A NEW CRITERION FOR STABILITY OF SMOKE LAYER UNDER SPRINKLER SPRAY

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ABSTRACT

A model has been developed for the interaction of the buoyant smoke layer and the sprinkler spray. Based on the theoretical analysis, the ratio of the maximal drag force of unit area D_0 and the maximal buoyancy force of unit area B_0 in the spray region is proposed as a new criterion for predicting the stability of smoke layer under sprinkler spray. For validating the criterion, the sprinkler operating pressure and the smoke temperature are measured by using an experiment system located at the PolyU/USTC Atrium for sprinkler spray-smoke layer interaction. D_0 and B_0 are calculated by using 3rd-order Simpson method. The experimental results show that the smoke layer remains stable when the D_0 / B_0 ratio is less than 1, and a downward smoke plume which represents the instability of the smoke layer forms when the D_0 / B_0 ratio is more than 1. The driving force of the down- flow is the difference between D_0 and B_0.

KEYWORDS: Sprinkler spray, Instability of smoke layer, Interaction of smoke layer and sprinkler spray, Drag force, Buoyancy force

INTRODUCTION

Automatic sprinkler systems are required to be installed in many buildings such as hotels, factories and shopping malls in China. The automatic sprinkler systems are very reliable in protecting buildings against fire. The insurance premium for a sprinklered building would be greatly reduced in comparison with one without a sprinkler [1, 2].

However, whether or not the operation of the sprinkler system can protect evacuees is uncertain. The results of several researches had shown that the sprinkler spray can cool the burning material and the hot smoke layer so as to control the fire from growing; on the other hand, the spray may pull down the smoke and result in “smoke logging” as well. The smoke logging is a risk to evacuation and firefighting [3-8].

Stability of the smoke layer under the sprinkler spray was firstly studied by M.L. Bullen in 1974. As in Fig. 1, the smoke region covered by spray was studied and the ratio of the total drag D_t and the total buoyancy force B_t in spray region is presented by Bullen as the criterion for the stability of the smoke layer. Bullen believed that the smoke layer will become unstable and the smoke logging

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will form when the ratio is more than 1. The criterion had been validated by Chow through several experiments and the results had shown that the smoke layer might lose stability when D_t / B_t <1 (the critical number of instability is almost 0.6). Based on the conclusion of Chow, Zhang processed a series of experiments to propose the ratio of the drag force of unit volume D_L and the buoyancy force of unit volume B_L on the smoke-air interface as a criterion. The results showed that D_L is less than B_L when instability occurred and the critical number of instability $D_L / B_L \approx 0.8$. The theory of Zhang cannot explain the experimental results.

In this article, a simple model was developed to simulate the interaction of the buoyant smoke layer and the sprinkler spray. A new criterion for the stability was proposed according with the model and a series of full-scale burning tests was then conducted for verifying the criterion by using an experiment system located at the PolyU/USTC Atrium for sprinkler spray-smoke layer interaction. The experimental results are compared with those calculated by the criterion of Bullen and the criterion of Zhang respectively to see whether the criterion presented in this article is suitable for predicting the instability of the smoke layer.

