A NUMERICAL STUDY OF BALCONY SPILL PLUMES

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ABSTRACT

This paper presents a study on the investigation of air entrainment in balcony spill plumes in the rotating region using CFD modeling and full-scale experiments. This study examines limiting conditions of the approach flow for the free balcony spill plume. The CFD model, Fire Dynamics Simulator (FDS) was used to investigate the impact of temperature and velocity on the balcony spill plume and the effect of critical components, such as balcony length, draft curtain and fascia, on the flow of the plume. The results of this study show that the trajectory of the flow is governed by its buoyancy and jet momentum. These effects can be represented by the Richardson number (Ri), which can be calculated from the temperature and velocity of the flow. The limiting Richardson number criteria was found to be approximately 0.7, which can be used to assess whether the balcony spill plume is free-unbounded.

KEYWORDS: Balcony spill plume, CFD model

INTRODUCTION

A balcony spill plume refers to the vertical plume generated from the horizontally moving smoke layer at the edge of a balcony generated by a fire in a compartment connected to the atrium. Fig. 1 shows the typical smoke movement of a balcony spill plume originating from a room that is adjacent to an atrium. The plume from the fire initially forms the smoke layer in the upper part of the fire compartment. If there is no means to confine the smoke in the room of origin, the buoyant smoke layer moves horizontally beneath the balcony and enters the atrium area. To maintain the required minimum clear layer height in the atrium, venting of the buoyant layer of hot gas is commonly used. The mass flow rate of the exhaust depends on the clear height and the amount of air entrainment in the plume. Consequently, a key to the effective performance of the smoke management system is our ability to estimate the required amount of smoke that is generated from the balcony spill plume (M_a) shown in Fig. 1.

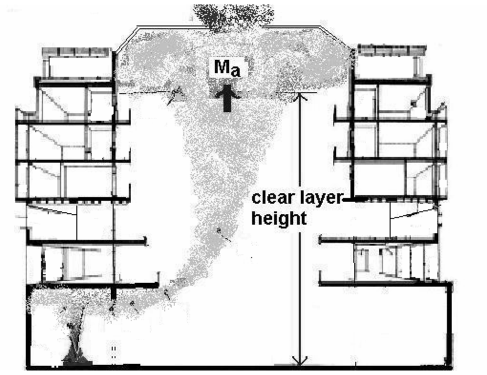


FIGURE 1. Free balcony spill plume scenario [1]

The balcony spill plume generates a significant amount of smoke, since the flow of hot gas initially mixes with air due to the initial fire plume, the room ceiling and door, the balcony and other obstructions. At the edge of the balcony, the horizontally moving smoke rotates and rises up into the atrium. The trajectory of the vertical spill plume depends to a large extent on the temperature and velocity of the initial horizontal flow. This is, in fact, an important feature of the balcony spill plume, which affects the amount of air entrainment. If the projection of the balcony is relatively short or the plume temperature is exceedingly high, the vertical spill plume rises close to the wall and tends to adhere to the wall above the balcony [2]. A number of calculation methods to estimate the mass flow rate of the balcony spill plume (M_a) have been developed considering only the case of a free balcony spill plume, which does not adhere on the wall and entrains air from all sides of the plume.

This study examines the limiting conditions of the approach flow for the free balcony spill plume and investigates the impact of temperature and velocity on the balcony spill plume and the effect of critical components, such as balcony length, draft curtain and fascia, on plume entrainment. This study is part of a project on balcony spill plumes in which full-scale experiments and CFD modeling under a variety of conditions were employed [1, 3].

METHODOLOGY

The modelling of complex, large-scale systems is often more difficult than the modelling of simple representative physical systems. To simplify the problem of the balcony spill plume and minimize the number of factors affecting the smoke flow under a balcony, the flow generated from a fire in a compartment was replaced with a layer of flow with an imposed temperature and velocity.

