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Magnetic Field Associated with an Internal Fire Whirl: A Simple Model

C.H. Cheng, S.S. Han and W.K. Chow*
Research Centre for Fire Engineering
Department of Building Services Engineering
The Hong Kong Polytechnic University
Hong Kong, China

C.L. Chow
Department of Architecture and Civil Engineering
City University of Hong Kong
Hong Kong, China

*Corresponding author:
Fax: (852) 2765 7198; Tel: (852) 2766 5843
Email: beelize@polyu.edu.hk; bewkchow@polyu.edu.hk
Postal address: Department of Building Services Engineering, The Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong

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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.

KEYWORDS: modelling; internal fire whirl; magnetic field

NOMENCLATURE

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

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 1950's. 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 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:

$$MR_1^2\omega_1=MR_2^2\omega_2 \qquad (1)$$

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 $\quad F_h = MR_1\omega_1^2 \qquad (2)$

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

where $qR_2\ \omega_2 B_v$ is the Lorentz force acting on the positive charge.

Eliminating F_h from (2) and (3):

$$qR_2\ \omega_2 B_v = MR_2\omega_2^2 - MR_1\omega_1^2 \qquad (4)$$

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

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

Or: $r^3 - kr - 1 = 0$ (5)

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

$$r^3 + kr - 1 = 0 \qquad (6)$$

The solution for *r* (change in radius) is determined by the coefficient *k*, which depends of the nature of the charged particle (q/M), the external vertical field (B_v), and the angular velocity of the whirl (ω_1).

For positive charge, using (5), $r \geq 1$, and the radius is decreased by the presence of the Earth's magnetic field B_v. On the other hand, for negative charge, $r \leq 1$, and the radius is increased.

4. EFFECTIVE CHARGE DISTRIBUTION

Applying this change to all charged particles in the fire, it means that the paths of all negative charges expand while those of the positive charges shrink.

To take into account all the charged particles in the fire whirl, one can think of a larger cylinder of negative charge overlapping with a smaller cylinder of positive charge. To a first approximation (neglecting change in charge density), the net effect of B_v is to create a negative charge layer at radius R_2 (original whirl radius is R_1), and a core of positive charge (of some radius), both being of equal magnitude in charge. (See Fig. 1 below). The positive and negative charges in between are equal and opposite, cancelling out each other. To calculate the magnetic field produced by the fire whirl, one only needs to calculate the magnetic fields due to the outer layer and the core. As another approximation, the contribution of the core to the magnetic field outside the fire whirl can be neglected since the magnetic moment (current x area of current loop) becomes negligible for a core of small radius.

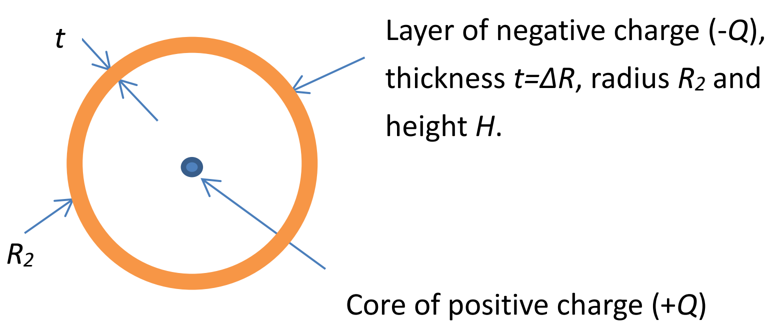


Fig. 1. Effective charge distribution in fire whirl.

5. CURRENT ON SURFACE OF WHIRL

A charge q revolving with angular velocity ω is equivalent to a current given by

$$i = \frac{Q\omega}{2\pi} \tag{7}$$

A layer of charge (thickness t, radius R and height H) revolving at an angular velocity ω is equivalent to a current sheet of magnitude I. The total charge Q in this layer is given by

$$Q = 2\pi RHt\rho \tag{8}$$

where ρ is the charge density and is given by

$$\rho = e\, n_i \tag{9}$$

where e is the magnitude of the electronic charge and n_i is the number of ions per unit volume, assuming that the ions are singly charged.

