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Comparison between Experiments and Numerical Simulations of Fire Whirls Due to a Single Flame in a Vertical Square Channel with Symmetrical Corner Gaps

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ABSTRACT

Although fire whirls in large urban fires are known to cause many fire victims and extensive property damages, detailed mechanisms and physical effects of fire whirls still remain largely unknown, since real big fire whirls are relatively rare and their studies are too difficult to carry out. However, such large-scale fire whirls, until recently, can be conveniently studied by computer-based numerical simulation techniques. On the other hand, computer simulations for large-scale phenomena are only realistic if they can be validated in advance by the results of scale-modeled experiments. Despite recent studies in this regard, uncertainties of the whirling-fire phenomena are still abound. The purpose of this study was to compare quantitatively the fire-whirl temperature and velocity fields of the numerical simulations with those from laboratory experiments for the case of fire whirls generated with a single flame located in a vertical square channel with symmetrical corner gaps. Successful results of such comparisons have been obtained.

KEYWORDS

Fire Whirl, Urban Fire, Numerical Simulation, Vertical Channel, High Speed Motion Video

INTRODUCTION

It is well-known that fire whirls in large urban fires, such as those due to gigantic earthquakes in Tokyo, 1923, are known to claim many fire victims and cause extensive property damages, primarily because of their extreme destructive power. In addition, it is also known recently that such violent fire whirls help to disperse large amount of fire particles to a wide area, and also affect the safety of the fire-fighting helicopters flying over the big fire whirls.

Despite the extreme significance associated with the need for the assessments of extensive damages by fire whirls, their detailed mechanisms and physical effects still remain very uncertain. Unfortunately from the viewpoint of studies, the real big fire whirls only occur rarely, and are therefore too difficult to study them directly. Consequently, alternatives must be found so that the dynamics of the fire whirls can be effectively studied. A few laboratory-based small scale studies focused on whirling fires generated by active and passive means are available (Emmons and Ying, 1967; Saito and Cremers, 1995; Satoh and Yang, 1996). Even then, measurements were very difficult because of sensor placement problems, elevated temperatures, and high velocities involved in the complex rotating flow fields associated with the dynamic fire plumes. As a result, in most such studies only experimental observations on the dynamic swirling flames could be made.

In recent times, the authors have carried out such observational studies of whirling fires in a vertical channel with four symmetrically-placed vertical corner gaps. The airflow entrained by the buoyant flame enters into the channel, thus imparting an angular momentum to the rising flame (Satoh and Yang, 1996). In a subsequent numerical simulation study it is shown that the simulations do produce all the essential dynamic behaviors of the whirling fire and that the generation mechanism of the fire whirls is essentially hydrodynamic in nature (Satoh and Yang, 1997, 1998). However, no detailed velocity and temperature field comparisons were possible because of the lack of detailed measurements.

It must be noted that the whirling fires inside such vertical channels have some relevance to that occurring in large urban fires, due to the existence of tall buildings and free air passages between them towards the fires. It is also of significance to mention that even though the configurations studied are very specialized, the dynamics of the whirling flame and its maintenance are expected to be universal, since the observed flame envelope is quite stable and well contained inside the channel. In the present study, numerical simulations were attempted corresponding to the conditions of the previous experimental study (Satoh and Yang, 1999) of the enclosed whirling fires in a vertical channel with four symmetrical corner gaps and one single flame located at the center of the channel base.

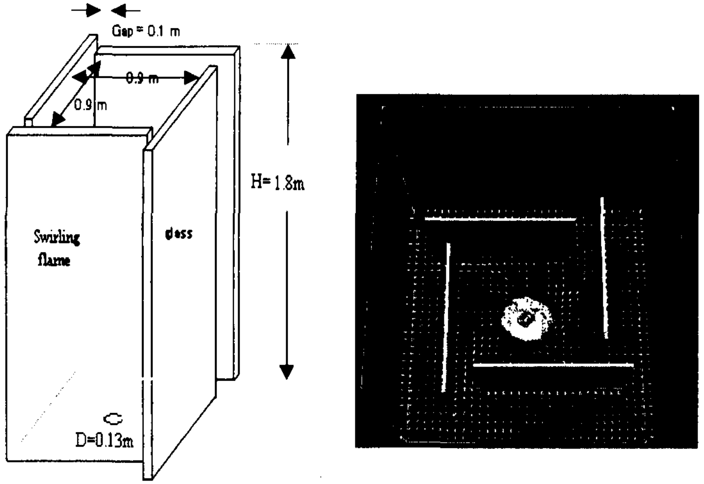

Fig.1 Experimental Apparatus of Swirling Flame in a Channel with Equal Size Corner Gaps (left) and Corresponding Simulation Schematics (right)

