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Magnetic field associated with an internal fire whirl: A simple model

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ABSTRACT

A fire whirl can be generated by a pool fire in vertical shafts in tall buildings under certain ventilation conditions. Internal fire whirls are much more dangerous and destructive than non-whirling fires in the shaft and deserve more attention. As fires or flames consist of ions in motion, the characteristics of the magnetic field generated by a fire whirl would provide important information. The present study aims at measuring the magnetic field generated by a fire whirl and at building a simple model to explain the generated magnetic field. The physical origin of the magnetic field associated with a fire whirl is proposed, which consists in the interaction of the moving ions with the Earth's magnetic field. It is shown that as far as the magnetic field around a fire whirl is concerned, the fire whirl is equivalent to a solenoid carrying a current I_s, which is related to characteristics pertinent to the fire whirl. The vertical component of the magnetic field obtained from this model (B_{zm}) is compared with experimental results (B_{ze}) acquired in fire whirls in a shaft model. The two sets of values (B_{zm} and B_{ze}) are well correlated, with deviations which are reasonably acceptable. The results of the present work could be of value as a diagnostic tool in monitoring internal fire whirl and in studying various aspects of the whirl.

1. Introduction

Vertical shafts are essential parts in modern tall buildings and they serve various purposes such as transportation for occupants and objects. The unique characteristics of vertical shafts have attracted the interests of researchers in fire science and engineering [1–3]. One important aspect in fire safety related to vertical shafts is the study of fire characteristics in such shafts. Under certain ventilation conditions, a fire in a vertical shaft may develop into a fire whirl due to vorticity effect, characterized by flame rotating vigorously about a vertical axis [2]. Compared with a fire of similar size but without whirling, fire whirling increases the fuel burning rate, generates a higher heat release rate, and has a much larger flame height. This can be called an internal fire whirl (IFW) to distinguish from fire whirls generated in mass fires which can move over some distances [1–3].

A rotating flame also introduces new physical phenomenon compared with non-whirling fire. A fire or flame is a volume of hot gas at high temperature and a fraction of the gas in the flame becomes ionized. Thus a flame consists of charged particles, with equal amounts of positive and negative charges, rendering the flame as a whole electrically neutral. In a fire whirl, the flame rotates about a vertical axis, meaning that the charges are also rotating collectively. These charges, which move collectively, constitute electric currents and generate magnetic field in its neighborhood. On the other hand, in a non-whirling flame, there is no such collective motion of charges and no magnetic field is produced. This is an important physical phenomenon that distinguishes a fire whirl from a non-whirling fire. Knowledge of the magnetic field associated with a fire whirl, in particular an internal fire whirl, could be used to monitor an IFW and even to control or suppress the fire whirl [4–6].

Since a flame is made up of charged particles, the interaction of electromagnetic field with fire has attracted the attention of scientists since many years ago [7]. The effects of an external electric field on flame shape [8] and on the spectra of hydrocarbon diffusion [9] were reported in the 1950s. Effects of an electric field on stabilizing flames, reducing carbon formation, increasing flame velocity, extending flammability limits, increasing flame luminosity and flame extinction have been described in the literature [10–12]. The effect of applied magnetic field on flame was first reported in 1847 by Faraday [13], who observed deflection of candle flame by a strong non-uniform magnetic field. This observation was later explained by a model proposed by von Engle and Cozen [14], and Ueno and Haraka [15]. As an interesting and pragmatic problem which lies in the intersection of science and engineering, the use of magnetic field information from a system as a diagnostic tool or the interaction between electromagnetic field and flame continues to attract the attentions of researchers from various fields [16–21]. In view of these experimental observations, it is natural that there have been attempts to control fires by

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Nomenclature

B_v	magnitude of vertical component of Earth's magnetic field (T)
B_z	z-component of magnetic field induced by fire whirl (T)
B_H	horizontal component of magnetic field induced by fire whirl (T)
e	magnitude of electronic charge (C)
F_h	hydrodynamic force (N)
H	height of fire whirl (m), height of equivalent solenoid (m)
I, i	current (A)
I_s	current in solenoid (A)
k	a dimensionless quantity
M	mass (kg)
N	number of turns in solenoid
n_i	number density of ion (m^{-3})
P_r, P_z	position coordinates of point P (m)
Q, q	charge (C)
R	radius of path of charged particle (m)
r	ratio of radii of paths
S	number of segments in one turn
t	thickness of charge layer (m)
z_n	z-coordinate of n^{th} turn in solenoid (m)
α	geometrical factor of solenoid
β	normalized radial distance
ρ	charge density ($C\,m^{-3}$)
$\Delta\theta$	angle subtended by segment (rad)
ϕ	azimuth angle of point P (rad)
μ_0	permeability of free space (H/m)
ω	angular velocity ($rad\,s^{-1}$)

electromagnetic means [22–25]. Though the effects of electromagnetic field on fire have been widely reported, studies on the effect of electric or magnetic field on fire whirl are scarce. Xia [4–6] reported on preliminary experimental and theoretical analysis of the effect of magnetic field or electric field on fire whirl.

