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Applications of the Equivalent Gap Fraction Criterion Method for Fire Whirl Risk Evaluation and Prevention in a Real Fire Disaster

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Abstract. In this paper, a method is proposed for spontaneous fire whirl analysis and prediction due to non-regularly or randomly distributed flame sources, by defining an equivalent gap fraction and providing an adapted criterion. The topological structure of the flame source configuration, the eccentric direction of each equivalent gap and the integrated effect of all the gaps are considered. By the application of the equivalent gap fraction criterion, predictions can be made in a real fire disaster for the likelihood, the rotating direction and the rough intensity of the swirl and then suggestions can be provided for configuration design to prevent fire whirls or to reduce the damage.

Keywords: Fire whirl, Equivalent gap fraction, Criterion, Risk evaluation, Prevention

1. Introduction

The fire whirl is a peculiar phenomenon in natural fires, of great destructive power though it happens infrequently. Fire whirls are highly destructive since intense rising due to spiraling spreads burning scraps far away to generate new fire sources. Thus it is one of the greatest troubles in fire safety for its unpredictability and disastrous effects [1, 2]. However, due to the complex nonlinearity and multi-scales of the problem, so far there is still limited knowledge about the origins and mechanisms of fire whirls, which are of great importance in both fire protection applications and fire sciences. In order to make a prediction for preventing or suppressing fire whirls in a real fire disaster, it is necessary to study the formation mechanisms under natural conditions, especially emphasizing its spontaneity and practicality.

For natural origins of fire whirls, it was initially thought that flames were driven to rotate by an external source of angular momentum due to atmospheric instability or the interplay between wind and topography [2]. After that, two significant models for fire whirl studies were put forward by using a rotating cylinder to impose [3, 4] or a gapped structure to induce [5–8] an external circulation,

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respectively. Emmons and Ying [3] conducted one of the earliest experimental studies, in which a fire whirl was formed from a liquid-fuel pool at the centre of a rotating cylindrical screen that imposed a controlled angular momentum to the ambient air. The rotating cylinder model was followed by Chigier et al. [4] and the pool fire flame was replaced with a jet flame. Afterwards, Battaglia et al. [9] investigated fire whirls by the means of numerical simulation and compared the computed results with what had been discovered during Emmons and Ying's experimental studies [3]. For numerical studies, they artificially created a virtual circulation to work equivalently as a rotating cylinder, which was a convenient way to control boundary conditions and obtain required data for flow field analysis and mechanism studies though it was far different from natural formation.

Without an imposed circulation either by a rotating cylinder or by virtual boundary conditions, Satoh and Yang [5] obtained a fire whirl in laboratory by a four-walled square channel with symmetric corner gaps through which ambient air was continuously entrained to produce a swirl as a fire burning in the centre. Later they took the measurements of fire whirls with a high speed camera and an infrared thermal imager based on the same model [6]. They also extended the original model to 2×2 flames in a channel with single corner gap and conducted a series of experiments and numerical simulations [7]. Compared with the rotating cylinder model, the gapped structure model like all above seems to be closer to some actual scenarios. For example, gapped channel structures are common in urban layouts and a fire whirl may occur spontaneously if there is a fire plume in the centre of the channel. So Farouk et al. [8] called them "naturally induced fire whirls" in their numerical studies.

Recently, for the actual coexistence of flame sources in natural fires, multiple flame sources for large-scale city fires were considered. Satoh et al. [10] experimentally studied interaction among multiple fires in equidistant fire arrays and found that the vigorous burning in the central region tended to cause the fires there to merge and the merging flames grew into a gigantic fire whirl if wind was blowing into one corner of the array. This is an example of fire whirl induced by interaction between multiple fires and wind. Wind, a common phenomenon in the nature, was experimentally proved to be able to increase the risk of fire whirls by some investigators [11–13].

Kuwana et al. [14, 15] conducted a significant study on the generation mechanism of a real fire whirl as was experienced in Hifukusho-ato, Tokyo, after the Great Kanto Earthquake in 1921. In their work, mass fire generating fire whirls have been investigated under a fixed configuration and different wind conditions. Almost at the same time, Zhou and Wu [16] studied fire-induced-flow generating fire whirls under a calm wind condition and different multi-flame-wall distributions. They proved that fire whirls could also occur spontaneously in the absence of external causes which had been investigated in the past.

Zhou and Wu [16] used numerical simulations by FDS and laboratory experiments to show that fire whirls could be generated spontaneously for the distribution of a central flame and surrounding flame walls with symmetrical gaps. As the flames burning, surrounding fame walls partially blocked the inward air flow and favored the passage of the air stream through the gaps, provided that this air stream was aligned approximately with a particular circumferential direction, and thus autorotation occurred on the central flame. Besides, they quantitatively studied the role of the gap length in the rotation speed and concluded a criterion for whether a fire whirl can occur spontaneously. Further, they conducted the first numerical simulation for spontaneous fire whirls due to randomly distributed flame sources in natural circumstances, proving that the interaction effects among multiple flame sources was indeed one of the natural origins for fire whirls. But at that time, they thought the criterion was only available for a regularly distributed flame wall model and they were unable to give a general criterion for non-regularly or randomly distributed flame sources.

The purpose of the present study is to show, with a definition of equivalent gap fraction and some more specific issues, that the gap fraction criterion can be adapted qualitatively for non-regularly or randomly distributed flame sources to evaluate the risk of fire whirl generated by surrounding flame sources in a real fire disaster (Sect. 2). Significantly, two representative cases of the past reported fire whirls are given to show the applications of the criterion in fire safety, by which the layout can be proposed for places with high fire risks such as urban areas, storages, wood farms and grasslands to prevent them from fire whirls, or to reduce the damage (Sect. 3). All the mechanism analysis and evaluation tests are supported by numerical computations performed with the fire dynamics simulator (FDS) code [17]. The major conclusions of this paper will be summarized in the end (Sect. 4).

