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SIMULATION OF CAR PARK FIRES USING ZONE MODELS

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SUMMARY

The fire environment in car parks of volumes varying from 2,000 m³ to 50,000 m³, ceiling heights of 3 m, 4 m and 5 m are simulated using three fire zone models, namely CFAST and CCFM.VENTS developed at the Building and Fire Research Laboratory, NIST in U.S.A., and the NBTC one-room hot layer model of the fire engineers' calculator FIRECALC developed at the Division of Building and Construction, CSIRO, Australia. The model CFAST is found to be very suitable and the average hot gas temperatures predicted by it are correlated with the volume of the car parks. A time constant taking into account the size geometry and design fire is proposed to assess the fire risks of a car park. Ten local car parks of volume up to 50,000 m³ are surveyed with the fire environment simulated. The derived correlation relation on the average hot temperature fits well with the volume and the time constant. The experimental data on small car park fires are also used to compare with the results predicted by these three zone models.

INTRODUCTION

In Hong Kong, a large number of enclosed big car parks are found in commercial buildings, shopping mall complexes and residential buildings. As the usable land in the town area is very limited, most of the car parks are constructed underground. Apart from the entrance openings, fresh air has to be supplied through mechanical ventilation systems. This would of course give lots of problems related to indoor air quality, especially on the carbon monoxide concentration emitted by cars. The problem will be addressed separately—in another paper. However, the fire safety aspect has to be dealt with carefully also. The fire services installations required are the fire hydrant, hose reel, sprinkler and fire detection system. If the volume is greater than 7,000 m³, a smoke extraction system is required as well. All are described clearly in the local Fire Services Regulations[1]. Whether this is good or not is unknown. Concerning the smoke extraction systems for underground spaces of volume greater than 7,000 m³, the detailed design of the system[2,3] is not specified apart from the smoke extraction rate in terms of air changes per hour. Obviously, the use of such a single macroscopic flow number on the air change rate is not good because as whether complete mixing of the fresh air with smoke would occur is a question. Also the location of the air intake, smoke extract and the entrance openings are important but not specified. Good design of the fire services systems is impossible if the fire environment of the car park is not well understood. To the best knowledge, not much research had been carried out on the fire environment for car parks in Hong Kong. There are some reported in overseas such as the earlier work by Butcher[4] on the fire load in car parks and the associated fire resistance of the steel structures. Experimental studies were also reported by Bennetts *et. al.*[5] on small opened and closed car parks. Also the fire growth rate in a car park was modelled by Bengtson and Ramachandran[6]. Fire environment due to automobiles fuel on a passenger ship was also studied[7] which might be related to that due to a car park fire. Full-scale experimental studies would give a clear picture on exactly what would happen in a fire. The disadvantage is the high cost in carry out such a test, and it is quite difficult to repeat the conditions for testing. On the other hand, mathematical fire models[8,9] are developed and well validated in the literature. Fire field models[10] can be used for simulating the smoke movement and evaluating the smoke control systems. Zone models[8] are suitable for simulating the fire environment taking into account almost all the physical processes. More important, they are well-validated[11,12] for compartments of general size and can be run in personal computers.

The objective of this paper is to study the fire environment in car parks in Hong Kong using zone models. The general shape of the car parks is taken to be a square space of volume varying, from 2,000 m^3 to 50,000 m^3 and ceiling height 3 m to 5 m. The fire environment specified by the average hot gas temperature and smoke layer interface height under a 5 MW fire of size 3 m by 3 m is simulated. The zone models selected are the CFAST[13,14] and CCFM.VENTS [15-18] developed at the Building and Fire Research Laboratories, NIST, U.S.A. and the NBTC one-room hot layer model of the FIRECALC[19] developed at the Division of Building and Construction, CSIRO, Australia. Ten actual local car parks of volume up to 50,000 m^3 are used as cases included in the study. The full-scale experimental data on a small car park reported by Bennett *et. al.*[5] are used for comparing the results.

