The Numerical Study of Merged Flame Height in n × n Square Array with Different HRR

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Abstract

When two or more pool fires happen to burn so close to each other that they interact, they are termed 'multiple pool fires' (MPF). Past accident analysis reveals that MPFs occur quite frequently in chemical process industries. Controlled experiments done so far to study MPFs have indicated that MPFs lead to increase in the fuel burning rate, flame height and heat release rate (HRR) but the nature and the extent of the impacts of different factors on these manifestations is as yet poorly understood. In this context computational fluid dynamics (CFD) appears to be a tool which can enable more detailed and realistic simulation of MPFs than other possible approaches, especially due to its ability to closely approximate the underlying physical phenomena. The effect of the pool fire and the number of each pool fire heat release rate for fire flame characteristics is scarce. Therefore, this study will become more significant. This study found that the numerical simulation results well fit the experimental results, further proved the significance CFD simulation. At the same heat release rate of each burner the merge fire flame height will increasing with the number of burners increase. After burners arrangement was fixed, with the increase of single burner heat release rate, flame height gradually increased. The influence of separation distances of each burners on merge flame height was investigated in this study is not obvious, but also can finding that with the increase of distance, the flame height decreased.

Keywords

Multifire sources, Heat release rate, Merged flame, Flame height, CFD simulation.

1. Introduction

When two or more pool fires burn in such close proximity of one another that they can influence each other, they are termed 'multiple pool fires' (MPF), there is substantial impact on the burning rate of the fuel, the size of the flame, and the rate of heat transfer from the flame to the surroundings. From 1950 to the present more than 500 accidents have been reported of pool fires involving one or more fuel reservoirs. The most notable one is the earthquake fire that took place in Japan on March 11, 2011 [1]. A tsunami induced by the massive earthquake damaged and ignited a 980 kL gasoline tank, the resultant fire spread to the tanks nearby and caused a significant multi-fire accident [1]. MPFs seem to have characteristics significantly different from stand-alone or non interacting pool fires; for example in several accidents interaction of the flames emerging from the tanks placed close to each other was seen to increase the severity of the fires[2]. Even though MPFs have known to occur fairly often in chemical process industries, much lesser work has been done towards simulation, modelling and control of MPFs as compared to stand-alone pool fires. The flame merging will make the fire more destructive, leading to difficulties in firefighting and may even lead to fire whirls. Therefore, it is worthwhile to study the interacting fires.

From 1960s, the flame merger behavior began to concern. Most of the researchers tried to develop empirical models for describing fire merging behavior, by adding the fire spacing and the number of fire points into general single pool fire models. However, most of them were conducted to investigate the effects of fuel type, fire shape, size, number, spacing and array pattern on the mass loss rate

(MLR), flame height, flame merging, heat feedback, fire whirl, etc.. Putnam and Speich[3] studied different arrangements of fuel piles to generate MPFs and found that when the spacing factor was about two, the individual diffusion flames began to interact. Thomas et al.[4] reported the height of merged flames from two square fire sources supplied with town gas as a function of dimensionless separation distance between fire sources, and provided a simple pressure gradient argument to describe flame merging based on entrainment for adjacent flames. Arguably the earliest experiments on MPFs generated by pools of liquid fuels were performed by Huffman, Welker, and Sliepcevich (1969)[5] who reported that interaction of number of fires burning in close proximity has substantial effect on the burning rate of the fuel, the size of the flame, and the rate of heat transfer from the flame to the surroundings. They observed that individual pool fires start to burn more intensely with higher flames as the distance between them is decreased. In 1990s, Sugawa et al.[6] carried out experiments with multiple rectangular fire sources using liquid fuel with and without floor, and presented theoretical analysis about the relationship among the flame height and heat release rate. They also experimentally investigated the flame height from two rectangular fire sources in a parallel configuration and from three and four circular pools in a symmetrical configuration using gas and liquid fuels[7]. Liu et al. conducted experiments with burner configurations from 3 by 3 to 7 by 7 square fire arrays using heptane as fuel. They also analyzed burnout and global burning rate data on interaction effects among multiple fire sources[8-10]. Weng and Kamikawa[11,12] studied the effects of fire spacing and heat release rate (HRR) on the merging flame height of multiple fires in N $\times$N square arrays (N varied from 2 to 4). They concluded that the spacing has a weaker impact on the flame merging compared to the fire number and HRR. Delichatsios[13] theoretically deduced the merging flame height for multiple fires in open space by taking into account the air entrainment. In recent years, Weng et al. [14] studied multiple wood crib fires and found that increasing the spacing and the burner number enhanced the combustion efficiency. Lu et al.[15] studied the merging behaviors of flames ejected from two parallel windows and concluded that the flame height is affected by the height of merging point.

