An Experimental Study of Venting Process of Gas-Air Mixture Combustion in a Cylindrical Vessel

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Introduction

Venting technique is popular and effective method to reduce the possible explosion damages of flammable gases, liquids or powders [1].

The design parameters of venting technique include venting position, area, pressure and some other data. Selection procedure of these parameters requires an understanding of the venting process for a given vessel under considered boundary conditions.

Processes of flame front evolution [2] and pressure variations [3] in spherical or cubic vessels with venting were studied in details. Some analysis and vent design calculation methods were also proposed [4, 5, 6]. Venting studies of cylindrical vessels with large aspect ratios (L/D) are very useful because such vessels are of great industrial application importance. The combustion characteristics for closed cylindrical vessels with large aspect ratios (L/D>4) have some features different from those specific for vessels with small aspect ratio. Two-stage flame development [7, 8] and tulip flame front evolution [9] are among these features.

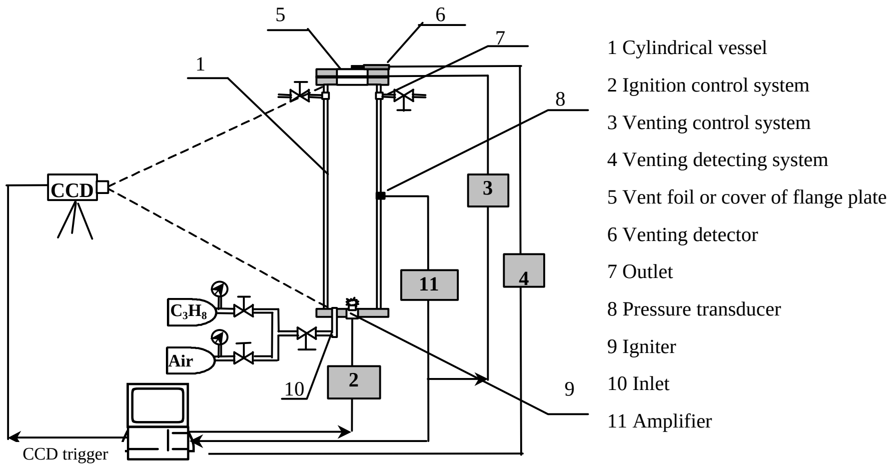

Fig.1. Schematic diagram of the experimental arrangement.

The objective of the present study is to obtain basic information on flame development and pressure variation throughout venting processes for a cylindrical vessel with large aspect ratio (L/D=5.6) under various initial and boundary conditions.

Experimental details

Experimental facilities include gas mixer, cylindrical venting vessel, igniter, pressure transducer, high-speed CCD camera and data transmission system (storage system, signal amplifier and process timer), venting arrangements; and so on (Fig.1).

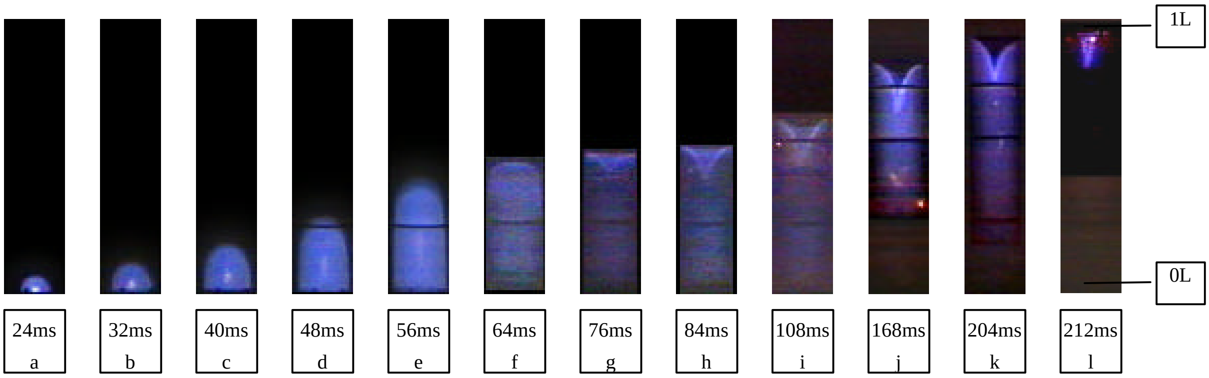

Fig.2. Flame propagation in constant volume combustion.

Both, constant volume and venting combustion experiments were conducted in a transparent cylindrical vessels of 1m long 0.18m in diameter made of perplex glass. From safety consideration, in the experiments with constant volume combustion the process was terminated by the pressure rise up to 0.4 MPa. Further pressure increase was limited by discharging the gases from the vessel outlet. High-speed CCD camera recorded the events at 500 frames per second and the data were transmitted to the storage.

