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Wildfires and the Generation of Fire Whirls

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Nomenclature

c_p	specific heat of air, kJ/kg·K
D	diameter of fuel surface, m
E	energy density, GJ/ha
$Fr_f^{0.5}$	fuel Froude number = $q/(c_p\rho_0\Delta T(gL)^{0.5}$
g	acceleration due to gravity, m/s^2
ha	hectare
L	horizontal length scale of burning area, m
q	heat release rate per unit burning area, kW/m^2
s	rate of spread of fire, m/s
S_L	maximum laminar burning velocity of the fuel/air, m/s
T_o	ambient temperature, K
u	fuel velocity, m/s
U_c	critical lateral velocity, at which whirls are generated, m/s
U^*	Flow number = $(u/S_L)(\delta_k/L)^{0.4}$
Greek	
δ_k	laminar flame thickness, derived from the expression in [19], m
$\Delta\rho$	difference between density at ambient and flame temperatures, kg/m^3
ΔT	difference between flame temperature and T_o, K

ρ_o ambient air density, kg/m^3

Abstract

The paper first reviews the mode of generation of fire whirls, their properties, and operational regimes, under well-controlled experimental conditions. The situation is different with wildfires. These are uncontrolled and less well understood. A modified analytical approach is described for these conditions. This is based on global energy levels, per unit ground area, for different fuels, and their associated rates of fire spread, under different conditions. These enable regimes of possible fire whirl generation in wildfires to be defined. The associated accuracy is not that of a laboratory flame, but it is probably practically sufficient. Only in two instances were atmospheric fires experimentally controlled. In the remainder, the rate of fire spread was a more meaningful parameter than a burning velocity, and the critical lateral velocity was seldom known accurately. Nevertheless, it was possible to relate it to the heat release rate, with both in dimensionless form.

Keywords: Fire storms; fuel Froude number; critical tangential velocity; Flow number; fire spread rate; fire plumes.

1. Introduction

There is a variety of ways in which fuel and air can be brought together and reacted. Six of the diverse regimes in which this occurs are described in [1]. Of these, probably fire whirls, which are created by tangentially circulating air flow around a plentiful supply of fuel, are currently the least practical, and most hazardous. Increased circulation increases both fuel entrainment and air mixing. The burn rate within the created vortex increases, the fire plume radius decreases, and the flame height increases. In a laboratory, the fuel can be readily supplied from a central pool of liquid, and the air from a carefully directed tangential air flow.

In the renowned studies of Emmons and Ying [2], the tangential flow was generated by a 3 m high cylindrical screen, rotating at 0.8 to 10 rpm about a 2.4 m diameter table. At its centre was a 10 cm diameter pool of acetone. The circulation was able to cause a 10-fold increase in flame height, with an associated increase in burn rate. Such well-controlled experiments are amenable to mathematical analysis [3]. The key factor is the presence of the tangential circulating atmospheric air flow to initiate the whirl. Figure 1 shows the tangential recirculation streamlines in the computer study of Snegirev et al. [4].

Figure 2 shows the fire whirl, created by Huahua Xiao et al. [5]. This was generated on a pool of *n*-heptane, that had been poured on to a surface of quiescent water. Surrounding air entered tangentially. A fire whirl was initiated at a critical value of the tangential velocity, U_c. This generated sufficient vorticity to induce whirl along the chimney of fire. To aid generalisation, this is normalised by the gravitational velocity $(gL)^{0.5}$. Here L provides an appropriate length scale, and is commonly the horizontal length scale of the burning area.

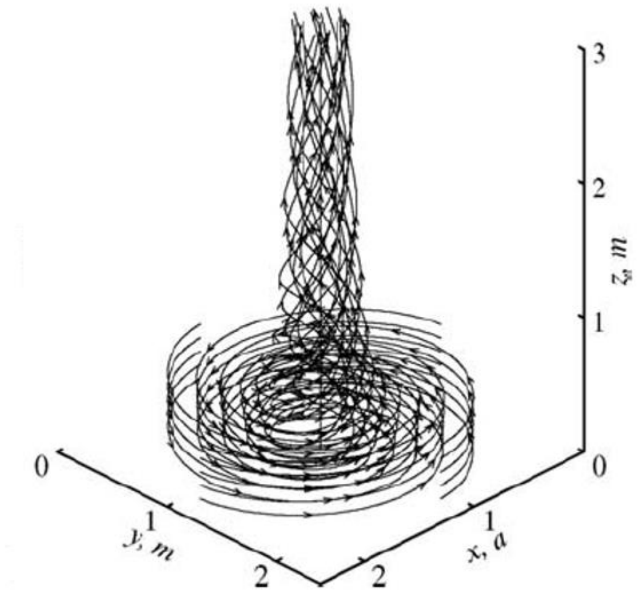

Fig. 1. Computed tangential air flow. From [4].