The specific objective of this study is to validate the numerical simulations by comparing the numerical simulation results with that from the experiments. It is clear that the eventual purpose of these simulations is to search for conditions, which will enable us to mitigate the high destructive power of fire whirls relevant to large urban fires. Such validation is critical for the simulation studies because of several well-known weaknesses in the simulation models. Once validated, such models can then be used to delineate all significant mechanisms associated with the dynamic fire whirl behaviors. Furthermore, together with the numerical simulations, additional measurements of the swirling motion were also made, using the same experimental apparatus as those used in the previous experimental study (Satoh and Yang, 1999).

EXPERIMENTS

In these experiments, a burning n-heptane flame was centrally placed at the base of a square channel with dimensions of 0.9 m x 0.9 m x 1.8 m (height), as schematically shown in Fig 1, which was the same experimental setup and numerical grids employed in the previous study (Satoh and Yang, 1999). The channel top was open and each channel wall had a uniform 10 cm wide vertical gap at each corner. Therefore the air entrained by the buoyancy of the burning flame enters into the channel through the four corner gaps, interacting with the buoyant flame. In the previous study dealing with the experimental observation of a single swirling flame placed in a channel, measured by conventional tools such as thermocouples and pitot tubes together with the new tools of image processing of high speed video pictures, the following results were found:

(1) The average temperature in the swirling flame at heights slightly lower than 30 cm, measured by a thermocouple, was a little less than 900 deg.C and the average velocity measured by a pitot tube was about 4 to 5 m/s. In the range of heights from 30 cm to 90 cm, the average temperature was about 950 deg.C and the velocity was 5 to 6 m/s. At the 120 cm level, the average temperature was about 900 deg.C with an average velocity of 3.0 m/s. This trend persists to the level at 150 cm, where the swirling flame is intermittent, with a temperature of about 750 deg.C and a velocity of about 2.0 m/s.

(2) The magnitudes of the velocity vectors at the mid-height (60 cm to 90 cm) of the swirling flame in the channel were in the range of 5-6 m/s, measured by a high-speed motion video camera and analyzed by image-processing software.

(3) In the analysis of the high-speed motion images provided an estimated dominant rotational speed of about 17 revolutions per second, or 17 Hz.

(4) In the swirling flame the highest temperatures were concentrated in the middle-height region of the flame, and

(5) The liquid n-heptane fuel in a round fuel pan of 13 cm in diameter was placed at the center of the channel base. In the full-burn region of the swirling fire, the power output could be estimated between 25-30 kW, based on both a measured average fuel-loss rate of 0.67 g/s and a heating value of 42 kJ/g for n-heptane.

It is clear that the just-mentioned results, especially the measured centerline velocity and temperature data and the non-uniform complex behaviors in the lower half of the whirling flame, would provide a good basis to validate numerical simulations. In addition to the previous experimental measurements, more detailed measurements were conducted. Two images at different times within 500 frames per second are shown in Fig.2. Such images at consecutive times could then be used to deter-

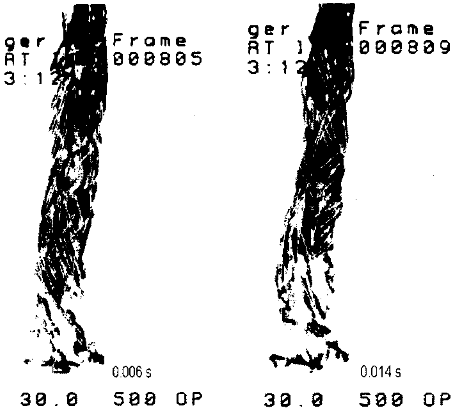

Fig.2 High Speed Motion Pictures (500 Frames per Second) and Analyzed Velocity Vectors of Swirling Flame