In recent years, CFD has emerged as a powerful technique which has the potential to handle the kind of complexities that are associated with MPFs. But, so far, only a few attempts have been made to use CFD in MPF simulation, essentially due to a lack of relevant experimental data. Weng et al.[16] used large-eddy simulation (LES) to simulate the merging of flames, and found that numerical results agreed well with the experimental data. Satoh et al. (2007)[17] also found that CFD esimulated profiles of iso-thermal surfaces of merging flames were quite similar to that which was found experimentally, including the critical merging distance. Satoh et al.[18] found that the swirling conditions of fires in square arrays in the presence of wind were strongly influenced by the inter-fire distance in the array, the heat release rate (HRR), and the mass flow rate. In recent year, Vasanth et al.[19-21] attempts to study the effects of two different fuels (iso-octane and Jet A), pool fires situated at differing elevation and different pool size and separation distance between pools on the interaction of the concerned MPFs using CFD. However, Numerical simulation the studies of numerical simulation on the characteristics of flame in a multiple pool fire with square array are very few.

In this paper, we try to investigate the effect of the number of fuel bed on the interaction of the MPFs using CFD. Therefore, the quantitative merged flame characteristics from multiple fire sources with different amounts are still needed, and the heat feedback to the fuel surface, the radiative heat flux from the merged flame and the combustion efficiency due to air supply restriction should be further investigated to understand the interaction mechanism and the effects of the merged flame. The mass loss rate, the heat release rate, the heat feedback to the fuel surface, and the radiative heat flux from the merged flame using CFD were compared with the results of empirical model calculation and experimental measurement value to quantitatively study the merged flame characteristics.

For validation, the experimental data obtained by Kamikawa[12] has been chosen because it is one of the very few experimental data in which measurements have been done on MPFs at different amounts.

2. Theoretical consideration

In multiple burning fires, there exist two major fire interaction mechanisms which may affect the burning rates significantly (Fig. 1). One is heat feedback enhancement, which means that the fuel surface of any fire not only receives heat feedback from its own flame, but also experiences heat transfer from the surrounding fires, mainly by radiation. This will in response induce a burning rate increase. The accelerated burning fire will then in turn release more heat to the fuels of the surrounding flames. Another interaction mechanism is air supply restriction, which specifies that at smaller fire spacing, the air supply for inner fires may be suppressed, decreasing combustion efficiency and thus reducing the heat feedback to the fuel surface, which will in turn decrease the burning rate. The two mechanisms obviously depend on fire spacing and fire array size. Within certain ranges of these parameters, the two mechanisms may have comparable or competitive effects on burning rate.

