Prediction of Premixed Flame Propagation in a Vented Cylindrical Vessel

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Abstract: A numerical model based on $k-\varepsilon$ turbulent model and EBU-Arrhenius turbulent combustion model is applied to simulate the venting process in cylindrical vessel (L/D =5.6).The flow fields of venting occurred at venting pressure of 0.02 MPa through different vent area show that during venting process the flame propagation and deformation is intensified by a venting induced flow; vent area is the main factor for determining the vent inducing flow. Small vent area and low venting pressure produce weak venting induced flow; large vent area usually produces a relatively strong venting induced flow; even the venting pressure is low. The squish flow and reverse flow which induced the velocity gradient is the possible mechanism of tulip flame.

Keywords: explosion venting; flame propagation; tulip flam; numerical simulation

1 Introduction

A design guideline of venting technique that is an effective means[1] to reduce the possible explosion damages of flammable gases, liquids or powders demands a proper understanding of the flame propagation during interaction of the flame front with flow induced by venting.

Propagation of flames in enclosed tubes has been extensively investigated by experimental and numerical methods[2~8], Ellis[2], studying experimentally the propagation of flames in closed cylinders, put into evidence that for an aspect ratio greater than 2 the flame front may undergo a radical change in its curvature, that is, the appearance, during the last stage of combustion, of a backward directed cusp that was called "tulip flame" by Salamandra et al.[3].Various possible mechanisms have been put forward: quenching and viscosity effects, burned gases vortex motion effects, the Darrieus-Landau flame instability and a flame-pressure wave interaction. Anyhow, each of their studies is focused on some particular aspect of the phenomenon and does not conform the whole problem, which in fact is very complicated; most likely, the tulip-shaped flame is generated under the simultaneous actions of combined mechanisms.[8]

Above mentioned studies are carried out in a closed or opened vessel. Some special phenomena[9,10] including a tulip-shaped flame are observed in venting experiments carried out in cylindrical vessels with large aspect ratio. Presented studies give out a numerical model for the prediction of flame propagation during venting process, the numerical results are compared with experimental data, and the possible mechanisms of flame propagation as well as the form of tulip flame are discussed.

2 Mathematical Model and Algorithm

A combustion process of premixed air-gas (4.1%C_3H_8) in a cylindrical venting vessel with aspect ratio of 5.6 is considered. The ignition and venting conditions adopted in the study are the same as those in the experiments[9,10]. A mathematical model capable of predicting the reacting compressible flows was formulated based on the following assumption: the system is axisymmetric; the initial mixture is quiescent and homogeneous; the reaction is simplified as global one-step irreversible process; radiation is ignored. The EBU-Arrhenius and k-ε models were adopted to deal with the unsteady turbulent combustion process. Physical properties such as density, viscosity, conductivity and specific heat capacity are defined as functions of temperature or composition.

Spatial discretization is performed with a finite volume technique, and time discretization uses the Gauss-Seidel one order implicit approach. Multi-grid method and self-adaptive grids technology were used for the flame front capture. The computation was performed for a cylindrical vessel of 0.18 m inner diameter and 1m length. The walls were assumed to be adiabatic and no slip. A given static pressure value is specified at the vent as boundary conditions. When the flow becomes locally supersonic, pressure and other flow quantities are extrapolated from the interior flow field. The details of the model are available in Ref.[11].

3 Results and Discussion

Flow field computation was conducted for series of parameters. The model used was validated[11] by satisfactory agreement of calculated data with measured pressure history and flame propagation. The influence of two vent diameters 50 mm and 100 mm on venting process was analyzed to illustrate main features of this process in vessels with large aspect ratio. In both cases venting pressure was 0.02 MPa.

3.1 Small Diameter (50 mm) of Venting Orifice

Figure 3 shows the simulated streamlines of venting process produced by 50mm diameter venting orifice, at 0.02 MPa venting pressure and 49 ms venting time.

The flame shape evolves from semispherical surface into an elongated semi ellipsoidal one, before it approaches the sidewall. The flame front inside the vessel is driven by the expansion of high temperature combustion gases and flow induced by venting. All velocity vectors are directed toward the vent end. The process can be considered as adiabatic.

In a short time after ignition (55-70 ms) the expanding cylindrical flame front touches the sidewall of the vessel. Due to the quenching effect of the wall the lateral part of the flame front disappear quickly and its preserved part is gradually flattened. The sharp decrease of lateral flame front surface results in a significant reduction of the amount of expanding burned gases and, thereby, in a relative low-pressure region in the ignition end. Then the burned zone is divided into two reverse flow regions around the contact surface of the lateral flame front with the wall (62 ms): part of gases flows toward the ignition end but new burned gases are generated and they push the flame front toward unburned mixture. When the lateral flame front disappears completely (70 ms), gas in the burned zone flows in direction opposite to flame propagation. At the ignition end of the tube the flow is transferred into a vortex ring.