Fig. 2. Controlled generation of fire whirl. From [5].

In contrast, for the study of forest type fuels in wildfires, a laboratory scale Fire Whirl Generator has been developed by Pinto et al. [6]. Wild and Urban Fires contrast sharply with laboratory experiments. The scale of events is much larger, tangential flows depend upon the vagaries of the atmosphere, and the physico-chemical nature of the fuels is more variable, and often unknown. A rotating chimney of fire can create a high upwards reacting flow rate and a lower ground pressure. On a large scale, the combination of the high vertical flow rate and high combustion intensity can create a fire storm at the base. Urban firestorms can be no less damaging. In the case of the huge Hamburg warfare fire, this covered an area of about 11 km^2 [7], generating a huge firestorm.

The next Section is devoted to three large scale firestorms. The fires are characterised by relevant parameters that generalise their effects. These are subsequently used, often in an amended form, to analyse the whirls generated in nine diverse wildfires.

2. Structure of Fire Whirls

2.1 An early and later tragedy

An early tragic firestorm, of exceptional severity, occurred at Williamsonville, Wisconsin, in October 1871 [8]. All but 17 of the 77 inhabitants perished. It was of exceptional severity in a heavily forested, sparsely populated, region, in which wasteful logging practices had created a severe fire hazard. At the end of a hot summer, the winds would be strong enough to create a "sheet" of fire that would probably roll along over the tree tops, uprooting trees and generating fire whirls. Albini [9] comments that such crown fires, although relatively rare, are highly destructive, spreading at 10 km/hr, with heat release rates of 10 MW/m intensity. To analyse their effects, recourse must be made to generalisations concerning both the combustion energy available, and the spread rate of the fire. In the Williamsville fire storm there was a high probability of flame propagation along the crowns, with a suggested, relatively high, spread velocity, *s*, of 2.8 m/s.

The propagation speed of tree crown fires is particularly destructive. Similarly, the Black Dragon Fire in Heilongjiang Province, in 1987, one of the most massive in China, covered about 10,000 km^2. Initially, it was a moderate-surface fire, but developed into high-intensity crown fires [10].

Although high heat release rates can generate powerful whirls, quite weak whirls can be generated at very low heat release rates. A creeping fire in forest litter in spring may leave almost no trace of its occurrence. Albini [9] has pointed out that small ground fires can be started by spontaneous combustion, or lightning, and spread mostly by smouldering combustion, at a rate of the order mm/s, with little indication of their existence, and a small intensity of the order of 0.1 kW/m.

2.2 Atmospheric experiments

Uniquely, Dessens [11] created informative experimental simulations of large fire whirls by employing an array of burners to generate them and reveal their different characteristics. In later work [12] a total flame power of 100 MW, was generated from 105 fuel oil burners, spread, within a 140 m x 140 m square. Each burner produced a single plume, which soon merged with others, to form a single buoyant, composite plume, with diameters ranging from 30 to 60 m. Fire whirls were generated at values of U_c between 1 and 6 m/s, taking on a variety of physical appearances. At heights of about 1,000 to 2,000 m, the plume became almost horizontal, and 30-40 m above that point, the column bifurcated into two counter-rotating vortices [12].

2.3 Wind tunnel studies

A study with important theoretical and practical aspects is that of Kazunori Kuwana et al. [13]. It reports large scale simulations of intense fire whirls, with pool burning. It arose from the fire associated with Great Kanto Earthquake. It involved 1/1000th scale simulations at Japan's Building Research Institute, with 14 rectangular open-top, 12 cm deep, pans of heptane. Eight were 30 cm x 41 cm and six were 25 cm x 36 cm, all located within a large wind tunnel.

It was found that a strong critical lateral wind velocity was crucial to the generation of intense fire whirls, and this is embodied in the scaling law. The critical lateral velocity, U_c, for whirl generation was varied between 0.5 and 2 m/s, to study its effect on the generation. The strongest whirl generation occurred at approximately U_c = 1 m/s. Whirls were very weak with U_c = 0.5 m/s. They periodically spun off from the burning area, remained for 2-3 s in the unburned area, before moving downwind. With L the horizontal length scale of the burning area, the lateral velocity was normalised by the gravitational velocity, $(gL)^{0.5}$, creating $U_c/(gL)^{0.5}$, as a dimensionless critical velocity, as a function of the fuel Froude number, $Fr_f^{\ 0.5}$. Respective values of these parameters were 0.2 and 0.17 [7]. It was shown in [1] that it is also possible to express $U_c/(gL)^{0.5}$ as a function of a dimensionless Flow number, U^*, which arose from studies of jet flame combustion with blow-off [14-17].

