A STUDY OF THERMAL RADIATION SPREADING DISTANCE ABOUT MOTORCYCLE FIRES IN ARCADE BUILDINGS

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ABSTRACT

Arcades are very popular in street buildings and motorcycles are one of the most popular transportation vehicles in Taiwan. Local motorcyclists are accustomed to parking their vehicles near the arcades along the street. The common phenomenon of an arcade crowded with motorcycles makes a fire in such an arcade, whether it is by accident or arson, highly dangerous as it can lead to disastrous losses of human lives and properties. This study aims at collecting data regarding thermal radiation to nearby buildings and combustibles during a motorcycle fire in the arcade. Four experiments were done with actual-size motorcycles at a two-story three-span full-scale RC building. The results showed that when eight motorcycles were burning in an arcade of 4.5 m (wide) × 3 m (high), the fire zone temperature could be as high as 983 ^{o}C. To avoid thermal radiation spreading, the safety distance needed between lumber and the geometric center of the arcade front would be 6.6 m. As for plastic materials used in the external structure of a motorcycle, ABS, PMMA, PP, PU and PVC, their safety distances from the geometric center would be from 5.98 m to 10.79 m. Further analysis demonstrated that whether the arcade front was in square or rectangle, the surface, which was x_c away from the geometric center, had received the maximum thermal radiation. The edges of this surface had received the minimum thermal radiation. In addition, the thermal radiation received on this surface was axially symmetric.

1. INTRODUCTION

Taiwan is a populated island. Because of too many people and too little space for parking in Taiwan cities, the motorcycle, which is easy and quick to move and park, has become a convenient and efficient vehicle. No wonder it has now become the most important daily transportation means in Taiwan. According to figures released by the Ministry of Transportation and Communications, there were 12,747,013 registered motorcycles in Taiwan by the end of October 2004, an average of 356.4 motorcycles per square kilometer, and one motorcycle for every 1.8 persons. Surveys and Ministry of the Interior figures show the average length of a motorcycle is 1.5 m and Taiwan's coastline is 1139.25 km long. If we line up one by one all these motorcycles, the total length would be 19,120.52 km, which can go around the coastline for 16.8 rounds.

As the per capita income of residents in metropolitan areas is higher, they tend to buy more cars. So theoretically there should be fewer motorcycles in big cities. However, on the contrary, we keep seeing more and more motorcycles running in metropolitan areas in Taiwan. The density is getting higher and higher without any signs of improvement. In Taipei City, for example, there were 1,017,964 registered motorcycles by the end of October 2004 (only those owned by registered residents, excluding those entering from other counties and cities). This equaled to 3,745.3 motorcycles per square kilometer and one motorcycle for every 2.6 persons. See Table 1.

As motorcycles keep increasing in Taiwan, the danger of a motorcycle fire has become a serious safety concern and a potential source of disasters. To make things worse, most of the motorcycle fires reported thus far were caused by deliberate arson. Taipei City Government fire statistics show there were 383 motorcycle fires in total between 1999 and 2002. Among them, 199 (51.9%) resulted from arson. During the same period, there were 532 arson fires and 199 (37.4%) of them were motorcycle fires. See Table 2.

Table 1: Motorcycle density and ratio of population and motorcycle in Taiwan and Taipei city (Oct. 2004)

Items	Taiwan	Taipei city
Motorcycle	12,747,013	1,017,964
Area (km^2)	35,765.7	271.8
Population	22,604,550	2,627,138
Ratio of motorcycle / area (per km^2)	356.4	3,745.3
Ratio of population / motorcycle	1.8	2.6

Table 2: Causes and numbers of fires reported in Taipei city (1999~2002)

Fire causes	Total	Fire patterns	
		Motorcycle fire	Non-motorcycle fire
Arson	532	199	333
Other	2786	184	2602
Total	3318	383	2935

With the crowded parking patterns in Taiwan, regardless of being caused by inappropriate usage of fire sources, deliberate arson, self-burning, or natural factors, whenever a motorcycle fire occurs, it would result in heavy casualties and property loses. This kind of fires may even arouse social instability. Two noticeable examples are the fire in Lu Chou, Taipei County, at a residential complex on August 31, 2003, and the fire at a Taipei County Hsin-Ban motorcycle parking lot on July 14, 2004. Fifteen persons were dead, 69 injured and 64 motorcycles burnt out after the first fire spread from motorcycles parked nearby, two eight-story apartment buildings seriously damaged also. Although there was no casualty in the second fire, 97 motorcycles were completely burnt and 150 half destroyed.

As for arcaded buildings, many were built in the past because the authorities once encouraged such buildings by providing incentives, including higher building coverage ratio, with a view to promoting commercial development, protecting pedestrian safety, and maintaining an efficient traffic flow. Consequently, the arcaded building has become a unique and popular building style in Taiwan.

Unfortunately, the authorities do not provide any proper management and planning of motorcycle parking while motorcyclists only care about parking convenience rather than safety. Thus, crowded motorcycles are frequently seen under or around the arcades in front of street buildings. Should a motorcycle fire break out; it would burn fiercely and spread quickly. Not only will the motorcycles and neighboring buildings be burnt, the flames and heavy smoke will make it difficult for those inside the buildings to escape. Major casualties and property losses will be inevitable.

According to the results of the full-scale burning tests done in this study, when a motorcycle fire broke out in an arcade, the arcade itself would be filled with flames and smoke. The fire would spread to the ceiling by up-going flames and continue along the ceiling to reach the façade of the second floor. Any combustible items close to the window, such as curtains or wooden furniture, would be easily ignited. Then the flames of first and second floors would join together and go in the vertical direction. Meanwhile, the thermal radiation accumulated on the ceiling and the flames extending to the right and left sides would ignite not only neighboring motorcycles but also any combustible objects in the arcade. This means the flames would also go horizontally. The fire spread from one span to another while moving still upward. In the end, the fire would devour the whole arcaded building.

We know from these results that it is important to find out how factors such as flame height, fire zone temperature, and thermal radiation affect the arcaded building itself and surrounding combustibles during a motorcycle fire. The information is very useful for preventing the fire from spreading.

2. SURVEYS ON CURRENT STATUS

This study did two surveys before the fire experiments. One was on the models and usage patterns of motorcycles in Taiwan. The other was on how these vehicles were parked under and around the arcade.

2.1 Market Shares of Different Motorcycle Models in Taiwan

According to figures released by the Taiwan Transportation Vehicle Manufacturers Association, the most popular motorcycle models on the island were the 50CC, 100CC, and 125CC. In 2003, for example, their market shares were 23.86%, 25.27%, and 45.17%, respectively, as listed in Table 3. They accounted for 94.30% of the market in total.

2.2 The Types and Nature of Motorcycle Materials

In general the materials found in a motorcycle can be divided into the metallic and the non-metallic. The non-metallic can be further divided into plastic and rubber materials. Plastic materials are widely used in the external structure. They account for 16% of the motorcycle weight [1]. See Fig. 1.

Plastic materials used for the motorcycle body and seat cushion are mostly PP, ABS, PMMA, PU, and PVC [2]. Among them, PP's weight accounts for 63% of all the plastic materials [3], as shown in Fig. 2. The materials of the cushion, the body and tires are shown in Fig. 3.

Table 3: Market shares of different motorcycle models in Taiwan (%)

Model	2002	2003	2004 (Jan~ Oct)
50CC	28.49	23.86	14.48
80CC	1.89	0.00	0.00
90CC	11.19	3.14	1.37
100CC	17.79	25.27	32.08
110CC	0.07	0.01	0.00
125CC	36.15	45.17	49.47
135CC	0.00	0.00	0.00
150CC	3.28	2.26	2.15
180CC	0.16	0.22	0.15
250CC	0.97	0.06	0.29
Other	0.01	0.01	0.01