Thus the current of this rotating charge layer is given by

$$I = \frac{Q\omega}{2\pi} = \frac{2\pi RHten_i\omega}{2\pi} = (RHt)(en_i)\omega \tag{10}$$

In the derivation above only one type of charged particles is considered. For other types of charged particles having a different (q/M) ratio, the thickness of net charge layer t and the number density n_i per unit volume are also different. As a first approximation, the change in the radius of the path is assumed to be small and the same values of R may be used for calculating the charge and current. Then the total current I can be obtained by adding the contributions from individual types of charged particles:

$$I = \sum I_j = \sum (RHt_j)(en_{i,j})\omega \tag{11}$$

where j refers to the j^{th} type of charged particles.

When the angular velocity of the fire whirl is $\omega\hat{z}$, as in the derivation above, the charge layer on the surface of the whirl is negative. On the other hand, if the angular velocity is in the $-\omega\hat{z}$ direction, the charge layer on the surface of the whirl is positive. It is interesting to note that in both cases the currents are in the same direction, as is clear from Fig. 2.

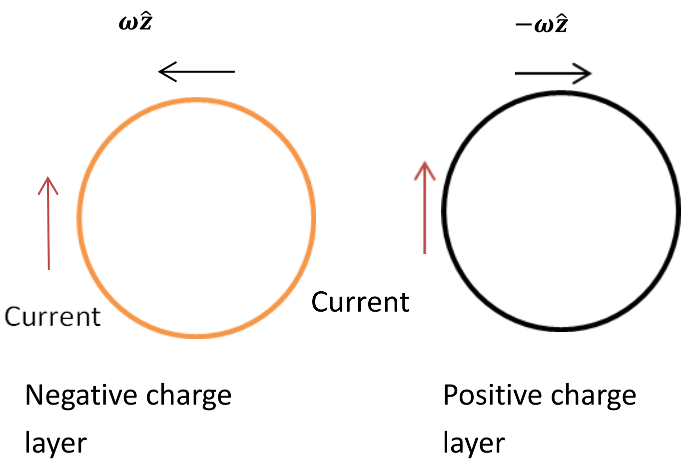


Fig. 2. Direction of current on surface of fire whirl is independent of direction of whirl (view looking along the $-\hat{z}$ direction).

6. MAGNETIC FIELD ASSOCIATED WITH FIRE WHIRL

Assume that the thickness of the current sheet due to redistribution of charge is small. Then this current configuration may be regarded as a solenoid of radius R and height H (where R and H are the radius and height of the fire whirl), containing N turns and carrying a current I_s, where I_s is given by

$$I_s = \frac{I}{N} \tag{12}$$

A solenoid carrying a current will produce a magnetic field $\vec{B}$ in its neighborhood (Fig. 3), and $\vec{B}$ at a point depends on its position relative to the solenoid. In the discussion above, I_s takes the direction shown in Fig. 3 and the solenoid behaves like a bar magnet with its north pole downward.

As pointed out above, the surface current (or solenoidal current I_s) is always in the direction shown in Fig. 3 irrespective of the direction of the fire whirl. Thus at points on the mid-plane outside the fire whirl, the magnetic field associated with the whirl is always pointing upward.

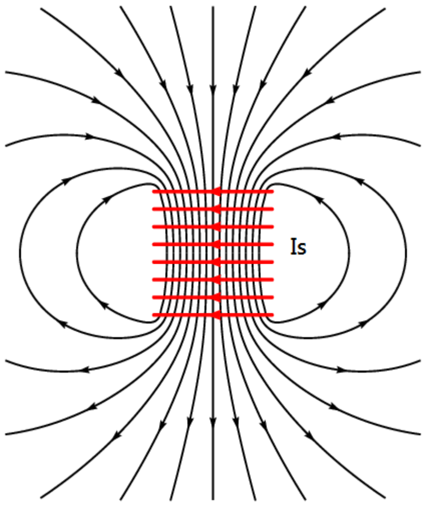


Fig. 3. Magnetic field due to current I_s in a solenoid.