The ignition and venting were executed precisely at the specified moment by means of specially designed electronic circuit.

Nothing but 4.1% propane-air and 9.5% methane–air mixtures were employed in the experiments.

Results

In both, closed and venting vessels, the flame configuration evolution and pressure variation in the combustion processes was measured. The data were collected and compared.

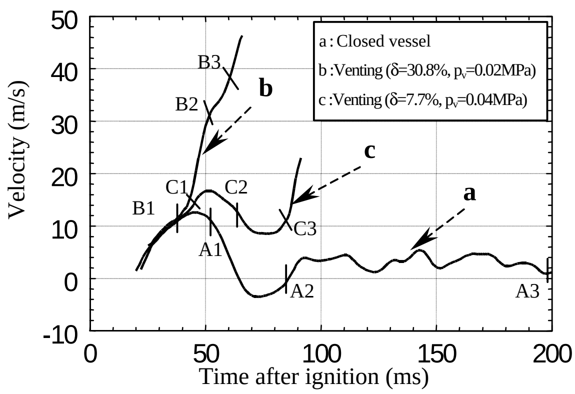

Fig.3. Comparison of flame propagation velocities for closed and venting vessels. A, B, C indicate characteristic points on velocity curves.

Figure 2 shows the photo sequence of flame propagation in 4.1% propane-air mixture, which indicates the "two-stage" behavior of flame front evolution in closed cylindrical vessel [7, 8]. During the first stage of its propagation from t=0 to t_{A1}=54ms, the flame front evolves from a semispherical surface into an elongated semi ellipsoidal one (Fig.2, from a to e). At the beginning of the second stage of its propagation the flame front touches the vessel wall, it suddenly decreases its surface, and heat from the combustion gases are transferred to the wall (Fig.2, from e to g). From the end of the second stage (t_{A2}=76ms) the flame front is deformed drastically into a typical tulip shape and kept so through to the end of combustion.

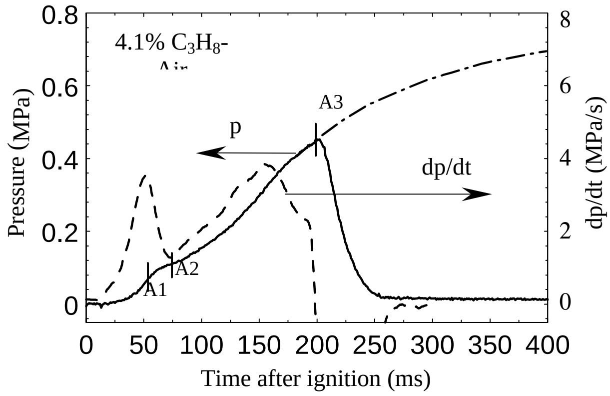

Fig.4. Pressure history and rate of pressure rise in constant volume explosion.

Typical examples of flame front propagation velocity and pressure evolution as a function of time, taken from constant volume experiments with 4.1% propane–air mixture, are shown in Fig. 3 and Fig. 4, respectively.

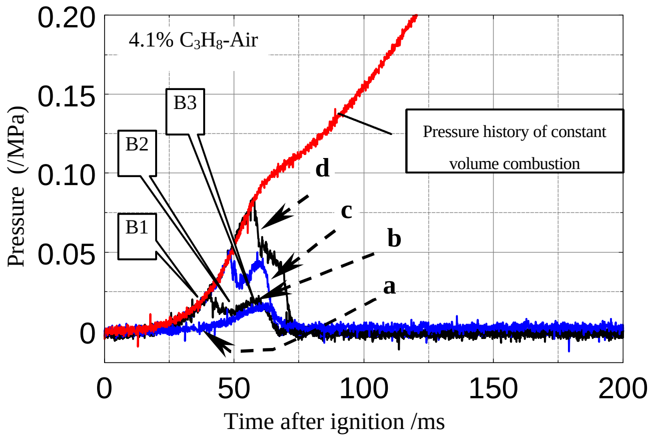

Fig.5. Pressure history for at different venting pressures and for vent diameter 100mm (venting pressure in MPa: a—0.005 ; b—0.02 ; c—0.05 ; d—0.08).

The constant volume combustion was compared with combustion with venting. In the present study, the examined parameters were mainly vent area and vent pressure. The circular vent was located at the top end of the tube opposite to the ignition bottom end of it. It was centered at the axis of the cylinder. Three different vent diameters of 50, 80, 100mm were used in experiments. The ratios of vent area to the cross-section area of the vessel (δ) were 7.7%, 19.7%, 30.8% respectively. The examined venting pressures were in the range of 0-0.18MPa, which is in agreement with safety engineering interests. The pressure development during the venting process is the consequent manifestation of two competing factors. One is the rate of gas production due to combustion, which is mainly determined by the flame surface and burning velocity. The other is the rate of outflowing gases from the vent, which is mainly determined by vent area and venting pressure.

