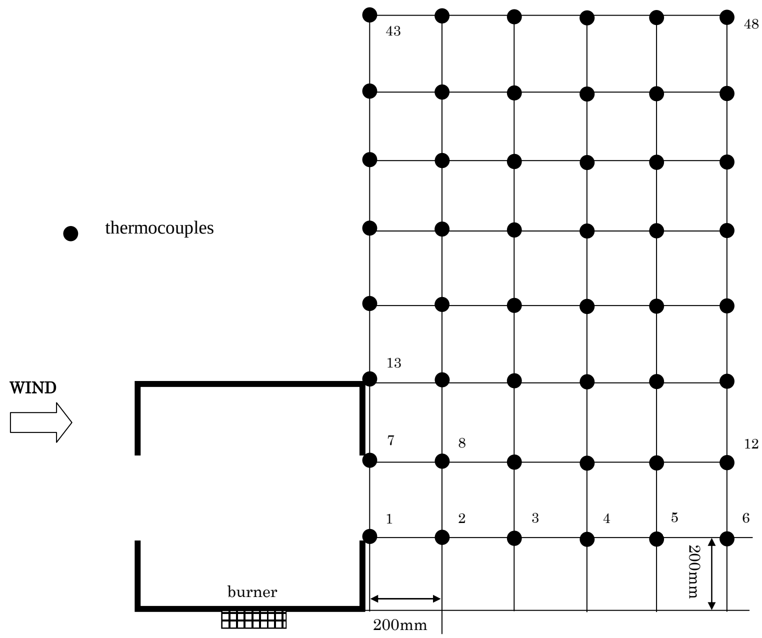


Fig. 2. The arrangement of outside thermocouples (dimension in mm)

Table 1. Experimental details

Cases	Ambient wind velocity (m/s)	Tray position	Fuel volume (ml)	Ambient temperature (°C)
Case a	0	center	250	11
Case b	1.5	center	250	11
Case c	3	center	250	10
Case A	0	center	500	11
Case B	1.5	center	500	11
Case C	3	center	500	11
FR# a	0	center	250	11
FR b	1.5	center	250	11
FR c	3	center	250	11
FR A	0	center	500	11
FR B	1.5	center	500	11
FR C	3	center	500	11
Case 1	0	downwind*	250	10
Case 2	1.5	upwind	250	12
Case 3	1.5	downwind	250	6
Case 4	3	upwind	250	9
Case 5	3	downwind	250	10

* For symmetry, the upwind case is identical to the downwind one
\# Free burning fire experiments