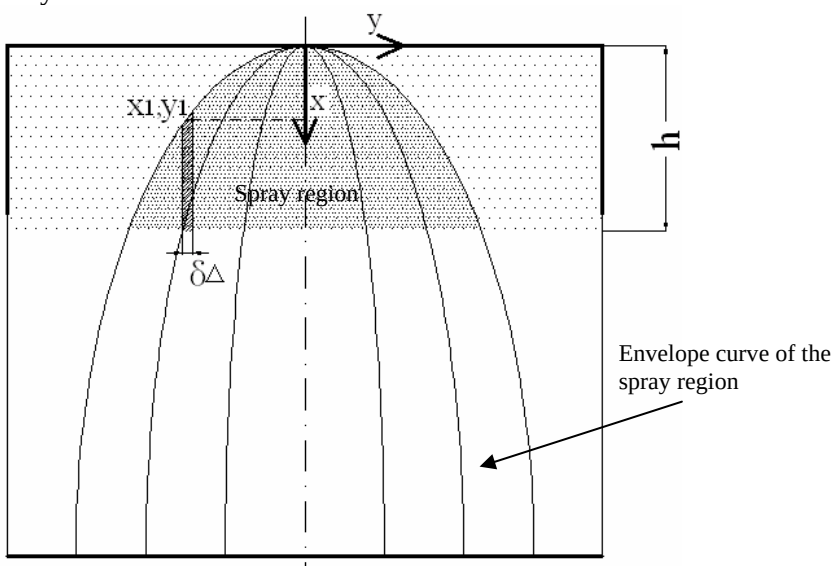

FIGURE 1. Sketch map of interaction between hot layer and spray

MATHMATICAL MODEL

The Drag Force of Unit Area

As in Fig. 1, the thickness of the smoke layer is h and the region affected by the spray is darkened and noted in the figure. The column element whose base area is $\delta\Delta$ was studied in this article. The vertical drag force caused by the spray droplet is calculated by:

$$D(x) = kv^2 \quad [1]$$

$$k_d = \frac{\rho_g(x) C_D A_d}{2} \quad [2]$$

where $D(x)$ is the drag force of unit volume at x coordinate, v is the vertical velocity, $\rho_g(x)$ is the density of the smoke, C_D is the drag coefficient and is assigned to be 0.6 when Re is

10^1~10^2 [4] and A_d is the surface area of the droplet. Then the motion equation of the droplet is presented as:

$$m_d g - k_d v^2 = m_d \frac{dv}{dt} = m_d v \frac{dv}{dx} \quad [3]$$

The vertical velocity may be assumed to be zero when the spray droplet starts to form [2]. Then the vertical velocity v can be expressed by integrating equation [3]:

$$v^2 = \frac{m_d g}{k_d}\left[1 - \exp(-\frac{2k_d x}{m_d})\right] \quad [4]$$

The envelope curve of the region is approximately parabolic according to the NFPA 13 [6] and the shape is defined as:

$$y^2 = Cx \quad [5]$$

and the cross-section area of the spray region at x coordinate is:

$$S(x) = \pi C x \quad [6]$$

where $S(x)$ is the area of the cross-section and coefficient C is defined as 3 according to the NFPA 13. Then the droplet number of unit volume at x coordinate is:

$$n(x) = \frac{\dot{M}}{m_d S(x) v} \quad [7]$$

where $\dot{M}$ is the flow rate of sprinkler and can be calculated by:

$$\dot{M} = \frac{\rho_d K \sqrt{10 p_d}}{60 \times 10^3} \quad [8]$$

where p_d is the operation pressure of the sprinkler, ρ_d is density of the water, K is the flow coefficient of the sprinkler and is defined to be 120 and 80 when the diameter of the sprinkler head is $13.5\,mm$ and $12.7\,mm$ respectively. Then the drag force of unit volume at x coordinate can be calculated by:

$$D'(x) = n(x)D(x) = \frac{\dot{M}}{S(x)}\sqrt{\frac{k_d g}{m_d}\left[1 - \exp(-\frac{2k_d x}{m_d})\right]} \quad [9]$$

where

$$k_d \Big/ m_d = [\frac{1}{8}\rho_g(x) C_D \pi {d_d}^2 \Big/ \frac{1}{6}\rho_d \pi {d_d}^3] = \frac{3\rho_g(x) C_D}{4\rho_d d_d} \quad [10]$$

where d_d is diameter of the droplet. The diameter of different droplets are assumed to be unique and replaced by the mean diameter d_m in this article for simplifying the equation [10]. The d_m can be calculated by equations [11] to [13]:

$$d_m = C_m d_n We^{-(\frac{1}{3})} \quad [11]$$

$$We = \frac{\rho_d U^2 d_n}{\sigma_w} \quad [12]$$

$$U = \frac{\dot{M}}{\rho_d \pi {d_n}^2 / 4} \quad [13]$$

where U is speed of the water spraying out of the sprinkler head, σ_w is the surface tension of water and is defined to be $72.8 \times 10^{-3} N/m$, We is the Weber number and d_n is the diameter of the sprinkler head. Coefficient C_m is defined to be 2.98 and 2.33 when the diameter of the sprinkler head is $13.5\,mm$ and $12.7\,mm$ respectively [7].

As in Fig. 1, the total drag force of unit area is:

$$D_{x1} = \int_{x1}^{h} D'(x)dx = \int_{x1}^{h} \frac{\dot{M}}{S(x)} \sqrt{\frac{k_d g}{m_d}\left[1 - \exp(-\frac{2k_d x}{m_d})\right]}dx \quad [14]$$

Substituting equations [3] and [10] into equation [14] gives:

$$D_{x1} = \int_{x1}^{h} \frac{\dot{M}}{\pi C x} \sqrt{\frac{3\rho_g(x) C_D g}{4\rho_d d_m}\left[1 - \exp(-\frac{6\rho_g(x) C_D x}{4\rho_d d_m})\right]}dx \quad [15]$$

The Buoyancy Force of Unit Area

The buoyancy force of unit volume $B'(x)$ varies with the smoke temperature:

$$B'(x) = [\rho_0 - \rho_g(x)]g = \frac{T(x) - T_0}{T(x)} \rho_0 g \quad [16]$$

where ρ_0 is the density of the air at ambient temperature, $T(x)$ is the smoke temperature and T_0 is the ambient temperature. Then the total buoyancy force of unit area as in Fig. 1 is:

$$B_{x1} = \int_{x1}^{h} B'(x)dx = \int_{x1}^{h} \frac{T(x) - T_0}{T(x)} \rho_0 g dx \quad [17]$$

$T(x) - T_0$ in equation [17] can be substituted by the average temperature rise of the smoke layer as the temperature gradient of the layer is small and the equation [17] can be simplified as:

$$B_{x1} = \int_{x1}^{h} \frac{T(x) - T_0}{T(x)} \rho_0 g dx = \frac{\overline{\Delta T}}{\overline{\Delta T} + T_0} \rho_0 g (h - x1) \quad [18]$$

The Criterion for Stability of the Smoke Layer

In this article, the smoke of unit area is assumed to lose stability when $D_{x1}/B_{x1}>1$ according to the model in Fig. 1. The value of D_{x1}/B_{x1} varies with the change of $x1$ in the spray region. The curve of $D'(x)$ and $B'(x)$ varying with height ($x1=0.5m$, $y1=1.2m$) is shown in Fig. 2 (the diameter of the sprinkler head is 13.5 mm and the operation pressure is 0.15 MPa). As in Fig. 2, the value of $D'(x)$ and $B'(x)$ increases with elevation and the increasing extent of $D'(x)$ is much larger than the one of $B'(x)$. According to this regularity, the ratio of the maximal drag force of unit area D_0 and the maximal buoyancy force of unit area B_0 directly under the sprinkler head is the maximum in spray region and is proposed as the criterion for predicting the stability of the smoke layer in this article because the smoke layer directly under the sprinkler head is the most easily to lose the stability. The expression of D_0/B_0 is:

$$\frac{D_0}{B_0}=\frac{\int_0^h \frac{\dot{M}}{\pi C x}\sqrt{\frac{3\rho_g(x)C_D g}{4\rho_d d_m}\left[1-\exp(-\frac{6\rho_g(x)C_D x}{4\rho_d d_m})\right]}dx}{\left[\frac{\overline{\Delta T}}{\overline{\Delta T}+T_0}\rho_0 gh\right]} \qquad [19]$$

A series of tests had been conducted by the author to validate the criterion.