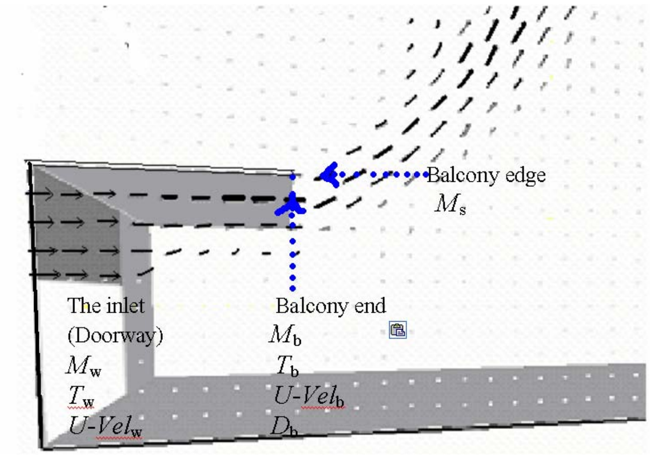


FIGURE 2. The problem of the buoyant jet in the simple modelling study

This layer of hot gas flow was horizontally injected at one end of the balcony (at the inlet), allowed to flow under the balcony, and eventually released into the large reservoir. The behaviour of the resulting buoyant jet was investigated. A depiction of the set-up of this buoyant jet system to represent a balcony spill plume is given in Fig. 2. The injected air has an initial mass flow rate M_w, temperature T_w and Velocity $U\text{-}Vel_w$. As the flow moves under the balcony, the flow characteristics change. When the horizontal flow reaches the end of the balcony and before it starts to rotate upwards, the flow characteristics are: mass flow rate M_b, temperature T_b, and velocity $U\text{-}Vel_b$. This simple model using a coarse grid size of 500 mm allowed the examination of fundamental aspects of the problem of balcony spill plumes under various conditions, with a relatively short CPU time.

Two distinct sets of modelling were undertaken.
- Temperature and velocity effects
- Parameter sensitivity test

Description of Modelling

Temperature and velocity effects

The topic of this study is to investigate the characteristics of a buoyant jet discharging into a large reservoir with a uniform stationary ambient environment, which represents an atrium. The study focuses on the flow behaviour at the rotating region at the edge of the balcony under various temperature and velocity conditions.

An inlet flow representing the horizontal flow at the end of the balcony was injected into the reservoir. The dimensions of the injected flow were 5 m (width) and 2 m (depth). For each simulation, the initial source flow was defined as a horizontal jet with an assigned uniform temperature and velocity. Table 1 summarizes the conditions of each scenario. Simulations were carried out to examine the effect of temperature and velocity on the characteristics of the balcony spill plume.

In the first four simulations, TV1 to TV4, the temperature was kept constant at 197°C, and the velocity was varied from 0.1 m/s to 3.98 m/s. In the second series, in VT1 to VT4, the velocity was kept constant at 2.65m/s and the temperature varied from 28.9°C to 285.3°C. Additional simulations, T1V3 to T3V1 were also carried out to examine the effect of various flow characteristics. The depth of the flow layer was set to be 2 m for all cases, and the width of the flow was 5 m.

TABLE 1. Series of simple simulations: temperature and velocity effects

Simulation ID	Temperature (˚C)	U-Velocity (m/s)	Ri
TV1	197	0.1	886.60
TV2	197	1.3	5.20
TV3	197	2.65	1.26
TV4	197	3.98	0.56
VT1	28.9	2.65	0.10
VT2	46.55	2.65	0.28
VT3	108.5	2.65	0.78
VT4	285.3	2.65	1.60
T1V3	176	5.0	0.33
T2V2	91	3.3	0.42
T3V1	203	0.3	100.6

Since a buoyant jet is driven by both buoyancy and momentum, the Richardson number (Ri) of each flow, a dimensionless characteristic of the flow, was calculated to determine the ratio of its buoyancy to momentum [4].

$$Ri = \frac{g(\rho_0 - \rho)D}{\rho \upsilon^2} \qquad [1]$$

where

ρ = source fluid density (kg m^{-3})

ρ_o = ambient density (kg m^{-3})

υ = injecting velocity (m s^{-1})

D = layer depth (m)

The mass flow rate (M_b) is the horizontal mass flow rate at the balcony end. The mass flow rate (M_s) is the vertical mass flow rate at the balcony edge, where a horizontally injected flow starts to rotate. The ratio, M_s/M_b represents the increase of the flow rate due to air entrainment as the flow rotates from a horizontal flow to a vertical flow. The values of M_s/M_b are compared with Ri to ascertain whether a direct correlation exists.

Parameter sensitivity test

Another set of modelling simulations was conducted to check the effect of selected parameters on the behaviour of the plume. The parameters studied were those related to a balcony, a draft curtain, and a fascia.

Representing the door flow, a layer of hot gas at the inlet was injected into the reservoir (the atrium). The properties of the injected flow at the inlet were consistent in all simulations. The layer of the inlet flow was 5 m wide and 2 m deep. The temperature (T_w) and velocity ($U\text{-}Vel_w$) of the injected flow at the door were 197°C and 2.65 m/s respectively. These values were estimated from a room fire of a 5 MW heat source and a compartment opening with 5 m width.