2. The Equivalent Gap Fraction Criterion

Zhou and Wu [16] have given a gap fraction criterion for whether a regularly distributed flame wall model can generate a fire whirl spontaneously:

> Criterion. For a flame surrounded by regularly distributed flame walls, rotation occurs if the gap fraction lies between 0 and 1, and maximum rotation occurs when the gap fraction is 1/2.

For the case of non-regularly or randomly distributed flame sources, they pointed out that it was not convenient to relate the rotation speed with the gap fraction and even hard to give a quantitative criterion, since there were too many uncertainties in defining a parameter to quantitatively represent the role gaps act, like the gap fraction for regularly distributed flame walls. In this paper, we will try to have the gap fraction criterion adapted qualitatively for non-regularly or randomly distributed flame sources so that it can be helpful for fire whirl risk evaluation and prevention in a real fire disaster.

Now we consider dividing all randomly distributed flame sources into several equivalent flame walls by integrating those adjacent ones into an entire equivalent flame wall from the topological view. Locally, like for a side of the fire ground, it can be regarded as consisting of an equivalent flame wall and an equivalent gap. Then we can evaluate the equivalent gap fraction (EGF) in a similar way like the gap fraction definition for regularly distributed flame walls. Even so, the criterion mentioned above is not always available for predicting whether non-regularly or randomly distributed flame sources can generate a fire whirl spontaneously. In Figure 1, we present several representative instances in which EGF lies between 0 and 1 whereas the central flame does not rotate. They will be helpful for us to find out some more specific issues relevant to EGF and leading to a criterion for non-regularly or randomly distributed flame sources.

The gap fraction has been defined as the ratio of the gap length to the side length [16]. It is easy to see each gap is half as long as the side in Figure 1, resulting in the gap fraction of each is 1/2. Notice that the calculation deals with each gap respectively, without consideration of the integrated effect. Then the gap fraction criterion for regularly distributed flame wall models may not work like the following instances:

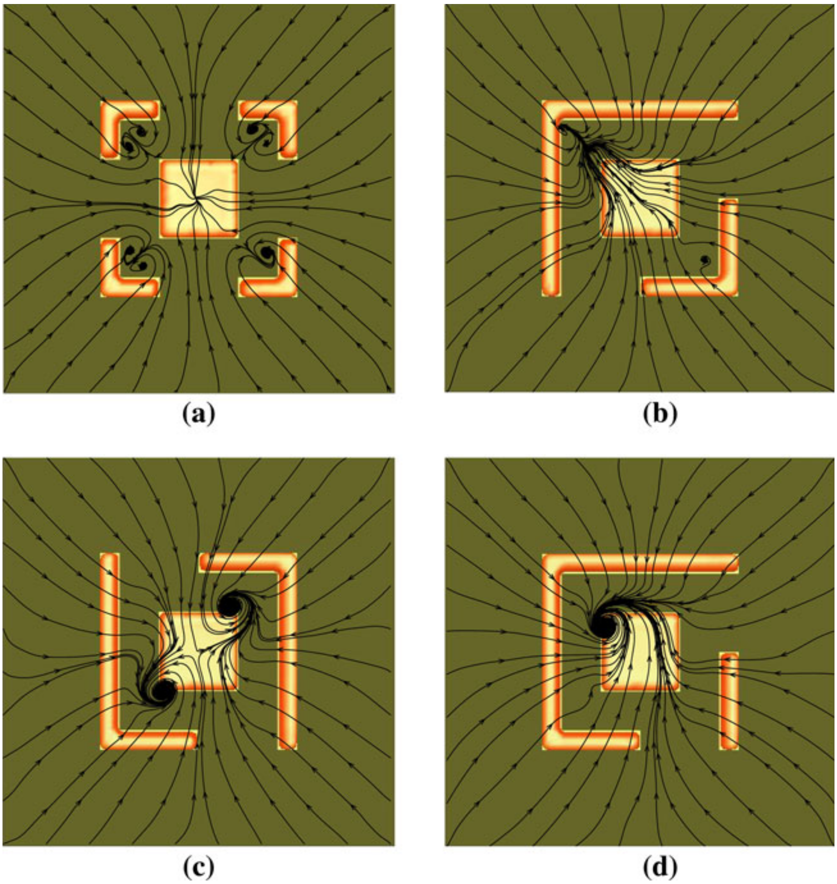


Figure 1. Representative instances for which EGF lies between 0 and 1 whereas the central flame does not rotate.

In Figure 1a, all the gaps are symmetrically distributed and there is no centralized swirl at the center of the flow field, which implies that a gap will add angular momentum to the central flame only if it is eccentric to one lateral side. The eccentric direction determines whether the gap induces a clockwise angular momentum or an anticlockwise one.

In Figure 1b, there are two gaps: one generates a stream in the clockwise direction and the other in the anticlockwise direction so that there is no swirl, which implies that the eccentric direction of each gap must be identified and the risk evaluation of swirl formation should depend on the integrated effect of all the gaps.

In Figure 1c, each gap generates an independent clockwise swirl that is captured by the corner between the two adjacent flame walls and does not add angular momentum to the central flame. In Figure 1d, the two gaps generate a unique swirl that is not right there where the central flame stays. These two cases imply that EGF is assuredly effective for evaluating the likelihood and direction of swirls but we are unable to determine the exact positions of the swirls, which is concerned with the particular configuration of flame sources.