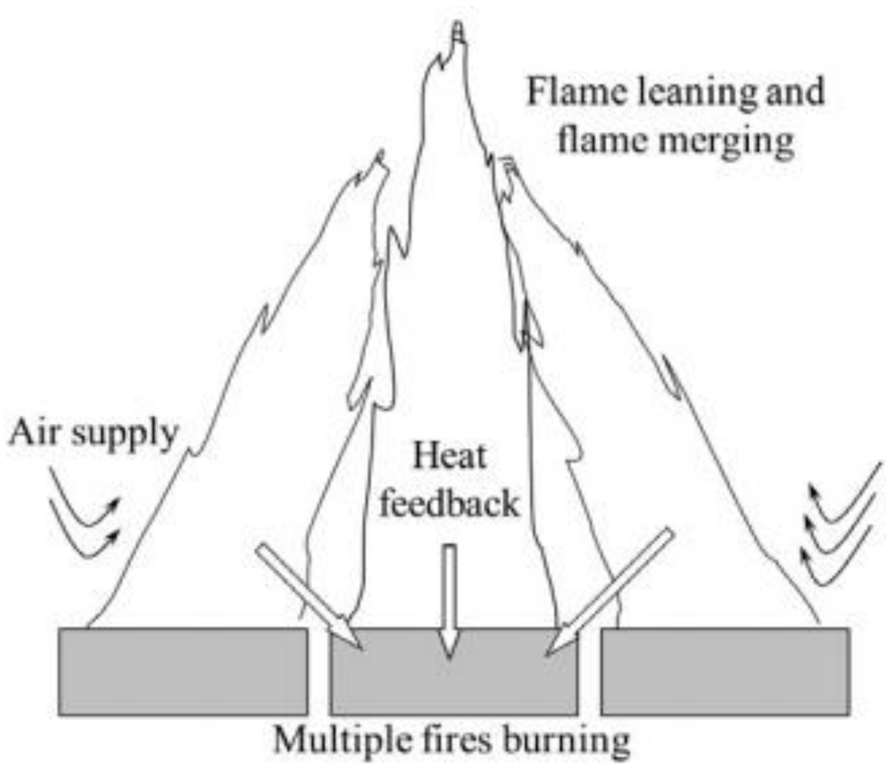

Fig. 1 Typical burning behavior of multiple fires

3. Methodology

For CFD simulations, the standard k-e model was used for turbulence because it has been found to be more effective, in compared to other turbulence models by Vasanth[22].Combustion was modelled using eddy dissipation concept (EDC)[23]. Finite volume method was used for the second order discretization of the Reynolds averaged Naviere-Stokes (RANS) equations. P1 radiation model, also known as Gibb's model, was used for radiation modeling as it has been found to be effective by several other authors[24,25]. The SIMPLE algorithm was utilized for pressure velocity coupling. The computations were done using the CFD code FLUENT 15.0.

3.1 Simulation of Kamikawa experimental data

In the experiments performed by Kamikawa, the effect of heat release rate and the pool distance on the characteristics of MPFs. All the burners used in the experiments had 0.15m on a side, 20 mm height and contained propane as fuel. The heat release rate of each burner was set as 0.50, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0 kW. The separation distance between burners was chosen as 0, 1, 2, and 3 cm, representing a typical urban block arrangement in a densely inhabited area. Experimental conditions are presented in Table 1.

Table 1 Experimental conditions of Kamikawa

Fuel	Number of burner	Separation distance (cm)	Heat-release rate per unit burner (kW)
Propane	2 ×2	0,1,2,3	0.50,0.75,1.0,1.25,1.5,1.75,2.0
	3 ×3	0,1,2,3	0.50,0.75,1.0,1.25,1.5,1.75,2.0
	4 ×4	0,1,2,3	0.50,0.75,1.0,1.25,1.5
	5 ×5	0,1,2,3	0.50,0.75

For the validation of the CFD-based code, from among several MPF studies reported by Kamikawa, numerical condition with a 2 × 2 configuration, S =0, 1, 2, 3 cm, and Q = 0.5,1.0,1.5,2.0 kW was undertaken. The 3D domains used for the simulations was configured using block mesh; fine mesh was used near the fuel burner which become coarser as one moved towards the domain boundaries. This enabled adequate detailing of the domain without increasing the number of cells beyond an optimal number. In turn it made it possible to keep the requirement of computational time down to the essential minimum[26]. For all the simulations with 2 × 2 configuration, a 3D domain of dimension 9m × 9m × 9m was used（Fig. 2）. The relatively large domain size that has been employed ensures that the flow variables have zero gradients across the domain boundaries and the possible computational errors, due to pressure gradient and back flow at the domain boundary are minimized. The total number of nodes that resulted from meshing of the domain for simulations with 2 × 2 configuration and S = 0,1,2,3 were 1514800, 1515412, 1541245, 1567296, respectively. For all the simulation the dimensions of the domain and the total number of nodes that resulted from meshing the domain are summarized in Table 2.