Table 2 summarizes the series of simulations carried out and the conditions used. To examine the parameters altering the flow characteristics of the initial inlet doorway flow, a balcony, draft curtains, and fascia were added to the initial model, 'TV0'. Two breadth of the balcony (*b*) were used, 2 m and 4.2 m. The width of the balcony was extended to the end of the computational domain. For Simulation DC, the distance between draft curtains was the width of the inlet, that is, the width of the door flow. A thermally inert boundary condition was applied to the balcony and draft curtains.

TABLE 2. Series of simple model used for sensitivity testing

ID	T_w (˚C)	$U\text{-}Vel_w$ (m s^{-1})	Fascia depth (D_f)	Balcony breadth (*b*)	Draft curtain depth (D_c)
TV0	197.0	2.65	No	No	No
B-1	197.0	2.65	No	b = 2m	No
B-2	197.0	2.65	No	b = 4.2m	No
DC	197.0	2.65	No	b = 4.2m	D_c = 3m
F	197.0	2.65	D_f = 1.6m	b = 4.2m	No

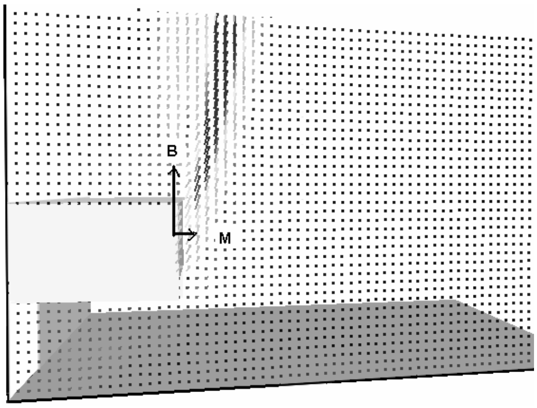
RESULTS

Temperature and velocity effects

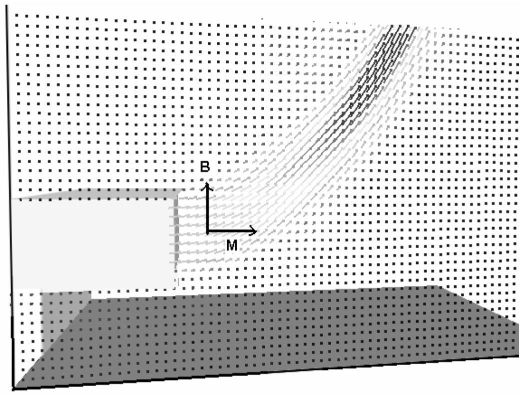
Fig. 3 shows simulated results from TV2 and T2V2. The trajectory of the flow is determined by its buoyancy (B) and jet momentum (M). The entrainment takes place due to the plume motion, and this motion can be represented by the trajectory of the buoyant plume jet. As flow rises up, the trajectory of flow motion is continuously adjusted due to dilution and loss of momentum. Eventually, the buoyant jets will be converted to fully buoyant plumes, which will have only upward momentum due to density differences.

The horizontal flow with a large Richardson number (Ri), Fig. 3 (a), once it reaches the balcony starts to rotate upwards and it quickly becomes a vertical flow. The rotating region is thus very small resulting in small entrainment. On the other hand, for flows with low Ri, as Fig. 3(b) shows the rotating region extends into the atrium as a result of the high flow momentum. The complete transition from horizontal flow to a fully vertical plume is achieved at greater height of rise and distance from the balcony edge. This results in a larger air entrainment in the rotating region.

In the rotating region, buoyancy forces and jet momentum compete, and the flow rotates up only if the density of the flow is less than that of ambient air. The air entrainment rate into the rotating flow, M_s/M_b, increases with a rise in temperature and decreases with a rise in horizontal U-velocity. In fact, the value of M_s/M_b depends on both the temperature and velocity of the initial flow. In Fig. 4, M_s/M_b is plotted as a function of Richardson number (Ri) on a log scale.