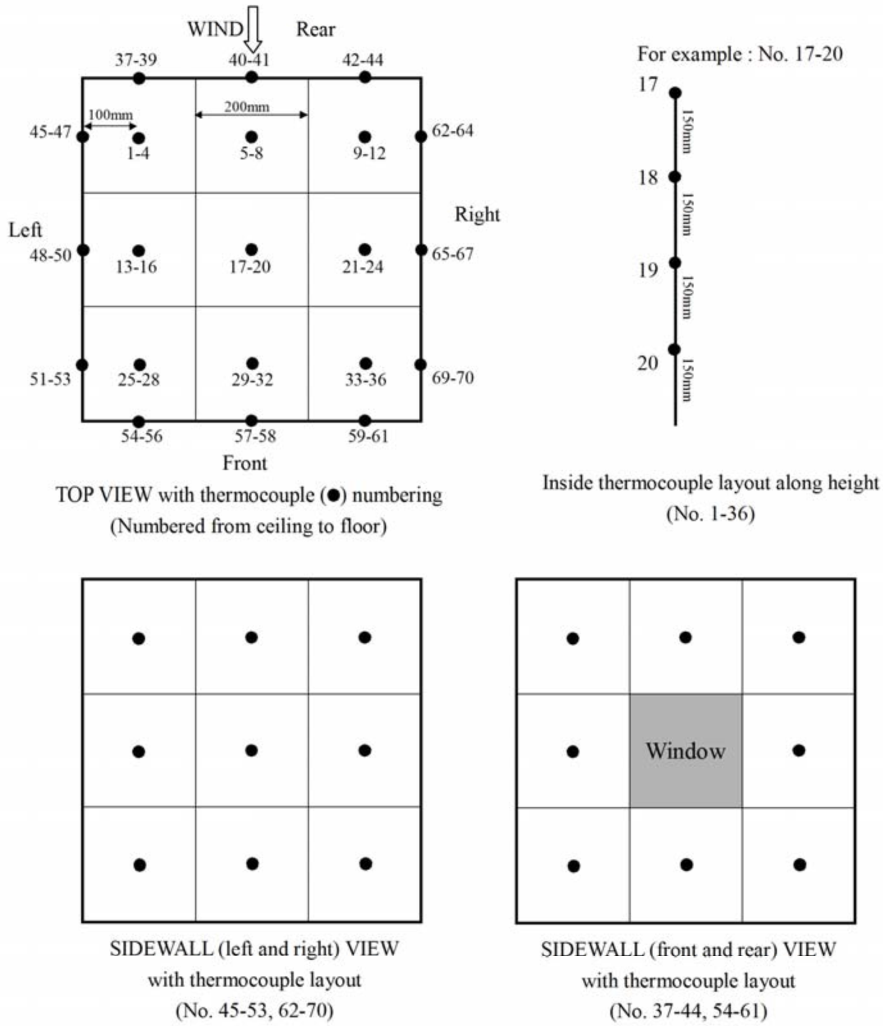


Fig. 3. The arrangement of inside thermocouples (dimension in mm)

RESULTS AND DISCUSSIONS

Typical compartment fire behavior

Experimental observations under different conditions can give us a direct understanding of cross-ventilation compartment fire behavior. In Cases a-c or A-C, the ambient wind velocity was changed from zero to 3m/s, to investigate the wind effect on fire behavior. Compared with Cases a-c with 250ml fuel, Cases A-C held double fuel quantity (500ml) to represent higher fire intensity. Fig. 4 shows some typical instantaneous pictures of fully-developed fires (here denoting the fire being most severe in each experiment) for Cases a-c & A-C. As indicated, flashover (observed as all combustible materials in the compartment ignited instantaneously) occurred in Cases A-C but did not in Cases a-c in the fully-developed fire stage. Another evidence is that after the fire, the fir boards mounted on the sidewalls were charred deeply in Cases A-C while were kept nearly un-charred in Cases a-c. This difference is obviously caused by different fire intensities.

4-a.Case a, 7'01" after ignition

4-b. Case b, 4'09" after ignition

4-c. Case c, 5'30" after ignition

4-A. Case A, 2'17" after ignition

4-B. Case B, 2'21" after ignition

4-C. Case C, 2'18" after ignition

Fig. 4. Typical fully-developed fire scenarios under different fuel and wind conditions

In still (without wind) cases (a & A), the fires appeared symmetrical. In Fig. 4-a, it is obviously observed that there are three zones in the compartment: flame zone, upper smoke zone and lower air zone. The traditional zone modeling may be valid in this case. In Fig. 4-A, the compartment was nearly full of flame and one zone modeling may be more reasonable. The recorded inside temperatures at different locations can provide more information about all fire stages. As an example, the vertical inside temperature distribution near the window is shown in Fig. 5. In fire developing stage of both cases, the smoke zone covered thermocouples 1005-1007, leaving 1008 in air zone. In fire decaying stage, temperature decreased gradually. The lower the thermocouple position, the faster the decrease of temperature. In fire fully-developed stage, the temperatures in Case A at different locations were nearly same (about 600^{o}C) due to flashover, while in Case a the temperature of 1007 was lower and that of 1008 was much lower. As we know, there is one neutral plane (NP) in Case a, whose height above the windowsill can be estimated as $H_N = H/[1+(T_g/T_a)^{1/3}] \approx 0.4H$ [11], a little lower (2cm) than the window center level. As indicated in Fig. 3, 1007 locates at the window center level and 1008 at the windowsill level. Therefore 1008 records the cold air temperature and 1007 records lower smoke temperature (because of more heat loss by radiation) near the interface in fire fully-developed stage.