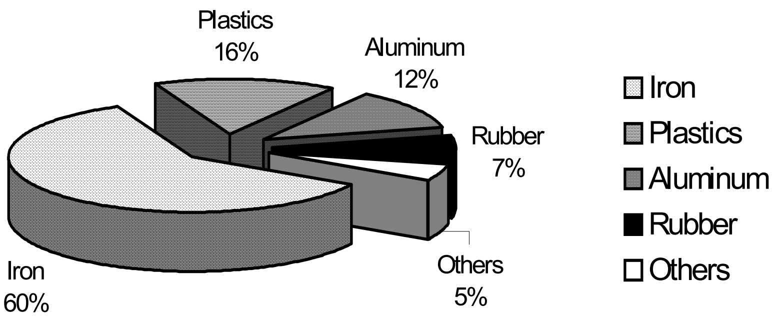


Fig. 1: Percentage of motorcycle materials by weight

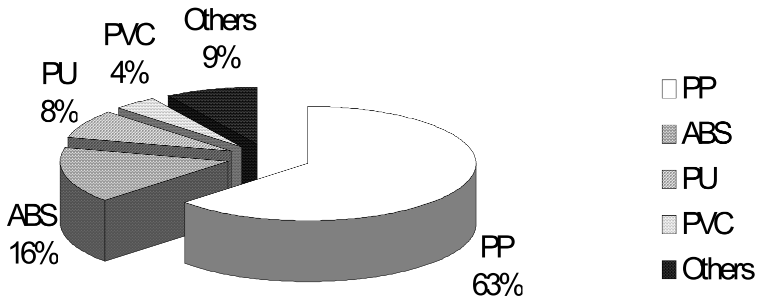


Fig. 2: Types of plastic materials used by motorcycles and percentage by weight

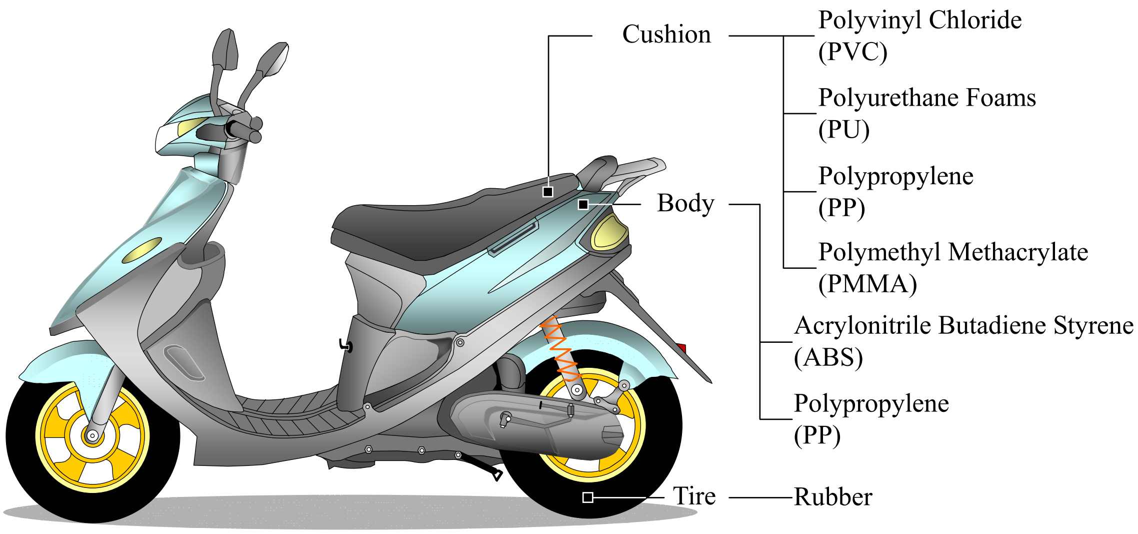


Fig. 3: Plastic materials of seat cushion and body

Table 4: The ignition temperature, decomposition temperature and radiation ignition threshold of plastic materials used by motorcycle

Plastic Material	Ignition temperature * (^{o}C)	Decomposition temperature (^{o}C)	Radiation ignition threshold ** (kWm^{-2})
ABS	455	400	14.9
PMMA	440	340	14.7
PP	565	400	14.8
PU	405	400	5.0
PVC	440	400	14.9

*Setchkin Test, ASTM D1929
**Cone Calorimeter Test, ASTM E1354

The decomposition temperature [4], ignition temperature and radiation ignition threshold [5] of plastic materials used in the motorcycle are listed in Table 4. From previous experiments we know that lighters sold in the marketplace can produce flame temperature as high as 600~700^{o}C in a windless environment. Therefore, if any improper fire source such as a torch or a petrol bomb reaches the outer plastic components of a motorcycle, it is quite easy to ignite a fire. In this perspective, we can conclude that crowded motorcycles parked in the arcade do pose danger to lives and properties.

2.3 Motorcycle Parking Patterns

A survey of motorcycles parked under and around the arcade in Taipei City indicated that there are in general four patterns: directly under the arcade, only in front of the arcade, both under and in front of the arcade, and those parked in other ways. The survey was done on streets downtown Taipei, including Roosevelt Road, Kee-lung Road, Ho-ping East and West Roads, Nan-yang Street, Tun-hua South Road and Po-ai Road with 674 valid samples. One sample means an arcade in front of a store. From Table 5 we can see the pattern of parking motorcycles directly under the arcade accounted for 62.9%, the highest percentage among the four.

3. EXPERIMENT PLAN

In order to know the nature of motorcycle fires and their damaging effects to arcaded buildings, this study, based on past study results [6] and data research, had targeted at exploring the burning behavior of 50CC and 125CC motorcycles in arcaded buildings. Four experiments were planned as seen in Table 6.

3.1 Experiment Description

The arcaded building used in the experiments was a full-scale two-story, three-span RC building. The floor area of both stories was 86.25 m^2. Fig. 4 shows its outlook and detailed measurements. Regardless of the quantity, motorcycles were all parked in a line and close to the front edge. This is the most common way seen in Taipei streets. From Fig. 4 we can tell the three spans of the building did not equal in width. The middle span was 4.5 m wide and the side spans were 3.5 m wide. Before each experiment started, all fuel tanks of the motorcycles would be emptied. The deployment of thermocouples, radiometers and other measurement equipment is shown in Fig. 5.

Table 5: Motorcycle parking patterns under and around arcade

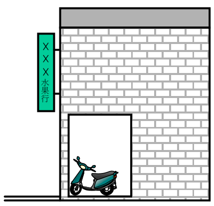
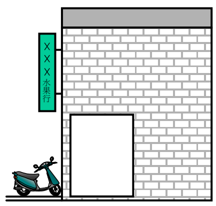
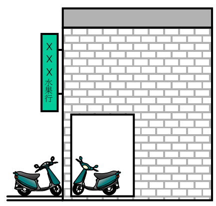
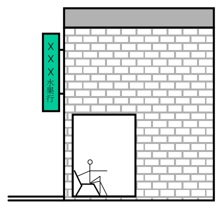
Under	In front	Both under and in front	Other
			
62.9%	18.6%	12.0%	6.5%

Table 6: Experiment plan for motorcycle fires in arcades

Ex. No.	Motorcycle model	Motorcycle quantity	Experiment place	Ignition position
1	50 CC	8	Within the arcade	IPc_8
2	125 CC	8	Within the arcade	IPc_8
3	50 CC	8	Within the arcade	IPs_8
4	50 CC	3	Within the arcade	IPc_3

Note: I: ignition, P: position, c: center, s: side, 8: eight motorcycles, 3: three motorcycles.

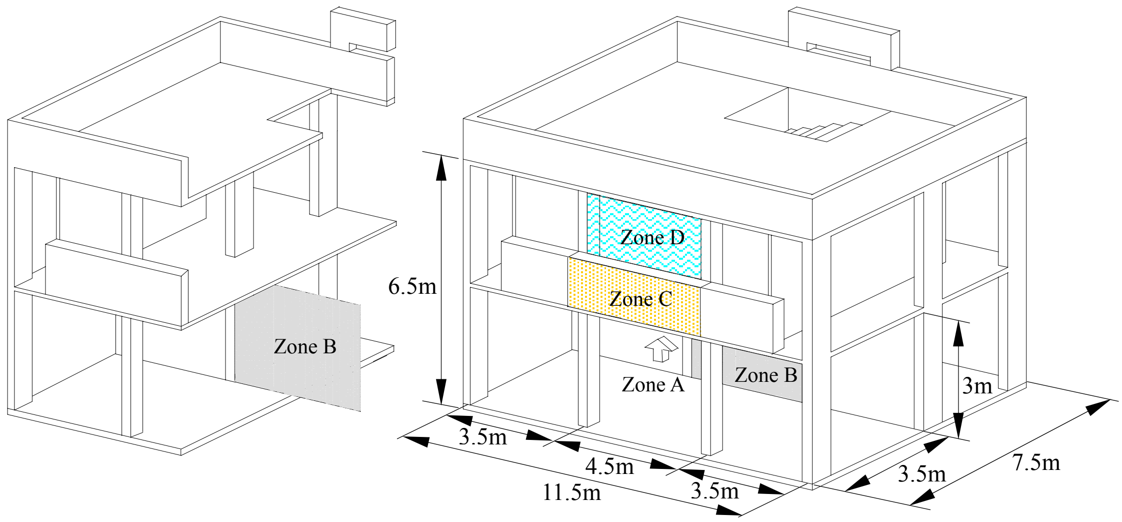


Fig. 4: Full-scale arcaded building used in the experiments (two-story and three-span)