(a) TV2 : T = 197˚C. *U-Vel* = 1.3 m/s, Ri = 5.20



(b) T2V2 : T = 91˚C. *U-Vel* = 3.3 m/s, Ri = 0.42

FIGURE 3. Velocity vector slice of simulation (a) TV2 and (b) T2V2

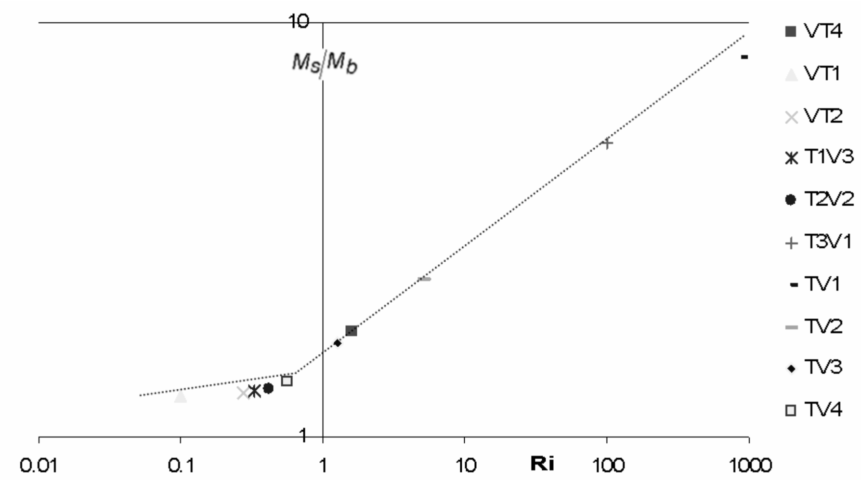


FIGURE 4. Simple model results displayed as a plot of M_s/M_b with respect to Ri

With Ri values higher than 0.7, the flow behaves more like an axisymmetric plume in which buoyancy governs, and M_s/M_b increases in a power-law fashion, the slope of power-law correlation being 1/4.

$$\frac{M_s}{M_b} = 1.6Ri^{1/4}, \qquad \text{for Ri} > 0.7 \qquad [2]$$

However, the correlation displays a discontinuity at a Ri value of 0.7. With Ri values lower than 0.7, the flow behaves more like a jet. In Equation [2], M_s/M_b is expected to be valid in actual physical experiments only for the same conditions of layer depth and width as in this simple model test. In practice, such a well-defined correlation as in Equation [2] is difficult to obtain from flows induced by fires. Nonetheless, the results of this simple model reasonably describe the physics of the buoyant jet in the flows induced by fire. The limiting value of Ri determines whether buoyancy governs the flow or jet momentum governs the flow. In general, balcony spill plumes are categorized as either “free balcony spill plumes” or “adhered balcony spill plumes” [5, 2]. An adhered balcony spill plume has buoyancy governing flows, which is likely to occur if the projection of the balcony is relatively short or the plume temperature is exceedingly high [2]. On the other hand, a free balcony spill plume has jet momentum governing flows.

Parameter effect on flow characteristics and the air entrainment

Fig. 5 shows the simulation results of the parameter sensitivity test. The trajectory of the flow at the end of the balcony is determined by the flow characteristics that are affected by parameter conditions: the breadth of the balcony; and the presence of the draft curtain and fascia.

With no balcony (TV0), the horizontal inlet flow immediately rotates up due to its buoyancy. This buoyancy of the horizontal inlet flow results in rapid transition to a vertical flow, which can cause the vertical flow to adhere or bound back to the wall above the balcony. On the other hand, the buoyancy of flows running under a balcony, shown in Fig. 5(b) and 5(c), is impeded since the horizontal velocity increases under the balcony. When there is a longer balcony and a draft curtain, shown in Fig. 5(d), the momentum of the buoyant jet becomes stronger. When there is a fascia, as shown in Fig. 5(e), the momentum of the horizontal flow also increases significantly, and the flow appears more turbulent than the flow with no fascia.

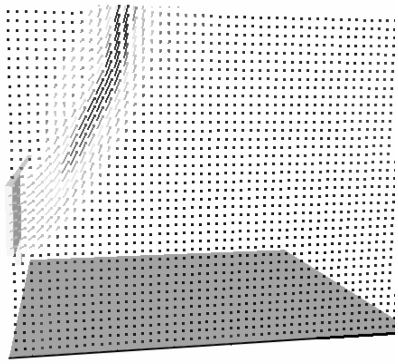
The maximum temperature (T_b) and velocity of the horizontal flow ($U\text{-}Vel_b$), as well as the layer depth (D_b) were measured at the end of the balcony. The Ri number of the flow at the end of the balcony was then calculated based on these values. Mass flow rates (M_b) at the end of the balcony and mass flow rates(M_s) at the spill edge were calculated. Results are presented in Table 3.

