EXPERIMENTAL STUDIES ON THE EFFECT OF THE FIRE POSITION ON PLUME ENTRAINMENT IN A LARGE SPACE

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ABSTRACT

Experiments were carried out in a full-scale burning facility to study the characteristics of plume entrainment for different fires located at the center, near wall and at the corner in a large space. From the results of the smoke layer height, it was found that the plume entrainment rate was the highest for fires at the center, and the lowest for fires at the corner. The results obtained basically agreed with those in the literature, but the entrainment coefficient has to be modified for different positions of the fire plume.

Keywords: smoke plume, entrainment, smoke layer height

1. INTRODUCTION

Smoke produced from a fire has a relatively strong obscuration, and contains many toxic substances. It is the major hazard to people in building fires. It is very important to study the smoke production and development for better smoke control in buildings. Smoke production rate has a large effect on smoke development, and it depends on the amount of air entrained by the plume. In a fire, the combustion products will move upward due to buoyancy. During this process, the surrounding cool air will be entrained into the smoke and a smoke plume will be formed. The entrained air is the major source for smoke production. Thus, investigating the plume entrainment characteristics would provide a basis for studying smoke control. When the fire source is located at different positions inside a building, the amount of air entrained will be different due to different entrainment conditions; and different forms of plume will be formed. Common plume models include axisymmetric plume (non-restricted plume), wall plume and corner plume. In this paper, based on the empirical formula in the literature, the entrainment characteristics of smoke plume for fires at the center, near wall and at the corner were studied by full-scale burning tests.

2. ENTRAINMENT FOR FIRES AT DIFFERENT POSITIONS

- **Axisymmetric plume**

Axisymmetric plume is also called non-restricted plume or free plume, meaning that the smoke entrainment is not affected by walls or other obstructions, so that air can be entrained from any directions along the height. When the fire source is located at the center in a large space, since it is far from the walls, smoke development is not greatly affected by the walls so that air can be entrained freely. Under this condition, the plume can be approximated as an axisymmetric plume, which can be simplified as a cone from a virtual point source [1]. Based on this, plume experiments were conducted by Zukoski on fires with radius 0.10 m to 0.50 m. The following mass entrainment formula was proposed [2]:

$$\dot{m} = 0.071 \times Q_c^{1/3} \times z^{5/3} \quad (1)$$

where $\dot{m}$ is the mass flow rate of the entrained air (kgs^{-1}), Q_c is the heat release rate (kW) due to convection, and z is the height of the plume above floor (m).

- **Wall plume**

When the fire source is located near the wall, air is mainly entrained on the other side far from the wall. Under this situation, it can be approximated that the smoke entrainment rate is half of that of a non-restricted plume from two identical fire sources [3,4]. Substituting 2Q (two times the heat release rate Q) into equation (1) and then dividing the equation by two gives the mass entrainment of a wall plume:

$$\dot{m} = 0.045 \times Q_c^{1/3} \times Z^{5/3} \quad (2)$$

- **Corner plume**

When the fire source is located at the corner, air entrainment is affected by two sidewalls, and so the entrainment rate would be even smaller. Under this condition, the entrainment rate can be approximated as 1/4 of that of an axisymmetric plume. Substituting 4Q into equation (1) and then dividing the equation by 4 gives the mass entrainment of a corner plume:

$$\dot{m} = 0.028 \times Q_c^{1/3} \times Z^{5/3} \qquad (3)$$

In the experiments, assuming that the mass entrainment rate can be expressed by:

$$\dot{m} = CQ_c^{1/3} Z^{5/3} \qquad (4)$$

where C is a constant of which the value is to be determined.

- **Smoke layer height**

By using the zone concept, simplifying the conservation equations of mass, energy and momentum, the equation for smoke layer height can be obtained [5].

$$Z^{-2/3} - H^{-2/3} = \frac{2CQ_c^{1/3}}{3A\rho_0} t = kt \qquad (5)$$

By fitting a line on the plot of $Z^{-2/3}$ – t of the smoke filling experiments, the gradient k can be obtained, and then the value of C can be approximated.

$$C = \frac{3kA\rho_0}{2(0.7Q)^{1/3}} \qquad (6)$$

3. EXPERIMENTS

Experiments were carried out at the full-scale burning facility [5,6] jointly built by the University of Science and Technology of China and The Hong Kong Polytechnic University in Hefei, Anhui, China. Fifteen sets of experiments were conducted with the fires at the center, near wall and at the corner in the large space. Five different heat release rates were used with the oil pan size varying from 0.60 m to 1.0 m. The experimental conditions are listed in Table 1. All the vents were closed in the experiments, but there were openings at the bottom of the room for air supply. Four openings of size 0.26 x 1.06 m^2 were located at the bottom of the eastern side, all of them were opened throughout the experiments. There was another opening of size 4 x 0.3 m^2 at the bottom of the western side, which remained closed during the experiment.