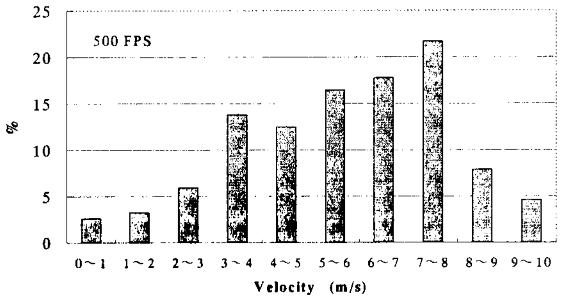

Fig.3 Histogram of Velocity Vectors Analyzed by Image-Processing Software FLOWVEC-32

mine quantitatively the almost instantaneous projected velocity vectors by means of a digital image-processing software known as FLOW VEC32 (Kaga et al., 1992, 1994). The velocities at the middle height of the Swirling flame were analyzed by the pattern matching method and their distributions are shown in Fig.3. The distribution is slightly larger than the previous data, where the velocity in the range of 7 to 8 m/s was dominant. Furthermore, the high-speed motion video pictures showed slightly fast rotation of the swirling flame, namely 18 to 20 Hz.

NUMERICAL SIMULATIONS

This numerical study corresponds to the same geometry of the vertical channel with four corner gaps as in the experimental setup shown in Fig.1. However, it is important to note that this simulation is not attempting directly to predict the entire dynamics of the swirling flames and flows entrained into the channel with corner gaps, but mainly to provide additional insight to the flow features in the channel for the purpose to discover and understand the physical mechanisms for the whirling fires. Therefore, this simulation model is simplified appropriately, particularly in the flame, as long as the

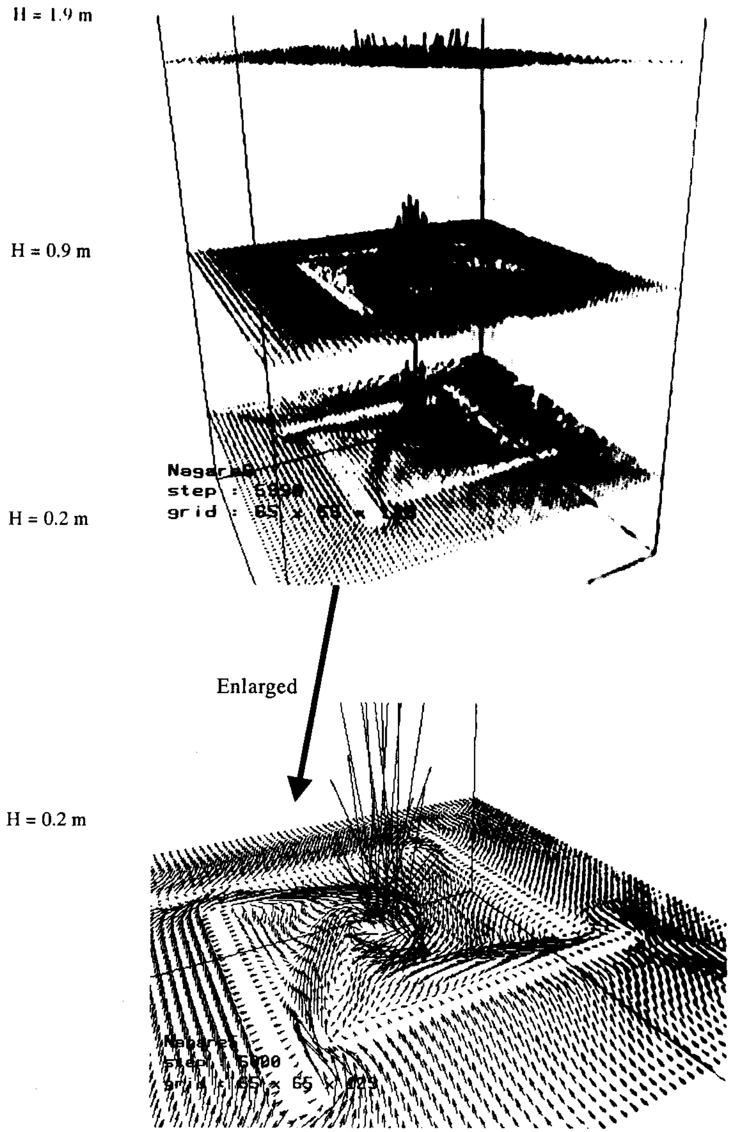

Fig.4 Velocity Vector Distributions at Three Horizontal Levels Based on the NAGARE Simulation Model

important physical concepts are retained.