On the way of its development the flame front is finally transformed into a tulip shape. This shape is influenced by a drag effect of venting outflow. The flow in the burned zone changed to the venting flow direction and symmetrical vortex ring was created in the central region of the tube.

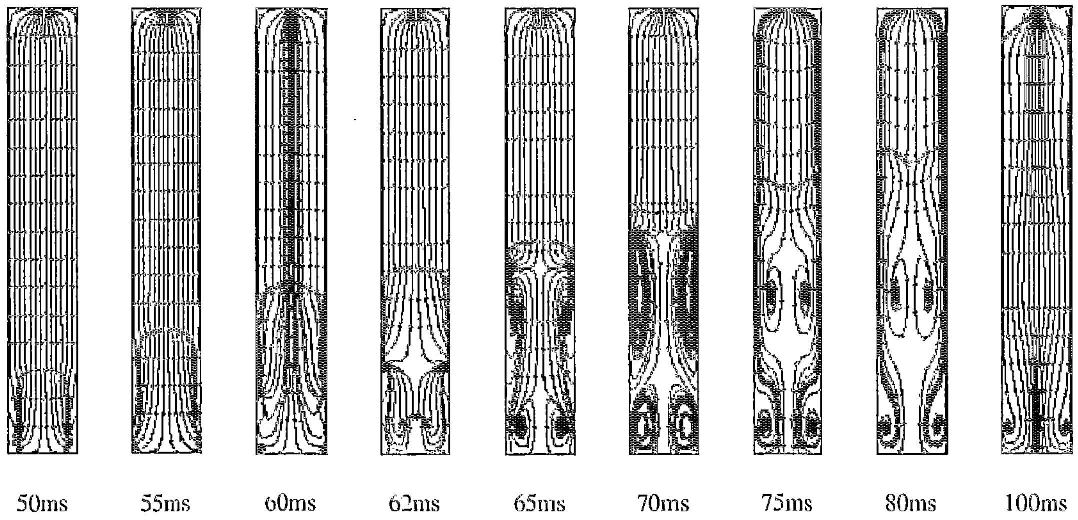


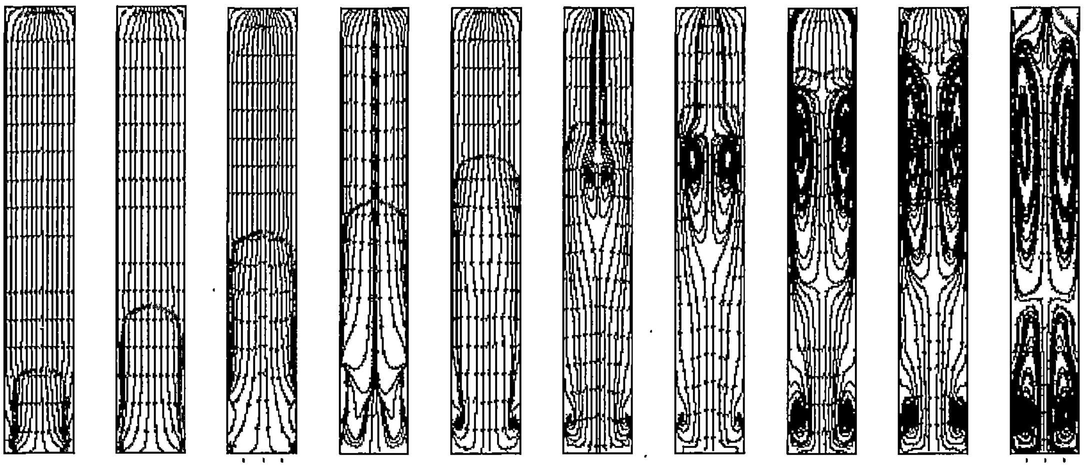
Fig.1 Flowfield of venting process with vent diameter 50 mm (P_v=0.02 MPa, t_v=49 ms)

3.2 Large Diameter (100mm) of Venting Orifice

Figure 4 shows the simulated streamlines of venting process produced by 100 mm diameter venting orifice at

0.02 MPa venting pressure and 49ms venting time.

Comparison of Fig.4 with Fig.3 indicates that the common feature is the appearance of tulip flame shape. Because venting flow is for 100 mm orifice much stronger than that for 50mm the flame front deformation and flame propagation are faster. It can be noticed that gas flows in burn and unburned zone toward the venting orifice. At the last stage of venting process two elongated axisymmetric vortex rings are dominated in the burned zone.



50ms 55ms 60ms 62ms 65ms 68ms 70ms 75ms 80ms 85ms

Fig.2 Flowfield of venting process with vent diameter 100 mm(P_v=0.02 MPa, t_v=49 ms)

3.3 The Formation of Tulip Flame

The streamline flowfield of two venting process display the flame propagation and the appearance of tulip flame, a detailed description of the tulip flame formation is presented with the numerical results of velocity field.