Consider a cylindrical coordinate system with its origin O at the center of the solenoid and with the z-axis in the vertical upward direction (Fig. 4). Then by symmetry $\vec{B}$ depends only on P_r, P_z, where P_r, is its radial distance from the z-axis and P_z is its height above the center, but not on its azimuth angle ϕ, which can be taken to be zero without loss of generality because of symmetry.

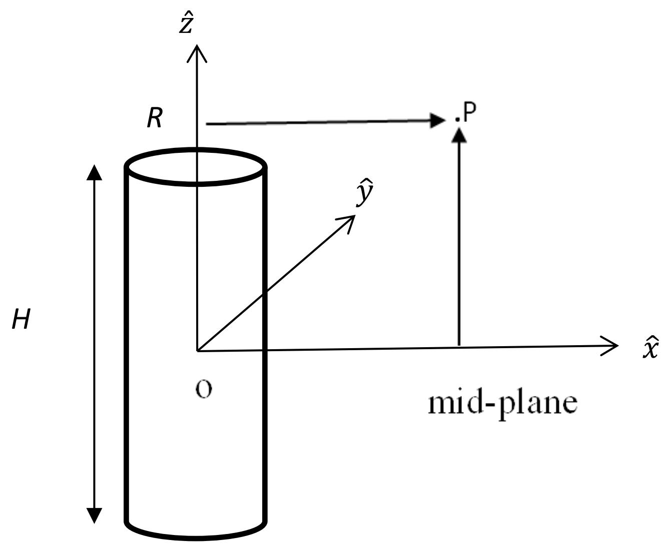


Fig. 4. Equivalent solenoid of a fire whirl of radius *R* and height *H*.

The vertical component B_z of the magnetic field due to current in the solenoid can be obtained by dividing each turn into *S* segments and applying the Biot-Savart Law [27] to current I_s in each segment $R\Delta\theta$ of the turn in the solenoid. Then

$$B_z = \frac{\mu_o}{4\pi}\sum_{n=1}^{n=N}\sum_{s=1}^{s=S}\frac{I_s R[P_r\cos(s\Delta\theta)-R]\Delta\theta}{\left[P_r^2+(P_z-z_n)^2+R^2-2P_rR\cos(s\Delta\theta)\right]^{3/2}} \tag{13}$$

where $\Delta\theta = \frac{2\pi}{S}$ (14)

z_n is the *z*-coordinate of the n^{th} turn in the solenoid (of *N* turns) and is given by

$$z_n = \left(-0.5H + \frac{(n-1)}{N}H\right) \tag{15}$$

and μ_0 is the permeability of free space.

Similarly, the horizontal component of the magnetic field B_H due to current in the solenoid is given by

$$B_H = \frac{\mu_o}{4\pi}\sum_{n=1}^{n=N}\sum_{s=1}^{s=S}\frac{I_s R[P_z-z_n]\Delta\theta}{\left[P_r^2+(P_z-z_n)^2+R^2-2P_rR\cos(s\Delta\theta)\right]^{3/2}} \tag{16}$$

As a particular case, consider the variation of the $B(P_r)$ field at points on the mid-plane of the solenoid (that is, $P_z = 0$). By symmetry, the $B(P_r)$ is vertical, that is B_H is zero. Let the magnetic field at the center of the solenoid be B_0.

Let $\alpha = \frac{R}{H}$ (17)

where is α a geometrical factor for the solenoid.