Simulations on General Car Parks

The car parks can be simplified as a square floor with height about 4 m. Most of them are located underground as shown in Figure 1. Simulations using the fire zone models CFAST[13,14], CCFM.VENTS[15-18] and the NBTC

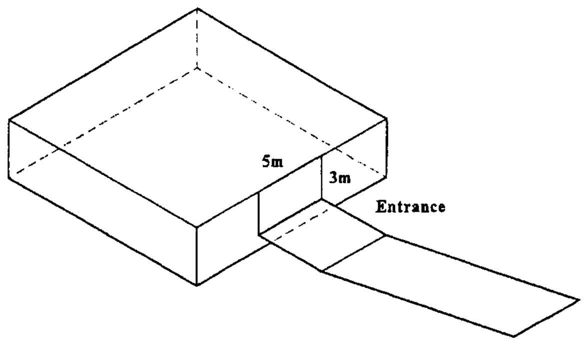

Figure 1. Configuration of Car Park.

one-room hot layer model of FIRECALC[19] are performed for car parks with volume V varying from 2,000 m^3 to 50,000 m^3 with details as shown in Table 1. In each case, an opening of width and height 3 m is constructed for the car park. A 5 MW fire of size 3 m x 3 m (an 'a prior' design fire used in U.K.[2]) with duration of 60 minutes is assumed. Typical results predicted by CFAST[13,14] on temperature time curves for volumes of 2,000 m^3, 7,000 m^3 (critical volume by the Fire Services Department for underground space) 15,000 m^3 and 50,000 m^3 with ceiling height 4 m are shown in Figure 2 and the curves for transient development of the smoke layer interface height are shown in Figure 3. The average hot gas temperature T_g predicted by CFAST[13,14] at different volumes of car parks are shown in Figure 4. The minimum smoke layer interface height was found to be between 2.5 to 3.0 m. Concerning the simulations using CCFM.VENTS[15-18], the value of the parameter λ_T specifying heat lost from the fire to the room has to be selected carefully[20]. A constant value of λ_T equal to 0.75 would give a predicted average hot gas temperature quite different from those in CFAST[13,14] as shown in Figure 5 by plotting values predicted from CFAST[13,14] as the horizontal axis. But if λ_T is increased, values of the hot gas temperature would give a much better agree-

Table 1. Car Parks for General Simulation

	Height: 3 m			Height: 4 m			Height: 5 m					
Volume /m^3	Length /m	Width /m	Area /m^2	Length /m	Width /m	Area /m^2	Length /m	Width /m	Area /m^2	Vent width/m	Vent height/m	Vent area/m^2
2000	25.8	25.8	667	22.4	22.4	500	20	20	400	5	3	15
5000	40.8	40.8	1667	35.4	35.4	1250	31.6	31.6	1000	5	3	15
7000	48.3	48.3	2333	41.8	41.8	1750	37.4	37.4	1400	5	3	15
10000	57.7	57.7	3333	50	50	2500	44.7	44.7	2000	5	3	15
15000	70.7	70.7	5000	61.2	61.2	3750	54.8	54.8	3000	5	3	15
20000	81.6	81.6	6667	70.7	70.7	5000	63.2	63.2	4000	5	3	15
25000	91.3	91.3	8333	79	79	6250	70.7	70.7	5000	5	3	15
28000	96.6	96.6	9333	83.7	83.7	7000	74.8	74.8	5600	5	3	15
30000	100	100	10000	86.6	86.6	7500	77.5	77.5	6000	5	3	15
35000	108	108	11667	93.5	93.5	8750	83.7	83.7	7000	5	3	15
40000	115.5	115.5	13333	100	100	10000	89.4	89.4	8000	5	3	15
50000	129.1	129.1	16667	111.8	111.8	12500	100	100	10000	5	3	15

ment with those from CFAST[13,14]. Values of λ_T would be up to 0.90 when the volume of car park is 50,000 m^3. For the NBTC one-room hot layer model[19], the flame temperature T_f is important. It is taken to be 500 °C as a higher value would give higher values of average hot gas temperature T_g. Values on the average hot gas temperature predictcd by the NBTC one-room hot layer model[19] are also plotted in Figure 5. Since there are not many adjustable parameters such as selecting λ_T for CCFM.VENTS and T_f for NBTC one-room hot layer model, the model CFAST[13,14] is used as the fire simulator in this paper.

