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 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 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 the operation of the sprinkler system is good or not for people evacuation 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 growing, on the other hand, the spray may pull down the smoke and result in the “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 Figure 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 smoke layer. Bullen believed that the smoke layer will become instable and the smoke logging will form when the ratio is more than 1. But 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 can’t 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.

![Fig1 Sketch map of interaction between hot layer and spray](image)

**MATHMATICAL MODEL**

**The drag force of unit area**

As in Figure 1, 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:

$$D(x) = kv^2$$  \hfill (1)

$$k_d = \frac{\rho_s(x)C_d A_d}{2}$$  \hfill (2)

where $D(x)$ is the drag force of unit volume at $x$ coordinate, $v$ is the vertical velocity, $\rho_s(x)$ is the density of the smoke, $C_d$ is the drag coefficient and is assigned to be 0.6 when $Re$ is $10^1 \sim 10^2$ and $A_d$ is the surface area of the droplet. Then the motion equation of the droplet is presented as:

$$m_d g - k_d v^2 = m_d \frac{dv}{dt} = m_d \frac{dv}{dx}$$  \hfill (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 the equation (3):

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

The envelope curve of the region is approximately parabolic according to the NFPA 13[6] and the shape is defined as:
\[ y^2 = Cx \]  
and the cross-section area of the spray region at \( x \) coordinate is:

\[ S(x) = \pi Cx \]  

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:

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

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

\[ \dot{M} = \frac{\rho_d K_{p,0} \sqrt{10 \rho_d}}{60 \times 10^3} \]  

where \( \rho_d \) is the operation pressure of the sprinkler, \( \rho_d \) 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:

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

where:

\[ k_d \sqrt{m_d} = \left[ \frac{1}{8} \rho_g(x) C_D \pi d^2 / \frac{1}{6} \rho_d \pi d^3 \right] = \frac{3 \rho_g(x) C_D}{4 \rho_d d_d} \]  

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 equation (11) – (13):

\[ d_m = C_m d_n W e^{-\frac{1}{2}} \]  

\[ W e = \frac{\rho_d U^2 d_n}{\sigma_w} \]  

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

where \( U \) is speed of the water spraying out of the sprinkler head, \( \sigma_w \) is the surface tension of water and is defined to be 72.8 \( \times 10^{-3} \) \( N/m \), \( W e \) 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 Figure 1, the total drag force of unit area is:

\[ D_{x1} = \int_{x_1}^{x_2} D'(x) dx = \int_{x_1}^{x_2} \frac{\dot{M}}{S(x)} \sqrt{\frac{k_d g}{m_d}} \left[ 1 - \exp\left(\frac{-2k_d x}{m_d}\right) \right] dx \]  

Substituting equation (3) and (10) into equation (14) gives:

\[ D_{x1} = \frac{\dot{M}}{\pi Cx} \left[ \frac{3 \rho_g(x) C_D g}{4 \rho_d d_m} \left[ 1 - \exp\left(\frac{-6 \rho_g(x) C_D x}{4 \rho_d d_m}\right) \right] \right] \]
The buoyancy force of unit area

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

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

(16)

where $\rho_0$ 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 Figure 1 is:

$$B_{x_1} = \int_{x_1}^{b} B'(x) dx = \int_{x_1}^{b} \frac{T(x) - T_0}{T(x)} \rho_0 g dx$$

(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:

$$B_{x_1} = \int_{x_1}^{b} \frac{T(x) - T_0}{T(x)} \rho_0 g dx = \frac{\Delta T}{\Delta T + T_0} \rho_0 g (h - x_1)$$

(18)

The criterion for stability of the smoke layer

In this article, the smoke of unit area is assumed to lose the stability when $D_{x_1} / B_{x_1} > 1$ according to the model in Figure 1. The value of $D_{x_1} / B_{x_1}$ varies with the change of $x_1$ in spray region. The curve of $D'(x)$ and $B'(x)$ varying with height ($x_1 = 0.5m$, $y_1 = 1.2m$) is shown in Figure 2 (the diameter of the sprinkler head is $13.5\ mm$ and the operation pressure is $0.15\ MPa$). As in Figure 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:

$$D_0 / B_0 = \int_{x_1}^{b} \frac{M}{\pi Cx} \left[ \frac{3 \rho_g(x) C_D g}{4 \rho_D d_m} \left[ 1 - \exp\left( -\frac{6 \rho_g(x) C_D x}{4 \rho_D d_m} \right) \right] \right] dx$$