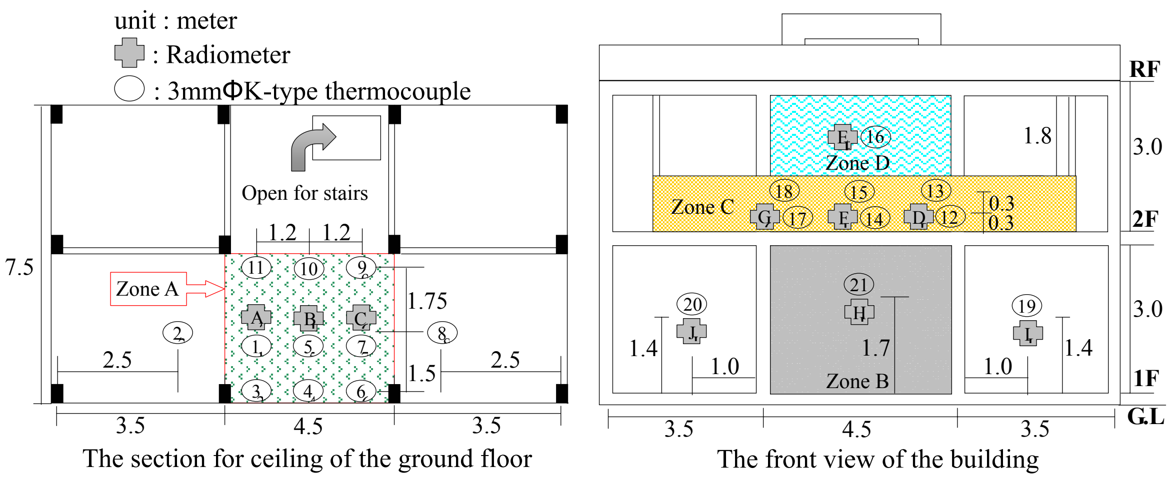


Fig. 5: Deployments of thermocouples and radiometers

3.2 Experiment Process

1. Thermal radiation from the flames was measured by water-cooling radiometers (Two types, 500kWm^{-2} and 1000 kWm^{-2}, were used).
2. Fire zone temperature was measured by K type thermocouples (0.3 mm Φ).
3. Flame height was recorded by video camera all through the experiments.
4. All digital data collected during the experimental process were recorded by the data logger every two seconds.
5. The hygrometer and anemometer were used to measure the humidity and wind velocity in the surrounding environment.
6. Motorcycles were ignited by kerosene. A round metal box, 0.3 m in diameter and containing 200 ml kerosene, would be placed on the floor beneath the motorcycle, which was to be lit up.
7. The 50CC motorcycle used to enjoy a larger market share than the 100CC model for it is more convenient for woman motorcyclists. In 2002, the 50CC model accounted for 28.49% of the market and the 100CC for 17.79%. Only starting from 2003, there were gradually more 100CC models sold than 50CC models due to production technology improvements. But there are still more 50CC motorcycles running in the streets in Taiwan. This study then chose the 50CC and 125CC models to be fire-testing specimens.

4. EXPERIMENT RESULTS

Flame height, fire zone temperature and thermal radiation are all important factors that would affect the safety of buildings and human beings should a motorcycle fire break out. This study, therefore, focused on these three areas during the experiment process and gained the following results.

4.1 Burning Behavior of Different Models

Eight 50CC motorcycles were parked in a line along the front edge of the arcade during the first experiment. They were situated between the two columns of the middle span. Fire ignition position was IPc_8. See Fig. 6.

During the second experiment all conditions remained the same as the first one except that the specimens were changed into 125CC motorcycles. According to data collected in the first two testing, there was not much difference between the burning behavior of both the 50CC and 125CC models as reflected in maximum flame height, highest arcade ceiling temperature, and maximum thermal radiation. See Table 7, Figs. 7 and 8.

4.2 Motorcycle Fire Behavior Affected by Different Ignition Positions

The third test aimed at finding out the relationship between ignition position and fire behavior of motorcycles. The ignition position was changed from IPc_8 to IPs_8 while other conditions remained the same as the first test. See Fig. 6 for ignition position of this test. The results from comparison between the first and third tests are shown in Table 8 and Figs. 9 and 10. We can see in Table 9 that it took less time to reach the highest fire zone temperature and the maximum thermal radiation when a fire was ignited at IPc_8 than at IPs_8.

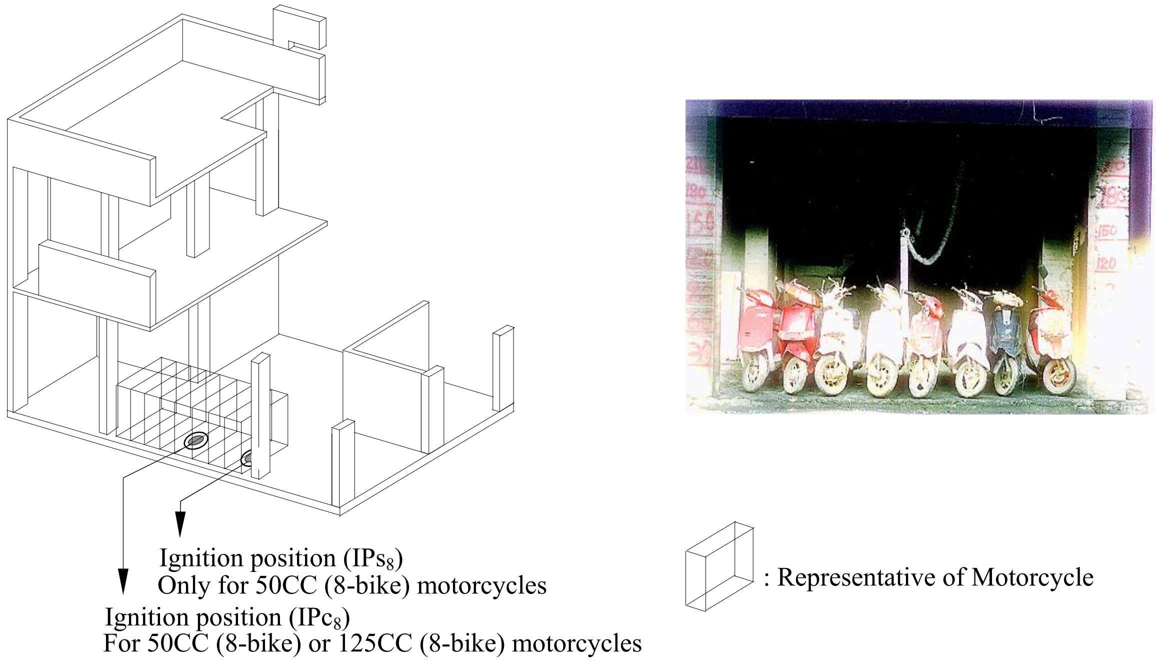
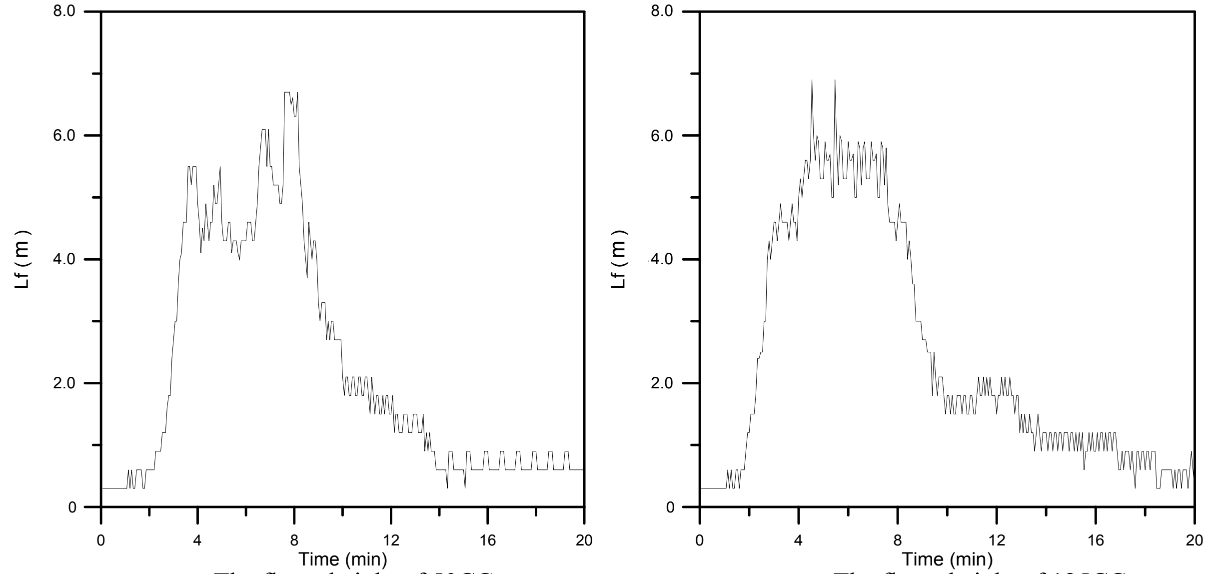