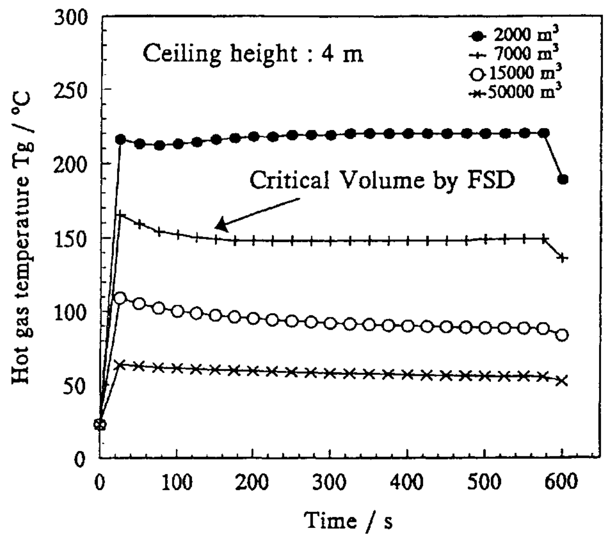

Figure 2. Transient Variation of the Hot Gas Temperature.

To illustrate the change of fire environment in car parks of different heights, simulations are performed on car parks with same volumes as above but heights at 3 m and 5 m. A summary on the geometry is listed in Table 1. The averaged hot gas temperatures T_g predicted by CFAST[13,14] are plotted against volumes in Figure 2 as well. Note that same volume of car parks but of different ceiling heights would give a different average hot gas temperature. In all cases, the average hot gas temperature is below 300 °C and flashover is unlikely to occur. The minimum values of the smoke layer interface heights predicted by CFAST[13,14] are found to be 1.83 m to 2.83 m for car parks of ceiling height 3 m; and 3.22 m to 4.07 m for car parks of

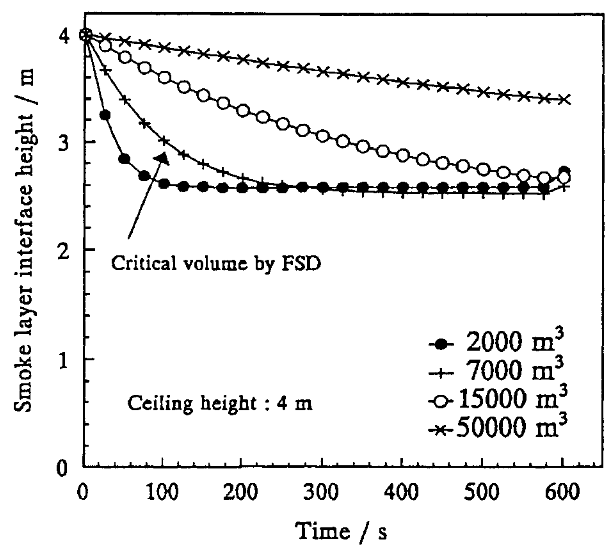

Figure 3. Transient Variation of the Smoke Layer.

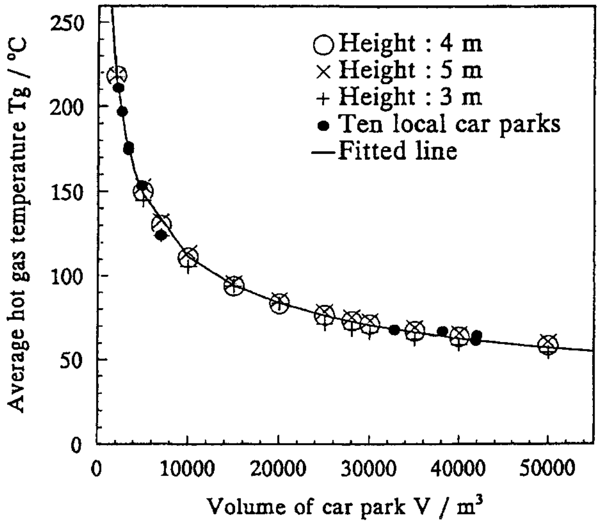

Figure 4. Average Hot Gas Temperature against the Volume of Car Park.