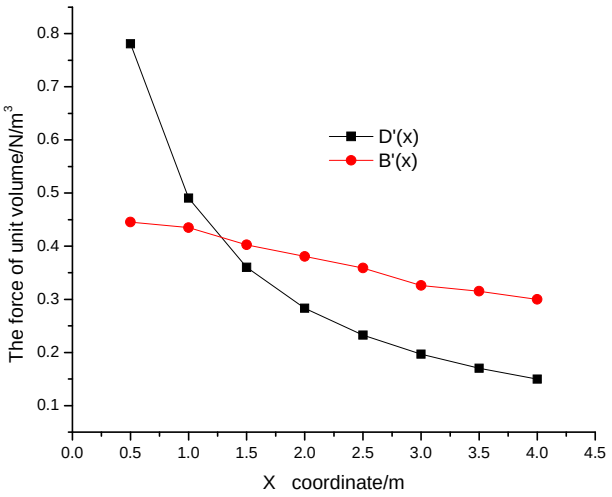

FIGURE 2. Curve of $D'(x)$ and $B'(x)$ varying with height

FULL-SCALE TESTS

Introduction of the Experiment System

The experiment system is shown in Fig. 3. The system is divided into two parts: the burning cabin and the measuring cabin. As in Fig. 3, the cabin in the left is the burning cabin in which the pool fires are placed. The cabin is a cube with length of 4 m, width of 2 m and height of 2.5 m. Six air supplying vents with length of 0.8 m and height of 0.4 m are settled on both sides of the cabin for the combustion. The measuring cabin is a cube with length of 4.2 m, width of 4.2 m and height of 4.0 m. A fire shutter with width of 1.2 m is installed on the top of the cabin to make a smoke layer with a thickness

of 1.2 m. A measuring stick with length of 4m is put in front of the cabin for measuring the thickness of the smoke layer. The sprinkler is installed in the central location of the cabin roof and 4 thermocouple trees are disposed at a circle with diameter of 1.2 m whose center is the sprinkler. The distance of the thermocouples is 0.5 m. Parameters of the sprinklers are shown in Table 1.

16 tests were conducted for all the sprinklers. The fuel was diesel and the opening time of the sprinkler spray was 120s after burning when the top of the measuring cabin had filled with smoke. The total time of each test was about 400 s. Operating pressure of the sprinkler varied between 0.05 to 0.15 MPa .

