A global model for flame pulsation frequency of buoyancy-controlled rectangular gas fuel fire with different boundaries

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Abstract

Pulsation frequency is an important characteristic parameter for buoyancy-controlled fuel diffusion flames. Fire experiments of a rectangular source with different aspect ratios were conducted in an open space and against sidewalls made from a calcium silicate board. Due to the blocking effect to restrict air entrainment to fire plumes, sidewall significantly reduced the flame pulsation frequency. Furthermore, the effect of the fuel exit velocity on the pulsation frequency became intense as the aspect ratio of the rectangle was increased to 7.45. Based on the modified hydraulic diameter for a rectangular fire source with a sidewall and corner, a global model was developed for predicting the flame pulsation frequency of the rectangular fire source with free, sidewall, and corner boundaries. The coefficient of determination of this improved model is 0.9991, and the local errors of this model are less than 15% considering all of the experimental data in the present work and available in the literature. This work provides a method for predicting flame pulsation frequency, accounting for sidewall effect and aspect ratio.

Keywords: Flame pulsation frequency; Rectangular fire source; Global model; Buoyancy-controlled gas flame; Boundaries

1. Introduction

Rectangular fire sources are commonly used and have recently attracted considerable attention from the research community. The flame height, centerline temperature and thermal radiation of a flame generated by a rectangular fire source has been widely investigated [1-8]. The effect of atmospheric pressure on the burning behavior of a rectangular fire source was studied numerically [9-15]. Liu et al. [16] and He et al. [17] studied the interaction of two rectangular fires. Tang et al. [18] investigated the maximum ceiling jet temperature generated by a rectangular-source fire in a tunnel. Recently, Ji et al. [19, 20] and Zhang et al. [21] investigated the influence of sidewalls on the burning behavior of a rectangular fire source; and found their effect to be of significance.

Generally, sidewalls next to fire exert blocking effect to restrict air entrainment to fire plumes. In related studies, Zukoski et al. [22] found that the air entrainment of a fire source located against a sidewall was reduced to 43% of that of a fire in an open space. Hasemi and Tokunaga [23] measured the height of flame tips and continuous flames generated of wall fire. Poreh and Garrad [24] investigated the flame height of wall and corner fire plumes and proposed two similar correlations to estimate the effect of walls on the mean flame height were developed. Recently, several investigators [19-21, 25-27] studied the influence of sidewalls on the burning behavior of pool fire. Hu et al. [28, 29] investigated the fire behavior of gas fires constrained by two parallel side walls and wall-attached fire impinging upon an inclined ceiling. Tao et al. [30] investigated the flame characteristics of buoyancy-controlled gas fire bounded by a sidewall and ceiling. Tang et al. [31,32] studied the fire dynamics of the rectangular burner in a tunnel.

Flame pulsation is one of the basic characteristic parameters of pool fire [33, 34]. Malalasekera et al. [35] reviewed the experimental technique and scaling relationships for buoyancy-controlled flame pulsation. The hydrodynamic nature of flame puffing was set as the interplay of buoyancy and fluid motion. Based on an analysis of experimental data on the frequency of pulsation in different burners, the pulsation frequency of flame can be described by

$$f = C_1 (1/D)^{0.5} \tag{1}$$

where D is effective diameter of burner, m; C_1 is an experimentally determined coefficient with a value of 1.5,1.6, and 1.68 in the models proposed by Malalasekera et al. [35], Cetegen and Ahmed [36], McCaffrey [37], respectively.

Recently, Zhang et al. [38] studied the flame pulsation frequencies of buoyant turbulent diffusion flames under free, sidewall, and corner conditions. Based on the mirror approach, they proposed global models of flame pulsation using the effective perimeter of the burner as the length scale for the fire source under sidewall and corner conditions. These models can be expressed as [38]

$$f = \begin{cases} 0.53\sqrt{\frac{g}{D_{eff}}} & \text{free flames} \\ 0.52\sqrt{\frac{g}{D_{eff}^*}} & \text{sidewall and corner flames} \end{cases} \tag{2}$$

where g is acceleration due to gravity, m/s^2. The perimeter-equivalent diameter D_{eff} was developed for the free flames. Furthermore, based on the mirror model, a modified perimeter-equivalent diameter D_{eff}^* was applied for the models of the sidewall and corner flames. Based on the mirror approach, the modified perimeter-equivalent diameter was expressed as [38]

$$D_{eff}^{*} = \begin{cases} \frac{2W+2L}{\pi} & \text{free flames} \\ \frac{4W+2L}{\pi} & \text{sidewall flames} \\ \frac{4W+4L}{\pi} & \text{corner flames} \end{cases} \tag{3}$$

where W and L is the width and length of the rectangular source, m. According to the expressions in Eqs. (1)–(3), these models ignore the effects of the fuel flow rate on the flame pulsation frequency.