TABLE 3. Flow characteristics at the end of the balcony and M_s/M_b

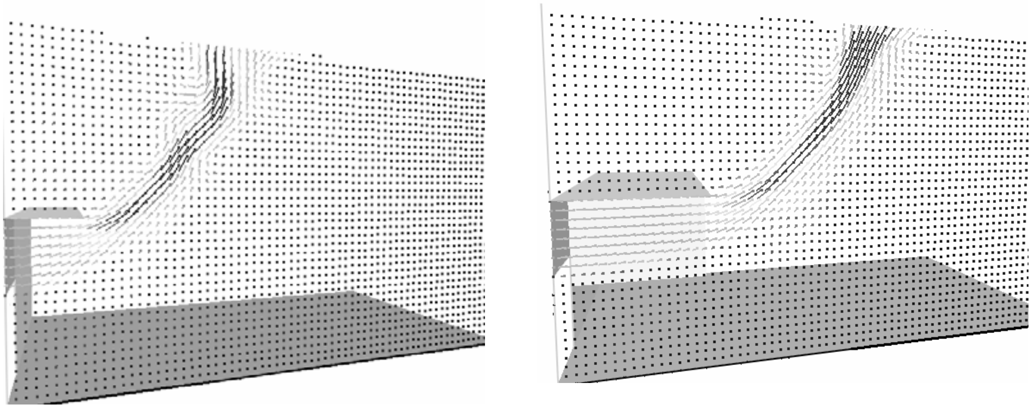
ID	T_b (˚C)	$U\text{-}Vel_b$ (m s^{-1})	D_b (m)	Ri	M_s/M_b	
TV0	197.0*	2.65*	2*	1.26*	1.70	* initial condition
B-1	196.2	3.62	1.5	0.54	1.18	b = 2m
B-2	188.1	3.65	1	0.35	1.16	b = 4.2m
DC	194.4	4.28	1.5	0.39	1.07	D_c = 3m
F	179.1	4.48	1.55	0.34	1.54	D_f = 1.6m

In Fig. 6, the values of M_s/M_b are plotted with respect to Ri on a log scale, and compared with the correlation obtained from the temperature and velocity effect tests. Fig. 6 shows that the results from simulations of this sensitivity test appear to obey the general pattern of M_s/M_b correlation with Ri.

Under the initial conditions used (TV0), the doorway flow induced by fire has initially both momentum and buoyancy. This initial condition had Ri = 1.26 with a temperature of 197°C and velocity of 2.65m/s, as shown for Simulation ‘TV0’ in Table 3.



(a) Simulation TV0 (Tw = 197’C, U-Velw 2.65m/s)

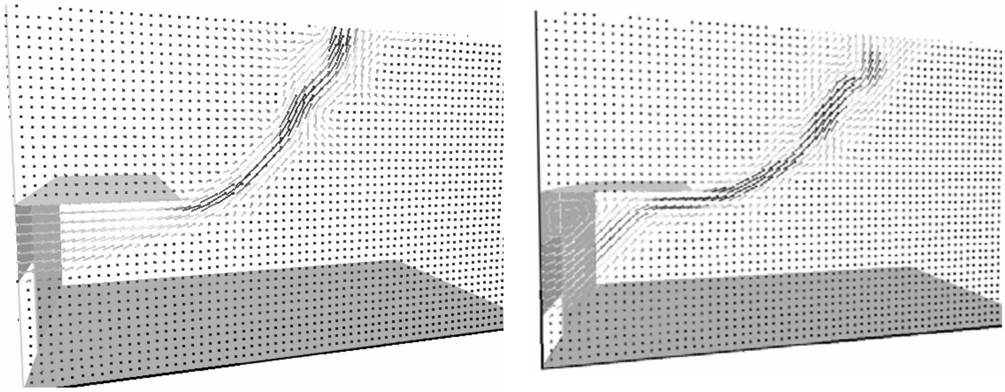


(b) Simulation B-1

Under short projecting balcony (*b*=2m)

(c) Simulation DC

With draft curtain



(d) Simulation B-2

Under long projecting balcony (*b*=4.2m)

(e) Simulation F

With fascia

FIGURE 5. Velocity vector slices of simulation of the sensitivity test, (a) no balcony, (b) short balcony, (c) with draft curtain, (d) long balcony, and (e) with fascia