Fig. 6: Fire ignition positions for eight 50CC or 125CC models

Table 7: Results of first two experiments

Ex. No.	Model	Ignition position	Maximum flame height	Arcade ceiling right above motorcycle (zone A)	
				Highest temperature	Maximum thermal radiation
				Testing point 5	Testing point B
1	50CC	IPc_8	6.7 m	876 °C	123 kWm^{-2}
2	125CC	IPc_8	6.9 m	815 °C	117 kWm^{-2}



The flame height of 50CC
Ignition position: IPc_8

The flame height of 125CC
Ignition position: IPc_8

Fig. 7: Comparison of flame height between 50CC and 125CC models burning tests

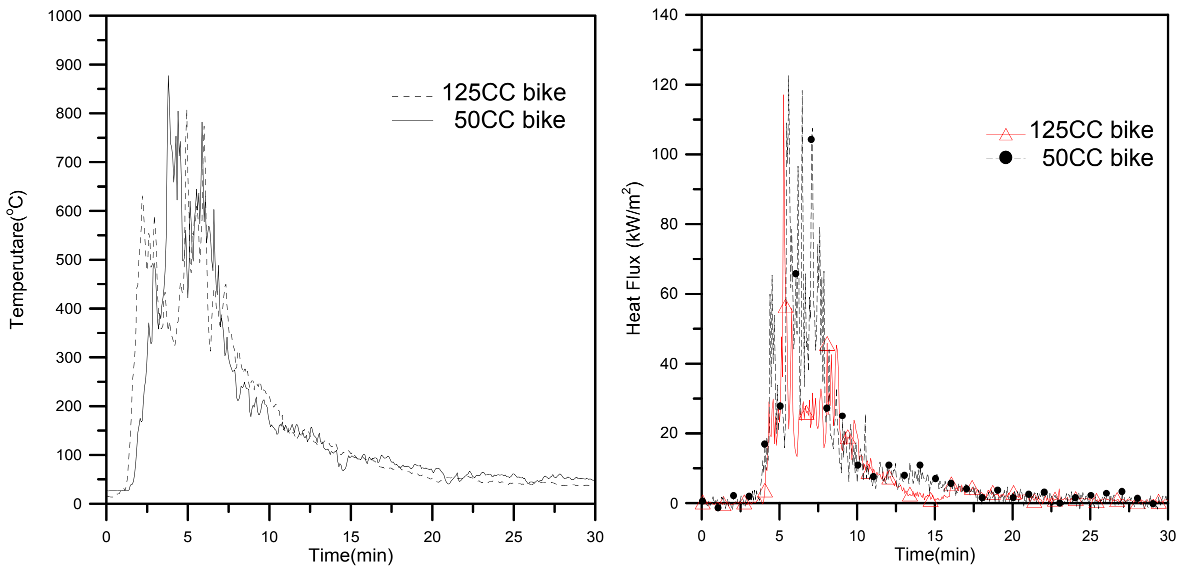
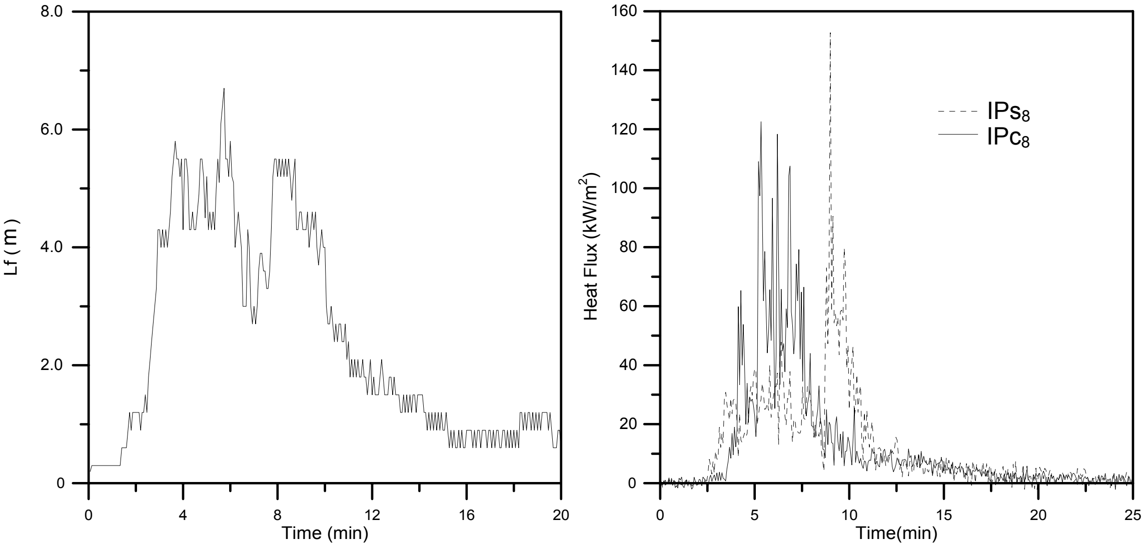


Fig. 8: Comparison of temperature and thermal radiation on ceiling between 50CC and 125CC models burning tests

Table 8: Experiment results of different ignition positions

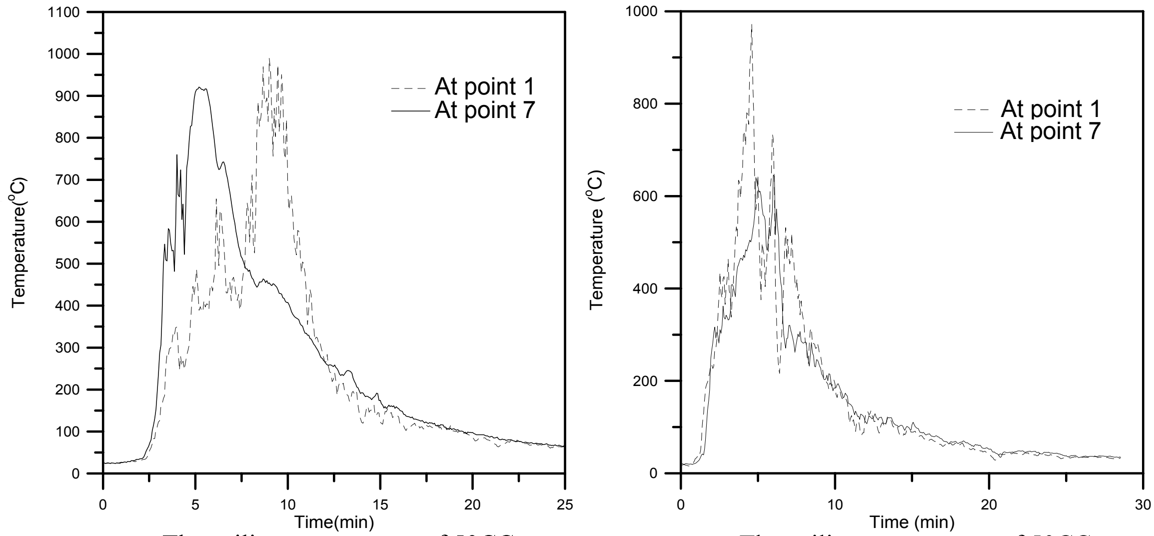
Ex. No.	Model	Ignition position	Maximum flame height	Arcade ceiling right above motorcycle (zone A)	
				Highest temperature	Maximum thermal radiation
				Testing point 1	Testing point B
1	50CC	IPc_8	6.7 m	977 °C	123 kWm^{-2}
3	50CC	IPs_8	6.7 m	983 °C	151 kWm^{-2}



The flame height of 50CC
Ignition position: IPs_8

The thermal radiation on ceiling of 50CC
Ignition position: IPc_8 and IPs_8

Fig. 9: Flame height and thermal radiation on ceiling during 50CC experiments



The ceiling temperature of 50CC
Ignition position: IPs_8

The ceiling temperature of 50CC
Ignition position: IPc_8

Fig. 10: Ceiling temperature for different ignition positions

Table 9: Time needed for different ignition positions to reach the highest temperature and the maximum thermal radiation

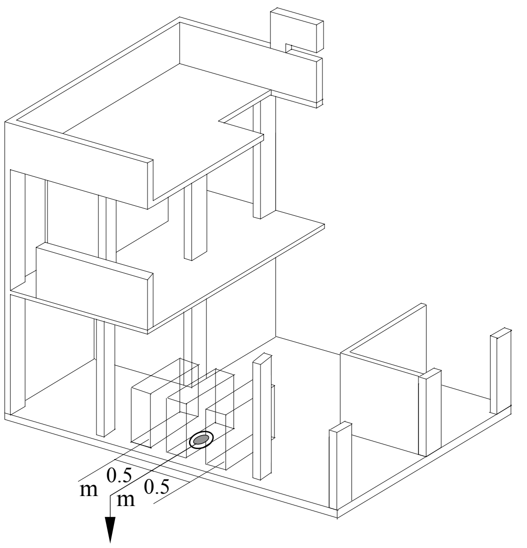
Ex. No.	Model	Ignition position	Arcade ceiling right above motorcycle (zone A)		
			Time needed to reach highest temperature		Time needed to reach maximum thermal radiation
			Testing point 1	Testing point 7	
1	50CC	IPc_8	4.5 min	5.0 min	5.8 min
3	50CC	IPs_8	9.0 min	5.4 min	8.8 min

4.3 Fire Behavior of Different Motorcycle Quantities

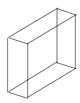
Since the fire behavior of the 50CC model in an arcaded building was similar to that of the 125CC model according to results of the third experiment, this study decided to use the 50CC bike to do the fourth experiment.