The fuel exit velocity has a small but finite effect on the pulsation frequency of axisymmetric fire source [35, 36]. The magnitude of this effect has been found to be related to the burner diameter and fuel flow [36]. Taking the burner diameter and fuel exit velocity into account, the relationship between the Strouhal and Froude numbers was developed as [35]

$$St = 0.52(1/Fr)^{0.505} \tag{4}$$

The Strouhal number, St , is expressed as

$$St = fL/U \tag{5}$$

where L is the characteristic length of pool, m; and U is the gas velocity at the burner surface, m/s; The Froude number, Fr, is expressed as

$$Fr = U^2/(gL) \tag{6}$$

where g is the gravitational acceleration, m/s^2.

For a rectangular fire, Cetegen et al. [39] studied the pulsation of planar buoyant plumes of helium and helium/air mixtures from a nozzle with different aspect ratios. Owing to the difference in mixing rates and the strength of the local buoyancy flux, the correlation of the plume pulsation frequency for planar plumes is different from that for axisymmetric plumes. The width of rectangular fire source was considered to be the characteristic length scale for the pulsation frequency correlation. This correlation can be expressed as [39]

$$\mathrm{St_w} = 0.55\mathrm{Ri_w^{0.45}} \tag{7}$$

where $\mathrm{St_w} = \mathrm{fW/U}$ and $\mathrm{Ri_w} = (\Delta\rho/\rho_\infty)\mathrm{gW/U^2}$. $\Delta\rho$ is characteristic density difference, kg/m^3; ρ_∞ is ambient density, kg/m^3;

Tang et al. [40] and Tu et al. [10] studied the effect of low air pressure on the flame pulsation behavior of rectangular pool fires. The hydraulic diameter was introduced as the characteristic length scale for the rectangular flame pulsation frequency correlation and can be expressed as [40]

$$\mathrm{D_{hyd}} = \frac{\mathrm{2LW}}{\mathrm{L+W}} \tag{8}$$

Then, the following flame pulsation frequency model for hydrocarbon pool fires was developed [40]:

$$\mathrm{St_{hyd}} = 0.86\mathrm{Fr_{hyd}^{-0.5}} \tag{9}$$

where $\mathrm{St_{hyd}} = \mathrm{fD_{hyd}}/\mathrm{U}$ and $\mathrm{Fr_{hyd}} = \mathrm{U}^2/\mathrm{gD_{hyd}}$. Eq. (9) was derived based on the experimental data obtained using a rectangular fire in an open space.

The approaches regarding the flame pulsation of a rectangular fire source drawn by Cetegen et al. [39] and Tang et al. [40] appear to be conflicting. Cetegen et al. [39] considered the width of a rectangular fire source as the characteristic length for the flame pulsation frequency model, while Tang et al. [40] used the hydraulic length. Furthermore, the sidewall effect on the flame pulsation frequency was not investigated in these studies. Hence, the applicability of these models to a rectangular fire source with a sidewall is unknown.

The present study focuses on the effect of sidewalls on the flame pulsation behavior of a rectangular fire source with different aspect ratios. Fire experiments with rectangular burners of the same surface area but different aspect ratios were conducted against a CS (calcium silicate) board. For comparison, similar fire experiments were conducted with the same rectangular fire source without a sidewall. The influence of sidewall and aspect ratios on the magnitude and frequency of flame pulsation was discussed. Furthermore, based on the experimental data in present work and available in the literature, a global model for predicting the frequency of flame pulsation was developed for a rectangular fire in free, sidewall, and corner boundaries.

2. Experimental method

The schematic of the experimental setup is shown in Fig. 1. Propane was used as the fuel. Fire tests were performed using one square, and three rectangular burners. The fire source was located against the sidewall and there was no space between them. Fig. 2 shows the flame morphology of a rectangular fire source located against a CS board ($\dot{Q} = 84.8$ kW). Fig. 3 presents sequential flame images taken from the side of a rectangular fire located against a CS board at time intervals of 0.08 s (R = 7.45, $\dot{Q} =$

84.8 kW). All the burners had the same surface area but different aspect ratios. The burning surface areas were 900 cm^2 for all the burners. The details of the tested scenarios are listed in Table 1. The thermal properties and dimensions of the CS board used as sidewalls are listed in Table 2. Each fire test was repeated two times to check repeatability. The tests were conducted in quiescent conditions with wind speed being zero.