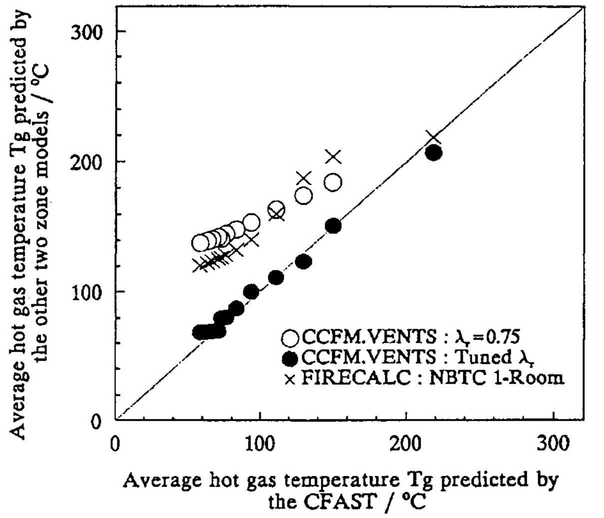

Figure 5 . Comparison of the Average Hot Gas Temperatures Predicted by the Three Zone Models.

height 5 m. This suggested that quite a large percentage of space will be filled up with smoke, *i.e.* a maximum of 39% for car park of height 3 m, 37.5% for 4 m and 35.6% for 5 m.

Use of the Time Constant

It is no good to specify only the volume as the geometrical shape especially when the height is not specified. If the height of a car park is changed, even the same volume of the car park space would give different fire environments. For example, the heights of the car parks are changed to 3 m and 5 m, but the volumes and the other conditions are kept the same with details of the configuration shown in Table 1, the predicted hot gas temperature T_g are plotted against the volume in Figure 2. It can be seen that, car parks of same volume would give different hot gas temperatures. A time constant is defined by using the empirical plume equation for calculating the amount of smoke produced (*e.g.*, in kgs^{-1}) used by Thomas *et. al.*[21], Hinkley[22], Morgan and Gardner[2] for large fires:

$$M_p = K \cdot p \cdot y^{3/2} \qquad (1)$$

Here, p is the perimeter of the design fire and y is the clear height. The quantity K is given in terms of the density ρ_o (1.22 kgm^{-3}) at temperature T_0 (17 °C), acceleration due to gravity g (9.81 ms^{-2}) and flame temperature T_f as:

$$K = 0.096\rho_0 \left(\frac{T_o}{T_f}\right)^{1/2} \qquad (2)$$

This equation has been experimentally validated by Hinkley[22] on nearly symmetric fires. With this equation, the natural filling of smoke in the car park is expressed in terms of the floor area A_f and height of the car park H by considering only mass transfer is:

$$\frac{d}{dt}\left[\rho \cdot A_f \cdot (H - y)\right] = Kpy^{3/2} \qquad (3)$$

This can be simplified to:

$$\frac{d}{dt}y = \frac{-Kp}{\rho A_f} y^{3/2} \qquad (4)$$

The development of smoke layer can be visualized by solving the clear height y in terms of time t:

$$\int_H^y y^{-3/2} dy = \frac{-K}{\rho A_f} \rho \int_0^t dt \qquad (5)$$

giving:

$$y = H\left(\frac{Kp}{2\rho}\frac{\sqrt{H}}{A_f}t+1\right)^{-2} \tag{6}$$

A time constant T has been defined by Chow[23] for the car park with a certain fire with perimeter p:

$$\tau = \left(\frac{2\rho}{Kp}\right)\left(\frac{A_f}{\sqrt{H}}\right) \tag{7}$$

The first part of the expression given by $\frac{2\rho}{Kp}$ depends on the fire. An 'a prior' design fire of size 3 m x 3 m and thermal power 5 MW was adopted in UK *e.g.* Morgan and Gardner[2]. Using this together with the assumed flame temperature of 1100 K would give K a value of 0.188[24], or $\frac{2\rho}{Kp}$ to be about 1.08. The second part $\frac{A_f}{\sqrt{H}}$ is related to the geometry of the car park. Development of the smoke layer or variation of the clear height depends on the time constant τ and when the design fire is fixed, variation of the smoke layer thickness depends only on the geometrial configuration of the car park. This parameter τ is suggested for collelating with the average hot gas temperature T_g. Another point to note is on the fire size in the car park. The time constant τ takes the advantage of allowing the fire size to be included.