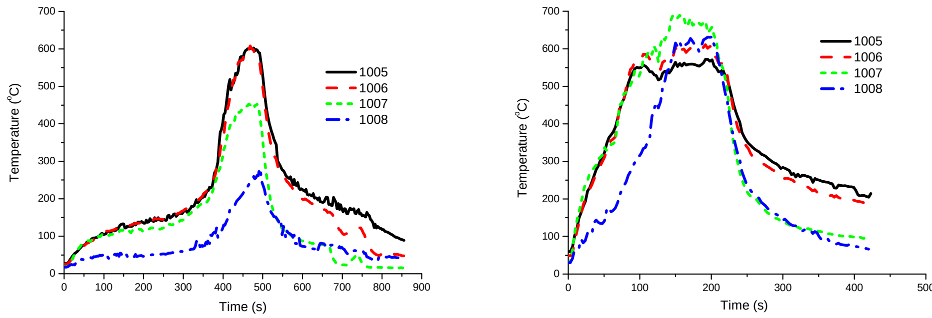


Fig. 5. Vertical inside temperature distribution along one thermocouple tree near the window.
Left: case a; Right: case A

The approaching wind has two contradictory effects on the compartment fire. One is to provide more oxygen for fuel burning which eventually enhances the fire temperature. The other is to dilute or cool down the hot gases so that fire becomes weaker and the temperature decreases. From Fig. 4-b, c, B, C, the flames were leaned to leeward by wind and ejected from the window. The spilled-out flame extended horizontally farther with the increase of wind speed, which reflected that the main air stream penetrated the compartment. The wind also produced some vortices/backflow areas at eight compartment corners, which caused the fire vibrates and puffs. This phenomenon was more obviously observed in the upwind and downwind fires shown in Fig. 6. In the upwind case, the vortices drove the fire to the rear wall and ignited it, and the flame near the window was blown to leeward by the main wind flow. In the downwind case, the vortices impelled the fire to the sidewall and ignited the fir board at the wall center firstly.

The fuel (n-heptane) burning time reflects some characteristics of the wind effect as shown in Fig. 7. As expected, the burning time decreased with wind speed rise in the free burning cases. However, in compartment fire cases with same fuel amount, Cases b/B had the shortest burning time, which implies that there exists compromise between the two opposite wind effects. The temporal variations of inside temperatures in the flowing will give more evidences.

6-1. Case 4, 5'11" after ignition

6-2. Case 5, 3'18" after ignition

Fig. 6. Typical developing fire scenarios when fuel is located at upwind or downwind corner

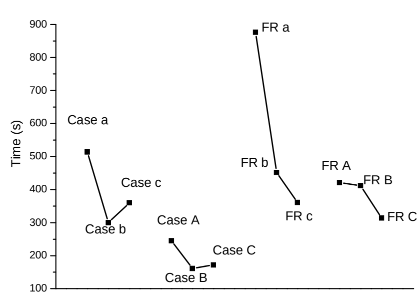


Fig. 7. The fuel (n-heptane) burning times

Temperatures inside the compartment

The inside thermocouple matrix recorded the temporal variations of inside gas temperatures throughout the fire, which can be utilized to compare with CFD modeling. As an example, Fig. 8 shows the temperatures at the measurement points 1007 and 1015, which were at the same height level of window center. 1007 at the upwind side reflects the cooling effect of the ambient wind to the fire, and 1015 at the inner side of fire (see Fig. 3) represents the room gas temperature.

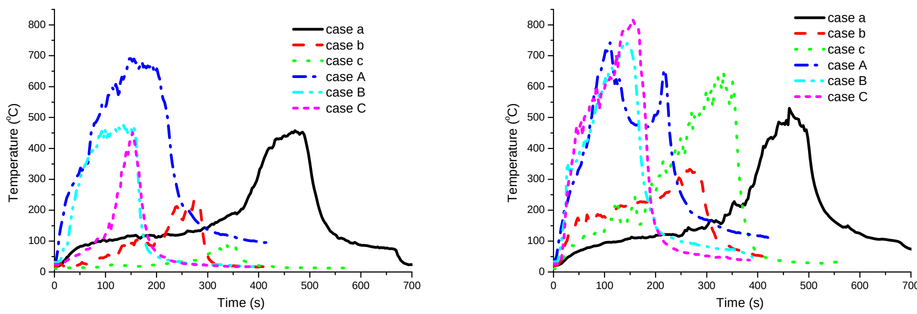


Fig. 8. The temporal variations of inside temperatures. a(Left): 1007; b(Right): 1015

By comparison of the temperatures in Cases a-b-c or A-B-C (Fig. 8-a), it can be found that the wind cooled down the 1007 temperatures. By the sequence of Cases a-b-c (wind speed increases), the peak value of temperature and the temperature value in the fire developing period decreased. The same tendency is also observed in Cases A-B-C.