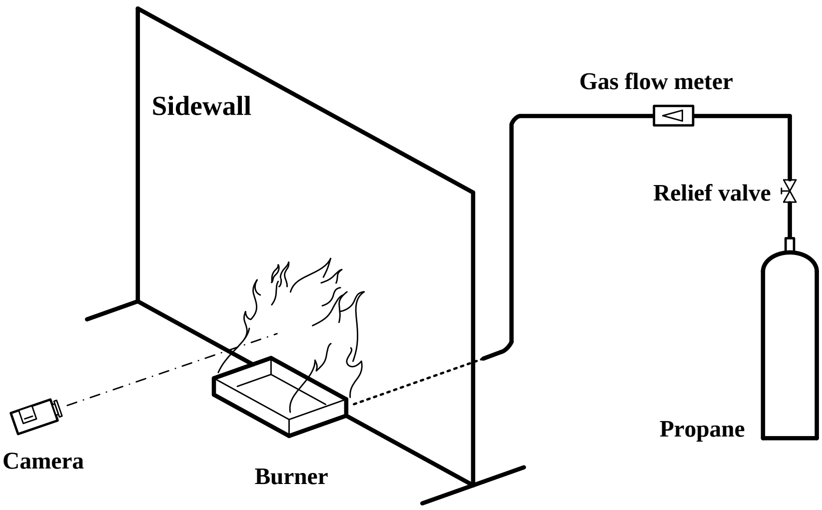
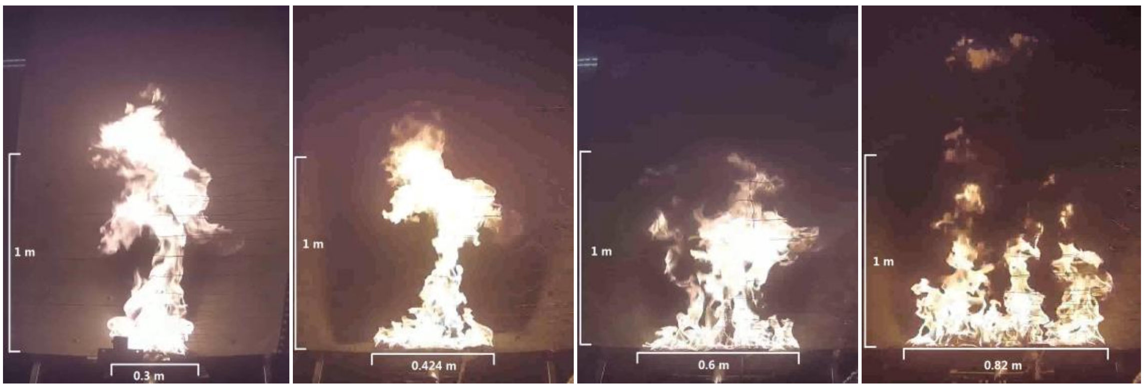


Fig. 1 Schematic of experimental setup



(a) R = 1 (b) R = 2 (c) R = 4 (d) R = 7.45

Fig. 2 Flame morphology of a rectangular fire source located against a CS board ($\dot{Q} = 84.8$ kW) [27]

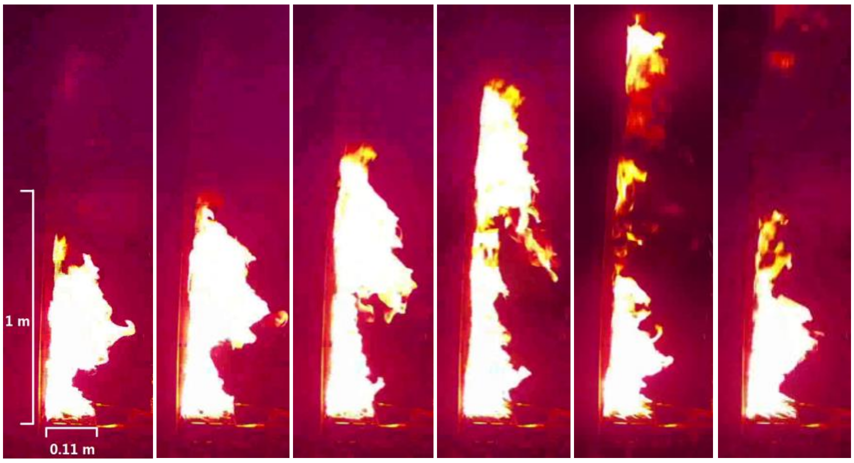


Fig. 3 Sequential flame images taken from the side of a rectangular fire located against a CS board at time intervals of 0.08 s (R = 7.45, $\dot{Q}$ = 84.8 kW)

Table 1 Summary of fire scenarios

Burner shape	Surface area (cm^2)	Burner Length (cm)	Burner Width (cm)	Aspect ratio R	Heat release rate $\dot{Q}$ (kW)
Square	900	30.0	30.0	1	28.3; 42.4; 56.5; 70.7; 84.8
Rectangular	900	42.4	21.2	2	
Rectangular	900	60.0	15.0	4	
Rectangular	900	82.0	11.0	7.4	

Table 2 Thermal properties of CS board

Materials	Density (kg/m^3)	Conductivity (W/mK)	Sp. ht. cap. (kJ/kgK)	Length (m)	Width (m)	Thickness (m)
calcium silicate	925	0.15	1.0	2.44	1.22	0.008

The flame shape was recorded using a digital CCD (Charge Coupled Device) camera (2592×1944 pixels) with a film of 25 frames/s. The binary image processing technology captures the flame shape and converts it into binary images. It first calculates the height of the flame in the binary image, and then converts it into real height. Based on continuous images of the transient flame height, the flame pulsation frequency was deduced by the Fast Fourier Transform method [41]. Fig. 4 presents the flame pulsation frequency of a square burner (R = 1, $\dot{Q}$ = 84.8 kW).