(19)

A series of tests had been conducted by the author to validate the criterion.
FULL-SCALE TESTS

Introduction of the experiment system

The experiment system is shown in Figure 3. The system is divided into two parts: the burning cabin and the measuring cabin. As in Figure 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 4m, width of 2m and height of 2.5m. Six air supplying vents with length of 0.8m and height of 0.4m are settled on both sides of the cabin for the combustion. The measuring cabin is a cube with length of 4.2m, width of 4.2m and height of 4.0m. Fire shutter with width of 1.2m is installed on the top of the cabin to make a smoke layer with a thickness of 1.2m. 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 thermocouples trees are disposed at a circle with diameter of 1.2m whose center is the sprinkler. The distance of the thermocouples is 0.5m. 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 400s. Operating pressure of the sprinkler varied between 0.05–0.15 MPa.
<table>
<thead>
<tr>
<th>Sprinkler</th>
<th>Style</th>
<th>Diameter of sprinkler head/mm</th>
<th>Flow coefficient K</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Upward</td>
<td>13.5</td>
<td>120</td>
</tr>
<tr>
<td>B</td>
<td>Upward</td>
<td>12.7</td>
<td>80</td>
</tr>
<tr>
<td>C</td>
<td>Downward</td>
<td>12.7</td>
<td>80</td>
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**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 Figure 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 had a little increasing because of the drag force but was less than 2.5m in all of the tests in this situation.

2. The smoke layer being instable.
   As in Figure 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 2.5m. The plume made the smoke layer to be bowl shape and would reach the floor when the operating pressure is 0.15 MPa.
Stability and instability of the smoke layer

The thickness of the smoke layer varied with the operating pressure of the sprinkler. As in Figure 5, there is a distinct value-jump of the thickness in 2.5m. The smoke layer remained stable when the thickness was less than 2.5m shown by the test results. The tests data was shown in Table 2 and the value of $D_0 / B_0$ and $D_L / B_L$ 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 $D_0 / B_0$ 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 $D_L / B_L$ (Bullen) and the criterion of $D_L / B_L$ (Zhang).

Comparison and analysis of the three criterions

The essence of the Bullen model may be expressed by:

$$\frac{D_L}{B_i} = \frac{\int_{x=0}^{x=\Delta k} D_{s1} d\Delta}{\int_{x=0}^{x=\Delta h} B_{s1} d\Delta}$$

which represented that 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 $D_i / B_i$. Then the smoke layer directly under the sprinkler head might lose its stability when $D_0 / B_0 > 1$ and the value of $D_i / B_i$ 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 $D_x$ and $B_x$ 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.

<table>
<thead>
<tr>
<th>Sprinkler No</th>
<th>HRR</th>
<th>Operating pressure $(MPa)$</th>
<th>Ambient temperature $(K)$</th>
<th>Average temperature rise $(K)$</th>
<th>Thickness</th>
<th>$D_i/B_i$</th>
<th>$D_L/B_L$</th>
<th>$D_0/B_0$</th>
</tr>
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<tbody>
<tr>
<td>A11</td>
<td>248</td>
<td>0.05</td>
<td>274</td>
<td>14.4</td>
<td>1.5</td>
<td>0.44</td>
<td>0.34</td>
<td>0.67</td>
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<tr>
<td>A12</td>
<td>248</td>
<td>0.1</td>
<td>274</td>
<td>13.5</td>
<td>2.9</td>
<td>0.80</td>
<td>0.82</td>
<td>1.26</td>
</tr>
<tr>
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<td>248</td>
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<td>274</td>
<td>12.7</td>
<td>4.0</td>
<td>1.17</td>
<td>1.10</td>
<td>1.85</td>
</tr>
<tr>
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<td>200</td>
<td>0.05</td>
<td>283</td>
<td>8.6</td>
<td>2.0</td>
<td>0.53</td>
<td>0.61</td>
<td>0.83</td>
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<tr>
<td>B12</td>
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<td>0.1</td>
<td>283</td>
<td>7.8</td>
<td>3.4</td>
<td>1.00</td>
<td>0.92</td>
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<td>B13</td>
<td>200</td>
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<td>283</td>
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<tr>
<td>B23</td>
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<td>283</td>
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<td>&gt;4.0</td>
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<td>1.38</td>
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<tr>
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<td>300</td>
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<td>1.22</td>
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</table>

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 $D_x/B_x$ and the criterion of $D_L/B_L$. The difference of $D_x$ and $B_x$ 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.

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