For the car parks with volumes varying from 5,000 m³ to 50,000 m³, and heights of 3 m, 4 m, and 5 m as listed in Table 1, the predicted average hot gas temperature T_g using the CFAST[13,14] are plotted against the time constants τ in Figure 6, and against the volume also in Figure 4. Correlation relationships of the average hot gas temperature T_g with the car park volume V and the time constant τ are proposed as:

$$T_g \propto V^{\alpha} \tag{8}$$

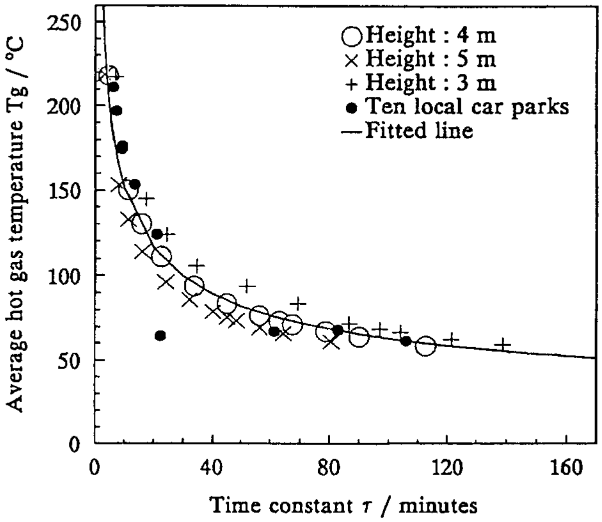

Figure 6. Average Hot Gas Temperatures against the Time Constant of Car Park.

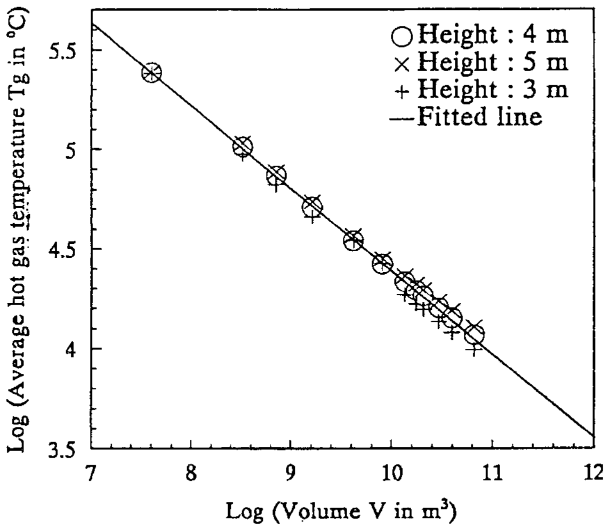

Figure 7. Plotting Log (Average Hot Gas Temperature) against Log (Volume of Car Park).

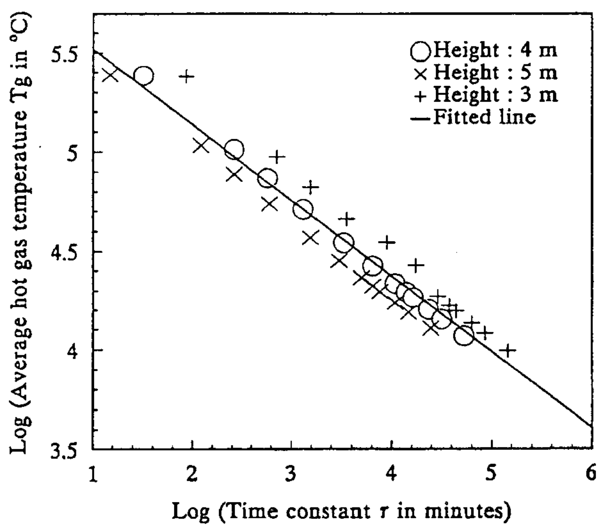

Figure 8. Plotting Log (Average Hot Gas Temperature) against Log (Time Constant of Car Park).

$$T_g \propto \tau^{\beta} \qquad (9)$$

where α and β are constants.