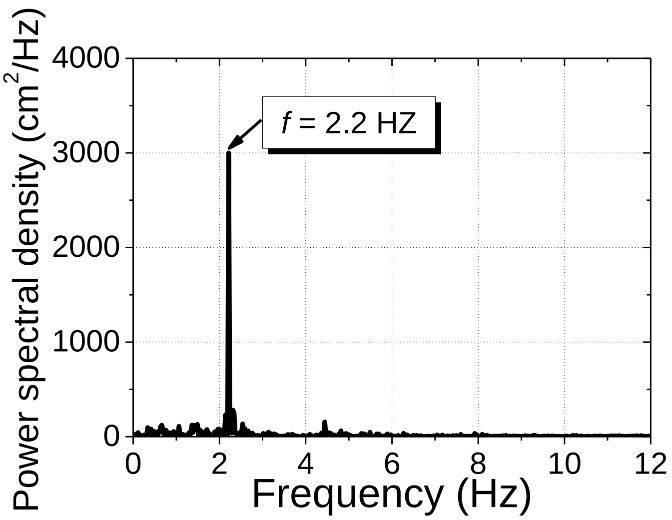
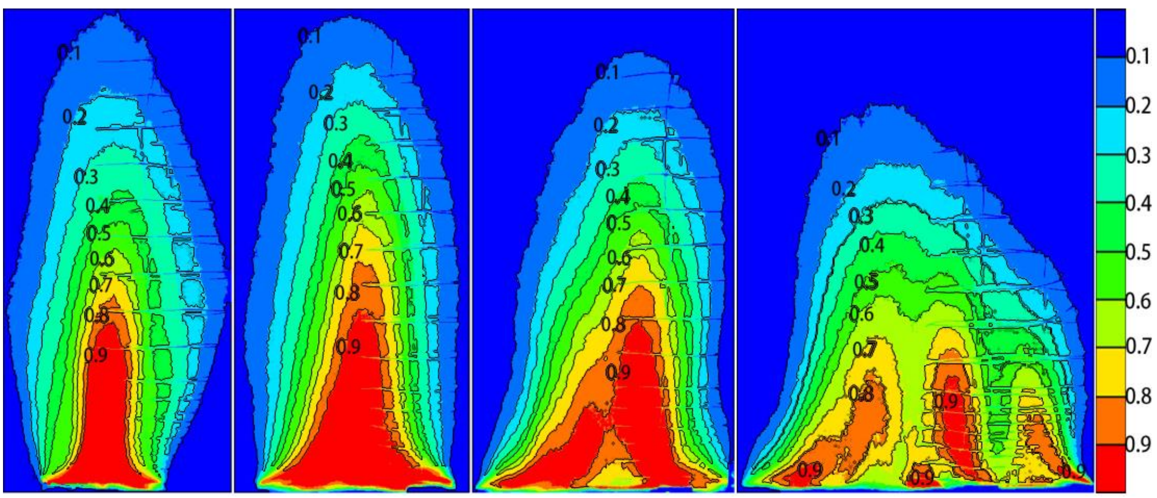


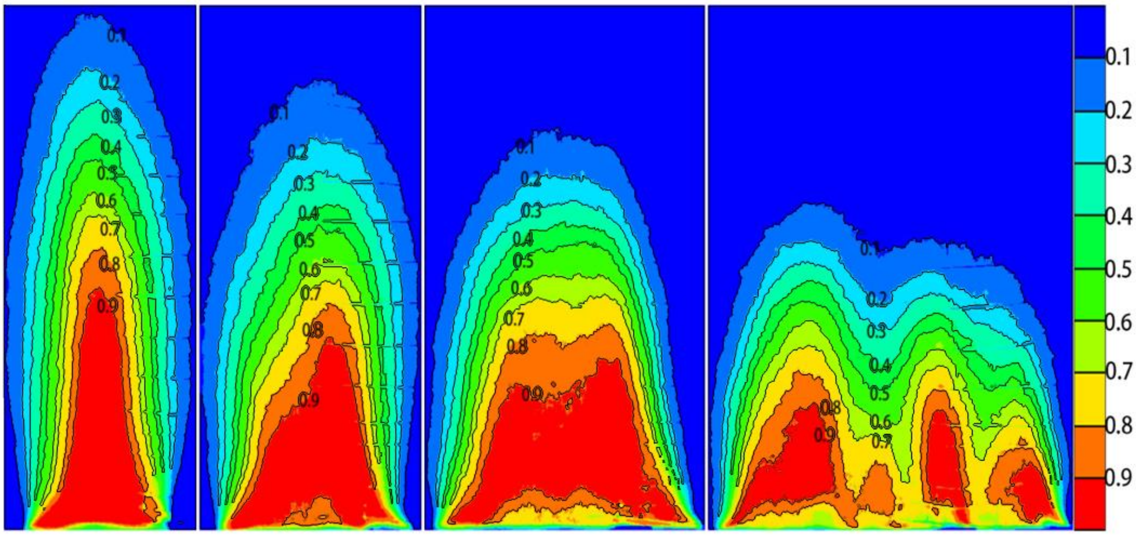
Fig. 4 Flame pulsation frequency of a square burner (R = 1, $\dot{Q}$ = 84.8 kW)

Figures 5 and 6 plot the contour image of flame height frequency for the rectangular fire source with a sidewall and in an open space, respectively. The flame diverged into several branches when the aspect ratio was increased to 7.45. This was in line with the observation in [6, 10]. It is likely that different air entrainment rates at different directions affected the local burning rates and flame shapes. As the length of the burner became longer than its width, more air was entrained from the length of burner. For a small section of rectangular fire source, the ratio of air to fuel increased with better air and fuel mixing. As the width of burner became smaller, the fuel flow injected from the burner was easier to be separated to give more sub-flames.