In conclusion, we provide an EGF criterion for whether non-regularly or randomly distributed flame sources can generate a fire whirl spontaneously:

Preprocessing. For non-regularly or randomly distributed flame sources, each equivalent gap adds an angular momentum with a particular magnitude, clockwise or anticlockwise. EGF should be evaluated respectively for each equivalent gap with the eccentric direction indicated by a plus or minus sign (default: minus sign for clockwise direction, plus sign for anticlockwise direction).
Criterion. Rotation occurs if the algebraic average of all EGF lies between -1 and 1, clockwise for a negative value and anticlockwise for a positive value. The larger the absolute value, the more intense the swirl.
Additional Comments. If rotation occurs in the fire ground, the spontaneous generation of a fire whirl mostly depends on whether the position of the swirl just coincides with that of any flame source, which is concerned with the particular configuration of flame sources.

Now we are able to make predictions in a real fire disaster for the likelihood, the rotating direction and the rough intensity of the swirl by the EGF criterion. Numerical computation could be an effective approach to find out whether the swirl interacts with any flame source to generate a fire whirl spontaneously. And further, according to the criterion, we can even provide suggestions for configuration design to prevent fire whirls and then test them by the means of numerical computation.

3. Analysis and Simulation for Reported Cases

In the past fire whirl reports, we have found some representative cases related with the configurations of flame sources. In this section, we will investigate two of them by the application of the EGF criterion method.

3.1. Numerical Simulation Method

The numerical simulations are performed by using the fire dynamics simulator (FDS) code [17]. FDS is a computational fluid dynamics (CFD) model of fire-driven flow, developed by NIST, USA, whose codes are in the public domain. It solves the form of the Navier–Stokes equations appropriate for low-speed, thermally driven flow with emphasis on smoke and heat transport from fires by means of large-eddy simulation. The subgrid-scale motions are modelled by the Smagorinsky model. The core algorithm of the FDS is an explicit predictor–corrector scheme, second-order accurate in space and time. For most applications, FDS uses a mixture fraction combustion model, which assumes that combustion is mixing-controlled, and that the reaction of fuel and oxygen is infinitely fast.

In our computations, the computational domain is 8.0 m $\times$ 8.0 m $\times$ 8.0 m. All the flame sources are modelled to scale and assumed to have a uniform height of 0.1 m, approximately according to the average height of trees (about 10 m). The heat release rate per unit area (HRRPUA), which represents the fire combustion intensity, is fixed at 2000 kW m^{-2}. The boundary condition for the floor of the computational domain is that of a cold inert wall. For the ceiling and the four side surfaces an open condition is used to describe a passive opening to the exterior atmosphere.

The FSD simulation results have been validated against typically configurations in our early work [16], under the same assumptions, conditions and parameters. For an isolated plume model, no rotation occurs. For a four-flame-wall model, the numerical results show a counterclockwise rotation of the centre plume with the flame height increasing. Then we performed experiments for the two models and the experimental observation confirms the numerical conclusions, as shown in Figure 2.

4. Results

4.1. Fire Whirl in a Storage Fire

A fire occurred in Manitoba, Canada, in the flax storage compound of Eucata Fibers on 19 April 2000. Bales were arranged in a rectangular array. There were 1000 bales per stack in 41 stacks packed 30 feet high. The stacks were separated by 200 feet and spread over 160 acres (2640 ft $\times$ 2640 ft; or 800 m$\times$ 800 m) Each stack was approximately 250 ft wide $\times$ 250 ft long $\times$ 30 ft high (75 m $\times$ 75 m $\times$ 10 m). This is very similar to an urban area with three-storey apartment complexes. Lightning hit the stacked bales, a fire started, and fire whirls were reported in the central region. A pickup truck driving by was lifted from the ground and flipped over.

Now we simulate the storage fire mentioned above by FDS. Since the number of each row was not specified, for general discussion, we conduct a series of numerical computations for different distributing configurations (Figures 3, 4, 5, 6, 7, 8). The scale of computation is 1/100. For convenience of explanation, numerical results are displayed with the following issues:

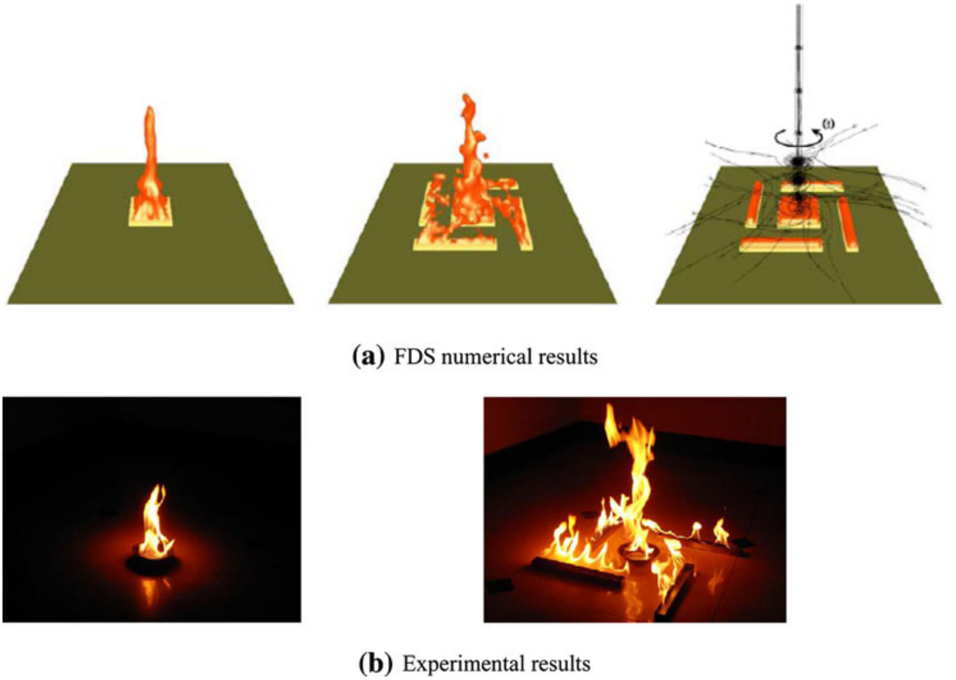


Figure 2. Validation for the FDS numerical results [16].

(i) Streamlines at height $z = D/2$ (D is the side length of each stack) are displayed by black lines with small arrowheads showing flow directions.

(ii) Streamlines distribute in several favored directions and then the general structure of the flow field can be treated into several large branches (dominating flow), each of which is indicated by a large semitransparent arrow and specified by a combination of a letter and a sign, the letter L or R representing the left or the right side of the figure and the plus or minus sign representing the upper or the lower part of the figure, like L+ representing the dominating flow on the upper left corner of the figure.

(iiI) Vacant area is indicated by a solid-line frame, representing an equivalent gap there in the flow field as well.

In Figure 3, stacks are arranged in such a way that each equivalent gap is in the similar position relative to its own side, which is defined as the similar-position mode (S-mode). As displayed in Figure 3a and b, the two equivalent gaps are on the opposite sides with EGF lying between −1 and 0 in a clockwise direction. According to the EGF criterion, a clockwise swirl can be generated spontaneously. From the computed results, the dominating flow on each side is drawn by the equivalent gap and deflected toward it, thus L− to the left while R+ to the

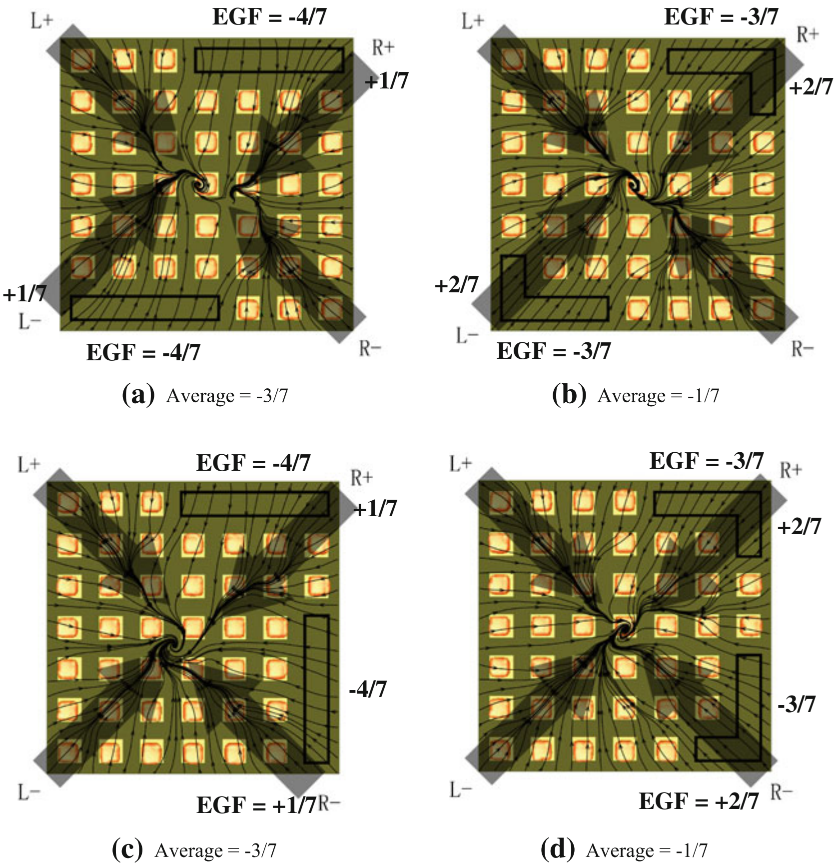


Figure 3. The similar-position mode (S-mode).

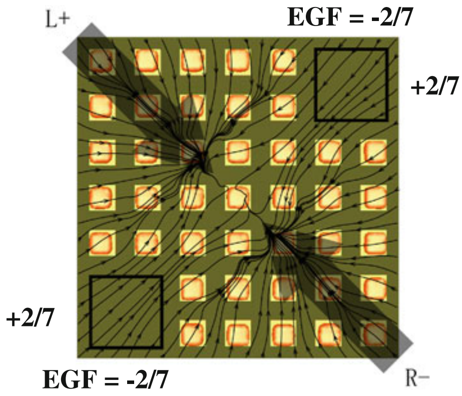


Figure 4. An exceptional case of the S-mode: average = 0.