In Fig. 8-b, Cases A-C showed nearly same temperatures and same rising time in the fire developing period, while Case A held a longer time at high temperatures (post-flashover period) because of lower oxygen supply than the other two windy cases. As stated before, no flashover occurred for cases with small fuel amount, in which Case c seemed special. In the fire developing period, Case c showed lower temperature than Case b because stronger wind cooled down the fire. However, when the fire was very strong and more air was needed for burning, Case c showed much higher temperatures than Case b, which implies that the wind effect of supplying oxygen became to be dominant.

External flame features

The flames ejected out of the compartment through the downwind window in all cases except Case a. The fire video, together with the temperatures recorded by the outside thermocouples, can provide information about external fire/plume structure. Since external flame is not steady in Case b & c (sometimes it appears or disappears), here the stable external flames in Case A, B & C are discussed. The side view of the flames is shown in Fig. 4. In still Case A, as well known, the fresh air was drawn into the compartment through the lower part of window with a height of H_N (about 8cm). The external flame spilled out from the upper part of window and was highly steady. In windy cases, the series of front-view pictures of external flame at the interval of 20''' (Fig. 9) show that the external flames were puffing within one second. Detail investigation reveals that the flame occupied the whole window opening in Case C while only upper part of the opening in Case B. There was a small gap above windowsill that the flame did not occupy (Fig. 4-B) in Case B. The thermocouples at the window-eave (3007) and windowsill (3001) may give some more clues about the external flame thickness. As shown in Fig. 10, thermocouple 3007 was undoubtedly affected by fire and recorded higher temperatures in all Cases A-C, and thermocouple 3001 recorded higher temperatures in Case C while lower values in Case A and B. It can be concluded that 3001 of Case B was not directly touched by fire as that of Case A. Since the flame was more close to windowsill in Case B than in Case A, 3001 of Case B recorded a little higher temperature values by receiving more fire radiation.

9-1. Case B, 2'15" after ignition, every 20''' one picture

9-2. Case C, 2'17" after ignition, every 20''' one picture

Fig. 9. The front view of the external flames in Case B and C

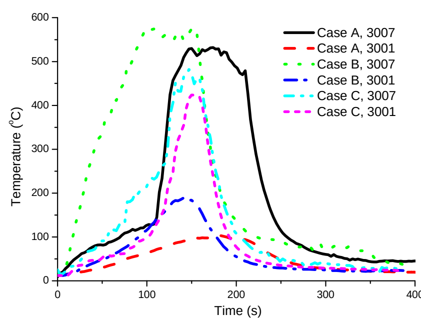


Fig. 10. The temperatures at 3007 (window-eave) and 3001 (windowsill) for Case A-C

Since the external flame occupied full window only in Case C, there is a question about the critical condition under which the flame just begins to occupy full opening, The following will estimate the criterion.

Denoting the ambient pressure as P_o and the inside gas pressure at windowsill level as P_i. The wind pressure is $\Lambda = C_p \rho_a V^2/2$. Here C_p is the wind pressure coefficient $C_{p,W}$ (windward) or $C_{p,L}$ (leeward), ρ_a is the ambient air density and V the ambient wind velocity. As stated before, the compartment is full of hot gases and the inside temperature is uniform in post-flashover fire phase (Cases A-C). Therefore the neutral plane (NP) height H_N can be determined as:

$$P_o + \Lambda - P_i = \rho_a g H_N - \rho_g g H_N, \quad H_N = \frac{\Lambda + P_o - P_i}{(\rho_a - \rho_g) g} \tag{1}$$

Here ρ_g is the hot gas density inside the compartment.

Considering the compartment fire scenario like Fig. 4-C, the inside flame (hot gases) spilled out through the whole leeward opening and didn't eject from the windward window, which indicates the NP heights for the two openings satisfy $H_{N,W} > H$ (windward) & $H_{N,L} < 0$ leeward), i.e.,

$$\frac{\Lambda_W + P_o - P_i}{(\rho_a - \rho_g)g} > H \quad \& \quad \frac{\Lambda_L + P_o - P_i}{(\rho_a - \rho_g)g} < 0 \tag{2}$$