(a) R = 1 (b) R = 2 (c) R = 4 (d) R = 7.45

Fig. 5 Contour image of flame height frequency for the rectangular fire source with different aspect ratios against the CS board.



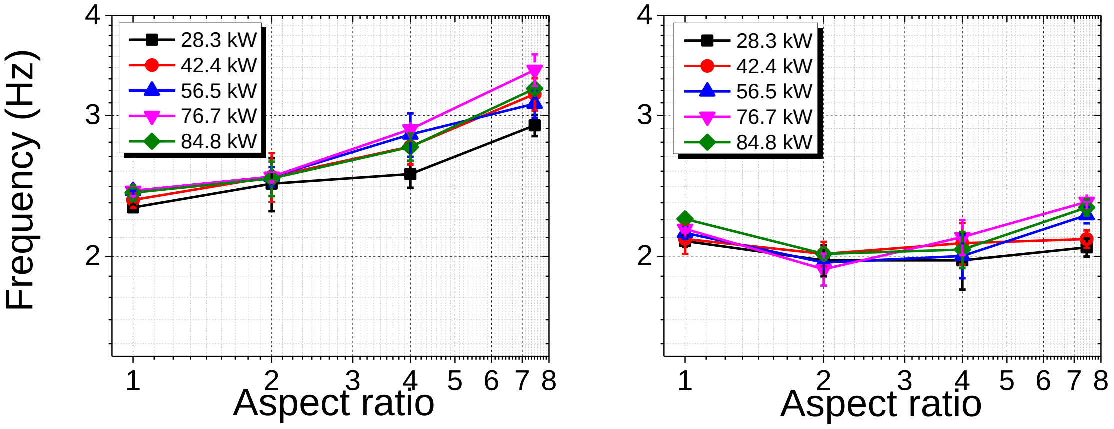
(a) R=1 (b) R=2 (c) R=4 (d) R=7.45

Fig. 6 Contour image of flame height frequency for the rectangular fire source with different aspect ratios in the open space ($\dot{Q} = 84.8$ kW).

3. Flame pulsation frequency

Figure 7 shows flame pulsation frequency of rectangular fire with different boundary conditions. Flame pulsation frequency is deduced from the variation of flame height. For the rectangular fire without the sidewall, flame pulsation frequency increased in a linear manner with the increase in aspect ratio. This was the same conclusion reached by Tu et al. [10] and Tang et al. [40]. As the fire source was located against a sidewall, the flame pulsation frequency decreased significantly. This was within 1.9 – 2.3 Hz as the aspect ratio increased from 1 to 7.45.

The effect of the fuel exit velocity on the pulsation frequency became intense as the aspect ratio of the rectangular burner became larger than 2 for fire source in the open space and 4 for fire source against the sidewall, as shown in Table 3. For the rectangular fire source in the open space, as the heat release rate increases, the maximum growth rate of the flame pulsation frequency is 13.7% and 17.3% for aspect ratios of 4 and 7.45, respectively. When the fire source was located against the sidewall, the maximum growth rate of the flame pulsation frequency increased suddenly from 7.0% to 14% as the aspect ratio was increased from 4 to 7.45. Therefore, the fuel exit velocity should be taken into account in the pulsation frequency model, especially for a rectangular fire source with a high aspect ratio.



(a) Open space (b) Sidewall

Fig. 7 Flame pulsation frequency of rectangular fire with different boundary conditions.

Table 3 Maximum growth rate of flame pulsation frequency

	Open space	Sidewall
RN1	4.9%	6.6%
RN2	0.5%	4.5%
RN4	13.7%	7.0%
RN7.45	17.3%	14%

4. A global model of flame pulsation frequency

According to previous studies [38-40], the burner width [39], perimeter-effective diameter [38], and hydraulic diameter [40] can be used as the characteristic length for the flame pulsation frequency model in an open space. For a rectangular fire source with a sidewall, the burner width cannot differentiate a rectangular fire source in an open space from the one with a sidewall. Thus, the perimeter-effective diameter and hydraulic diameter were used for the global flame pulsation frequency correlation under free, sidewall, and corner conditions.

The hydraulic diameter is considered as more suitable characteristic parameter for the pulsation frequency than the perimeter-effective diameter. The perimeter-effective diameter indicates the contact area of flame surface with stagnant surroundings. While the hydraulic diameter is mainly used for calculations involving turbulent flow. Based on the conclusion in [36], the pulsation frequency was found to be closely connected with the convection within one diameter height above the fire source. The convection between the buoyant plume gas and the stagnant surroundings was turbulent flow and reduced by the sidewall and the corner. Therefore, the hydraulic diameter can be used as correlation for the pulsation frequency.