Also, let $\beta = \frac{P_r}{R}$ (18)

where β is the normalized radial distance of the point P. Note that both α and β are pure numbers.

$$\frac{B_z}{B_0} = \frac{\sum_{n=1}^{n=N}\sum_{s=1}^{s=S}\frac{[\alpha\beta\cos(s\Delta\theta)-\alpha]\Delta\theta}{\left[\alpha^2\beta^2+\left(-0.5+\frac{(n-1)}{N}\right)^2+\alpha^2-2\alpha^2\beta\cos\theta(s\Delta\theta)\right]^{3/2}}}{\sum_{n=1}^{n=N}\sum_{s=1}^{s=S}\frac{-\alpha\Delta\theta}{\left[\left(-0.5+\frac{(n-1)}{N}\right)^2+\alpha^2\right]^{3/2}}} \tag{19}$$

Consider a particular case with the geometrical factor $\alpha = R/H = 0.2$, $N = 1000$ and $S = 1000$, the plot of the ratio $-\frac{B_z}{B_0}$ as a function of the normalized radial distance β is shown in Fig. 5. Note that on the mid-plane, the magnetic field inside and outside the solenoid are in opposite directions (see Fig. 3), and thus the ratio $\frac{B_z}{B_0}$ is always negative.

In the derivation above, the vertical component of the Earth's magnetic field is taken to be downward. If it is upward (southern hemisphere), it is easy to show that the direction of the solenoidal current I_s is reversed. The magnetic field of the fire whirl is then given by a bar magnet with its north pole upward.

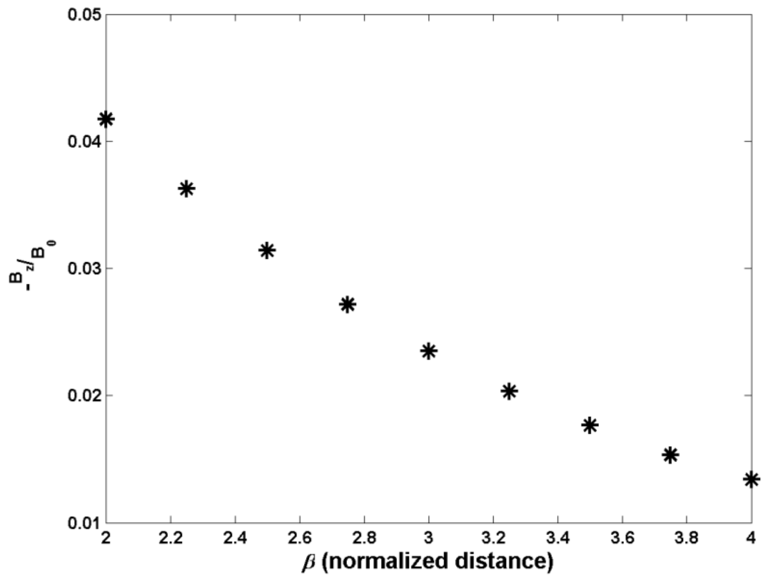


Fig. 5. Variation of the induced magnetic field outside the fire whirl at points on the mid-plane.

7. MAGNETIC FIELD DUE TO INTERNAL FIRE WHIRL IN SHAFT MODEL

The experimentally measured magnetic field due to an IFW was reported in a recent study by Chow [26] using a vertical shaft model. The scale model (Fig. 6(a)) was 1.45 m tall, 0.34 x 0.35 m in cross-section, open-roofed, and with ventilation provided by a side gap of width 0.036 m. Internal fire whirl was generated by a propanol pool fire of diameter 7 cm at the center of the shaft base (Fig. 6(b)). The magnetic field in the neighborhood of the shaft was measured using a magnetometer (AlphaLab DC Magnetometer, AlphaLab, Inc., USA) having a minimum usable resolution of 0.02 gauss and an accuracy of +/-2% in the temperature range (30 - 110) F. The magnetometers were placed at positions M1, M2 and M3 as shown in Fig. 6(c), where H_{shaft} is the height of the shaft and d is the distance outside the shaft. The magnetic fields at the same relative positions but for free burning were also captured. The difference in the magnetic fields acquired under fire whirl and free burning is taken to be the magnetic solely due the fire whirl, and not due to the earth's field. The measurement of magnetic field at each position was repeated twice and the average values of the experimentally measured magnetic field due to IFW are summarized in Table 1. Here only the vertical (z-) components are shown since the horizontal (x- and y-) components are affected by the vertical motion of the ions in flame, but not the whirling motion.