Table 2 Number of nodes used for the simulations based on various configuration and separation distance.

Burner layout	The computational domain size	Separation distance(cm)			
		0	1	2	3
2 ×2	9m ×9m ×9m	1514800	1515412	1541245	1567296
3 ×3	10m ×10m ×10m	1778800	1780672	1833616	1892448
4 ×4	12m ×12m ×12m	2062800	2066580	2157813	2251008
5 ×5	14m ×14m ×14m	2366800	2373136	2503936	2638224

The CFD-based simulations were done in 3D space. After setting the boundary conditions and selecting appropriate models consistent with the physics of pool fire burning, mass, energy, and momentum equations alongside combustion, turbulence and radiation models were solved in 3D space limited by the domain boundary. The convergence criterion was set as the residual RMS (root mean square) becoming equal to or less than 10-4[27]. The impact of grid size on simulation results is an important consideration for any computational fluid dynamics analysis. So in this study, a grid sensitivity analysis was performed to determine an appropriate number of cells considering numerical accuracy and computational efficiency. The study is intended to reveal the mesh sensitivity of the predicted flame height. As a test case, the numerical condition with a 2 ×2 configuration, S = 2cm, and Q = 1.5kW was undertaken.

3.2 Boundary conditions

The flow velocity or the flow rate were not known at the side boundaries marked boundary A, B, C, D, and E, since these boundaries were situated at a considerable distance from the pool fire epicentre. Hence it is assumed that pressure is atmospheric at these boundaries (gauge pressure set to zero). A no-slip condition is imposed for boundary F, because viscous fluids will have zero velocity relative to this ground solid boundary. The pools were modelled such that the n-heptane vapours were assumed to enter the domain from the boundary G (Fig. 2). The burning rate of propane was defined as a correlation of HRR is given by [28]:

$$\dot{Q} = \chi \cdot \dot{m} \cdot \Delta H_c \tag{1}$$

Where χ is the combustion efficiency, m is the mass loss rate, ΔHc is the heat of combustion per unit fuel mass, which is 46.36 MJ/kg for propane.