For a rectangular fire source with free, sidewall and corner boundaries, the expression of hydraulic diameter for the global pulsation model is

$$\mathrm{D_{hyd}} = \begin{cases} \frac{4\mathrm{LW}}{2(\mathrm{L}+\mathrm{W})} & \text{free flames} \\ \frac{4\mathrm{LW}}{2\mathrm{W}+\mathrm{L}} & \text{sidewall flames} \\ \frac{4\mathrm{LW}}{\mathrm{L}+\mathrm{W}} & \text{corner flames} \end{cases} \tag{10}$$

According to the assumption of the mirror model [38], the expression for the hydraulic diameter does not change if the mirror model is applied for sidewall and corner flames. The expressions of the perimeter-equivalent diameter for fire sources with different boundaries are shown in Eq. (3).

Figure 8 shows the global flame pulsation frequency correlation based on the perimeter-equivalent diameter. The fitted correlation is almost the same as that of the model proposed by Zhang et al. [38] (Eq. (2)). The coefficient of determination is only 0.8746. As the fuel flow rate is ignored, this global correlation has low accuracy in estimating the experimental data of rectangular burners with large aspect ratios (4 and 7.45). Furthermore, this global correlation over-estimates the flame pulsation frequency of the fire source in the corner, which can be proved by the experimental data from Zeinali et al. [42].

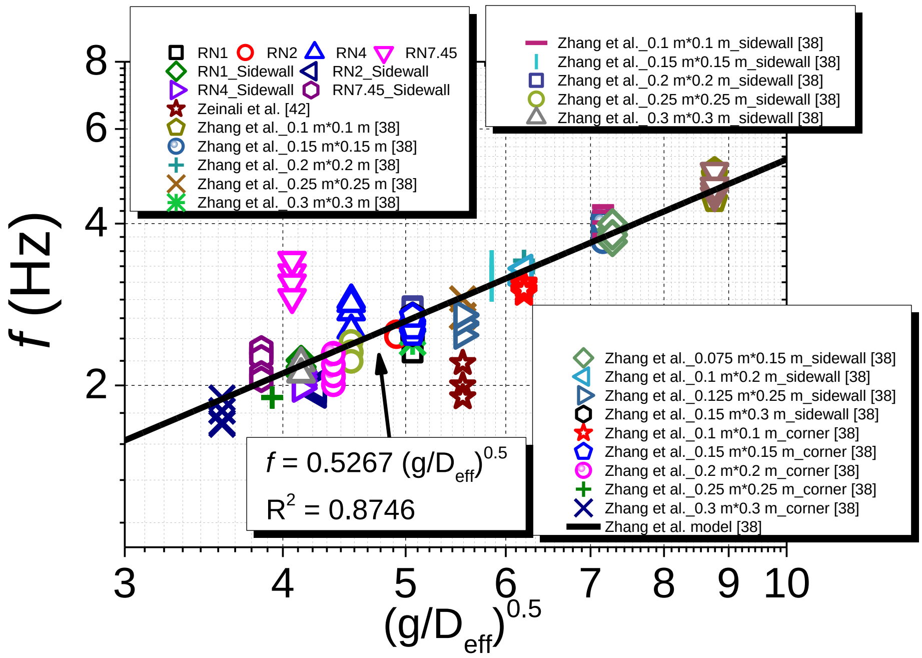


Fig. 8 Global flame pulsation frequency correlation based on the perimeter-equivalent diameter.

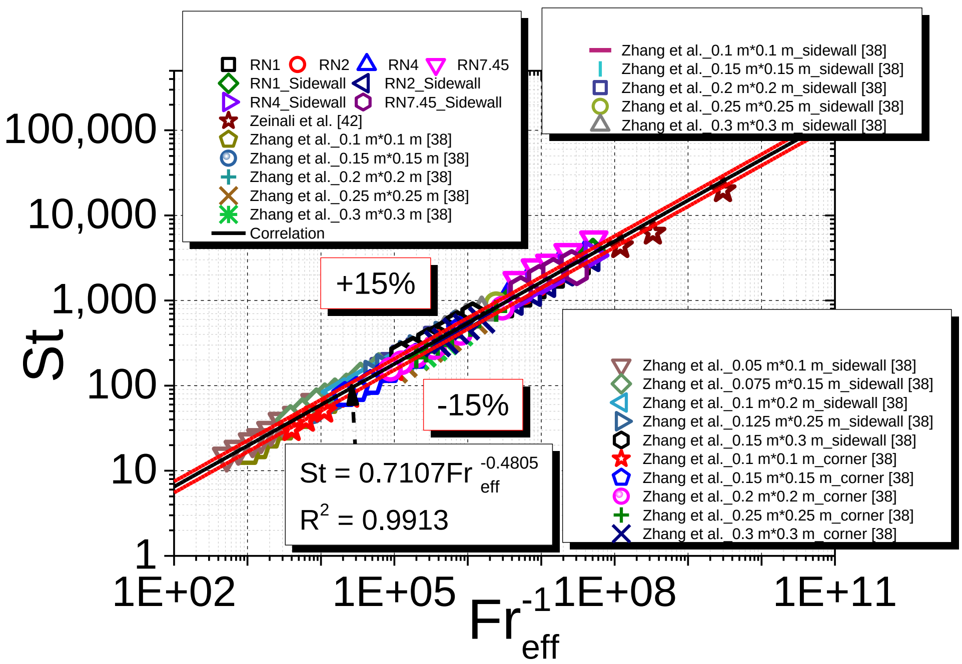
Based on the experimental results in present work and data available in the literature [38, 42], the global flame pulsation frequency correlation based on dimensionless parameters (Strouhal number and Froude number) with perimeter-equivalent diameter is fitted as