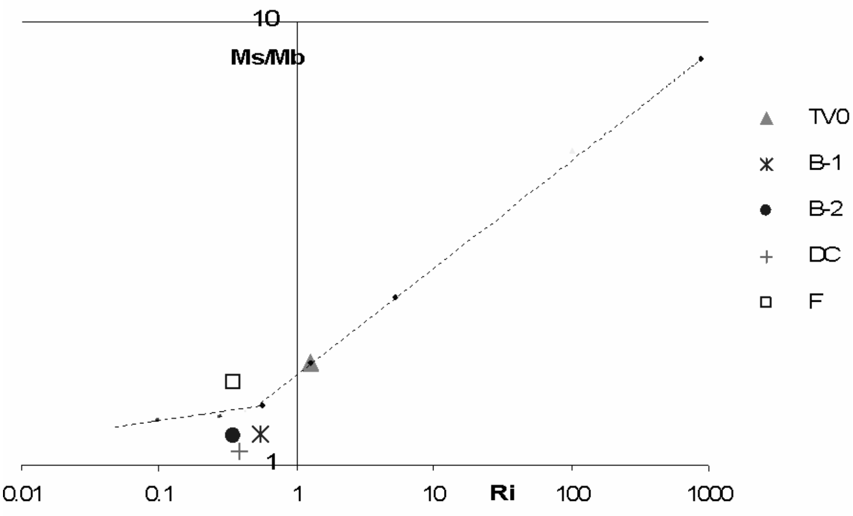


FIGURE 6. A plot of M_s/M_b with respect to Ri : from parameter sensitivity tests

When the balcony is introduced (Simulation 'B-2'), the characteristic of the flow is found to drop from its initial Ri = 1.26 to Ri = 0.35. The critical changes made to the flow due to the presence of a balcony is that the resultant Ri at the end of the balcony dropped below the limiting Ri criteria, 0.7, which was discussed in the temperature and velocity effect tests. The resulting buoyant jet due to the balcony behaves as a momentum-leading buoyant jet, which is more appreciably affected by its horizontal momentum, rather than its buoyancy.

For simulation 'B-1', the balcony breadth was set to at 2 m, which is at the limiting balcony breadth suggested by Hansell et al. As the resultant Ri was found to be below the limiting Ri, this relatively short projection of the balcony (b = 2 m) also causes the horizontal velocity of the flow to increase so the horizontal momentum becomes dominant when the flow spills up.

Compared with Simulation 'B-2', the presence of the draft curtain (Simulation 'DC') results in a reduced value of M_s/M_b despite a slightly greater Ri at the end of the balcony. A possible reason for this is that, for Simulation 'DC', the channelled flow did not spread out under the balcony so that the thick layer depth at the end of the balcony affects air entrainment. Using similar reasoning, greater air entrainments for Simulation 'F' than Simulation 'B-2' resulted from the fascia effect, which causes the layer of the flow to spread and causes the flow to be turbulent.

Comparison with Full-scale Simulation and Experimental Results

The results obtained from the simplified modeling study were compared with full-scale CFD simulation data and experimental data. Description of the simulations is provided in detail in Ko [1], and details of experiments can be found in Lougheed et al [3]. Fig. 7 shows the geometry of full-scale model.

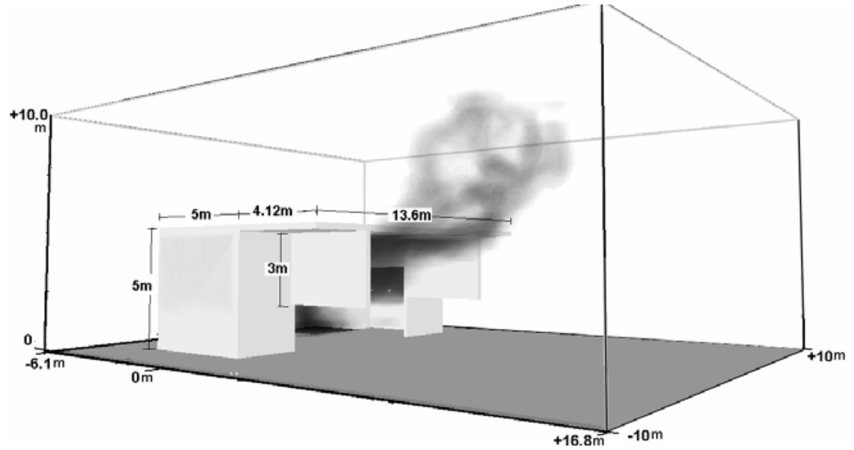


FIGURE 7. Description of the model

FIGURE 8. Full-scale experimental facility at NRC

The modeled fire compartment is 13.6 m by 5.0 m in floor area and 5.0 m high with an opening facing the atrium area. This compartment has the same dimensions as used for the full-scale experiments conducted at the National Research Council (NRC) shown in Fig. 8.

As shown in Fig. 7, the ceiling of the compartment extends out as a balcony, and the width of the balcony is the same as that of the compartment. For some cases, a 1.6 m deep fascia and 3 m deep channelling draft curtains were added. For investigating variations of the air entrainment rate, and in an attempt to quantify the effect of each parameter under the balcony area, various fire size and opening size were used. Table 4 shows parameter conditions used in each simulation and test.

Summary of 52 simulation results (S1~S52) and four experimental results (T1~T4) are shown in Table 4. The maximum temperature, horizontal velocity and the layer depth of the initial approach flow at the end of the balcony are also given in Table 4.