Table 1: Experimental conditions

Expt. no.	Position of oil pan	Size of oil pan
1	center	0.6 m x 0.6 m
2	center	0.7 m x 0.7 m
3	center	0.8 m x 0.8 m
4	center	0.9 m x 0.9 m
5	center	Two 0.7 m x 0.7 m
6	near wall	0.6 m x 0.6 m
7	near wall	0.7 m x 0.7 m
8	near wall	0.8 m x 0.8 m
9	near wall	0.9 m x 0.9 m
10	near wall	Two 0.7 m x 0.7 m
11	corner	0.6 m x 0.6 m
12	corner	0.7 m x 0.7 m
13	corner	0.8 m x 0.8 m
14	corner	0.9 m x 0.9 m
15	corner	Two 0.7 m x 0.7 m

4. RESULTS AND DISCUSSION

4.1 Experimental Observations

Once the oil was ignited, it burned rapidly into a pool fire and a large amount of hot smoke was produced. When the fire was located at the center, the rising smoke appeared as an axisymmetric plume. About 20 s later, smoke reached the ceiling (the larger the heat release rate, the faster the rate) and formed a ceiling jet. The ceiling jet continued to spread horizontally and upon hitting the sidewall, it turned to spread downwards and formed an anti-buoyant wall jet. It then rose again after descending for a certain distance. Along with the smoke development towards the center of the space, a smoke layer with rather uniform thickness was gradually formed.

When the fire was located near the wall, smoke appeared as semi-conical. The rising rate was faster than when the fire was at the center, and smoke reached the ceiling in a shorter time. The smoke entrainment rate was reduced significantly.

When the fire was located at the corner, smoke appeared as 1/4 of a cone. It had the fastest rising rate, the shortest time to reach the ceiling and also, the smallest smoke entrainment rate.

4.2 Results and Discussion

4.2.1 Comparison of smoke layer height for different fire sizes

The results of smoke layer height for different fire sizes with the fire at the center, near wall and at the corner are shown in Fig. 1. From the figures, similar trends of smoke layer height for the three different positions are observed. When the oil pan size increased, the smoke descending rate also increased. The descending rate was faster in the beginning, and then gradually decreased when smoke had descended to 10 m. It can also be seen that the smoke descending rate was the fastest when the fire was located at the center, and the rate was the slowest for the fire located at the corner.