We had learned from the third experiment that the damages to nearby buildings or human lives or properties were more serious when motorcycles were ignited at IPc_8 than at IPs_8. Since we wanted to simulate the most dangerous situation during a motorcycle fire in the arcade so that we could design the best prevention strategy to stop the fire from spreading, the ignition position for the fourth experiment was set at IPc_3, as shown in Fig. 11.

The only difference between the first and the fourth experiments were the numbers of bikes used. The first was eight and the fourth three. Other conditions remained the same. Comparing the results, we know that the highest temperature and maximum thermal radiation recorded at the fire zone would increase when there were more motorcycles. The time needed to reach the highest temperature and thermal radiation would decrease as the bike quantity increased. Table 10 compares the results of the first and fourth experiments. Figs. 12 and 13 demonstrate how the specimen bikes were burning in the arcade.



Ignition position (IPc_3)
Only for 50CC (3-bike) motorcycles



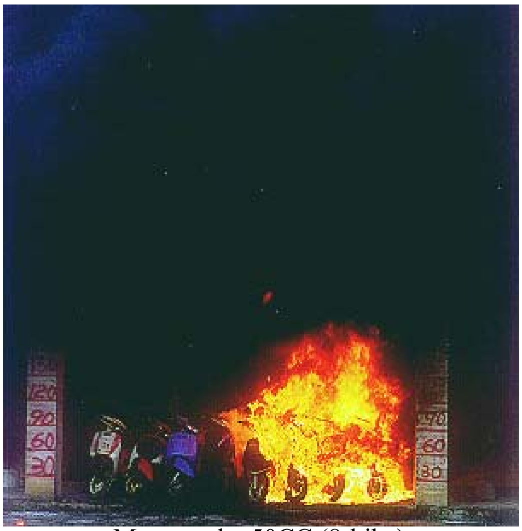
: Representative of Motorcycle

Fig. 11: The positions of three 50CC motorcycles in the fourth experiment

Table 10: Experimental results of different numbers of motorcycles

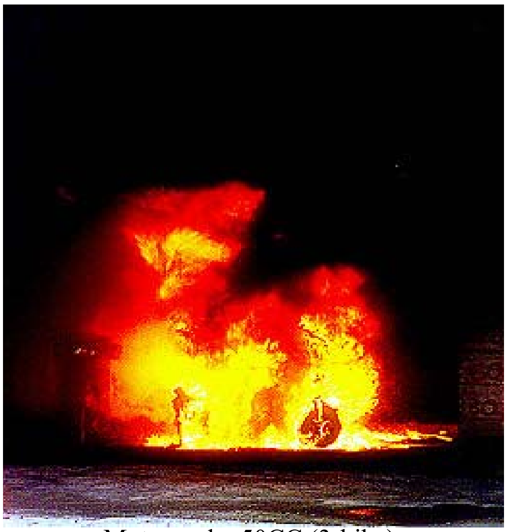
Item	Ex. No.	Ground floor		Second floor	
		Arcade ceiling (Zone A)	Store front (Zone B)	Window ledge (Zone C)	Window opening (Zone D)
Highest temperature (°C)	1	977.0	241.0	609.0	93.3
	4	576.0	92.3	227.0	58.0
Time needed to reach highest temperature (sec)	1	270.0	310.0	330.0	456.0
	4	696.0	652.0	788.0	794.0
Maximum thermal radiation (kWm^{-2})	1	123	3	7	22
	4	87	3	1	5
Time needed to reach maximum thermal radiation (sec)	1	348.0	318.0	319.0	428.0
	4	738.0	666.0	816.0	792.0

Motorcycle: 50CC (8-bike)
Ignition position: at IPc_8



Motorcycle: 50CC (8-bike)
Ignition position: at IPs_8

Fig. 12: Actual burning state at different ignition positions of 50CC bikes



Motorcycle: 50CC (3-bike)
Ignition position: at IPc_3

Motorcycle: 125CC (8-bike)
Ignition position: at IPc_8

Fig. 13: Actual burning state of 50CC and 125CC bikes in the arcade

4.4 Thermal Radiation Spending Distance of Motorcycle Fires in Arcades

When a motorcycle fire breaks out in an arcaded building, it can spread by way of conduction and convection to the building itself, to the pavement, and to combustible items across the fire lane or the street. There is also the third way, by thermal radiation. Thermal radiation is generally calculated by the Stefan and Boltzman law [7], as demonstrated by Formula (1):

$$q'' = \varepsilon \times \sigma \times (T^4 - T_a^4) \quad (1)$$

However, the distance between the combustible and the fire source as well as the thermal radiation angle of incidence will also affect the thermal radiation on the combustible from the fire source. According to Reference [8], when the fire source is rectangular, the thermal radiation on the small area which distance is c away from a fire source corner can be shown as Formula (2):

$$q'' = F_{1-2} \times \varepsilon \times \sigma \times (T^4 - T_a^4) \quad (2)$$

$$F_{1-2}=\frac{1}{2\pi}\times\left(\frac{X}{\sqrt{1^2+X^2}}\times\tan^{-1}\frac{Y}{\sqrt{1^2+X^2}}+\frac{Y}{\sqrt{1^2+Y^2}}\times\tan^{-1}\frac{X}{\sqrt{1^2+Y^2}}\right) \quad (3)$$

$$X=\frac{a}{c},Y=\frac{b}{c} \quad (4)$$

In addition to counting the thermal radiation on the surface of the combustible based on Formulas (2), (3), and (4), we can use the Formulas (5), (6) and (7) resulting from the analysis of this study. Formulas (5), (6) and (7) can be used to calculate the thermal radiation on the surface of 25 points (P_a ~ P_y), which vertical distance is x_c from the fire source. See Fig. 14.

$$R_c=\frac{\varepsilon\times[(\frac{T_r}{T_a})^4-1]}{2.2363+0.09294x_c+0.51283x_c{}^2} \quad (5)$$

$$R_i=\frac{R_c}{1+m_k\times\left\{1-\exp\left[\frac{n_k\times(x_c-x_i)}{x_c}\right]\right\}} \quad (6)$$

$$x_i=\sqrt{x_k{}^2+x_c{}^2} \quad (7)$$

Fig. 15 is a three-dimensional diagram of R_c, R_i, x_c, x_k and x_i.