TABLE 4. Parameter conditions and results

ID	Q(MW)	Q_c(kW)	Fascia	Draft curtain	W(m)	$\Delta T_{b\,max}$	U-vel $_{max}$	D_b (m)	Ri	M_s/M_b	
S1	1	532	N	N	5	78.91	2.62	0.99	0.29	2.07	Ta=20
S2	2	1088	N	N	5	123.86	3.45	1.08	0.31	2.20	
S3	3	1665	N	N	5	137.88	3.89	1.29	0.34	2.19	
S4	4	2244	N	N	5	170.74	4.42	1.29	0.33	2.28	
S5	1	573	N	N	7.5	75.29	2.34	1.32	0.44	2.63	
S6	2	1124	N	N	7.5	116.84	2.96	1.26	0.47	2.50	
S7	3	1689	N	N	7.5	130.51	3.58	1.33	0.39	2.04	
S8	4	2292	N	N	7.5	162.59	4.05	1.32	0.38	2.11	
S9	1	593	N	N	12	64.15	1.56	1.12	0.68	2.68	
S10	2	1164	N	N	12	95.03	2.18	1.07	0.57	2.52	
S11	3	1773	N	N	12	103.18	2.64	1.43	0.57	2.16	
S12	4	2400	N	N	12	127.23	2.89	1.41	0.60	2.07	
S13	1	462	Y	N	5	79.32	3.21	0.73	0.14	2.26	
S14	2	928	Y	N	5	124.33	4.18	0.80	0.16	2.33	
S15	3	1443	Y	N	5	177.17	5.00	0.94	0.20	2.49	
S16	4	1888	Y	N	5	215.76	5.57	0.97	0.20	2.50	
S17	1	506.6	Y	N	7.5	73.95	2.88	1.08	0.23	2.68	
S18	2	964	Y	N	7.5	116.21	2.96	1.26	0.46	2.29	
S19	3	1527	Y	N	7.5	126.89	3.58	1.33	0.37	2.19	
S20	4	2004	Y	N	7.5	161.31	5.01	1.09	0.20	2.21	
S21	1	535	Y	N	12	64.96	1.91	1.05	0.43	2.95	
S22	2	1028	Y	N	12	96.37	2.18	1.07	0.58	2.68	
S23	3	1638	Y	N	12	104.12	3.22	1.28	0.35	2.25	
S24	4	2136	Y	N	12	129.14	3.51	1.25	0.37	2.25	
S25	1	538	N	Y	5	87.17	2.63	1.27	0.41	1.63	
S26	2	1096	N	Y	5	134.19	3.43	1.31	0.42	1.68	
S27	3	1455	N	Y	5	167.24	5.16	1.05	0.19	1.92	
S28	4	1904	N	Y	5	204.22	5.80	1.09	0.20	2.00	
S29	1	576	N	Y	7.5	83.34	2.35	1.48	0.57	2.66	
S30	2	1132	N	Y	7.5	116.84	2.96	1.30	0.48	2.33	
S31	3	1695	N	Y	7.5	130.51	3.56	1.52	0.44	1.68	
S32	4	2280	N	Y	7.5	189.95	4.04	1.51	0.53	1.74	
S33	1	590	N	Y	12	64.17	1.76	1.13	0.54	2.77	
S34	2	1156	N	Y	12	95.03	2.23	1.08	0.55	2.51	
S35	3	1770	N	Y	12	118.14	2.70	1.49	0.67	2.03	
S36	4	2360	N	Y	12	144.25	2.95	1.48	0.71	1.90	
S37	1	472	Y	Y	5	91.25	3.31	0.86	0.19	1.92	
S38	2	934	Y	Y	5	144.41	4.29	0.93	0.21	2.01	
S39	3	1461	Y	Y	5	176.73	5.14	1.05	0.21	1.91	
S40	4	1912	Y	Y	5	217.15	5.81	1.09	0.21	1.99	
S41	1	510	Y	Y	7.5	84.70	2.83	1.18	0.32	2.73	
S42	2	968	Y	Y	7.5	129.73	3.58	1.05	0.30	2.05	
S43	3	1539	Y	Y	7.5	158.77	4.53	1.10	0.25	1.88	
S44	4	2020	Y	Y	7.5	194.78	4.99	1.14	0.27	1.89	
S45	1	536	Y	Y	12	65.77	1.93	0.98	0.40	2.78	
S46	2	1012	Y	Y	12	98.46	2.43	0.99	0.44	2.47	
S47	3	1635	Y	Y	12	122.22	3.30	1.27	0.40	2.10	
S48	4	2116	Y	Y	12	144.20	3.48	1.23	0.42	2.06	
S49	5	2805	N	N	5	202.99	4.87	1.30	0.33	2.32	
S50	5	2300	Y	N	5	216.03	5.98	0.99	0.18	1.82	
S51	5	2770	N	Y	5	235.98	4.93	1.47	0.44	2.06	
S52	5	2300	Y	Y	5	248.14	6.26	1.12	0.22	2.59	
T1	1		N	Y	5	91.0	2.52	1.1	0.46	2.60	Ta=14
T2	3		N	Y	5	197.5	5.56	1.2	0.23	1.05	Ta=20
T3	1		Y	Y	5	197.5	2.70	0.9	0.73	2.19	Ta=21
T4	3		Y	Y	5	245	5.30	1.1	0.30	1.97	Ta=20