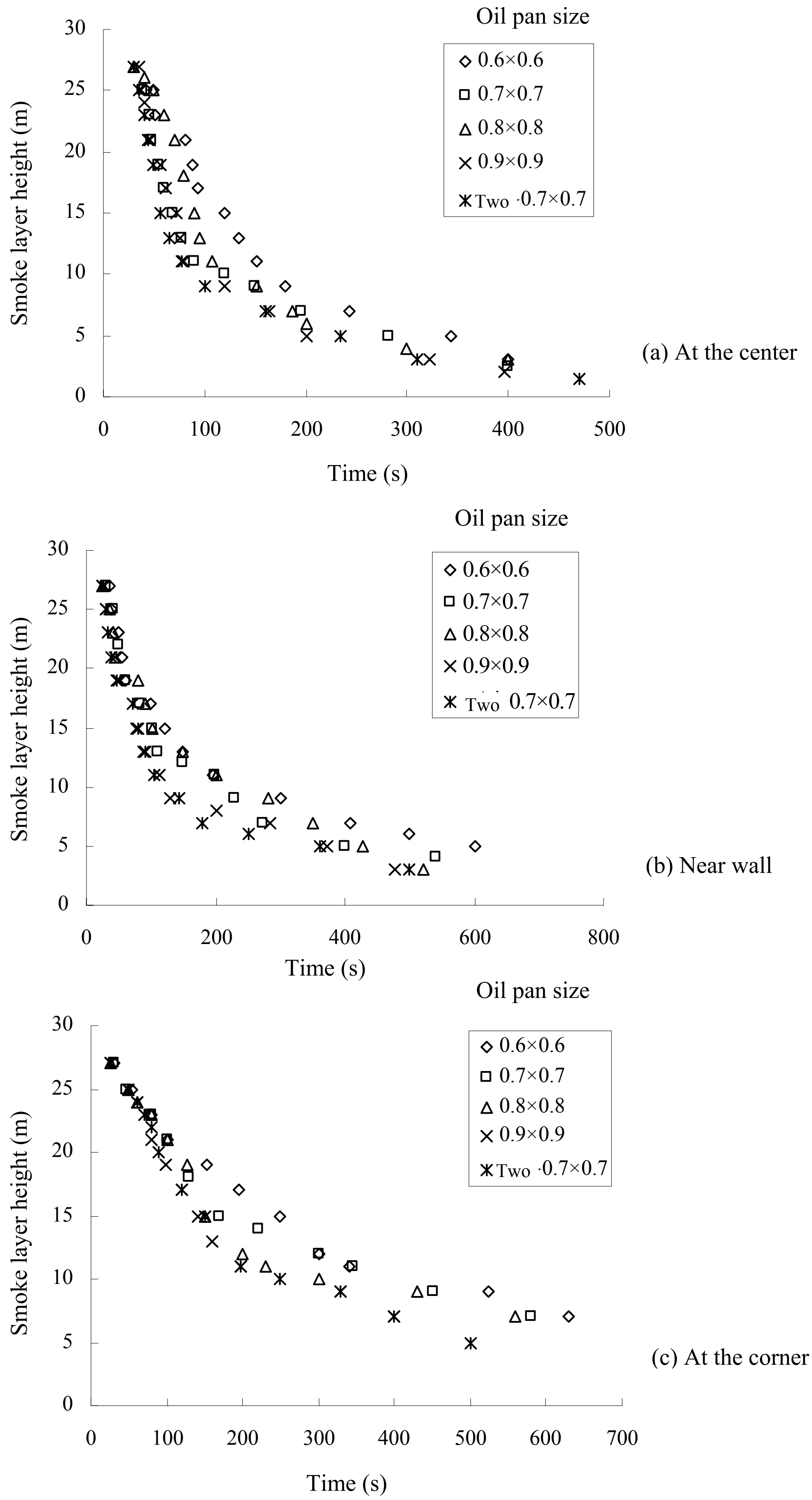
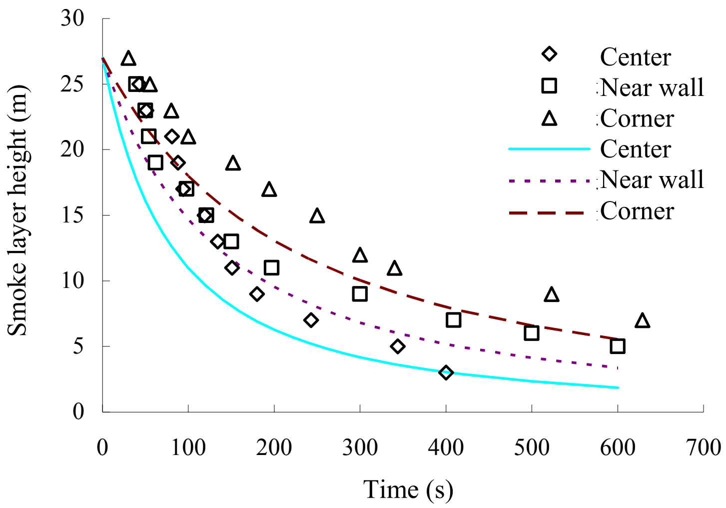