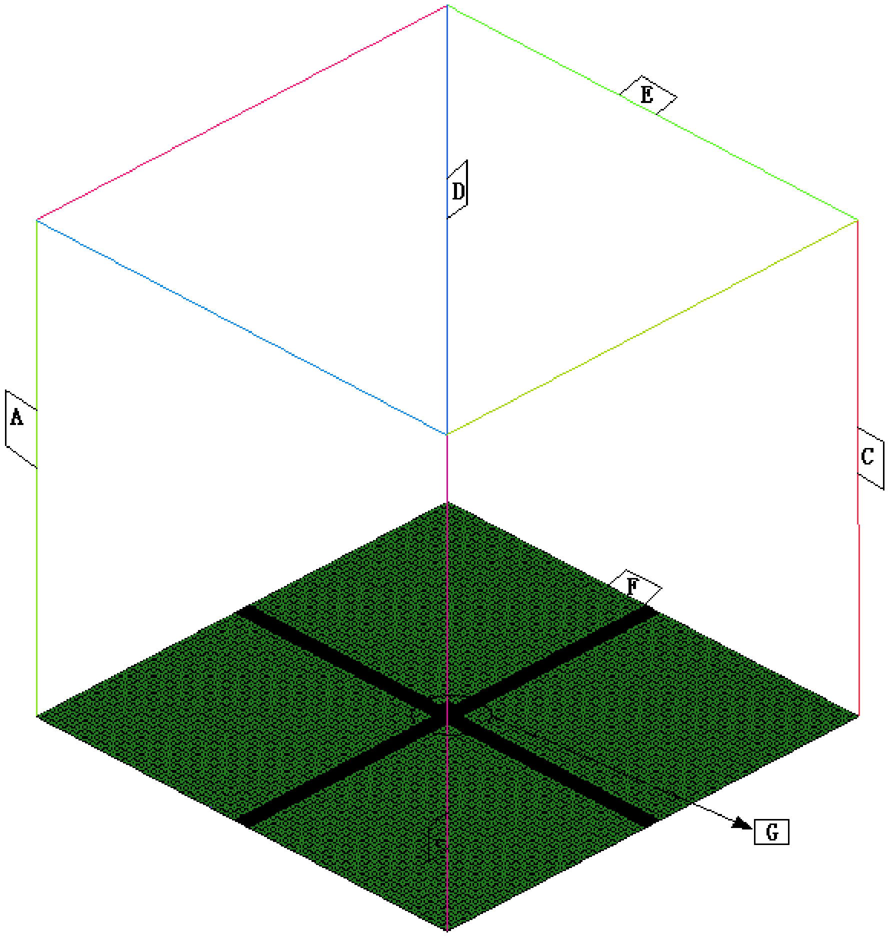

Fig. 2 A scheme of the 3-D meshes applied in simulations

4. Result and discussion

The flame length is one of the important parameters to describe the characteristics of fire, it directly affects the thermal radiation range of flame and the flame and the surrounding objects of the heat transfer process. The results of comparison of experimental data with numerical results of dependence of the flame height in dimensionless form at four separation distances (S = 0, 1, 2, and 3 cm) and four fire source configuration are shown in Table 3-6. As shown in table 4-6 above, the numerical simulation results are in good agreement with the experimental data, although the predicted flame height is a little higher than the experimental data. Weng et al. [16] showed that, it is shown in most of data predicted temperatures are a little higher than measured temperatures, which results from the mixture fraction combustion model in the CFD. This model is based on the assumption that the combustion is mixing controlled, which means the for combustion occurs much more rapidly than the resolvable convective and diffusive phenomena. This reason also results in a little difference of flame height between numerical results and experimental data. Despite this, the numerical results accord relatively well with the experimental data considering the numerical model limitation and the experimental precision. Therefore, it is believed that CFD correctly predicts flame height in simulating merged flame from multiple fire sources.

Table 3 Comparison of flame height for the experimental and the CFD findings of 2 × 2 burner configurations differing in HRR.

Separation	Results	Flame Height for differing HRR(m)						
		0.50	0.75	1.00	1.25	1.50	1.75	2.00
$S = 0$	Measurements	0.535	0.695	0.712	0.817	0.833	1.197	1.180
	Simulations	0.566	0.736	0.750	0.824	1.011	1.212	1.226
$S = 1$	Measurements	0.450	0.619	0.722	0.817	0.841	1.127	1.117
	Simulations	0.484	0.674	0.771	0.825	0.931	1.145	1.201
$S = 2$	Measurements	0.469	0.619	0.663	0.818	0.838	1.015	1.118
	Simulations	0.460	0.624	0.719	0.825	0.915	1.074	1.202
$S = 3$	Measurements	0.428	0.621	0.698	0.819	0.842	1.039	1.084
	Simulations	0.435	0.627	0.706	0.821	0.893	1.042	1.123

Table 4 Comparison of flame height for the experimental and the CFD findings of 3 × 3 burner configurations differing in HRR.

Separation	Results	Flame Height for differing HRR(m)						
		0.50	0.75	1.00	1.25	1.50	1.75	2.00
$S = 0$	Measurements	0.491	0.654	0.795	0.943	1.127	1.330	1.418
	Simulations	0.557	0.736	0.877	0.986	1.161	1.341	1.472
$S = 1$	Measurements	0.566	0.655	0.803	0.950	1.122	1.328	1.401
	Simulations	0.542	0.681	0.849	0.956	1.162	1.398	1.421
$S = 2$	Measurements	0.501	0.616	0.806	0.833	0.908	1.281	1.351
	Simulations	0.501	0.654	0.813	0.899	1.031	1.286	1.412
$S = 3$	Measurements	0.504	0.736	0.736	0.902	0.969	1.250	1.389
	Simulations	0.450	0.654	0.744	0.943	1.011	1.261	1.422

Table 5 Comparison of flame height for the experimental and the CFD findings of 4 × 4 burner configurations differing in HRR.