2.4 Quenching of fire whirls

Fig. 3. Generation and decay of Fire Whirls (Courtesy BBC).

A scrutiny of many images of fire storms found few showing fire whirl formation and quenching. An exception was Fig. 3. This shows a slow burning forest undergrowth, with both birth and death of small fire whirls within a small, fragmented structure. About five embryonic whirls, with diameters of a few mm, can be seen, generated by the fire and the small scale, localised air flow. During their formation and in their early stages, the whirls have a yellow intensity, indicative of combustion. This luminosity is maintained for distances of between about 0.5 and 2 m. It is followed by a fainter luminosity over a similar distance, that is suggestive of much diminished chemical reaction. The fuel supply was insufficient to sustain combustion in the later stages, and it appears that, as a result, no whirl was able to survive.

3. Generalised Characteristics of Fire Whirl Fuels

3.1 Generalised approach, with energy density, and spread rate

Valuable, generalised data, of the characteristics of wildfire, ground surface, fuels have been collated in [18]. This publication is a collaborative contribution devoted to the prediction of the spread of wildland and urban fires. The former fuels are classified into such categories as:

healthy forest, grass, tree crown, debris, surface, marginal, or good. The burning characteristics of these fuels are tabulated in [18], in terms of an energy density, *E*, expressed in GJoules/hectare (10^4 m^2), and the rate of spread of the fire, along the ground, *s*, in m/s. Clearly, this is a practical departure from heats of reaction and burning velocities.

In the present study, the following procedure was formulated, to evaluate the mean heat release rate, *q*, per unit horizontal burning area. The fuel is assumed to be uniformly distributed over the hectare, with the flame originally extending along one side, length, *L* = 100 m, of the hectare, whence it propagates, across the hectare to the opposite side. The time to cross the hectare is *L/s.* All the energy density, *E*, is released during this time and the overall heat release rate in the hectare is *Es/L*. The mean heat release rate per square metre is consequently Es/L^3. Values of *s* are given for the different categories of fuel in [12], as are values of *E. V*alues of *q* can be evaluated using this approach.

3.2 Properties of generated fire whirls

Eight diverse different examples of Fire Whirls in Wild Fires have been studied. These are grouped, A to H, in Table 1, where their principal derived properties are listed, for named fuels, or the categories in [12].

Table 1. Principal Parameters of the Eight Fire Whirl Groups Analysed.

Group	Ref.	Fuel, *E* and *s*	*q*, kW/m^2	$Fr_f^{0.5}$	*U**
A	[8-10,18]	Tree crown *E*=121 GJ/ha *s*=0.833 m/s	10 MW	0.0141	0.00896
B	[12]	Fuel oil	62.9	0.00149	0.03441
C	[13]	Heptane	1.13 MW	0.2	0.023
D	[18]	Marginal	1.1	$0.2 \cdot 10^{-5}$	$2 \cdot 10^{-5}$

		E=3.7 GJ/ha s=0.003 m/s			
E	[18]	Good E=36 GJ/ha s=2.77 m/s	9.97	1.4	0.0298
F	[18]	Debris E=370 GJ/ha s=0.277 m/s	10 MW	0.144	0.0138
G	[18]	Grass E=1.8 GJ/ha s=5.54 m/s	9.97	0.014	0.06
H	BBC	E=2.0 GJ/ha s=0.001 m/s	0.2	$3.5\cdot10^{-6}$	$7.9\cdot10^{-6}$

3.3 Values of $U_c(gL)^{0.5}$, $Fr_f^{0.5}$, and U^*

The induced whirl is dependent on two components: the fuel velocity that energises it, and the wind that creates the necessary tangential flow. The former is embodied in both the fuel Froude number, $Fr_f^{0.5}$, and the Flow number, U^*. The latter is embodied in the dimensionless critical wind velocity, $U_c/(gL)^{0.5}$. This can be expressed as a function of either $Fr_f^{0.5}$ or U^*. The fuel Froude number is given by:

$$Fr_f^{0.5} = q/(c_p\rho_o\Delta T(gL)^{0.5}. \quad (1)$$

Here q is the heat release rate per unit burning area, c_p, the specific heat of air, ρ_o, the air density at the ambient temperature, T_o, and ΔT is the difference between the flame and ambient temperature.