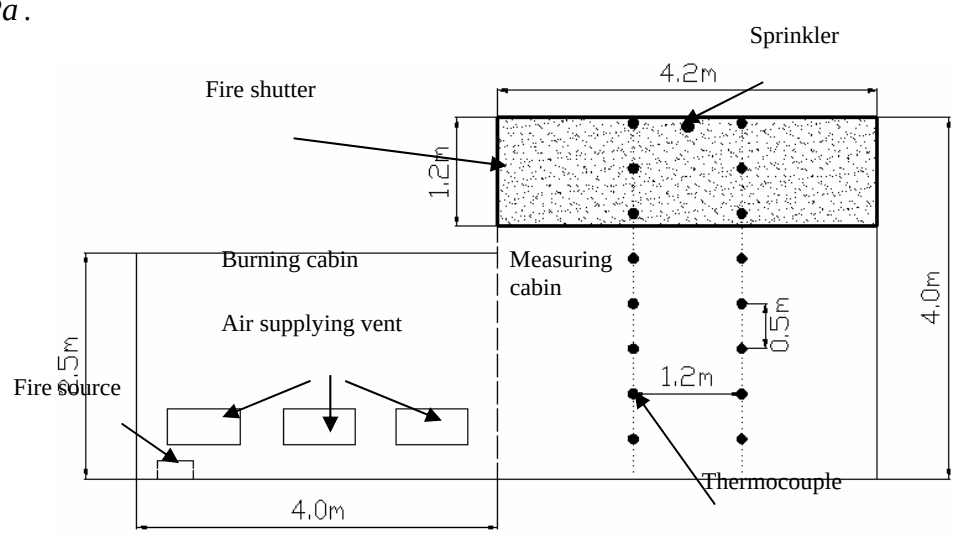

FIGURE 3. Sketch map of experimental system

TABLE 1. Parameters of sprinklers

Sprinkler	Style	Diameter of sprinkler head/ mm	Flow coefficient K
A	Upward	13.5	120
B	Upward	12.7	80
C	Downward	12.7	80

RESULTS AND DISCUSSION

Two Situations of the Smoke Layer

There are two situations of the smoke layer during the tests:

1. The smoke layer remained stable.
   As in Fig. 4(a), the smoke layer would remain stable when the operating pressure was relatively low and the smoke temperature was relatively high. In this situation, the structure of two zones was not broken and the interface between the smoke and air was clear in the measuring cabin. The thickness of the smoke layer increased slightly because of the drag force but was less than 2.5 m in all of the tests in this situation.

2. The smoke layer became unstable.
   As in Fig. 4(b) and 4(c), the smoke layer loses its stability when the operating pressure was relatively high and the smoke temperature was relatively low. In this situation, the structure of two zones was broken and a downward smoke plume which represents the instability of the smoke layer formed. The plume penetrated the interface and brought the smoke to the lower part

of the cabin. The thickness of the smoke layer exceeded 2.5 m. The plume shaped the smoke layer into a bowl and would reach the floor when the operating pressure is 0.15 MPa .

(a) Smoke layer remained stable

(b) Smoke layer being instable

(c) Smoke reaching the floor

FIGURE 4. Photos of the experiments

Stability and Instability of the Smoke Layer

The thickness of the smoke layer varied with the operating pressure of the sprinkler. As in Fig. 5, there is a distinct value-jump of the thickness in 2.5 m. The smoke layer remained stable when the thickness was less than 2.5 m shown by the test results. The tests data was shown in Table 2 and the value of D_t / B_t , D_L / B_L and D_0 / B_0 is calculated and noted in the Table as well. The value of D_0 was calculated by 3rd-order Simpson equation. The data showed that the thickness of the smoke layer was less than 2.5m when D_0 / B_0 <1. The value of D_0 / B_0 was greater than 1 when the thickness of the smoke layer was more than 2.5m but the value of D_t / B_t and D_L / B_L might be 0.8 at the same situation as in Table 2. So it is obvious that the criterion of D_0 / B_0 is suitable for predicting the instability of the smoke layer compared to the criterion of D_t / B_t (Bullen) and the criterion of D_L / B_L (Zhang).