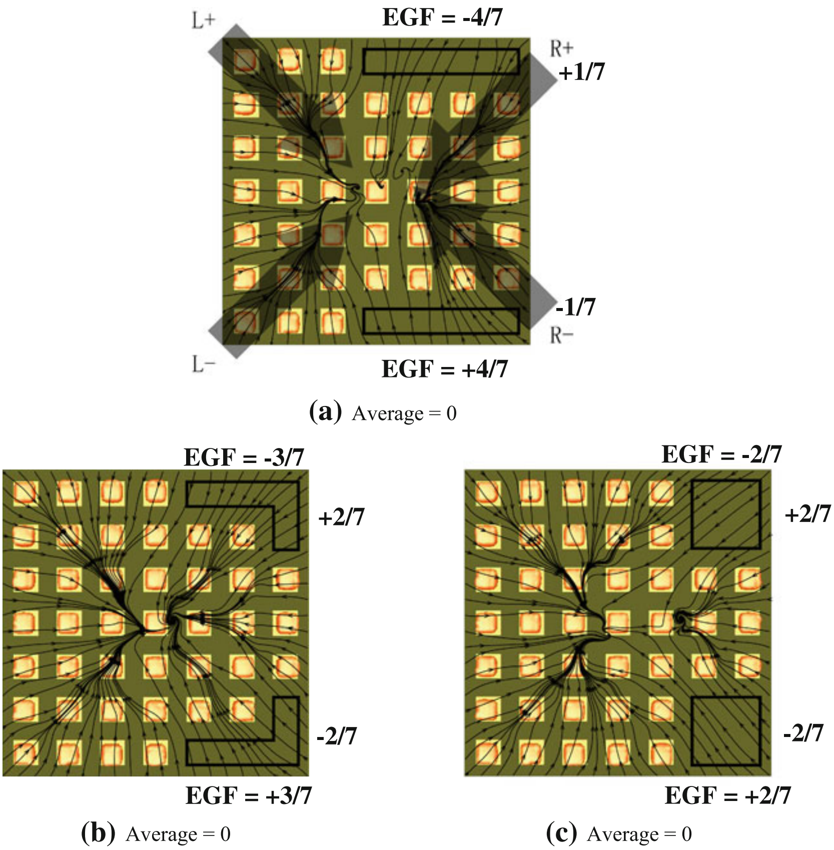


Figure 5. The opposite-position mode (O-mode).

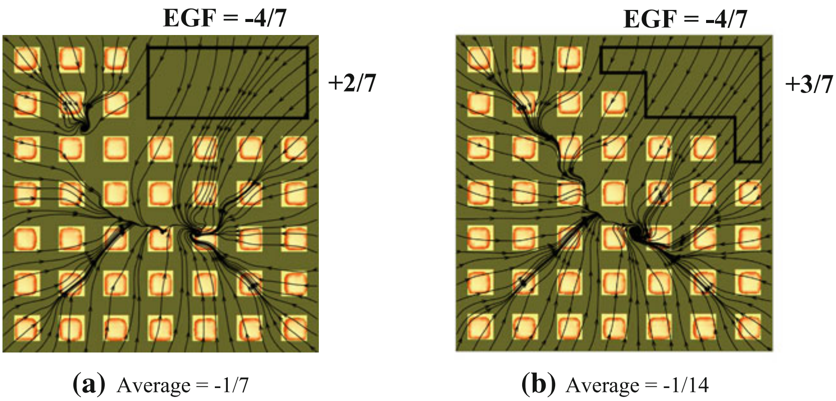


Figure 6. The integration mode (I-mode).

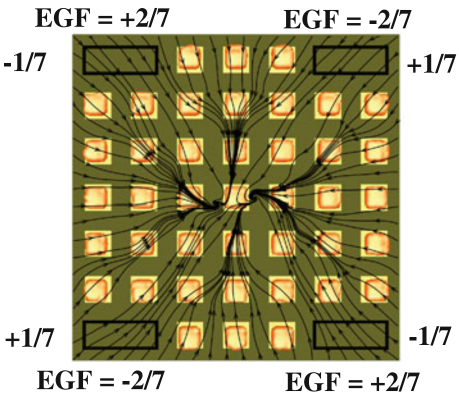


Figure 7. The dispersion mode (D-mode): average = 0.

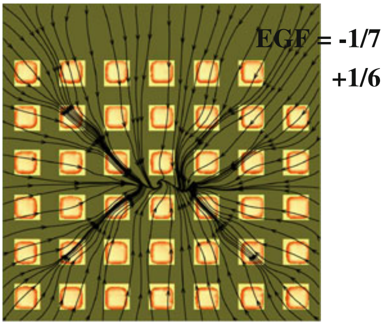


Figure 8. The minimum mode (M-mode): average = +1/84.

right. The relative displacement between the two dominating flows produces a clockwise torque generating a clockwise swirl in the flow field.

If the two equivalent gaps are on the adjacent sides as displayed in Figure 3c and d, a clockwise swirl can also be generated spontaneously. From the computed results, drawn by the equivalent gaps, R+ is deflected to the right and the relative displacement between R+ and L− produces a clockwise torque while R− is deflected lower and the relative displacement between R− and L+ produces a clockwise torque as well. As a result, a clockwise swirl is generated in the flow field.

Now note that if the two equivalent gaps are on the opposite sides (Figure 3a, b) or on the adjacent sides and the gap is not too long ($|EGF| < 1/2$, Figure 3d), the flow field is symmetric enough to have the swirl right there on the central burning stack and induce a fire whirl spontaneously. If the gap on the opposite side is too long ($|EGF| > 1/2$, Figure 3c), the symmetry of the flow field becomes poorer so that the swirl may be deviated from the center of the flow field. In this case, the occurrence of a fire whirl depends mostly on whether the position of the swirl just coincides with that of any other burning stack.

In a word, if equivalent gaps are arranged in the S-mode, the interaction between the diagonal dominating flows can generate a swirl spontaneously in the flow field. As an exceptional case (Figure 4), the length and width of the equivalent gap are the same, so that the flow field is distributed symmetrically along the diagonal line, which can not generate any swirl spontaneously. In terms of the EGF criterion, EGF on the two sides of the corner, of equal magnitude but of opposite sign, yield an average of zero, and as a result, it can be predicted that no swirl will be generated spontaneously. However, this case is not common and only for some particular number of stacks.