U^* is given by:

$$U^* = (u/S_L)(\delta_k/L)^{0.4}. \quad (2)$$

Here u, is the fuel velocity, S_L, the maximum laminar burning velocity of the fuel/air mixture, and δ_k, the laminar flame thickness, derived from the expression in [19]. Thermophysical values were obtained from the GasEq Code [20]. Along with the different fuels, Table 1 gives the derived values of q, $Fr_f^{0.5}$, and U^*.

The dimensionless critical air velocity, $U_c/(gL)^{0.5}$, is plotted against $Fr_f^{0.5}$ in Fig. 4, and against U^* in Fig. 5. All the plotted points are labelled with the appropriate Group identification letter in Table 1.

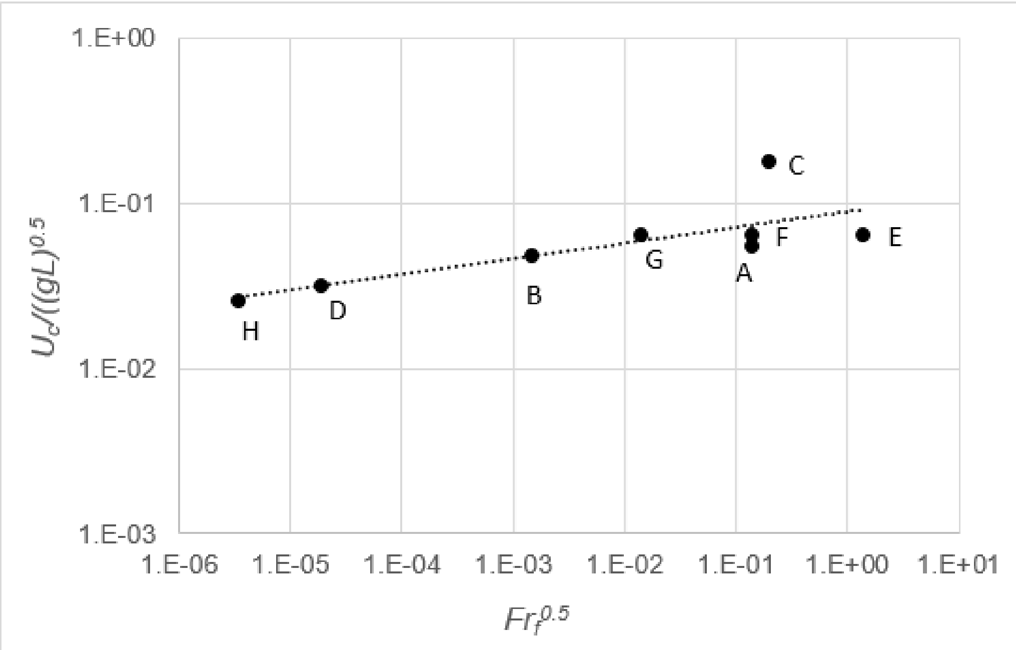

Fig. 4. $U_c/(gL)^{0.5}$ plotted against $Fr_f^{0.5}$.