The simulation model utilized here was the three-dimensional UNDSAFE fire field model, which was used for the previous study of swirling fires in a channel with a single corner gap (Satoh and Yang 1998). This field model accounts for full compressibility, buoyancy and turbulence, but does not incorporate a combustion sub-model. Combustion effects are accommodated by a prescribed non-uniform and time-dependent volumetric heat source. Although radiation effects are certainly important, it is also known that the origin of fire whirls is essentially hydrodynamic in nature, as already demonstrated in our earlier study (Satoh and Yang, 1997, Satoh and Yang, 1998). In addition to this model, also used was another three-dimensional fire field model, called NAGARE (Satoh, Yang and Kuwahara, 1999). Both computational models are based on the finite-volume formulation, including upwind differencing for advective and convective terms in the governing equations, which are not shown here due to the space limits. Boundary conditions for the UNDSAFE model for the velocities and temperature along the channel inner walls and the open top, and at each vertical gap were identical to those in our previous studies (Satoh and Yang, 1997;1998), and hence will not be repeated here. On the other hand, the details of NAGARE model is that the heat source temperature at the floor fuel-can base was prescribed.

The buoyant gas flow in the flame allows entrained air to enter the channel at each corner gap, as shown in Fig. 4. The entering air at the gap moves along the wall, but changes the direction toward the central upward plume, which imparts the swirling motion to the buoyant plume. As already reported in our previous studies (Satoh and Yang, 1997; Satoh and Yang, 1998), the overall flow patterns are well simulated by these simulation models, as shown in Figs.4 and 5, which are velocity vector distributions (at three horizontal levels at 0.2 m, 0.9 m and 1.9 m above the floor) and the isotherms of the hot region in the channel together with the experimental view of a swirling flame in the channel, respectively. The

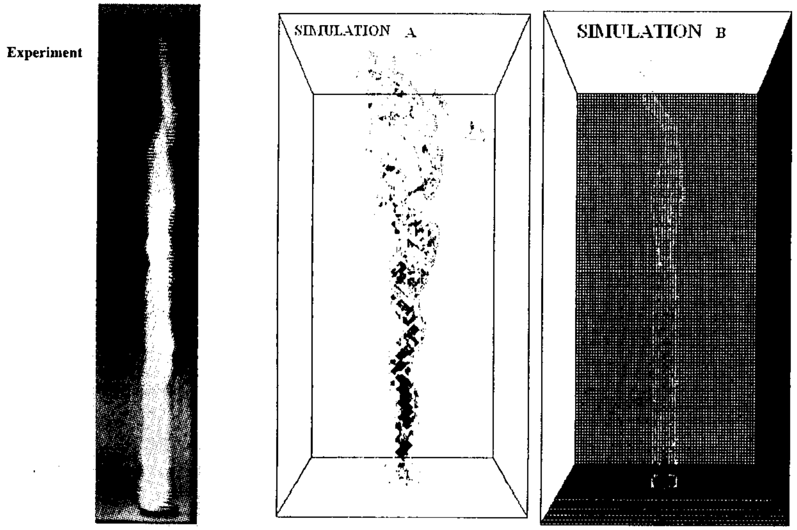

Fig. 5 Experimental Swirling Flame and Simulated Isothems (A and B) of Swirling Plume Based on the UNDSAFE Model