Using selected parameters of the approach flow ($T_{b\,maxx}$, $U\text{-}Vel_{b\,\max}$ and D_b), the Richardson number, Ri, was calculated using Equation 1. The ratio M_s/M_b is plotted as a function of Ri at the end of the balcony in Fig. 9. Calculated Ri values are in the range 0.14-0.73, which are around to or below the limiting Ri criteria (0.7). As discussed earlier, with Ri values lower than 0.7, the flow behaves as a momentum-leading buoyant jet, which is more affected by its horizontal momentum, rather than its buoyancy. Due to the balcony, the horizontal velocity of the flow increases so that the resultant Ri at the end of the balcony dropped below the limiting Ri criteria, 0.7. This comparison shows that free balcony spill plumes meet the limiting conditions of the approach flow (Ri < 0.7).

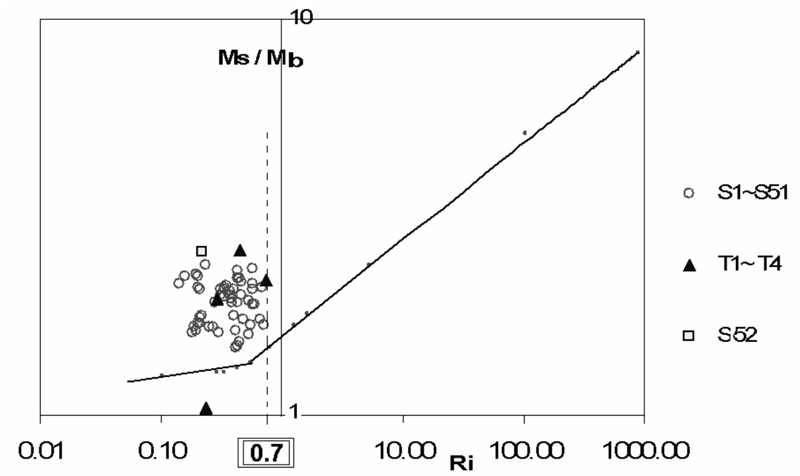


FIGURE 9. Variation of air entrainment rate at the rotating region with Ri of the initial flow

The maximum temperatures at the end of the balcony in all simulations are in the range 64-248°C. The temperature value of 248°C resulted from simulation S52, and almost reached the limiting temperature criteria suggested by Hansell et al [2] (250°C for a 5 m opening size). The corresponding Ri is 0.22, [marked with (□), from S52], and mass flow rate at the spill plume region behaves as expected with this Ri number.

DISCUSSION AND CONCLUSIONS

1. Temperature and velocity effect test: The trajectory of the flow is governed by its buoyancy and jet momentum. These effects can be represented by Ri, which can be calculated from the flow temperature and velocity. Although some variability of M_s/M_b is found depending on parameter conditions, it can be stated with some confidence that the air entrainment depends on the Ri of the flow. More importantly, Ri defines the flow behaviour, i.e., whether the buoyant plume behaviour is more dominant or not. The limiting Ri criteria is found to be approximately 0.7, below which the horizontal momentum appreciably affects the flow.

2. Parameter sensitivity test: It was found that the presence of a balcony is critical. The Ri value of the flow at the end of the balcony is lowered as the balcony increases the horizontal velocity of the flow. At the end of the balcony, the flow characteristic of the initial flow is found to be below the limiting Ri criteria.

3. The simple modelling study helps to understand the mechanisms of buoyant jets and in particular the air entrainment into the rotating flow of balcony spill plume. Comparisons made with full-scale experiments and CFD simulations show that free balcony spill plumes meet the limiting conditions of the approach flow (Ri < 0.7). Therefore, the limiting Ri criteria can be used to

assess whether the balcony spill plume is free-unbounded, along with the limiting temperature and balcony breadth criteria suggested by Hansell [2].

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