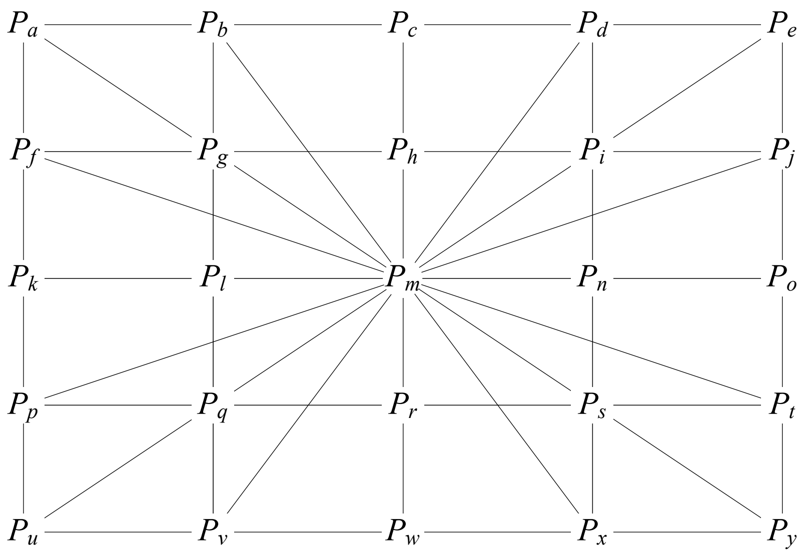


Fig. 14: The 25 points (P_a ~ P_y) on the surface x_c away from fire source

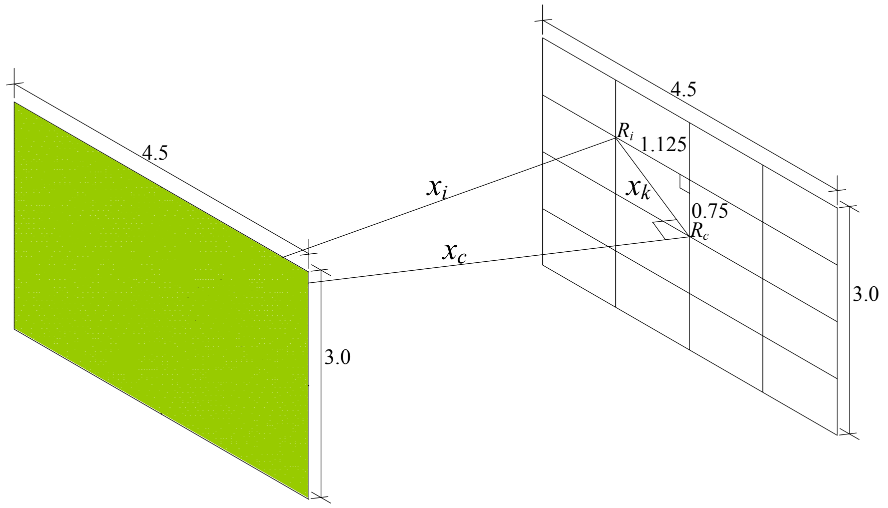


Fig. 15: Three-dimensional diagram of R_c, R_i, x_c, x_k and x_i

The middle span of the experimental arcade was 4.5 m wide and 3.0 m high, as seen in Fig. 4. When the surface, which is x_c away from the arcade front, was divided into 16 segments, each segment would be 1.125 m wide and 0.75 m high. Further analysis indicated that the thermal radiation on the 25 points on this surface was axially symmetric. That is, $P_a = P_e = P_u = P_y$, $P_b = P_d = P_v = P_x$, $P_c = P_w$, $P_f = P_j = P_p = P_t$, $P_k = P_o$, $P_g = P_i = P_q = P_s$, $P_l = P_n$, and $P_h = P_r$, as shown in Fig. 14. The points were defined with new names for the sake of easier differentiation. See Fig. 16.

The distance between the points on the thermal radiation on surface, P_2~P_9, and the geometric center of the surface, P_1, was x_k. The value of x_k is displayed in Table 11.

In Table 11, m_k is transformation coefficient and n_k is transformation index. The values of m_k and n_k are displayed in Table 12.

To confirm the applicability nature of the formulas produced by this study, we had randomly chosen one state for verification. The state was chosen from the third experiment and conditioned as 4.5 m of flame width, 3 m of flame height and 977°C of fire zone temperature, ε=1. The thermal radiation on the 25 points, as shown in Fig. 16, on the surface that was 4 m away from the arcade front is listed in Table 13. This table shows that the results from Formulas (5), (6), and (7) are very close to those of Professor T. Tanaka's Study.

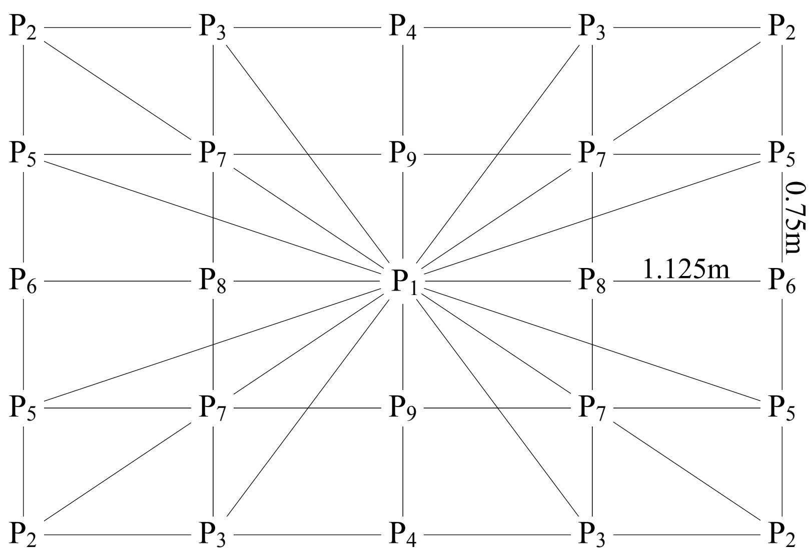


Fig. 16: The names of 25 points on the surface which vertical distance x_c away from fire source

Table 11: Distances between the surface P_2~P_9 and P_1 (m)

Position	x_k
P_1	0
P_2	$\sqrt{(2.25)^2 + (1.5)^2}$
P_3	$\sqrt{(1.125)^2 + (1.5)^2}$
P_4	1.5
P_5	$\sqrt{(2.25)^2 + (0.75)^2}$
P_6	2.25
P_7	$\sqrt{(1.125)^2 + (0.75)^2}$
P_8	1.125
P_9	0.75

Table 12: Values of m_k and n_k (4.5 m × 3.0 m)

Position	m_k	n_k
P_1	0	0
P_2	2.19757	1.72182
P_3	0.79878	4.70100
P_4	0.64469	5.80583
P_5	1.02499	3.64662
P_6	0.79924	4.63727
P_7	0.23025	16.73167
P_8	0.11443	35.11507
P_9	0.10952	35.25442

Table 13: Comparison of values of thermal radiation between this study and Tanaka's study

Position	x_k	x_i	m_k	n_k	This study (kWm^{-2})	Tanaka's study (kWm^{-2})	Error (kWm^{-2})
P_1	0	4	0	0	28.54	28.56	0.02
P_2	2.70416	4.8283	2.19757	1.72182	17.20	17.24	0.04
P_3	1.875	4.41765	0.79878	4.701	21.79	21.83	0.04
P_4	1.5	4.272	0.64469	5.80583	23.58	23.61	0.03
P_5	2.37171	4.65027	1.02499	3.64662	19.57	19.64	0.07
P_6	2.25	4.58939	0.79924	4.63727	20.45	20.53	0.08
P_7	1.35208	4.22234	0.23025	16.73167	25.05	25.09	0.04
P_8	1.125	4.15519	0.11443	35.11507	26.30	26.31	0.01
P_9	0.75	4.06971	0.10952	35.25442	27.17	27.21	0.04

Our analysis shows that the coefficients of the denominator in Formula (5) (2.2363, 0.09294, and 0.51283), and the values of m_k, n_k in Table 12 are only applicable when the arcade front is rectangular and 3 m high, 4.5 m wide. Should the height or width change, the coefficients and values of m_k, n_k will change accordingly. For example, when the arcade is 3 m high and wide, the coefficients in Formula (5) should change into 2.23629, 0.03547, and 0.77737 while values of m_k, n_k should be taken from Table 14.

The experimental results of this study indicate that, as long as the fire source is rectangular, the thermal radiation on the surface of any object is mainly affected by the distance between the object and the fire source (x_c or x_i) and the temperature of the fire source (T_r). When fire source temperature is certain, thermal radiation will reduce as the distance increases. See Fig. 17. When the distance between the fire source and the object is certain, thermal radiation will increase as the temperature increases. See Fig. 18. The thermal radiation on the receiving surface showed axial symmetry, as shown in Fig. 19. The other affecting factors are emissivity (ε) and ambient temperature (T_a). This means $R_c = f(\varepsilon, T_r, T_a, x_c)$. See Formula (8).

$$R_c = \frac{\varepsilon \times [(\frac{T_r}{T_a})^4 - 1]}{c_1 + c_2 x_c + c_3 x_c^2} \tag{8}$$

Table 14: Values of m_k, n_k (3.0 m × 3.0 m)

Position	m_k	n_k
P_1	0	0
P_2	2.69975	0.90818
P_3	0.75400	4.58207
P_4	0.69047	5.54708
P_5	1.01588	1.94362
P_6	0.75518	2.29683
P_7	0.25069	9.67697
P_8	0.11650	14.94986
P_9	0.11508	33.86674