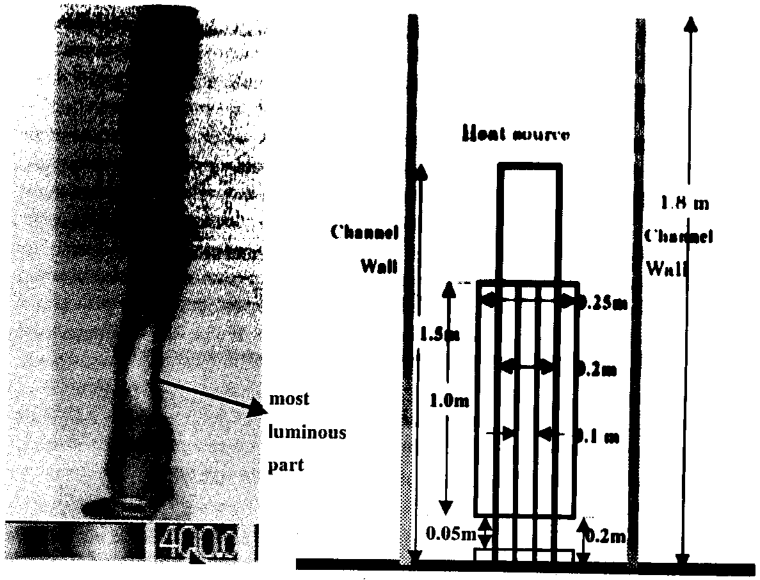

Fig. 6 Thermographic Infrared-Camera Image (left) and Overlapped Triple-Layer Model (right) for Volumetric Heat Source (30 kW)

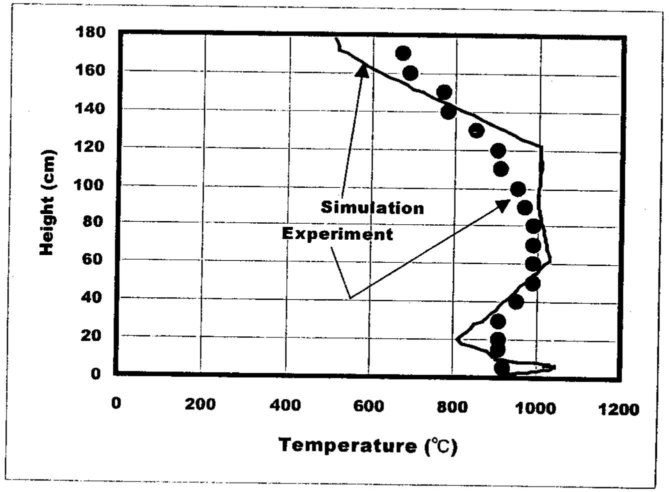

Fig. 7 Channel Centerline Temperatures vs. Height in Experiments (●) and Simulations (▬)

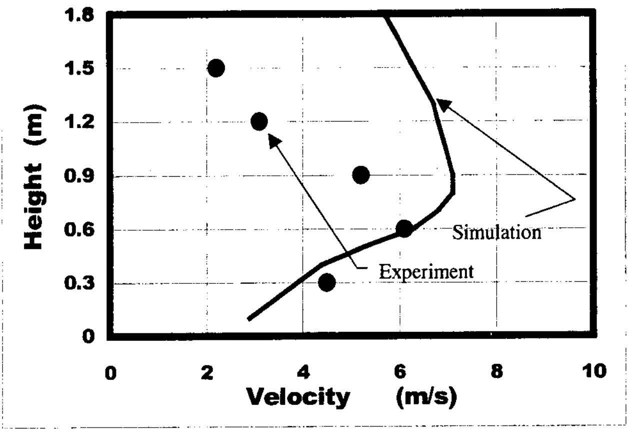

Fig. 8 Centerline Velocities vs. Height in Experiments (●) and Simulations (▬)

simulated isothermal flow patterns are time-dependent and changing in shape as shown in the graphics A and B of Fig.5. The apparent discrepancy between the photo of the swirling flame and the isotherms of the simulated hot plume is due to the fact that the hot plume accompanying the flame cannot be shown in the photo, but the simulated plume shows the whole profile of the hot plume.

The model Nagare obtained the results by solving the Navier Stokes Equations along with the solution to a Poisson Equation for the variable pressures, and also employs a constant high temperature (for example 1000 deg.C) for the heat source (15 cm x 15 cm) at the floor boundary. The calculated temperatures and velocities in the vertical direction reduced gradually and monotonically with the height along the central axis, although the entrained in-flow into the channel moving along the wall are well simulated.

On the other hand, the model UNDSAFE utilizes the volumetric heat source, as mentioned above. The comparison of the vertical temperature distribution in the heated plume between the experiments and simulations shows that the volumetric heat source model gives more reasonable distribution of the vertical centerline temperatures. The primary reason is that there is continued burning in the swirling flame and it therefore is more realistic as long as the unsteady non-uniform volumetric heat source matches closely with that in the flame, as shown in the thermographic infrared picture in Fig. 6 (left). The middle part of the swirling flame showed highly luminous in particular. Therefore, in the simulation study, a triple-layer overlapped volumetric heat source (partly single or double-layer), where the heat density is three times stronger compared with the single layer, was used in the computer model UNDSAFE, as shown in Fig.6 (right), to simulate the high-temperature zones in the flame. Here the flame envelope isotherm corresponds to a temperature of 50 deg.C.