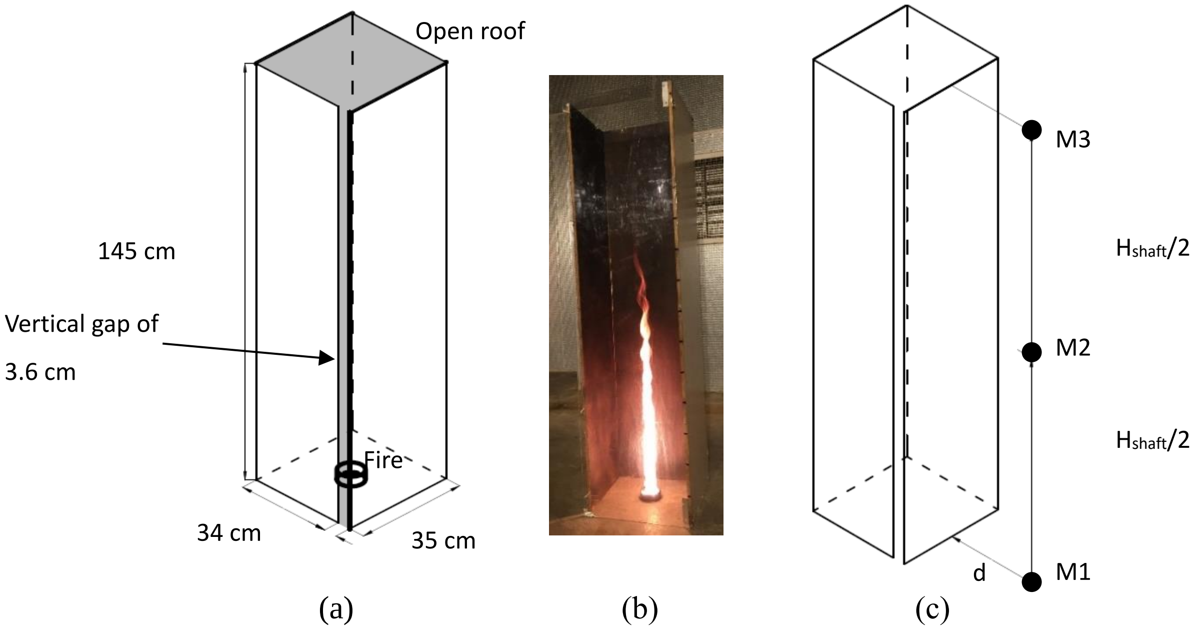


Fig. 6. (a) The vertical shaft model, (b) fire whirl and (c) magnetometer positions.

Table 1. Average experimental values of vertical component of the magnetic field B_{ze} (in gauss) at different positions due to IFW.

Level \ Distance d	0.1 m	0.15 m	0.20 m	0.25 m	0.30 m
Floor level	-1.01	-1.25	0.12	0.13	0.02
Middle level	-1.02	-0.66	-0.04	0.22	0.20
Top level	-1.05	-0.24	0.03	0.11	0.08