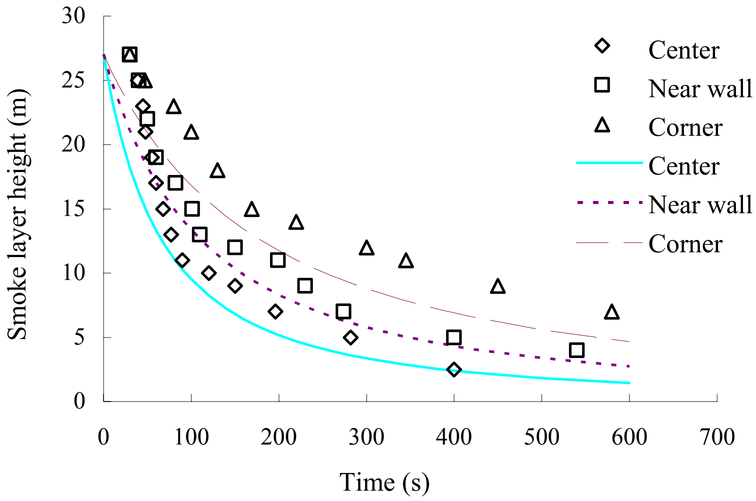
Fig. 1: Comparison of smoke layer height for fires at the same position but of different sizes

4.2.2 Comparison of smoke layer height for fires at different positions

The results of the smoke layer height under five different fire sizes at the center, near wall and at the corner are shown in Fig. 2. It can be seen that the smoke descending rate was the faster when the fire was located at the center, and the rate was the slowest for the fire located at the corner. For the case with the oil pan of size 0.6 m x 0.6 m, it took about 200 s for the smoke to descend to 7 m for the fire at the center, but it took about 410 s for the case with the fire near wall, and 600 s for the case with the fire at the corner. As the oil pan size increased, the smoke descending rate increased, and the effect of the fire position also decreased. For example, in the case with two oil pans of size 0.7 m x 0.7 m, it took about 200 s for the smoke to descend to 5 m for the fire at the center, but it took about 300 s for the case with the fire near wall, and 500 s for the case with the fire at the corner. The calculation results by substituting Zukoski's plume model into the equation for smoke layer height are shown as the curved line in the figure. It can be seen that the results agreed fairly well. The calculated smoke descending rates are generally faster than the experimental results.