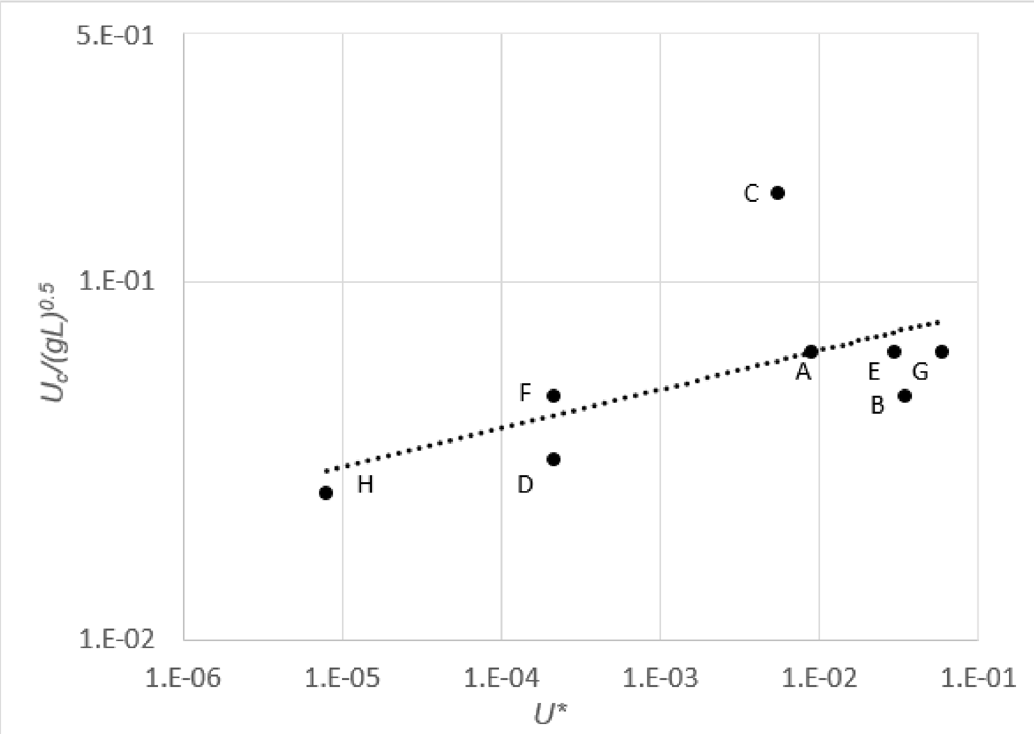

Fig. 5. $U_c/(gL)^{0.5}$ plotted against U^*.

4. Discussion

The relationship between $U_c/(gL)^{0.5}$ and $Fr_f^{0.5}$ in Fig. 4 is similar to that appearing in [13], with the exception of points C in Figs. 4 and 5. These exhibit significantly higher relative values of $U_c/(gL)^{0.5}$.

In [13] the measured values of U_c ranged from 0.5 to 2 m/s, and in [12] from 1 to 6 m/s. A range of U_c values could be achieved at fixed values of Fr_f. Ideally, plotted values of U_c would be comprised of just those at the onset or whirl formation. Although such selectivity was attempted in the present work, it was not easy to achieve, due to atmospheric and localised vagaries. Overall, this proved to be the area of greatest uncertainty in the study. The images of weak flames and whirls, in Fig. 3 of Section 2.4, although of limited precision, do enable minimal whirl sizes to be estimated. Measurements tentatively, suggest that fire whirls could not be sustained for values of $Fr_f^{0.5}$ less than about $3.5 \cdot 10^{-6}$, and, for U^*, less than about $8.0 \cdot 10^{-6}$.

There is no evidence of an upper limit value for fire whirl size, nor is there reason to anticipate one. All parameters are capable of upward scaling. Huge combustible energies, accompanied by sufficiently large spatial scaling are possible, generating powerful fire storms. The operational points for the Hamburg warfare fire [7] lie in the central region of the lines in Figs. 4 and 5.

Interestingly, the correlations of $U_c/(gL)^{0.5}$ with $Fr_f^{0.5}$, and also with U^*, in Figs. 4 and 5, are not dissimilar. From their definitions in Section 3.3, the fuel Froude number can be interpreted as the ratio of the combustion heat release rate/unit area, to that of the purely air heating rate/unit area in the fuel/air mixture. Not dissimilarly, the Flow number embodies the ratio of fuel velocity to the maximum laminar burning velocity of the mixture. In addition, changes in size have similar effects, with Fr_f proportional to $L^{0.5}$ and U^* proportional to $L^{0.4}$. The better curve fit for the Fr_f correlation suggests better accountability of the salient factors.

Only Groups B and C in Table 1 involved controlled experiments. Other properties of fire whirls in the other Groups rested upon generalised estimates from the energy densities and spread rates of the categorised fuels in Table 1. These were processed as described in Section 3.1. This procedure is perforce different from the more familiar ones, in which both fuels and flows are experimentally well defined, by such parameters as burning velocity and heat of reaction. Nevertheless, both procedures provided the reasonably matched overall performance characteristics, in Figs. 4 and 5.

5. Conclusions

1. Fire whirl formation and decay have been studied and correlated, for a variety of different fuels, under wildfire conditions, very different from controlled laboratory conditions.

2. Despite some difficulties, in all cases $U_c/(gL)^{0.5}$ could be plotted consistently against $Fr_f^{0.5}$ and U^*, with a rather more satisfactorily correlation with the former.

3. Extinction of combustion of low energy fire whirls, with diameters of a few mm, occurred, at whirl lengths of between 0.5 and 2 m. After a period without combustion, a whirl finally dissipated, after no more than a further 2 m propagation. In this regime, no whirl survived.

4. At whirl extinction, $Fr_f^{0.5}$ was less than about $3.5 \cdot 10^{-6}$ and $U_c/(gL)^{0.5} = 0.025$. There was no evidence of an extinction limit at high values of these parameters.

5. The necessarily approximated energy densities and fire spread velocities in [18] provide good guidance for correlating fire whirl formation. There were problems in obtaining relevant values of U_c.

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