8. COMPARISON OF CALCULATED B_Z WITH EXPERIMENTAL DATA

To check the validity of the proposed model, Eq. (13) is used to determine the values B_{zm} at the same positions as experimental values B_{ze}, where the subscript 'm' refers to calculated value using model and the subscript 'e' refers to experimental value. In using Eq. (13) a few parameters are needed. These include geometrical parameters: height of solenoid H (corresponding to the height of the whirling section), radius of solenoid R (approximately equal to the radius of the whirl), and the distance between the bottom of the solenoid and the floor level h; and the electrical parameter: the solenoidal current I_s (corresponding to the properties of the whirl). It is obvious from Eq. (13) that B_{zm} is directly proportional to I_s. Thus the value of I_s does not affect the correlation coefficient between model values B_{zm} and experimental values B_{ze}, according to the definition of correlation coefficient [28]. Instead, I_s

will affect the difference between B_{zm} and B_{ze}. Hence different sets of the geometrical parameters were first tried out to obtain the best correlation (as indicated by correlation coefficient r). With this set of geometric parameters, the solenoidal current I_s was then varied to obtain the minimum discrepancy between these two sets of values. The optimal parameters are shown in Table 2. With this set of parameters the calculated vertical component of magnetic field B_{zm} at different positions are shown in Table 3. The correlation between B_{zm} and B_{ze} at different heights is given in Fig. 7. The values for correlation coefficient r are shown in Table 4, together with the root-mean-square deviation (*RMSD*), defined by

$$RMSD = \left[\frac{1}{N}\sum_{i=1}^{N}\left(B_{zm,i} - B_{ze,i}\right)^2\right]^{1/2} \tag{20}$$

It can be observed from Table 3 that for the vertical magnetic fields B_{zm} and B_{ze} at different levels, the correlation coefficient r lies between 0.80 and 0.98, indicating significant correlation and partially supports the validity of the proposed model. The values of $RMSD$ lie in the range of 0.37-0.51 gauss. In view of the non-steady or even sporadic nature of fire whirl, such values may be regarded as reasonably acceptable.

Table 2. Optimal parameters of solenoidal model.

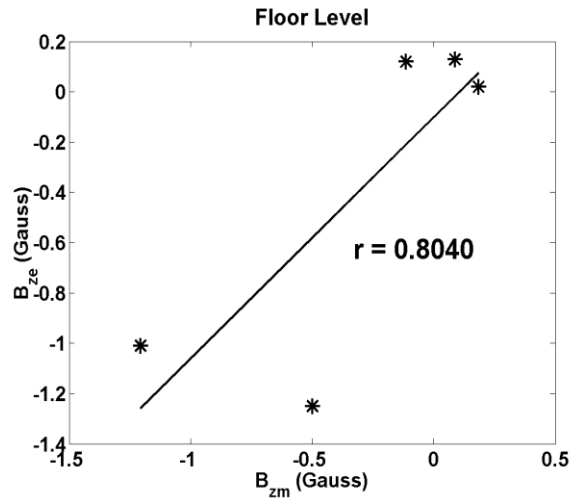
I_s (A)	H (m)	h (m)	R (m)
0.04	0.2	0.2	0.035

Table 3. Calculated vertical component of magnetic field B_{zm} (gauss) at different positions.

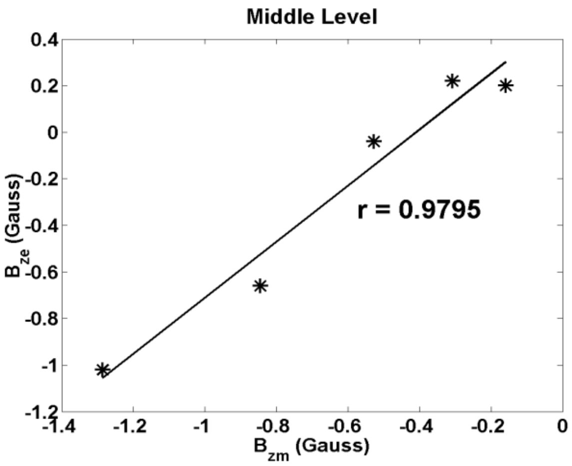
Level \ Distance d	0.1 m	0.15 m	0.20 m	0.25 m	0.30 m
Floor level	-1.21	-0.50	-0.11	-0.09	0.18
Middle level	-1.29	-0.85	-0.53	-0.31	-0.16
Top level	-0.172	-0.16	-0.15	-0.14	-0.12

Table 4. Correlation of the vertical components of the calculated B_{zm} and experimental magnetic field B_{ze}.