Effects of electric or magnetic field on fire were studied quite extensively. However, very little works were reported on the electric field or magnetic field induced by a fire. In an earlier study on IFW in a vertical shaft using a scale model experiment [26], magnetic field was measured, and this is the first time the magnetic field generated by and IFW is reported. The detailed mechanism of the production of magnetic field by a fire whirl, however, has not been proposed. It is the aim of the present study to propose a preliminary model to explain the creation of a magnetic field associated with a fire whirl.

2. Magnetic field due to fire whirl

There are positive and negative charges in a flame, with overall electrical neutrality. Thus it may be regarded as a plasma. In a fire whirl, the charges rotate about a central vertical axis in circles due to hydrodynamic force, in addition to upward motion. In the IFW described in [26], this hydrodynamic force originates from the ventilation through a side gap. Thus in a fire whirl the charged particles are moving in helical paths [2], which may be regarded as superposition of a vertical motion due to buoyancy and a circular motion. As the vertical velocity component in an IFW is much smaller than the circular component, only the circular motion of the charged particles in the fire will be considered in the present study. In addition, the vertical motion of the charged particles produces horizontal magnetic field only, but not vertical magnetic field.

Charges moving in circles are equivalent to currents in circular loops, and magnetic field is produced by these current loops. For positive and negative charges of equal magnitude and moving in the same manner (same radius, same angular velocity), the currents are equal and opposite. There is no net current, and no net magnetic field is produced. However, the scenario is different if an external vertical magnetic field is present at the location of the fire whirl. Such a field is actually present: it is the vertical component of the Earth's magnetic field.

Consider a pair of positive and negative charge of equal magnitude at a certain radial distance R from the central axis. The Lorentz forces (that is, magnetic forces) on the positive and the negative charge are in opposite directions along the radial direction. This magnetic force will thus increase or decrease the net centripetal force on the charged particle. Consequently the radius of the circular path of one type of charge will be increased and that of the other type will be decreased. Thus the current loops due to positive and negative charges are now of different radii, and the magnetic fields produced by these current loops will not cancel out each other. This is the physical origin of the magnetic field produced by a fire whirl.

3. Change of radius of circular path of charged particles

Let $\hat{z}$ be in the vertically upward direction and let the angular velocity of the whirl be $\omega\hat{z}$. Let the vertical component of the Earth's magnetic field be $-B_v\hat{z}$ (field in the northern hemisphere).

Let the subscript "1" refer to the case without external magnetic field and "2" refer to the case with external magnetic field. Assume that the hydrodynamic condition remains the same in both cases.

Assume that the fire is made up of positive and negative ions, both being singly charged, together with neutral particles. When the fire whirls in a vertical magnetic field, the charged particles will be pulled inward or pushed outward depending on the charge sign, and the radii of their paths will be changed. In establishing the new paths, via collision, the neutral particles are dragged along to move with either type of charged particles. From now on, for convenience, a charged "particle" will mean an ion together with neutral particles that are being dragged along.

Consider the motion of a charged particle without and with an external magnetic field. Then by conservation of angular momentum:

$$MR_1^2\omega_1 = MR_2^2\omega_2 \tag{1}$$

where R is the radius of the circular path of a charged particle and M is its mass (note that this is the total mass of ion plus some neutral particles)

Consider the circular motion of a positive charge q and let F_h be the hydrodynamic force that provides the centripetal force for the whirl and take the centripetal direction to be positive.

Without external magnetic field $\quad F_h = MR_1\omega_1^2$ (2)

With external magnetic field $\quad F_h + qR_2\omega_2B_v = MR_2\omega_2^2$ (3)

where $qR_2\omega_2B_v$ is the Lorentz force acting on the positive charge.

Eliminating F_h from (2) and (3):

$$qR_2\omega_2B_v = MR_2\omega_2^2 - MR_1\omega_1^2 \tag{4}$$

Let $r = \frac{R_1}{R_2}$, eliminate ω_2 in (4) using (1) and let $k = \frac{qB_v}{M\omega_1}$, which is a dimensionless quantity, we get

$$r^4 - kr^2 - r = 0$$

$$\text{Or: } r^3 - kr - 1 = 0 \tag{5}$$

If we consider a negative charge, then (5) would become

$$r^3 + kr - 1 = 0 \tag{6}$$

The solution for r (change in radius) is determined by the coefficient k, which depends on the nature of the charged particle (q/M), the external