Separation	Results	Flame Height for differing HRR(m)						
		0.50	0.75	1.00	1.25	1.50	1.75	2.00
$S = 0$	Measurements	0.622	0.809	0.934	1.369	1.469	—	—
	Simulations	0.583	0.813	1.060	1.371	1.471	—	—
$S = 1$	Measurements	0.517	0.682	0.941	1.293	1.470	—	—
	Simulations	0.534	0.695	0.968	1.347	1.468	—	—
$S = 2$	Measurements	0.535	0.685	0.929	1.231	1.465	—	—
	Simulations	0.493	0.657	0.942	1.255	1.355	—	—
$S = 3$	Measurements	0.510	0.649	0.742	1.023	1.466	—	—
	Simulations	0.459	0.574	0.813	1.079	1.306	—	—

Table 6 Comparison of flame height for the experimental and the CFD findings of 5 × 5 burner configurations differing in HRR.

Separation	Results	Flame Height for differing HRR(m)						
		0.50	0.75	1.00	1.25	1.50	1.75	2.00
$S = 0$	Measurements	0.633	0.860	1.365	—	—	—	—
	Simulations	0.604	0.866	1.385	—	—	—	—
$S = 1$	Measurements	0.554	0.776	1.392	—	—	—	—
	Simulations	0.549	0.776	1.384	—	—	—	—
$S = 2$	Measurements	0.557	0.706	1.139	—	—	—	—
	Simulations	0.512	0.669	1.156	—	—	—	—
$S = 3$	Measurements	0.499	0.624	1.172	—	—	—	—
	Simulations	0.455	0.665	1.167	—	—	—	—

Flame height from a diffusion fire source in a free boundary condition is corrected with the dimensionless heat release rate Q*, which depends on the geometry of the fire source and the potential intensity of the heat release rate. When N square fire sources located with square configuration, whose separation distance S is kept enough small, are ignited, the restriction of air entrainment by flames results in a pressure drop in the space among these fire sources. The variation trend of the combined flame height with the heat release rate in the square arrangement is shown in Fig. 3. It was also found that the combined flame height increased significantly with lower heat release rate. it was obvious that the flame height was showing a decreased trend, when the separation distance S was increased from 0 to 3cm. However, with the increase of heat release rate, this trend became more and more gentle.

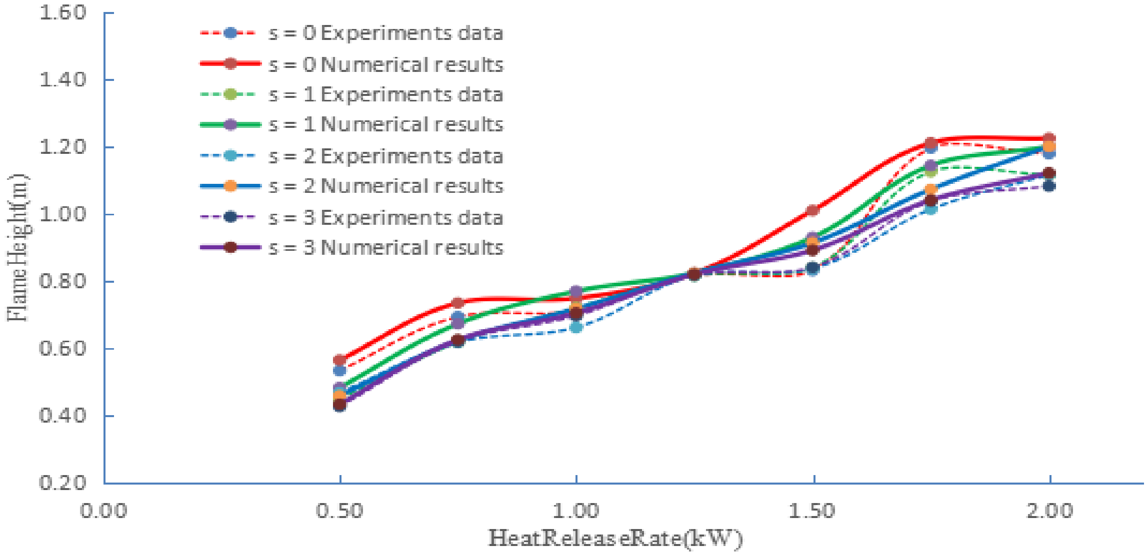

Fig. 3 Dependence of flame height in 2 ×2 configurations form on heat release rate for comparison of experimental data with numerical results