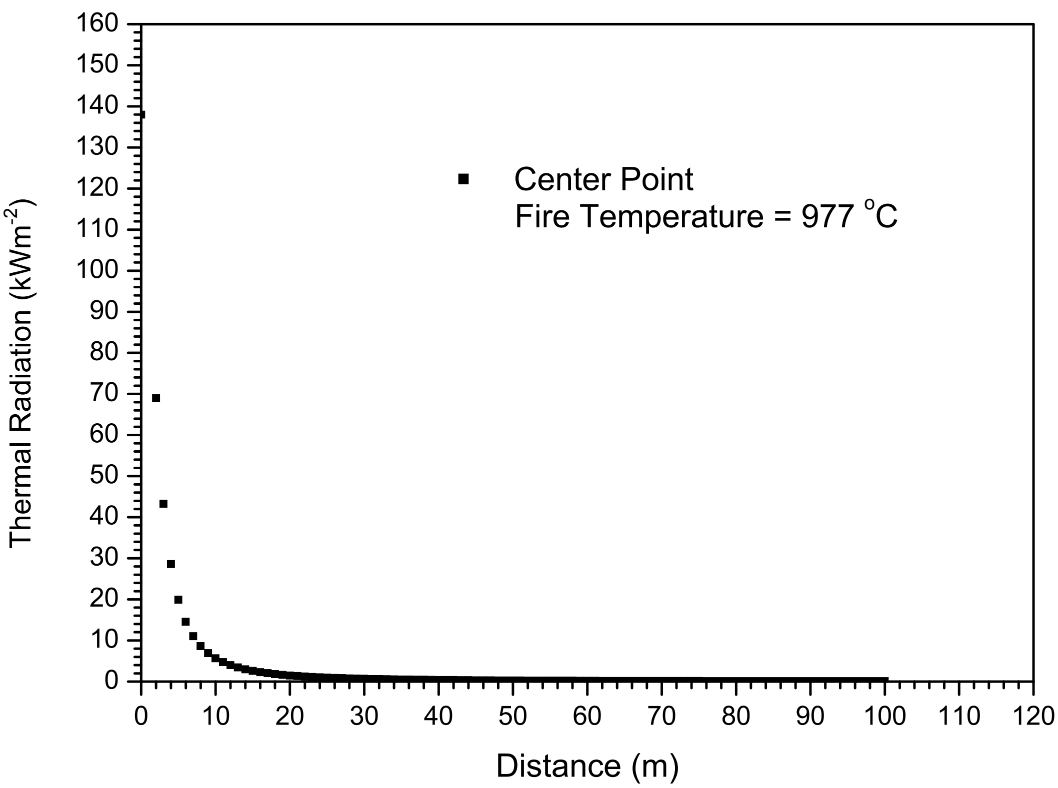


Fig. 17: Relationship between thermal radiation and distance when T_r = 977 °C

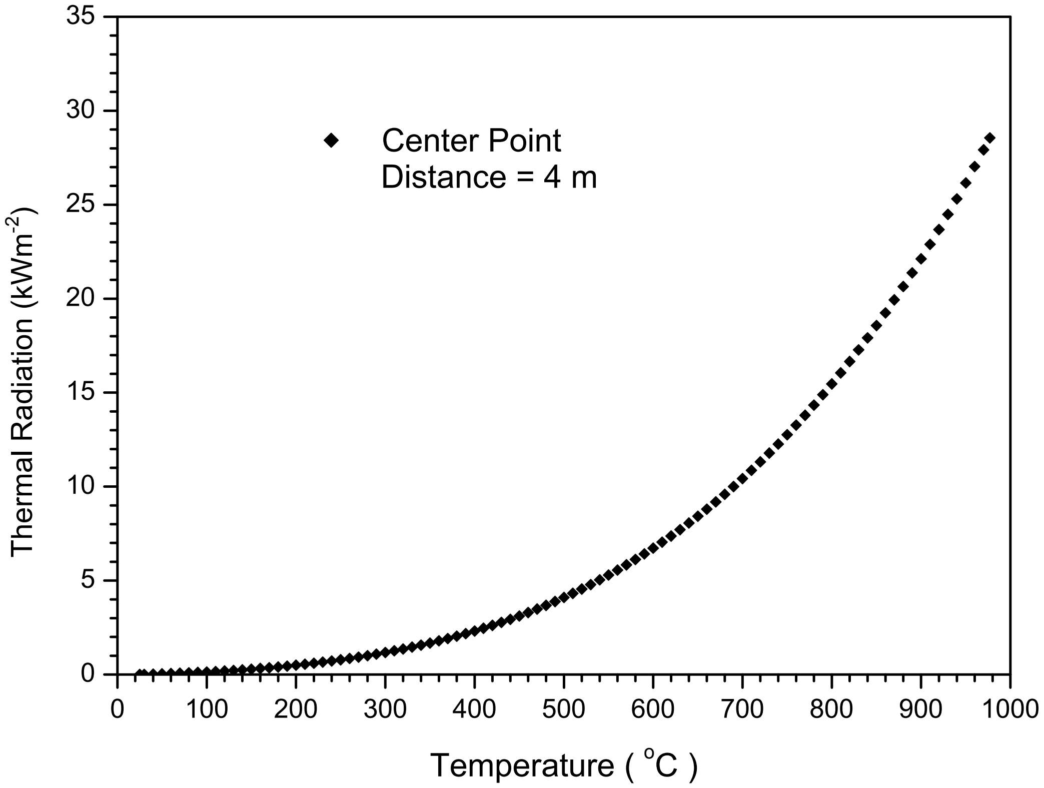


Fig. 18: Relationship between thermal radiation and temperature when x_c = 4 m

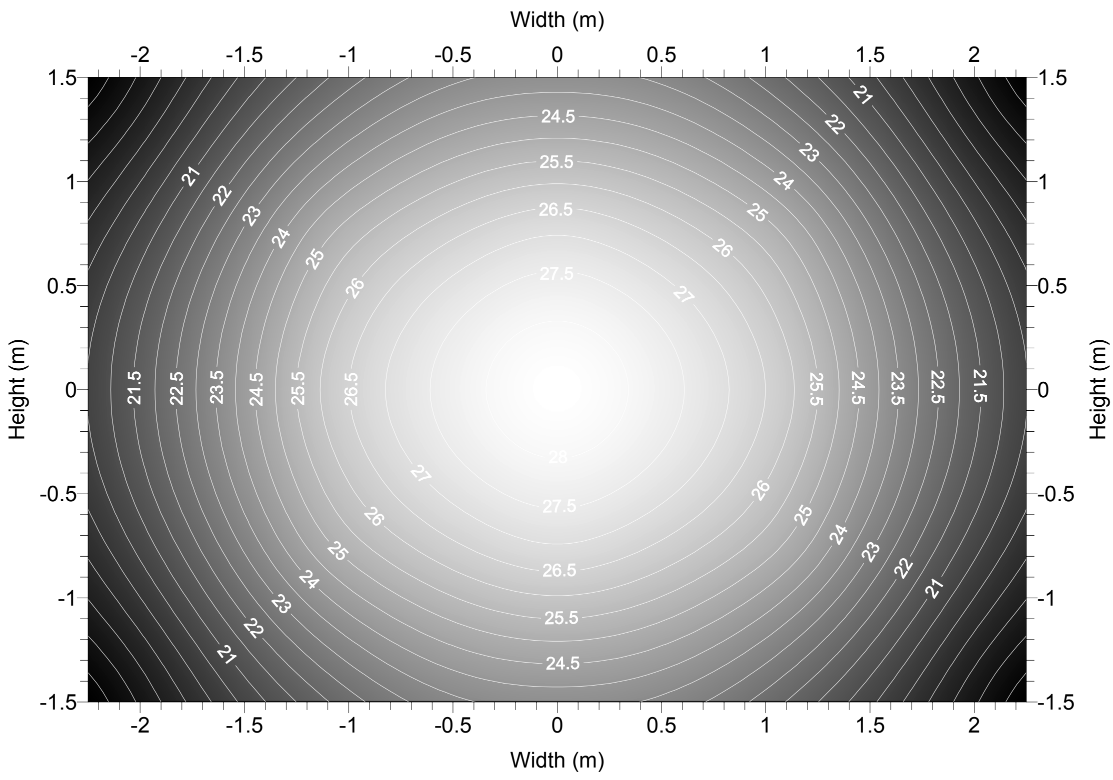


Fig. 19: Thermal radiation on surface (kWm^{-2}) (distance = 4 m, temperature = 977 °C)

4.5 Safety Distances to Prevent Motorcycle Fires Thermal Radiation Spreading in the Arcade

For safety reasons, three basic hypotheses need to be established before we calculate the safety distances of motorcycle fire in arcade buildings. First, fire zone temperatures are presumed to be the same throughout the arcade. Second, the emissivity of combustibles is presumed to be 1.0. Third, the entire space of the arcade is presumed to fill with flames when a motorcycle fire occurs. Based on these conditions and the experimental results of this study, we can calculate necessary safety distances for nearby combustibles such as wood products placed in the front of the arcade like shop signs or motorcycles on the pavement next to the arcade. When there is nothing in between to separate these combustibles from the fire source, a certain distance away from the arcade front will be needed to prevent ignition by thermal radiation. This distance is defined as safety distance.

We know the middle span of the experimental arcade used in this study was 4.5m wide and 3.0 m high. The thermal radiation ignition thresholds for lumber and spontaneous lumber are 12.5 (kWm^{-2}) and 28 (kWm^{-2}) [9], respectively. And the radiation ignition thresholds for plastic materials used in motorcycles are as shown in Table 4. Listed in Table 15 are the results of experiments done for this study. The safety distance needed for the combustibles, avoiding ignition by thermal radiation, and geometric center of arcade front was shown in Table 16. Since the highest fire zone temperature recorded was that of the third experiment, the safety distances needed are also the farthest, see Fig. 20.