$$\mathrm{St} = 0.71\ \mathrm{Fr}_{\mathrm{eff}}^{-0.48} \tag{11}$$

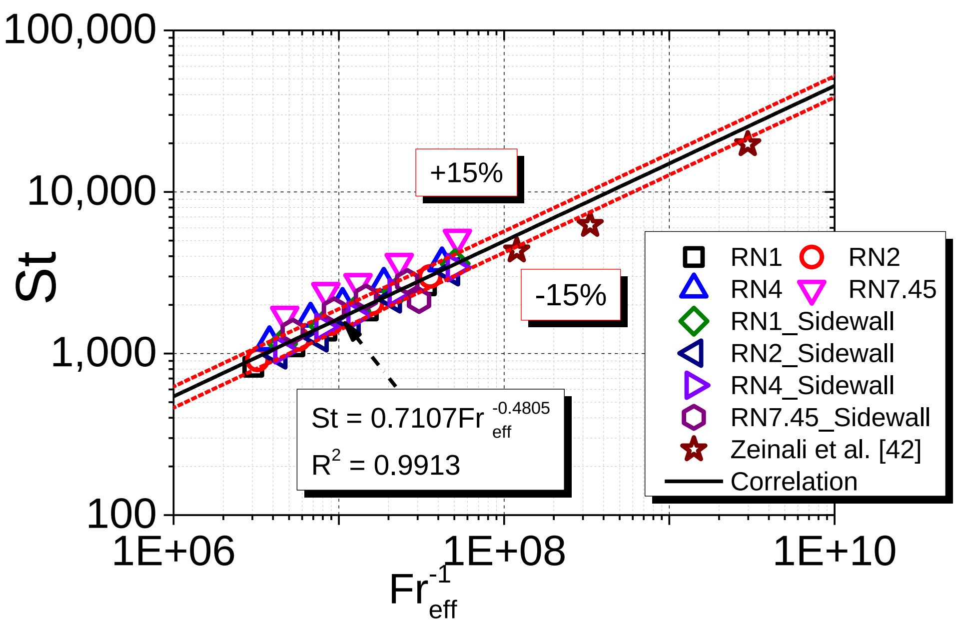
Global correlation of flame pulsation frequency based on dimensionless parameters (Strouhal number and Froude number) with hydraulic diameter is expressed as

$$\mathrm{St} = 0.53\ \mathrm{Fr}_{\mathrm{hyd}}^{-0.49} \tag{12}$$

Figures 9 and 10 show the global flame pulsation frequency correlations based on dimensionless parameters (Strouhal and Froude numbers) with the perimeter-equivalent diameter and hydraulic diameter, respectively. The global flame pulsation frequency correlation with the hydraulic diameter has better accuracy than that with the perimeter-equivalent diameter. Even though the coefficients of determination for these two global correlations are both greater than 0.99, the global correlation with the perimeter-equivalent diameter performed poorly for the rectangular fire source with an aspect ratio of 7.45 and the fire source in the corner. In this case, the local errors of the correlation are larger than 15%, as shown in Fig. 9(b). However, the local errors of the global correlation with hydraulic diameter for all the fire tests are less than 15%, as shown in Fig. 10. Evidently, the hydraulic diameter is a better characteristic length for the global flame pulsation frequency model.