Plotting $\ell n\,(T_g)$ against $\ell n\,(V)$ and $\ell n\,(\tau)$ in Figures 7 and 8 respectively would give:

$$\ell n\,(T_g)=-0.415V+8.539 \qquad (10)$$

$$\ell n\,(T_g)=-0.382V+5.900 \qquad (11)$$

It can be seen that there are not much difference between the variation of the average hot gas temperature T_g with the time constant τ and the volume V, because the height of the car parks varied only from 3 m to 5 m. This is different from the case of using the time constant to denote the smoke filling process of atrium space as the height can vary from 10 m to 50 m. Furthermore, heat is important in car parks as the ceiling heights are low. Equations 8 and 9 can be written as:

$$T_g = 5095\ V^{-0.415} \qquad (12)$$

$$T_g = 365\ \tau^{-0.382} \qquad (13)$$

The expected average hot gas temperature in a car park can be indicated by these two equations. For a 5 MW fire, the average hot gas temperature is unlikely to be higher than 300 °C in a car park of volume greater thall 1,000 m^3, and time constant of 1.67 minutes. For the case of taking 7,000 m^3 to be the critical volume as specified by the Fire Services Department[1], the average hot gas temperature will be less than 130 °C. Therefore, the requirement of installing sprinkler systems is good enough for controlling the spread of a fire, when only the thermal effect is considered. However, in views of Figure 3 on the transient development of the smoke layer interface height, the clear height would be higher than 2.6 m for all the cases with ceiling height of 4 m as listed in Table 1. It seems to be quite safe, but the volume filled up of smoke is quite large. For the car parks of ceiling height 4 m, a smoke layer thickness of 1.4 m means 35% at the upper part will be filled up with smoke at temperature up to 300 °C. It is much better to have smoke extraction systems installed in such cases.

Selected Examples of Simulation

Ten car parks of volume up to 50,000 m^3 are selected for surveying the probable fire environment resulted from a 5 MW fire of 10 minutes duration as in above. The average value of the hot gas temperature predicted by the zone model CFAST[13,14] is used to specify the fire environment. The geometrical details of the fourteen car parks are shown in Table 2 and the capacity (the number of parking spaces) in each car park is also listed. Results on the average hot gas temperature is T_g plotted against the car park volume Valid time constant τ respectively in Figures 4 and 6 as well.

Table 2. Ten Selected Car Parks

Car park number	Length /m	Width /m	Height /m	Area /m^2	Volume /m^3	Time constant τ/min	No. of parking spaces	Average area per parking space /m^2	Vent width/m	Vent height/m	Vent area/m^2	Smoke layer interface /m	Smoke layer height /% ceil height
1	38	25	3.5	950	3325	9.15	69	3.8	5	3	15	2.19	62.5
2	33	19	3.5	627	2195	6.04	24	26.1	4.6	3	13.8	2.16	61.7
3	141	54	5	7614	38070	61.38	500	15.2	10	4.8	48	3.99	79.8
4	111	36	10.5	3996	41958	22.23	160	25	8	3.8	30.4	7.47	71.1
5	30	25	3.5	750	2625	7.23	60	12.5	3.2	3.3	10.56	1.95	55.7
6	145	78	3.7	11310	41847	105.99	140	80.8	6	3.3	19.8	3.06	82.7
7	136	65	3.7	8840	32708	82.84	136	65	5.5	3.5	19.25	2.92	28.9
8	132	16	3.3	2112	6970	20.96	66	32	8.5	3.2	27.2	2.30	69.7
9	41	34	3.5	1394	4879	13.43	16	87.1	4	3.3	13.2	2.04	58.3
10	37	26	3.5	962	3367	9.27	19	50.6	4	3	12	2.06	58.9

The fitted curves given by Equation 11 and 12 are also shown. Very good agreement is found for the variation of the hot gas temperature with the volume.

Again, none of the ten car parks has an average hot gas temperature higher than 200 °C. Flashover is unlikely to occur and sprinkler systems are good enough for protecting the car parks. However, as observed in Table 2 on the minimum smoke layer interface height, over 20% of the volume space would be filled up with smoke. For car park number 5, the volume filled up with smoke is up to 44.3% of the total volume. Therefore, installing smoke extraction systems is necessary, although its volume is only 2,625 m^3, much less than 7,000 m^3.