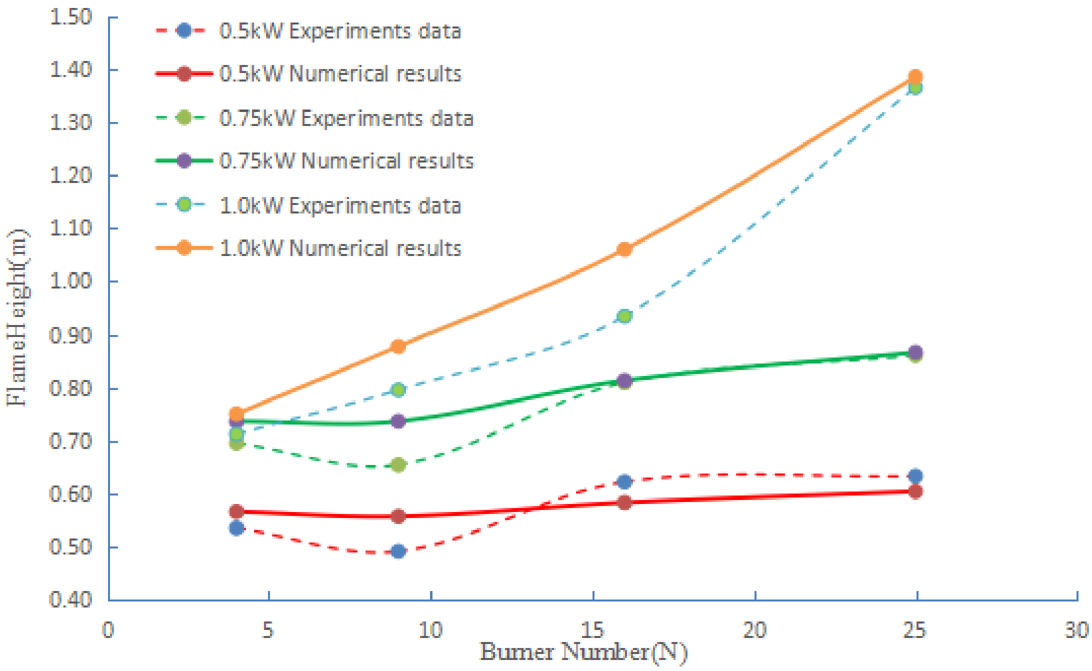

Fig. 4 Dependence of experimental and numerical flame height results in n ×n configurations fire sources

Comparing Table 3 with Table 4-6, with the same heat release rate for each burner, more fire sources lead to higher flame height (Fig. 4). And with the same fire source configuration, the higher heat release rate also results in a higher flame height. It is shown that with the increase of separation distance, flame height decreases. So to control the occurrence of merged flame in city fires, it is necessary to decrease the heat release rate of each burner and the number of fire sources, and increase the separation distance.

5. Conclusion

This paper presented the experimental data and numerical results on merged flame from multiple fire sources. The CFD was used to simulate the detailed flame structure for indicating the formation mechanism of merged flame. The flame height from numerical results was compared to the experimental data, and the validity of the empirical model was confirmed from the comparison with the simulation results. The main conclusions are as follows:

1.The CFD correctly predicts the flame height in simulating merged flame from multiple fire sources through comparison with experimental data.

2.With the same heat release rate for each burner, more fire sources leads to higher flame height. And the higher heat release rate also results in higher flame height with the same fire source configuration.

3.The merged flame from a symmetrical fire source configuration is close-symmetrical. The asymmetrical fire source configurations, result in the asymmetrical merged flame due to the imbalance of entrained air near the flame through the oxygen mass fraction profiles.

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