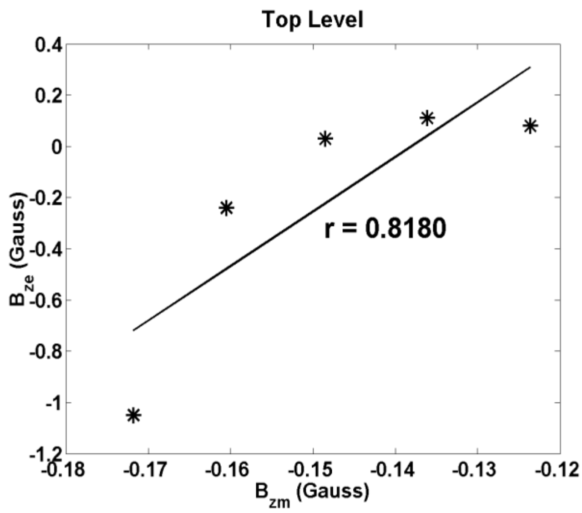
	RMSD (gauss)	r
Floor level	0.37	0.8040
Middle level	0.39	0.9795
Top level	0.51	0.8180



(a)



(b)



(c)

Fig. 7. Correlation between B_{zm} and B_{ze} at different heights for solenoid of dimensions H=0.2 m, h=0.2 m, and R= 0.035 m; Is = 0.04A: (a) Floor level, (b) Middle level, and (c) Top level.

9. CONCLUSION

The magnetic field due to an internal fire whirl in a vertical shaft model was measured in a previous study. The scale model was 1.45 m tall, 0.34 x 0.35 m in cross-section, open-roofed, and with ventilation provided by a side gap of width 0.036 m. Internal fire whirl was generated by a propanol pool fire of diameter 7 cm at the center of the shaft base. The magnetic field in the neighborhood of the shaft was measured using a magnetometer. In the present study a simple model has been proposed to explain the generation of magnetic field by the fire whirl. The physical origin of the field is attributed to the different responses of the motions of positive and negative charges in the Earth's magnetic field, leading to charge redistribution. The redistributed charges are represented by a negative charge layer at the fire whirl surface and a small positive charge core at the whirl axis. As an approximation, the contribution of the core to the magnetic field outside the fire whirl can be neglected since the magnetic moment becomes negligible for a core of small radius. Based on this model, the fire whirl is shown to be equivalent to a solenoid of radius R, height H and carrying current I_s, which can be expressed in terms of quantities pertinent to the fire whirl. Comparison of the calculated magnetic field B_{zm} based on model and experimental value B_{ze} shows reasonable agreement, as evidenced by correlation and deviation analysis. The model proposed would be useful in monitoring internal fire whirl and in studying various aspects of fire whirl. The simple model proposed in the present study mainly aims at elucidating the physical origin of the magnetic field due to fire whirl and at determining the magnetic field based on the model. On the other hand there are limitations of the simple model due to the approximations used in building the model. Real fire whirls are not cylindrical but are rather complex in shape. Nevertheless, the geometry of a fire whirl is reasonably symmetrical about its axis. Thus a fire whirl of complicated geometry can be modeled by superposition of a number of cylinders and truncated cones via extending the idea used in the present study. Another limitation of the applicability of the method used in the present study comes from the magnetic environment of the shaft. When the shaft is partly made of or enclosed by ferromagnetic materials, the magnetic field due to the fire whirl will be heavily distorted or even screened and detection of field outside the shaft is unreliable or impossible.

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