Table 15: Experimental results of this study

Experimental conditions	First test	Second test	Third test	Forth test
Arcade height (m)	3.0	3.0	3.0	3.0
Arcade width (m)	4.5	4.5	4.5	4.5
Motorcycle (No.)	8.0	8.0	8.0	3.0
Motorcycle model (CC)	50	125	50	50
Ignition position	IPc_8	IPc_8	IPs_8	IPc_3
Highest fire zone temperature (^oC)	977.0	815.0	983.0	576.0
Thermal radiation from fire source (kWm^{-2})	137.99	79.01	140.67	29.01

Table 16: Safety distances between combustibles and geometric center of arcade front (m)

Item	Material	First test	Second test	Third test	Forth test
Lumber	Lumber	6.53	4.73	6.60	2.32
	Spontaneous lumber	4.05	2.73	4.10	0.32
Motorcycle	ABS	5.92	4.25	5.98	1.95
	PMMA	5.96	4.28	6.03	1.98
	PP	5.95	4.26	6.00	1.96
	PU	10.68	7.95	10.79	4.49
	PVC	5.92	4.25	5.98	1.95

As mentioned before, the 25 points on the surface which vertical distance is x_c away from the geometric center of the fire source did not receive equal thermal radiation. And they were symmetrical to the axis as shown in Fig. 16 and Table 13. Furthermore, the radiation ignition threshold of a certain combustible is fixed. Therefore, the safety distance needed for each point was different when the fire source is rectangular. In other words, the combustible at the center point needs the longest distance while the edges the shortest. The surface constructed by numerous safety distance lines is not a flat but a curved one. See Fig. 21.

Suppose there are two buildings: A and B. One piece of spontaneous lumber (3 m high, 4.5 m wide) is placed in the center of the arcade of building A. When a motorcycle fire breaks out in the arcade of building B (fire zone temperature 977 ^{o}C), the safety distance needed for the center of the lumber in building A would be 4.05 m while that for its upper and lower edges would be 3.472 m, as indicated in Fig. 21. Despite that the safety distances are different, we still should use the distance for the center as the basis for designing fire retardant distance for the safety of the whole combustible object.

The three basic presumptions described above seem to be too conservative in calculating safety distances for preventing motorcycle fire spreading caused by thermal radiation. As we see in Table 16, the PU material used in a motorcycle, for example, requires a safety distance as far as 10.79 m. However, the calculating formulas (such as Formulas (5) and (6)) suggested by this study can provide designers with calculation tools and the safety distances suggested (as shown in Table 16) could be valuable references. In particular, when all the buildings in a community are wood structures, the distances suggested here can be applied when determining the width of roads or lawns between buildings. To protect people and properties from thermal radiation of fires, it is highly recommended that safety distances for fire prevention be designed by methods and values provided by this study.

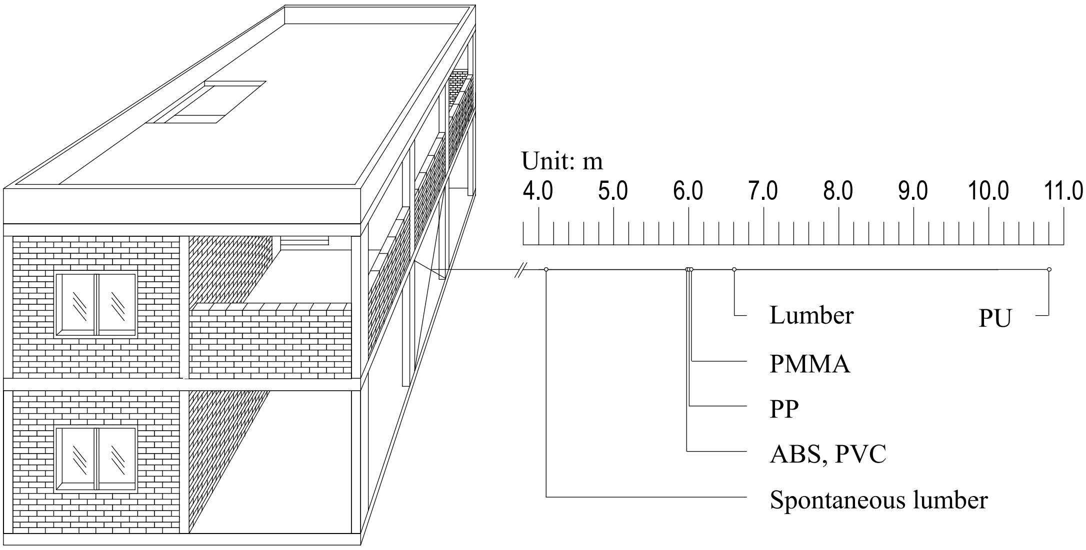


Fig. 20: Safety distances needed when fire zone temperature was 983 ^{o}C

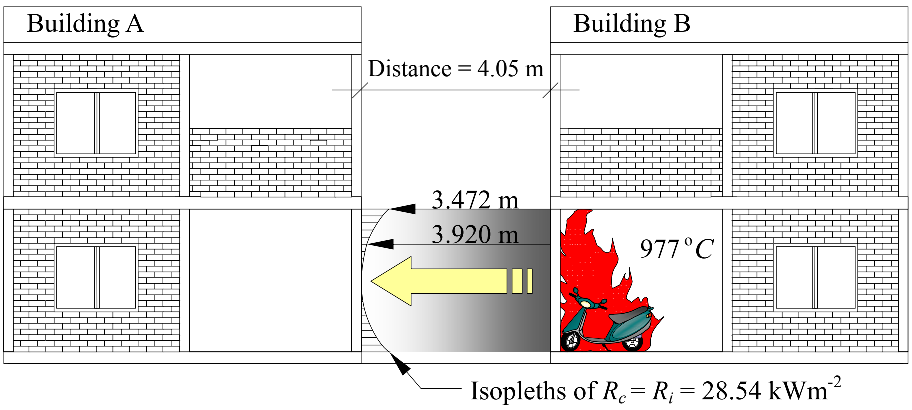


Fig. 21: Safety distances needed for spontaneous lumber when fire zone temperature was 977 ^{o}C

5. CONCLUSION

- When motorcycle fires broke out in an arcade, the 125CC and the 50CC bikes showed similar burning behavior.
- When the ignition position was in the center of the middle span as at IPc_8, the time needed to reach the highest flame temperature and maximum thermal radiation was shorter than when the position was on the edge of span as at IPs_8.
- Even if there were only three motorcycles, during a motorcycle fire the highest temperature and maximum thermal radiation recorded on the arcade ceiling were 576 ^oC and 87kWm^{-2}, respectively.
- The more motorcycles parked in the arcade, the higher fire zone temperature and the stronger thermal radiation would be when a fire broke out. And it would take less time for the fire to reach the highest fire zone temperature and the maximum thermal radiation. This means more motorcycles parked in the arcade pose higher fire risks to buildings and human lives.
- The geometric center of the surface with distance x_c from a rectangular fire source received the maximum thermal radiation while the edges received the minimum. The thermal radiation on points on this surface was axially symmetric.
- When the temperature of the fire source was certain, the thermal radiation would reduce as the distance increased. When the distance between the fire source and the receiving object was certain, the thermal radiation would increase as the temperature increased.
- When a fire broke out on eight motorcycles in a 4.5 m (wide) × 3 m (high) arcade, fire zone temperature being 983^oC, the safety distance needed for lumber would be 6.6 m from the geometric center of the arcade front. The necessary safety distances for plastic materials used for the external structure of a motorcycle would be from 5.98 m to 10.79 m.
- For the entire safety of the combustible, the safety distance needed for the geometric center of the fire source should be used as the basis for fire retardant distance.

NOMENCLATURE

q'' thermal radiation, kWm^{-2}
ε emissivity, ideal blackbody =1.0
σ Stefan-Boltzman constant = 5.6703 × 10^{-11}, kWm^{-2}K^{-4}
T heat source temperature, ^oC
T_a ambient temperature, ^oC
$F_{1\text{-}2}$ configuration factor
a height of fire source, m
b width of fire source, m
c distance between fire source corner and the small area, m
R_c thermal radiation on surface P_m , kWm^{-2}
T_r temperature of fire source, ^oC
x_c vertical distance between surface P_m and geometric center of fire source, m
R_i thermal radiation on surfaces $P_a \sim P_y$, kWm^{-2}
x_i distance between surfaces $P_a \sim P_y$ and geometric center of fire source, m
x_k distance between surfaces $P_a \sim P_y$ and P_m , m
m_k transformation coefficient
n_k transformation index
c_1 form factor
c_2 form factor
c_3 form factor

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