FULL-SCALE BURNING TESTS

Experimental data on a small car park reported by Bennetts *et. al.*[5] are used to assess the results described above. The car park concerned was of length 10.4 m, width 11.5 m and height 2.5 m, giving a volume of 299 m^3. Fourteeen tests labelled from C1 to C14 were performed with tests C1 to C3 on burning cars; and C4 to C14 on burning a petroleum tray of size either 0.5 m by 0.5 m or 1.0 m by 1.0 m located 4.6 m away from a side. In this paper, only tests C4 to C14 were simulated using the zone models CFAST[13,14], CCFM.VENTS[15-18] and NBTC one-room hot layer model of the FIRECALC[19]. The parameters λ_T specifying heat lost from the fire to the room used in CCFM.VENTS[15-18] was taken to be 0.8. The flame temperature for the NBTC one-room hot layer model[19] was 1026 °C. A summary of the testing conditions are shown in Table 3. The heat release rates of the fire are taken as input parameters to the models and are obtained from the reported data on duration of fire and maximum heat release rate as listed in Table 1. Since only the average heat release rate of the fire is described, the predicted hot gas temperature is the average value and has to be compared with the experimental average values deduced from the graphs in the report. The predicted results on the average hot gas temperature T_g by the three models are compared with the expected value as shown in Figure 9. The measured average hot gas temperature T_g is plotted against the volume in Figure 10. It can be seen that using the volume only is not good enough for specifying the fire risk of the car parks although the height normally varies from 3 m to 5 m as explained above. The time constant might be a better parameter to specify the fire risk. How-

Table 3. Summary of Tests Carried Out by BHP (from Bennetts *et. al.* [5])

Test	Type	Wall openings	Location of fire	Tray size /m x m	Quantity of petrol (ℓ)	Time constant τ /min	Duration of fire /min	Average heat release rate /MW
C4	Tray	1/4 N&S walls	West	0.5 x 0.5	10	4.51	13	0.3
C5	Tray	1/4 N&S walls	East	0.5 x 0.2	10	4.51	12	0.3
C6	Tray	1/4 N&S walls	West	1.0 x 1.0	10	2.75	7	0.8
C7	Tray	1/4 N&S walls	East	1.0 x 1.0	10	2.75	6	1.0
C8	Tray	1/4 N&S walls	East	1.0 x 1.0	30	2.86	10	1.3
C9	Tray	1/4 N&S walls	West	1.0 x 1.0	30	3.17	10.5	1.9
C10	Tray	1/4 N&S walls	East	1.0 x 1.0	60	3.63	15	2.9
C11	Tray	1/4 N&S walls	West	1.0 x 1.0	60	3.63	18	2.9
C12	Tray	1/2 N&S walls	West	1.0 x 1.0	60	3.63	19	2.9
C13	Tray	1/2 N&S walls	West	1.0 x 1.0	80	3.41	19	2.4
C14	Tank	1/2 N&S walls	East	Plastic petrol tank	60 in plastic tank 4 in tray	4.61	9	5.5

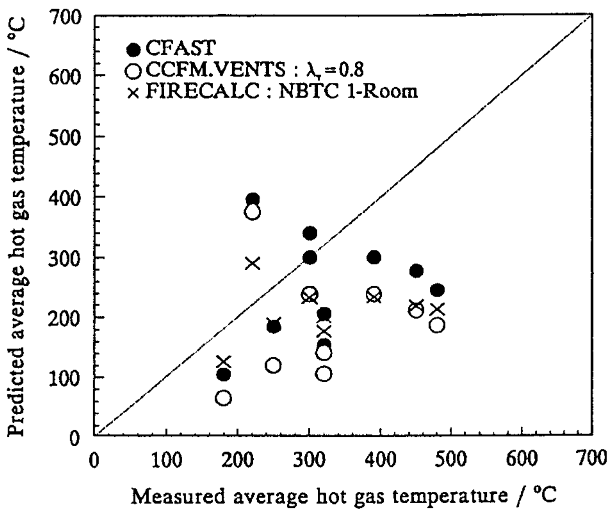

Figure 9. Comparison of the Average Hot Gas Temperature with the Experimental Data.