In Figure 5, stacks are arranged in such a way that equivalent gaps are opposite to each other, which is defined as the opposite-position mode (O-mode). It is easy to see that the average of EGF is always zero and to predict that no swirl will be generated spontaneously according to the EGF criterion. From the computed results, drawn by the equivalent gaps, R+ is deflected to the right and the relative displacement between R+ and L− produces a clockwise torque while R− is deflected to the right as well and the relative displacement between R− and L+ produces an anticlockwise torque of the same magnitude. As a result, no swirl is generated in the flow field (Figure 5a). In the O-mode, the interaction between the diagonal dominating flows is weak while that between the two on the same side (like R+ and R− in Figure 5a) is strong. Thus if the gaps become wider as displayed in Figure 5b and c, the dominating flows on the same side will be pushed closer to each other, which can easily intertwine together due to even only a small random disturbance, forming a swirl to a stable trend from the view of fluid dynamics. Generally, the swirl is deviated from the center of the flow field and rotates not intensely, thus the occurrence of a fire whirl depends mostly on whether the position of the swirl just coincides with that of any other burning stack and whether the swirl itself is intense enough to drive the flame to rotate.

In Figure 6, stacks are arranged in such a way that all vacant positions are integrated into a single equivalent gap on a corner of the flow field, which is defined as the integration mode (I-mode). In terms of the EGF criterion, it can be predicted that a clockwise swirl will be spontaneously generated. However, the position of the swirl can not be determined yet. A numerical computation is needed to conduct to see whether the position of the swirl just coincides with that of any burning stack and then to make a prediction about whether a fire whirl can occur.

In Figure 7, stacks are arranged in such a way that all vacant positions are dispersed into several equivalent gaps symmetrically on the four corners of the flow field, which is defined as the dispersion mode (D-mode). It is easy to see that the average of EGF is always zero and to predict that no swirl will be generated spontaneously according to the EGF criterion. From the computed results, due to the equivalent gaps, the dominating flows just have their directions changed from diagonal to vertical and horizontal, and no swirl is generated spontaneously in the flow field because of the symmetry.

In Figure 8, stacks are arranged in such a way that the array is as full as possible so that the vacant area achieves the minimum (M-mode). In this case, the equivalent gap is too small to induce a swirl, and it can be evaluated that the likelihood of inducing a swirl is very low. Further more, if the vacant positions are concentrated on a corner, the likelihood will become even lower, for EGF on the vertical side and that on the horizontal side counteract each other. The closer the length and width of the vacant area to each other is, the more the likelihood approaches zero. Now the 41 stacks can be arranged into an array of $7 \times 6 - 1$, with only one vacant position on a corner. Notice that the equivalent gap is as wide as it is long but the horizontal side (7 stacks) of the array is one stack longer than the vertical side (6 stacks), so the horizontal EGF (clockwise) is a little smaller than the vertical EGF (anticlockwise), which may lead to a very weak anticlockwise swirl in the flow field. This prediction is well verified by the computed results.

Based on the above mechanism analysis and numerical results, a few concluding items can be drawn as follows (Table 1):

Case 1: Equivalent gaps being arranged in the S-mode as shown in Figure 3, it is extremely possible that a fire whirl occurs spontaneously with a very intense rotation. Notice that the swirl is right there on the center stack of the storage in Figure 3a, b and d so that we guess the stacks might actually be arranged just like that, which caused the reported fire whirl. Thus in storage layout design, S-mode distribution should be strongly avoided.

Case 2: Equivalent gaps being arranged in the O-mode as shown in Figure 5, the risk of spontaneous fire whirls is lower and the swirl is weaker. Even so, O-mode is not recommended in storage layout design.

Case 3: Equivalent gaps being arranged in the I-mode as shown in Figure 6, the risk of spontaneous fire whirls is uncertain. Thus in storage layout design, I-mode is not recommended, either.

Case 4: Equivalent gaps being arranged in the D-mode as shown in Figure 7, fire whirls could scarcely occur spontaneously. Thus in storage layout design, D-mode distribution can be recommended.

Case 5: Equivalent gaps being arranged in the M-mode as shown in Figure 8, fire whirls could hardly occur spontaneously. Thus in storage layout design, M-mode distribution can be recommended as well. Besides, it may be more feasible compared with the D-mode in Case 4, for more continuous space is saved. Notice that if the total number of stacks can not form a full array, the vacant positions should be arranged together on a corner, with the length and width of the vacant area as close to each other as possible.

Table 1
Risk of Spontaneous Fire Whirls for Different Distribution Modes

Distribution mode	Risk of spontaneous fire whirls	Suggestion
S-mode	Very high	Strongly avoided
O-mode	Moderate	NOT recommended
I-mode	Uncertain	NOT recommended
D-mode	Very low	Recommended
M-mode	Very low	Recommended

In practical applications, those distribution modes recommended above should be chosen according to the actual situation and other conditions of the storage so that the risk of spontaneous fire whirls or the rotation intensity can be reduced as low as possible. In this way, the potential damage from fire whirls can be prevented or weakened in a storage fire.

4.2. Fire Whirl in a Wood Farm Fire

A wood farm near Old Fort Providence in the northwest part of Canada caught fire on July 4, 1997. A fire whirl was reported in the disaster (Figure 9a). The wood farm had been constructed as a piecewise distributing configuration, being captured in the picture taken just several days before the fire took place (Figure 9b).