The thermocouple measurements of the centerline temperatures at different heights of the swirling flame give the same trends as shown in Fig. 7, where in the lower zone the temperatures were less than 900 deg.C, but in the middle zone the temperatures were nearly 950 deg.C. The overlapped triple-layer volumetric heat source model is represented by the solid line in Fig. 7 for the vertical centerline temperatures in the hot plume, where a grid distribution of 32x32x61 uniform calculational cells for the channel geometry were used. Another grid system of 65 x 65 x 130 uniform cells was employed to compare both the calculated results by 32 x 32 x 61 and 65 x 65 x 130 cells. And a total heat of 30 kW was employed in the volumetric heat source. The overlapped triple layer in the middle height zone (from 0.2 m to 1.1 m) had the strongest heat input. In addition, the centerline velocities were overestimated, as shown in Fig.8, particularly in the region above the height of 60 cm, where the strongest heat input exists. It is believed that this discrepancy can be reduced by the further modification of the distribution of the volumetric heat source. Also, it should be noted that the velocity measurements by pitot tubes are also subjected to errors in such a high-temperature field (Satoh and Yang, 1999) and low velocity levels less than 2m/s.

The simulated rotational speed was about 4 m/s at the middle height of heat source and at the radius of 0.05 m from the centerline axis. Thus the estimated number of revolutions per second was 13 Hz, as compared to 20 Hz from the measurement. Since this rotational speed in Hz may be a complex function of locations, and the measured values are also subjected to some uncertainties, this comparison can still be considered to be reasonable.

CONCLUSIONS

(1) The overall flow patterns are well simulated by the simulation models and clearly show that the entrained in-flow into the channel moves along the wall and then changes its direction toward the central upward plume, thus imparting the swirling motion to the buoyant plume.

(2) Simulated isotherms of the hot plume in the channel show essentially the same features from the experimental view of the swirling flame. The discrepancy between the photo of the swirling flame and the isotherms of the simulated hot plume is due the fact that the hot plume accompanying the flame cannot be shown in the photo, but the simulated plume shows the whole profile of the hot plume.

(3) The comparison of the vertical centerline temperature distribution in the heated plume between the experiments and simulations showed that the volumetric heat source model gives much better agreement in the temperatures with that from the experiments. The volumetric heat source model is more flexible in that it can be made to conform to the actual burning characteristics of the flame.

(4) In the simulations based on the UNDSAFE model, the three-layered overlapped volumetric heat source was used to depict the same high-temperature zones as observed in the experimental infrared images. The results show good agreement in the vertical center-line temperatures, but give less satisfactory agreement in the vertical centerline velocities, especially in the region above 60 cm, and in the number of revolutions per second for the swirling plume. One reason could be in the difficulty of accurately measuring the velocities with pitot tubes in a high-temperature plume environment.

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Field Model Simulations on Air Movement of the Room-Corner Fire Test

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ABSTRACT

The air flow and temperature distribution induced by a fire in the ISO Room-Corner fire test was studied by field modelling technique. Two fire field models, UNSAFE-N and the one developed by Chow were applied. The experiment on melamine faced particle board carried out by SP was taken as the example to compare with, but not validate the predicted results. Combustion processes were not simulated and so the fire was taken as a heat source with varying heat release rate and burning area fitted from experimental data. It is found that both models can give good prediction on the indoor air flow and temperature induced by the fire.

KEY WORDS: Fire simulations, computational fluid dynamics, room-corner fire tests, aerodynamics.

NOMENCLATURE

a_i, a_p, b_i	coefficient of the linear equations
E_i	mass source errors
ρ	air density
k	turbulent kinetic energy
R_p	residual source term
R_ϕ	absolute residual error
R_{ref}	reference value of R_ϕ
T	absolute temperature
t	time
u, v, w	velocity components in directions x, y and z respectively
Γ_ϕ	effective exchange coefficient of the property ϕ
ε	dissipation rate of turbulent kinetic energy
ϕ	flow variables of air