Fig.3 shows the velocity vector field in the vicinity of the flame front before the lateral flame front touching side wall process, after ignition 50ms. As the figure shown, a "squish flow" is generated between lateral flame front and side wall, and result in an accelerated flow region just ahead of the frontal part of flame in the unburned region. The original curved flame front is gradually flattened.

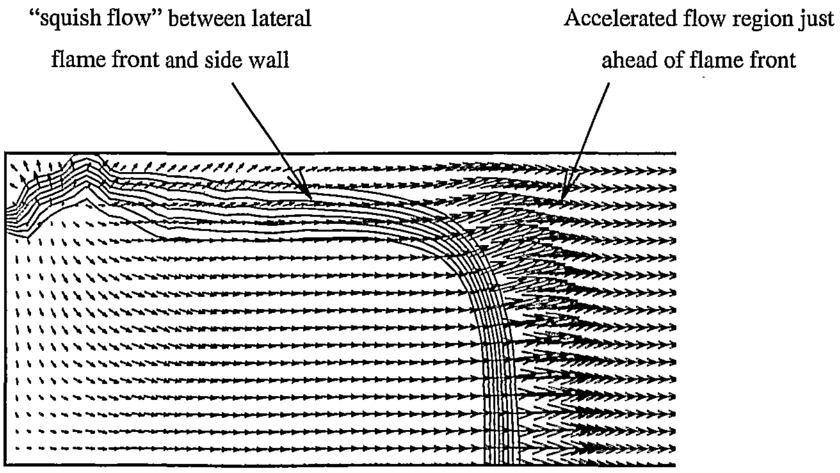


Fig.3 The velocity field in the vicinity of the flame front at t=50ms

Due to the quenching effect of the wall the lateral part of the flame front disappear quickly. Fig. 4 shows the velocity vector field in the vicinity of the flame front after ignition 64ms. In the unburned region, as the accelerated flow induced by the "squish flow" during the lateral flame front touching wall process, the magnitude of velocity nearby the side wall is greater than that of central part, a faster flow region on the "shoulder" of flame front is formed; in the burned region, due to limit of side wall and the disappearance of the main volume source after the lateral flame front have vanished at the wall, the velocity magnitude nearby the side wall is smaller than that of central pare, and a side toward center flow induce the reverse flow in burned region, the central part of flame front is folded with a backward direction. Accompany with the formation of the "shoulder" in the lateral part of flame front and the backward folded of the central part, tulip-shaped flame is gradually formed.

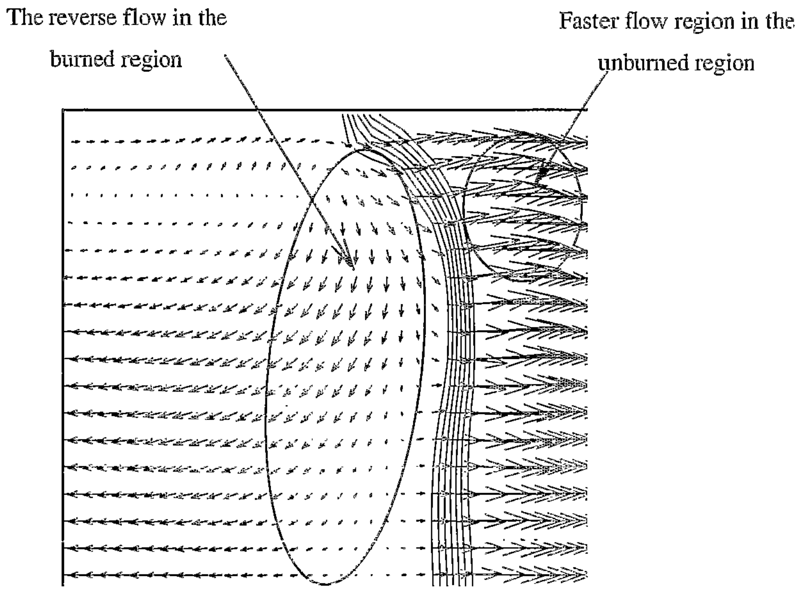


Fig.4 The velocity field in the vicinity of the flame front at t=64ms

4 Conclusions

Application of a simple mathematical model in numerical calculations made possible detailed flow field simulation of the venting process in a vessel with large aspect ratio. The following detailed conclusions can be drown up:

1) It was found in experiments and confirmed by numerical simulation that during venting process the flame propagation and deformation is intensified by a venting induced flow. The vent area is the main factor creating the flow induced by venting.

2) Small vent area and low venting pressure produce weak venting induced flow. Flame deformation and acceleration are dominated by the expansion of high temperature combustion gases primarily during the early stage of venting process.

3) Large vent area usually produces a relatively strong venting induced flow; even the venting pressure is low. The increase of flame surface and its acceleration are intensified by venting induced flow.

4) The "squish flow" during touching side wall process and reverse flow in burned region induce a radical velocity gradient in flame front, and finally result in the formation of tulip-shaped flame.

5) The numerical model adopted in the present study can be used for a primary prediction of flame evolution and its propagation under different venting condition.

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