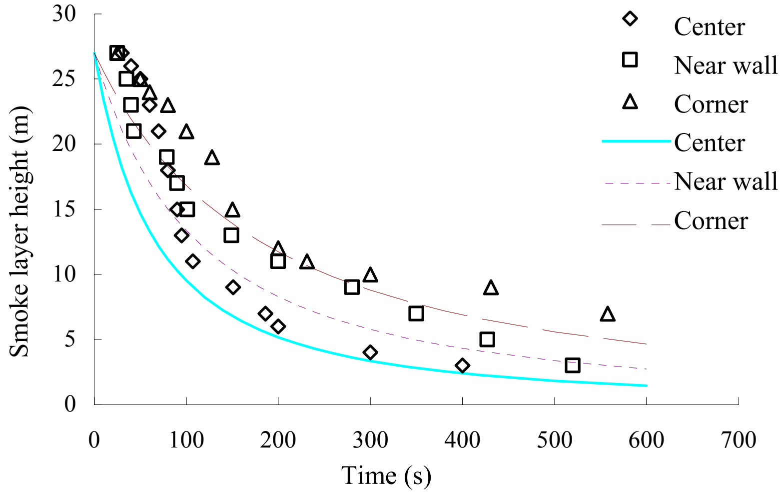


(a) 0.6 m × 0.6 m oil pan

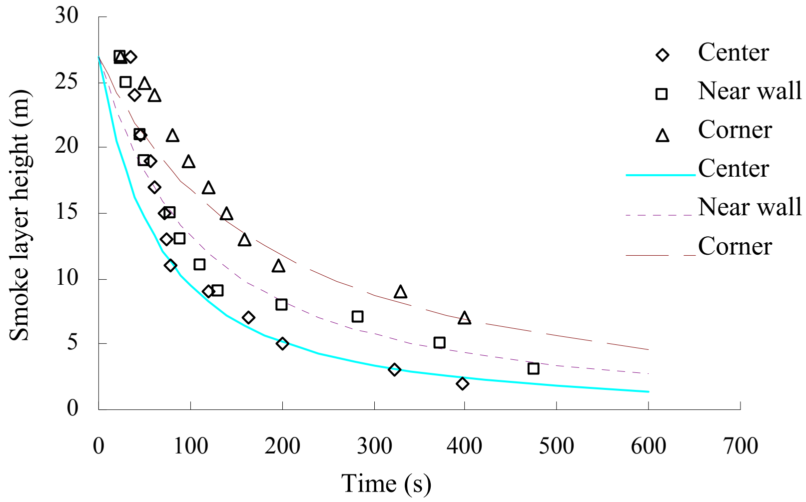


(b) 0.7m ×0.7m oil pan

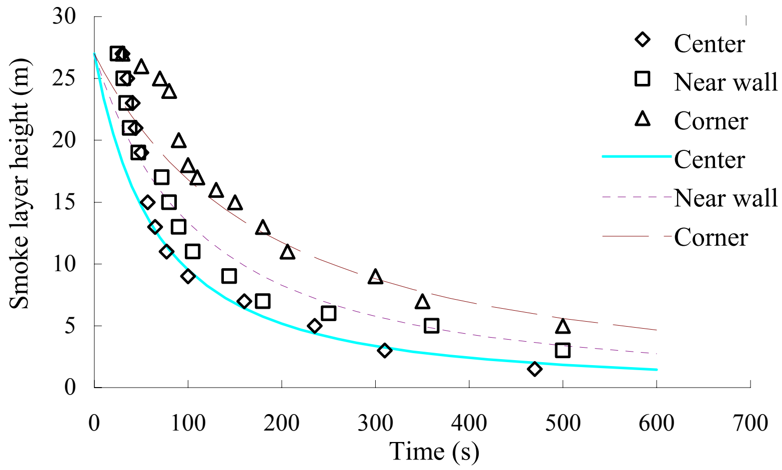
Fig. 2: Comparison of smoke layer height for fires of the same size but at different positions



(c) 0.8 m × 0.8 m oil pan



(d) 0.9 m × 0.9 m oil pan



(e) Two 0.7 m × 0.7 m oil pans

Fig. 2 (cont'd): Comparison of smoke layer height for fires of the same size but at different positions

4.3 Improvement of C Value

The values of $Z^{-2/3} - t$ for fires at the center, near wall and at the corner are plotted in Figs. 3 to 5. According to equation (6), the value of the entrainment coefficient C for each experiment can be calculated from the gradient k, heat release rate Q and the plane area A. In this study, the area of the large space is 266.56 m^2, the values of heat release rate Q, gradient k and entrainment coefficient C for each experiment are listed in Table 2.

The average plume entrainment coefficients for fires at different positions are:

At the center:

$$C_a = \frac{0.0707 + 0.0707 + 0.0709 + 0.0723 + 0.0732}{5} = 0.0716$$

Near wall:

$$C_w = \frac{0.0436 + 0.041 + 0.0406 + 0.0415 + 0.0433}{5} = 0.042$$

At the corner:

$$C_c = \frac{0.025 + 0.027 + 0.025 + 0.0236 + 0.025}{5} = 0.025$$

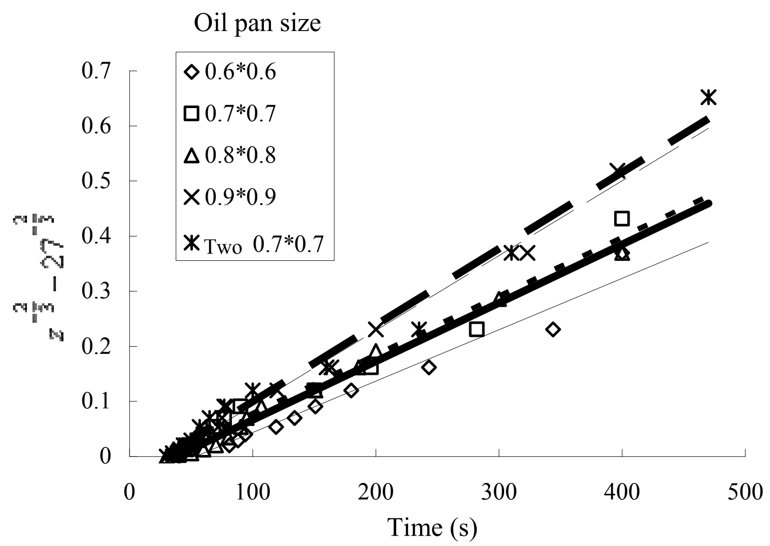


Fig. 3: Processed experimental data for fires at the center

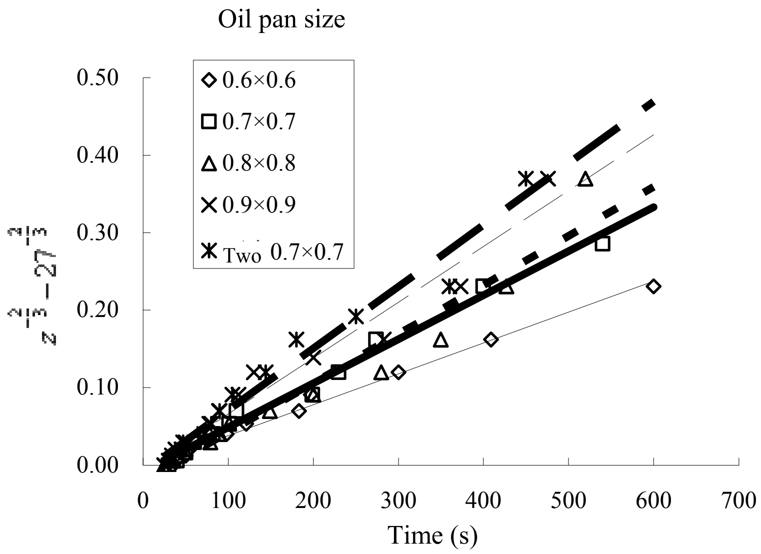


Fig. 4: Processed experimental data for fires near wall

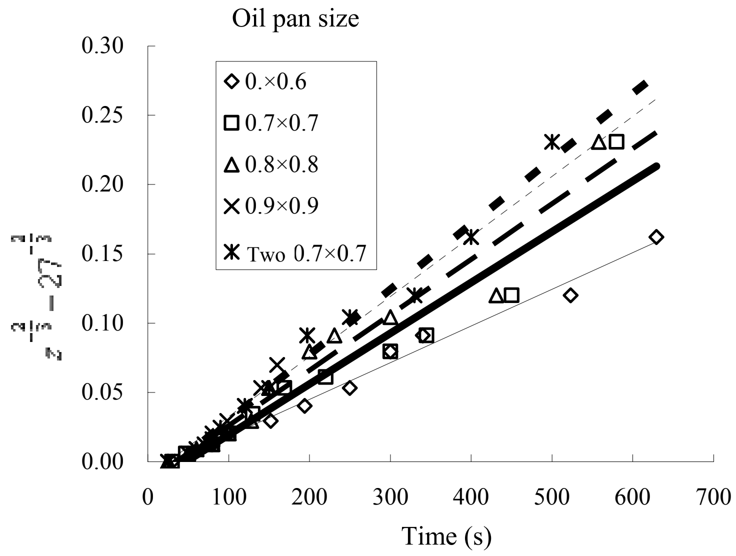


Fig. 5: Processed experimental data for fires at the corner

Table 2: Values of heat release rate Q, gradient k and entrainment coefficient C in each experiment

Expt. no.	Heat release rate (kW)	Gradient *k*	*C*
1	336	0.0009	0.0707
2	612.5	0.0011	0.0707
3	609	0.0011	0.0709
4	945	0.0014	0.0723
5	1142.4	0.0014	0.0732
6	298.2	0.0004	0.0436
7	509.6	0.0006	0.041
8	525	0.0006	0.0406
9	783	0.0007	0.0415
10	1024	0.0008	0.0433
11	298.2	0.0003	0.025
12	504	0.0004	0.027
13	676.2	0.0004	0.025
14	793.8	0.0004	0.0236
15	1302	0.0005	0.025

5. CONCLUSION

Fifteen sets of experiments were carried out with five different heat release rates and three different fire positions in a large space. It was found that the smoke descending rate is highly related to the heat release rate and the position of the fire source. The higher the heat release rate, the faster the smoke descending rate, which is approximately proportional to 1/3 power of the heat release rate. Also, the plume entrainment rates are different for different fire positions. The plume entrainment rates at the center, near wall and at the corner are 0.072, 0.042, and 0.025 respectively. The entrainment coefficients for fires near wall and at the corner are slightly smaller than the values obtained from mirror-reflection analysis.

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