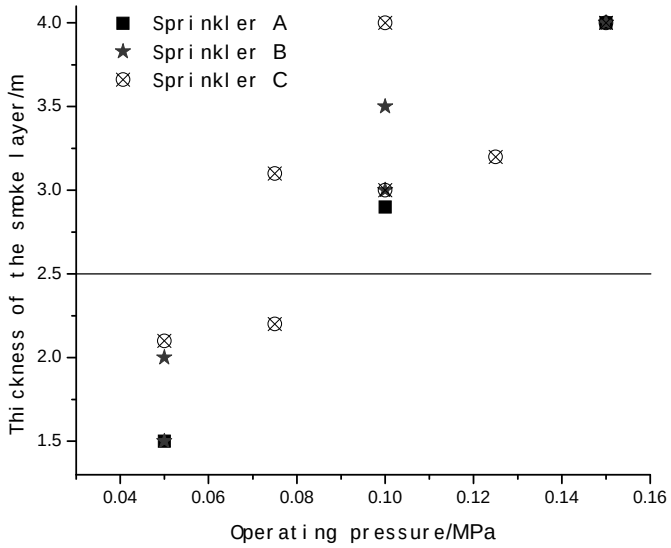

FIGURE 5. Layer depth against sprinkler pressure

TABLE 2. Tests data

Sprinkler	No	HRR	Operating pressure (MPa)	Ambient temperature (K)	Average temperature rise (K)	Thickness	D_t/B_t	D_L/B_L	D_0/B_0
A	A11	248	0.05	274	14.4	1.5	0.44	0.34	0.67
	A12	248	0.1	274	13.5	2.9	0.80	0.82	1.26
	A13	248	0.15	274	12.7	4.0	1.17	1.10	1.85
B	B11	200	0.05	283	8.6	2.0	0.53	0.61	0.83
	B12	200	0.1	283	7.8	3.4	1.00	0.92	1.61
	B13	200	0.15	283	5.6	>4.0	1.89	1.57	3.00
	B21	248	0.05	283	10.5	1.5	0.43	0.40	0.69
	B22	248	0.1	283	9.6	3.0	0.82	0.80	1.31
	B23	248	0.15	283	8.6	>4.0	1.24	1.38	2.00
C	C11	476	0.05	300	9.2	2.1	0.52	0.59	0.83
	C12	476	0.075	300	7.0	3.1	0.94	1.07	1.50
	C13	476	0.1	300	5.6	>4.0	1.46	1.48	2.36
	C21	810	0.075	300	11.1	2.2	0.60	0.65	0.96
	C22	810	0.1	300	9.8	3.0	0.85	0.92	1.36
	C23	810	0.125	300	9.6	3.2	1.03	1.20	1.67
	C24	810	0.15	300	9.3	>4.0	1.22	1.50	1.99

Comparison and Analysis of the Three Criterions

The essence of the Bullen model may be expressed by:

$$\frac{D_t}{B_t} = \frac{\int_0^{\pi Ch} D_{x1} d\Delta}{\int_0^{\pi Ch} B_{x1} d\Delta} \qquad [20]$$

which represented the ratio of the integral of the drag force of unit area and the integral of the buoyancy force of unit area in the spray region. Because the ratio of the maximal drag force of unit area D_0 and the maximal buoyancy force of unit area B_0 directly under the sprinkler head is

maximum in the spray region, the value of D_0 / B_0 is always greater than the one of D_t / B_t. Then the smoke layer directly under the sprinkler head might lose its stability when $D_0 / B_0 > 1$ and the value of D_t / B_t was less than 1 at this situation. The Bullen model neglected the variation of the drag force in the spray region which may cause the instability of the smoke layer locally. The model of Zhang included the variation of the drag force in the spray region but neglected the accumulation of the drag force and the buoyancy force at height direction. According to the increasing regularity of $D'(x)$ and $B'(x)$, D_L / B_L may be less than 1 when $D_0 / B_0 > 1$.

The model proposed in this article presents that the difference of D_{x1} and B_{x1} is the driving force of the downward flow which represents the instability. The drag force of the spray enhances with the increasing of the operating pressure and the smoke layer directly under the sprinkler head may take the lead in losing stability when D_0 / B_0 starts to be more than 1. Therefore, the change of the smoke layer in spray region may be predicted by D_0 / B_0 accurately.

CONCLUSION

Theoretical analysis and experimental studies with full-scale tests on the stability of the smoke layer were reported in this article. A new model which presented a new criterion was proposed and compared with the Bullen model and the Zhang model. The test results showed that the new criterion of D_0 / B_0 is suitable for predicting the instability of the smoke layer compared to the criterion of D_t / B_t and the criterion of D_L / B_L. The difference of D_{x1} and B_{x1} is the driving force of the downward smoke flow. The smoke layer directly under the sprinkler head would lose its stability once $D_0 / B_0 > 1$, which represents the instability of the smoke layer in spray region.

ACKNOWLEDGEMENT

The paper was partially supported by the National Natural Science Key Foundation of China (No. 50536030).

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