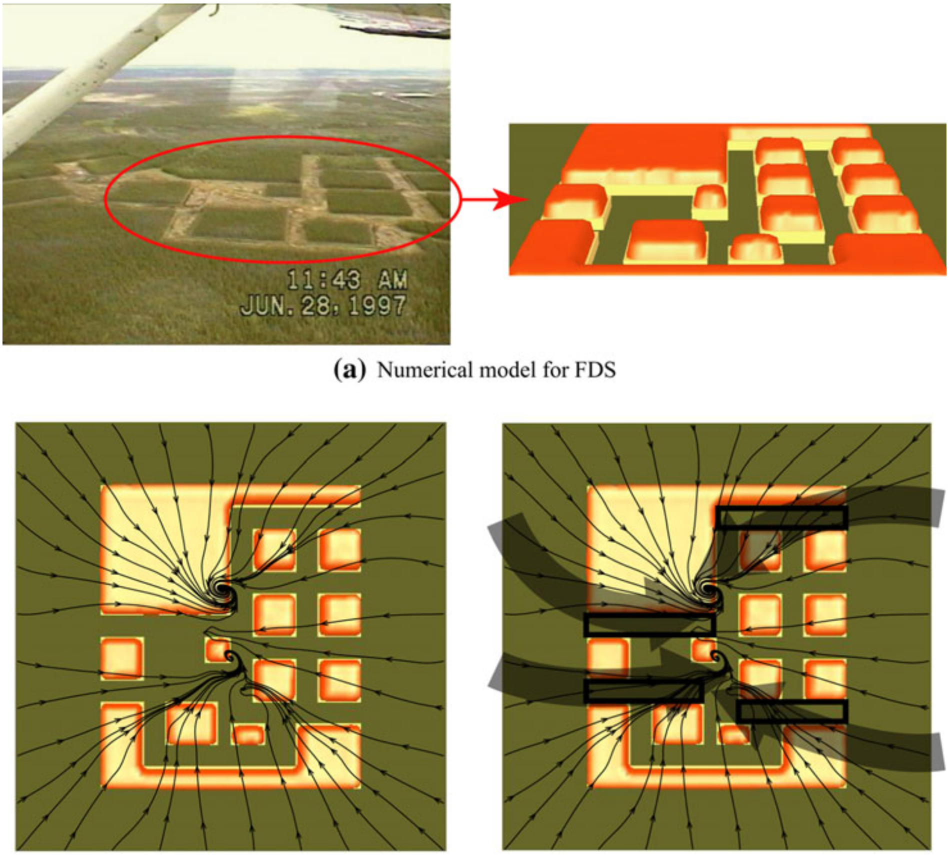
The piecewise distributed wood farm is modelled by FDS as shown in Figure 10a and the computed results are displayed in Figure 10b, showing two anticlockwise swirls were generated spontaneously. The upper swirl on the lower right corner of the largest flame source was rotating intensely, so that we guess the reported fire whirl might occur right there at the location. The lower swirl near a small flame source was rotating more weakly but still led to the likelihood of inducing a fire whirl.

Based on the numerically computed flow field, it can be analyzed that the cause of the spontaneous swirl is mostly contributed by the dominating flows favored by the equivalent gap shown in Figure 10c, whose EGF can be easily evaluated to lie between 0 and 1 in the anticlockwise direction. In terms of the EGF criterion, we have found out the mechanical cause of the spontaneous fire whirl reported in the wood farm fire. Further, we can even use the criterion to redesign a modified scheme for the wood farm configuration as follows.

In order to maintain the basic topological structure of the wood farm as possible, only a few pieces' positions will be adjusted a little to make the short gaps on the left part and those on the right part along an equal line, forming a long gap running through the whole area from the left to the right symmetrically, as

(a) Fire whirl in the wood farm　　**(b)** A part of the wood farm

Figure 9. A wood farm fire near Old Fort Providence.



(a) Numerical model for FDS

(b) Computed results

(c) Equivalent gaps and dominating flows

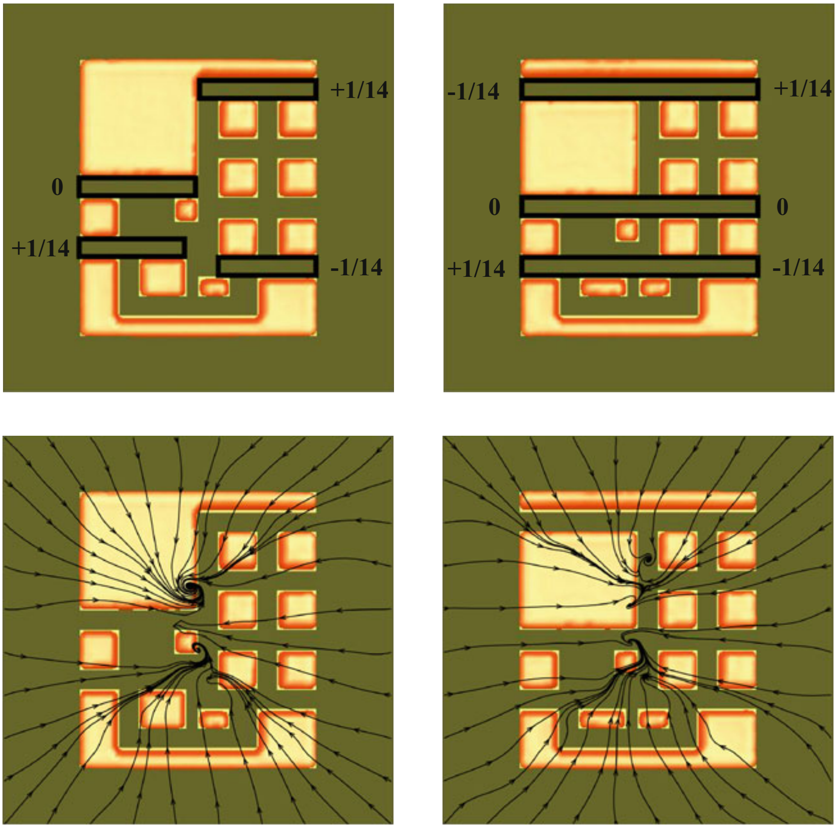
Figure 10. Numerical simulation for a piecewise distributing wood farm fire.