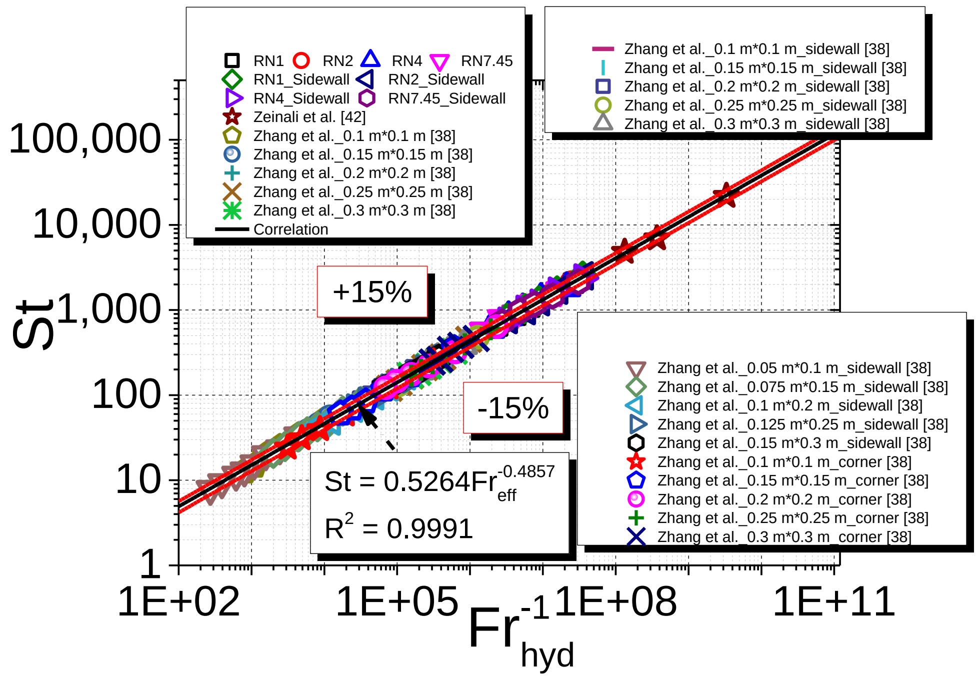


(a) All data

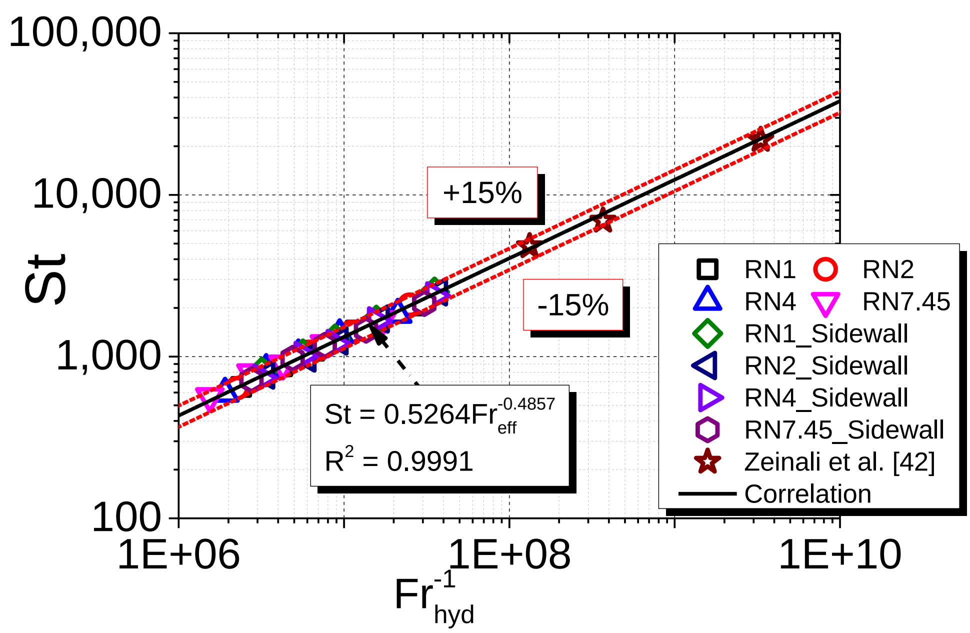


(b) Data from the present work and Zeinali et al. [42]

Fig. 9 Global flame pulsation frequency correlation based on dimensionless parameters (Strouhal number and Froude number) with perimeter-equivalent diameter.



(a) All data



(b) Data from the present work and Zeinali et al. [42]

Fig. 10 Global correlation of flame pulsation frequency based on dimensionless parameters (Strouhal number and Froude number) with hydraulic diameter.

5. Conclusions

This study focuses on the flame pulsation frequency of the rectangular fire with different boundaries. Rectangular fire experiments were conducted in an open space and with a CS board. The presence of a sidewall has significant effect on the flame pulsation behaviors of a rectangular fire source. The blockage of air entrainment by the sidewall significantly reduced frequency of flame pulsation. Furthermore, the effect of the fuel exit velocity on the pulsation frequency should be taken into account for the pulsation frequencies of rectangular fire sources with high aspect ratios.

A global correlation was developed for the frequency of flame pulsation generated by the rectangular fire source with different boundaries. The hydraulic diameter of the rectangular fire source was modified for the characteristic parameter for the global frequency model of flame pulsation. Then, based on the experimental data obtained in the present work and available in the literature, a global model for puffing frequency was improved for the rectangular fire source with free, sidewall, and corner boundaries. The coefficient of determination of this model is 0.9991 and the local error of this fitted correlation was less than 15%, which show that the experimental data can be expressed quite accurately with this correlation. Compared with the perimeter-effective diameter, the hydraulic diameter is a better characteristic length scale for the flame pulsation frequency correlation of the burner with different boundaries.

The flame pulsation frequency was determined by the convection between the buoyant plume gas and stagnant surroundings. The perimeter-effective diameter indicates the contact area of the flame surface with the stagnant surroundings and ignores the turbulence flow of the gas flame. The hydraulic diameter used for calculations involving turbulent flow more accurately describes the correlation of the flame pulsation frequency than the perimeter-effective diameter.

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