Interaction of Flame Front with Flow in Cylindrical Venting Vessel

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1.Introduction

Venting technique is one of the most popular means for reducing possible explosion damages in various industrial facilities [1]. A design guideline of venting technique demands a proper understanding of the processes going on during interaction of the flame front with flow induced by venting.

Most of the existing research work on explosion and venting problems was devoted to spherical or cubic vessels with small aspect ratio (L/D<2) [2-6]. On the other hand there is insufficient knowledge on venting problems in cylindrical vessels with large aspect ratio (L/D>4) [7-8]. Such vessels are important because they are used in industry.

Some special phenomena observed in venting experiments carried out in cylindrical vessels with large aspect ratio are simulated by numerical calculations in the present paper. The main results of calculated pressure history and flame front propagation are compared with experimental data.

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. Such physical properties 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 0.18m inner diameter and 1m length. The walls were assumed to be adiabatic. 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 by satisfactory agreement of calculated data with measured pressure history and flame propagation. The influence of two vent diameters 50mm and 100mm on venting process was analyzed to illustrate main features of this process in vessels with large aspect ratio. In both cases venting pressure was 0.02MPa.

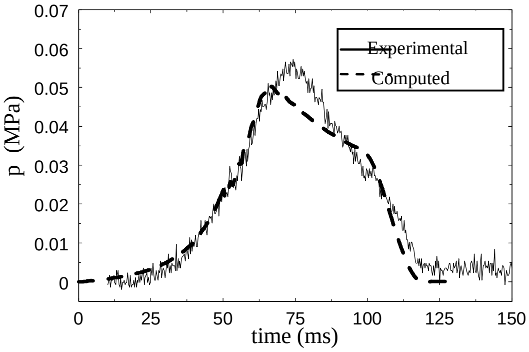

Fig.1The comparison of pressure history

ϕ=50mm, P_v=0.02MPa, t_v=49ms

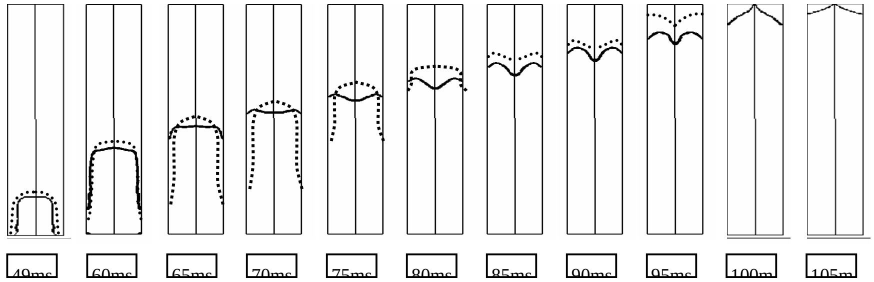

Fig.2 The comparison of flame propagation ϕ=50mm, P_v=0.02MPa, t_v=49ms

Calculated - - - - - - - Experimental

Validation of numerical model

Fig.1 and Fig.2 compare measured and calculated history of pressure and flame propagation during venting process with vent diameter 50mm and venting pressure 0.02MPa. The calculated curve in Fig.1 has a good consistency with experimental data. The corresponding modeling results of flame front evolution illustrated in Fig.2 also displayed the clear flame shape and procedure. We observe that the calculated flame propagates more slowly than that in experiment. The possible reasons are the lower initial turbulence and lower venting induced flow used in calculation comparing with actual experiment. However, the main characteristics such as pressure history and flame shape evolution are similar. Therefore, the mathematical model can be used to analyze the flow field and the interaction of the flow with the flame.

Small 50mm diameter of venting orifice

Figure 3 shows the simulated streamlines of venting process produced by 50mm diameter venting orifice, at 0.02MPa venting pressure and 49ms 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 (55-70ms) 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 to two reverse flow regions around the contact surface of the lateral flame front with the wall (62ms): 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 (70ms), 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.