This expression can be simplified to

$$\frac{1}{2}\rho_a C_{p,W} V^2 - \rho_a (1 - \frac{T_a}{T_g}) gH - \frac{1}{2}\rho_a C_{p,L} V^2 > 0 \tag{3}$$

$$V > V_{cr} = \sqrt{2(1 - \frac{T_a}{T_g}) gH / (C_{p,W} - C_{p,L})} \tag{4}$$

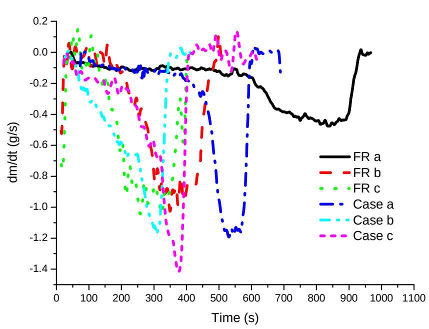
The criterion is found to be that the critical ambient wind velocity is $V_{cr} = \sqrt{2(1 - T_a / T_g) gH / (C_{p,W} - C_{p,L})}$. The wind pressure coefficients $C_{p,W}$ (windward) & $C_{p,L}$ (leeward) can be estimated as 0.8 & 0.2 respectively [12]. The inside hot gas temperature T_g is about 700^{o}C (see Fig. 8-b) and ambient temperature T_a is 11^{o}C (see Tab. 1). The opening height H is 0.2m. Thus $V_{cr} = 1.67 m/s$. It is obvious that wind speed of Case C (3m/s) is above the critical value and that of Case B (1.5m/s) is a little lower than it, which could explain the difference of external flame thickness in these two cases.

Mass loss rate of fuel

The mass loss of the n-heptane fuel for cases a-c & A-C compared with free burning cases is shown in Fig. 11. The time axis began when the balance was started to work and ignition took place some seconds later. Though the ignition time was different (within 20 seconds) in different cases, the time scale is useful in comparing the mass loss behavior. The accurate fire duration time is determined from video and shown in Fig.7.

Figure 11 indicates that the mass loss rate in the compartment fires is generally higher than that in free burning fires, especially in large fires. In Fig. 11-a, the peak values of mass loss rate in windy cases are comparable because the compartment fire does not transit to flashover fire and the heat flux from the increasing air and wall temperature in the compartment is not significant. However, in Fig. 11-a the peak values of Case B & C are much higher than those of free burning cases, which is due to the fact that the fuel receives much heat flux by the post-flashover compartment fire.

The ambient wind also increases the mass loss rate of fuel. Higher peak value of mass loss rate is shown in the case with faster approaching wind.



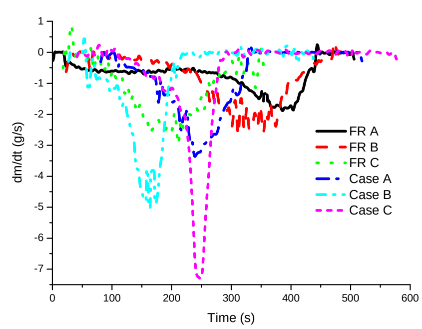


Fig. 11. Fuel mass loss rate. a (Left): 250ml fuel; b (Right): 500ml fuel

CONCLUSION

In this study, a series of experiments were conducted to investigate wind effect on compartment fire in cross ventilation condition. Totally 11 compartment fire experiments were carried out by varying the wind speed (0, 1.5m/s or 3m/s), the fuel amount (250ml and 500ml) and the fire location (center, upwind and downwind), together with 6 free burning experiments. The inside and outside gas temperature profiles at different vertical and horizontal locations were measured and the fire video was recorded. The experimental results are summarized as follows:

1. Compartment fire behavior differs with different fuel amounts. The cases with higher amount of fuel may reach post-flashover phase while those with lower amount of fuel do not.
2. The wind creates main flow (centerline) and backflow (corner) areas in the compartment, which influences the fire behavior. In center fire cases, the fire is blown to downward and ejected from the compartment. The spilled-out flame extends horizontally farther with the increase of wind speed. In the upwind and downwind cases, fire is impelled to upward by backflow.
3. Generally the approaching wind makes the fire severe. The wind has two contradictory effects on the compartment fire: promoting fire severity by more oxygen supplying and cooling the fire by heat removing and combustible gases diluting.
4. The external flame puffs in the windy cases. In large fire case with high wind speed (3m/s), the flame occupies the whole opening, while only upper part of the window in the case with lower wind speed (1.5m/s). An estimation on the critical wind velocity proves the experimental results.

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