displayed in Figure 11b. In this case, EGF on the two sides, of equal magnitude but of opposite sign, yield an average of zero, and as a result, it can be predicted according to the EGF criterion that no swirl will be generated spontaneously.

Compared with the computed results for the original configuration, as shown in Figure 11, with modifications according to the EGF criterion, the basic topological structure doesn't change a lot whereas the risk of spontaneous fire whirls is greatly reduced and especially the biggest trouble on the lower right corner of the largest flame source has been completely eliminated.

5. Concluding Remarks

In this paper, a method is proposed for fire whirl analysis and prediction due to non-regularly or randomly distributed flame sources, by defining an equivalent



(a) Original configuration: Average = +1/56 **(b)** Adjusted configuration: Average = 0

Figure 11. A modified scheme for the wood farm configuration and the computed results.

gap fraction and providing an adapted criterion. Then this method is applied to two reported fire whirl cases, analyzing the cause of fire whirl occurring spontaneously and making suggestions for configuration design. The major conclusions of this study may be summarized as follows:

(i) By dividing all randomly distributed flame sources into several equivalent flame walls from the topological view, the equivalent gap fraction (EGF) can be evaluated. An equivalent gap will add angular momentum to the central flame only if it is eccentric to one lateral side. The eccentric direction determines whether the gap induces a clockwise angular momentum or an anti-clockwise one and the risk evaluation of fire whirl should depend on the integrated effect of all the gaps.
(ii) By evaluating EGF respectively for each equivalent gap with the eccentric direction indicated by a plus or minus sign, rotation occurs if the algebraic

average of all EGF lies between -1 and 1. The leading sign indicates the rotating direction and the larger the absolute value is, the more intense the swirl will be. If the position of the swirl just coincides with that of any flame source, a fire whirl can occur spontaneously.

(iii) By the application of the EGF criterion, predictions can be made in a real fire disaster for the likelihood, the rotating direction and the rough intensity of the swirl, and then it is found out whether the swirl interacts with any flame source to generate a fire whirl spontaneously by the means of numerical computation. Significantly for fire safety, a layout can be proposed for places with high fire risks such as urban areas, storages, wood farms and grasslands to prevent them from fire whirls, or to reduce the damage.

Acknowledgments

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References

1. Graham HE (1952) A fire-whirlwind of tornadic violence. Fire Control Notes 13:22–24
2. Graham HE (1957) Fire whirlwind formation as favored by topography and upper winds. Fire Control Notes 18:20–24
3. Emmons HW, Ying SJ (1967) The fire whirl. In proceedings of the 11th international symposium on combustion. Combustion Institute, Pittsburgh, PA, pp 475–488
4. Chigier NA, Beer JM, Grecov D, Bassindale K (1970) Jet flames in rotating flow fields. Combust Flame 14(1–3):171–180
5. Satoh K, Yang KT (1996) Experimental observations of swirling fires. ASME HTD 335(4):393–400
6. Satoh K, Yang KT (1999) Measurements of fire whirls from a single flame in a vertical square channel with symmetrical corner gaps. ASME HTD 364(4):167–173
7. Satoh K, Yang KT (1998) Experiments and numerical simulations of swirling fires due to 2×2 flames in a channel with single corner gap. ASME HTD 361(2):49–56
8. Farouk B, McGrattan KB, Rehm RG (2000) Large eddy simulation of naturally induced fire whirls in a vertical square channel with corner gaps. ASME HTD 366(5):73–80
9. Battaglia F, McGrattan KB, Rehm RG et al (2000) Simulating fire whirls. Combust Theor Model 4(2):123–138
10. Satoh K., Liu N, Zhu JP, Yang KT (2005) Experiments and analysis of interaction among multiple fires in equidistant fire arrays. In Proceedings of ASME summer heat transfer conference, pp 709–712
11. Emori RI, Saito K (1982) Model experiment of hazardous forest fire whirl. Fire Technol 18(4):319–327
12. Soma S, Saito K (1991) Reconstruction of fire whirls using scale models. Combust Flame 86(3):269–284
13. Liu NA, Liu Q, Deng ZH et al (2007) Burn-out time data analysis on interaction effects among multiple fires in fire arrays. Proc Combust Inst 31:2589–2597

14. Kuwana K, Sekimoto K, Saio K et al (2007) Can we predict the occurrence of extreme fire whirls?. AIAA J 45(1):16–19
15. Kuwana K, Sekimoto K, Saito K et al (2008) Scaling fire whirls. Fire Saf J 43(4):252–257
16. Zhou R, Wu ZN (2007) Fire whirls due to surrounding flame sources and the influence of the rotation speed on the flame height. J Fluid Mech 583:313–345
17. McGrattan KB, Baum HR, Rehm RG et al (2004) Fire dynamics simulator (version 4)-technical reference guide. NIST Special Publication 1018, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899