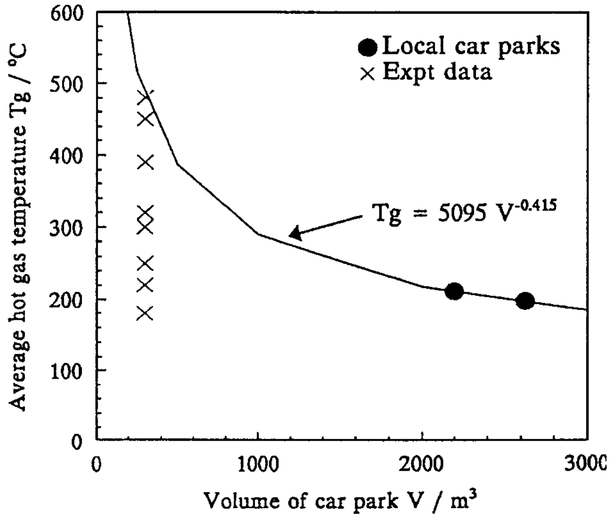

Figure 10. Average Hot Gas Temperature against Volume for the Experimental Data.

ever, the constant K in Equation 7 for the time constant τ is related to the flame temperature T_f. An expression is suggested to relate the flame temperature with the heat release rate Q (in MW), by the fact that the flame temperature for petrol is 1026 °C or 1299K[19]:

$$T_f = 273 + \frac{Q}{4.87 \times 10^{-3}} \tag{14}$$

Results on the measured hot gas temperatures for tests C4 to C14 are plotted against their time constants in Figure 11. Fairly good agreement is found for bigger values of time constants.

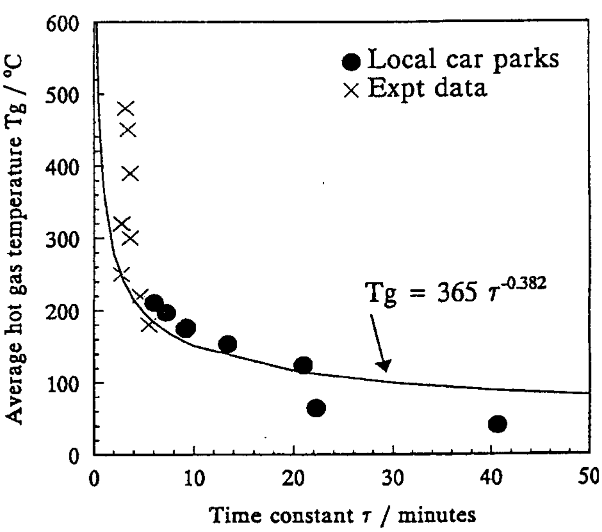

Figure 11. Average Hot Gas Temperature against Time Constant for the Experimental Data.

CONCLUSIONS

The fire environrnent for car parks in Hong Kong with volume varying from 2,000 m^3 to 50,000 m^3, and ceiling height from 3 m to 5 m are simulated using the zone models CFAST[13,14] CCFM.VENTS[15-18] and the NBTC single room hot-layer model of the FIRECALC[17]. Results predicted by these three zone models are compared. The parameter λ_T specifying the heat lost from the fire to surrounding is important in using CCFM.VENTS[15-18] and has to be selected carefully. The flame temperature would affect the results for the simulation with the NBTC single room hot-layer model[19]. The model CFAST[13,14] is chosen to be an appropriate fire simulator and an empirical relation is derived to correlate the average hot gas temperature with the volume of the car park for a 5 MW fire. A time constant describing the smoke filling process is also proposed to specify the geometry and the design fire concerned. The geometry of the car park, the fire perimeter and the flame temperature are included in this parameter. Empirical expression relating the average hot gas temperature and the time constant is derived. It is found in this study that the average hot gas temperature is unlikely to be higher than 300 °C with a 5 MW fire. Flashover would be unlikely to occur and the requirement of installing sprinkler systems would give quite a good control in case of fire. However, the volume of space filled up with smoke can be quite high, say 35% of the total volume in car parks of 4 m high. Installing smoke extraction systems seems to be necessary. Ten actual car parks of volume up to 50,000 m^3 are surveyed. Results on the predicted hot gas temperatures using CFAST fitted fairly well with the two empirical relations given by (12) and (13). Lastly, the experimental data on a small car park reported by Bennetts *et. al.*[5] is compared with those empirical relations. Fairly good results are found.

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