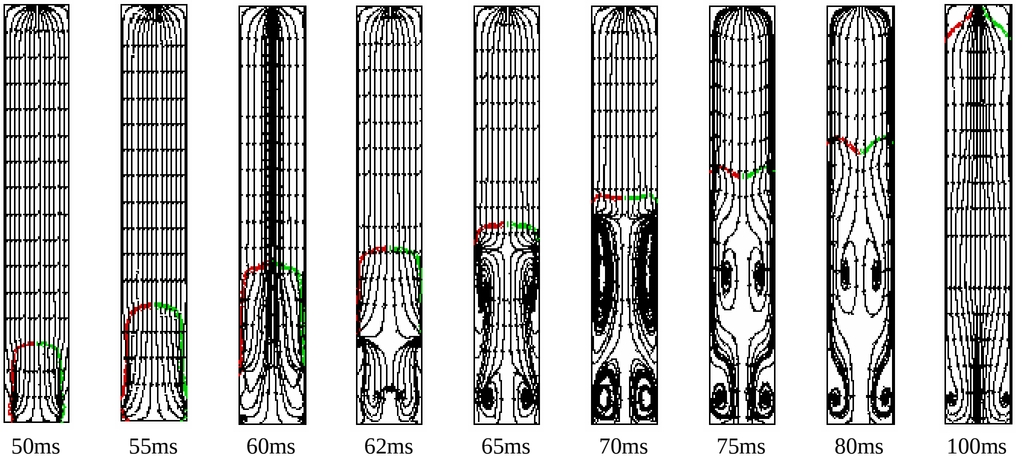

Fig.3 Flowfield of venting process with vent diameter 50mm (P_v=0.02MPa, t_v=49ms)

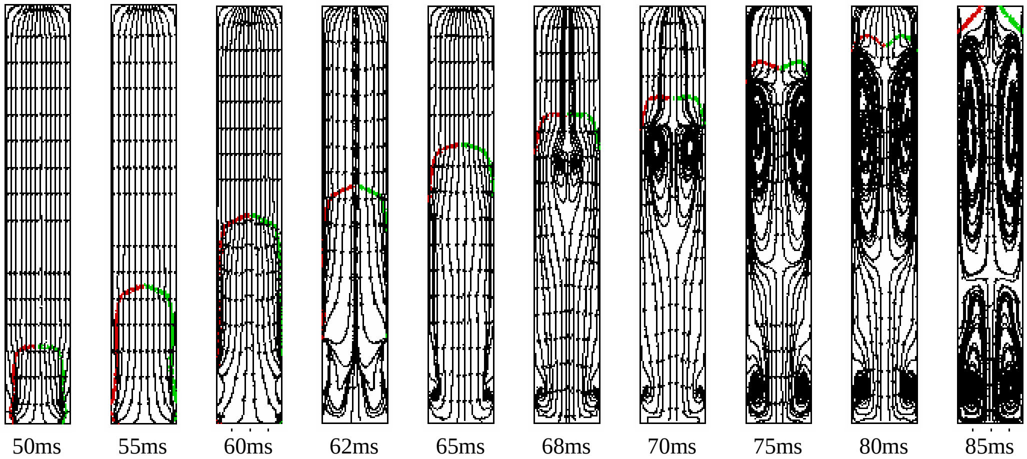

Fig.4 Flowfield of venting process with vent diameter 100mm(P_v=0.02MPa, t_v=49ms)

Large 100mm diameter of venting orifice

Figure 4 shows the simulated streamlines of venting process produced by 100mm diameter venting orifice at 0.02MPa 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 100mm 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.

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. A satisfactory agreement between simulated and measured pressure variation and flame propagation was obtain. The following detailed conclusions can be drown up:

1) It was found in experiments and confirmed by numerical simulation that during venting process the combustion is intensified by a venting induced flow. It was also found that 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 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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