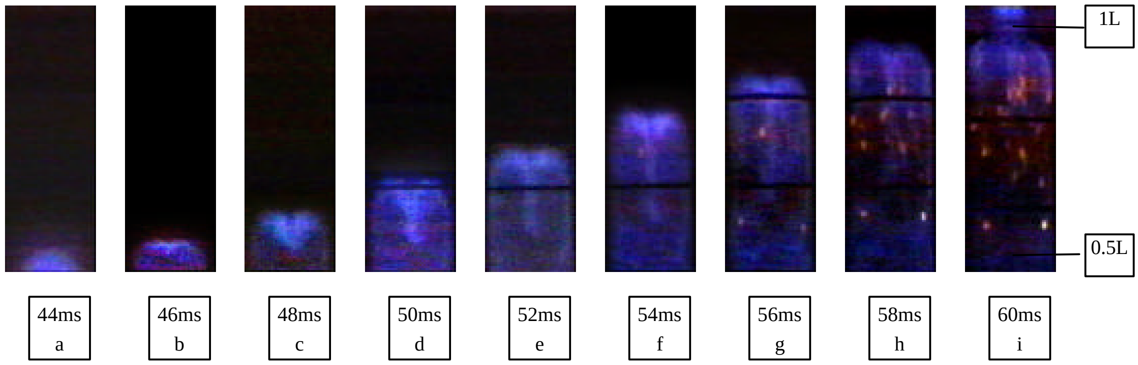

Fig.6. Flame propagation during venting with vent diameter 100mm and mixture concentration 4.1% C_3H_8 Pv=0.02MPa, tv=42ms, δ=30.8%.

An example of the pressure-time history related to venting combustion process with the biggest venting ratio of ä=30.8% is shown in Fig.5. Curves a, b, c, d correspond to different venting pressures of 0.005, 0.02, 0.05 and 0.08 MPa, respectively. The experimental results show that during the period from ignition to venting, the curve of pressure rise is in line with that of constant volume combustion process. The pressure started to decrease almost immediately after the vent opening. Soon after that pressure started to increase and decrease again and finally reached the environmental value forming a second pressure peak.

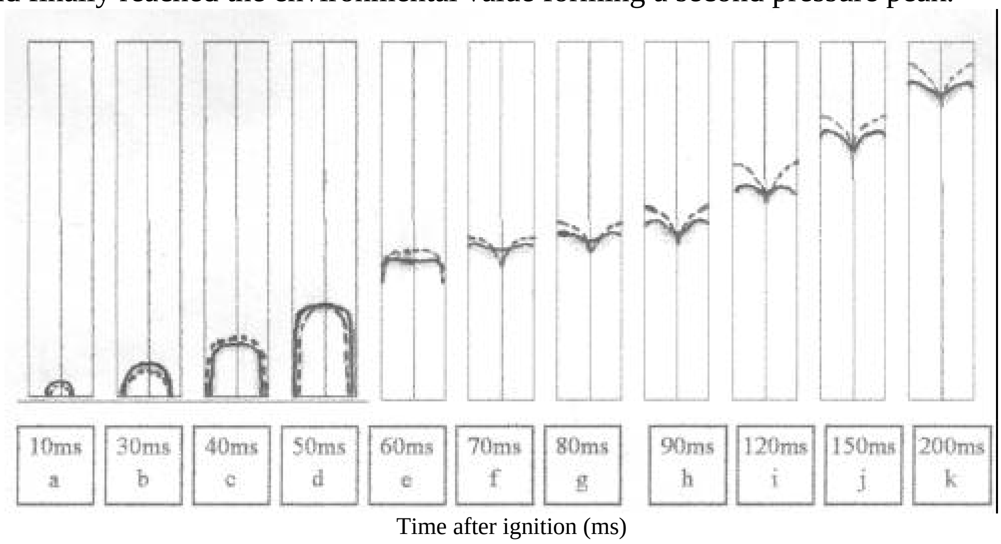

Fig.7. Comparison of calculated and measured results of flame front evolution in closed vessel. Calculated – continuous line. Measured – dashed line.

Flame propagating through the vessel at a venting pressure of 0.02Mpa is shown in Fig. 6 (the corresponding pressure history is indicated by the curve b in Fig.5). By comparison of the experimental results shown in Figs. 5 and 6 one can analyze combustion–venting process.

Numerical simulation and the comparison of computed and measured results

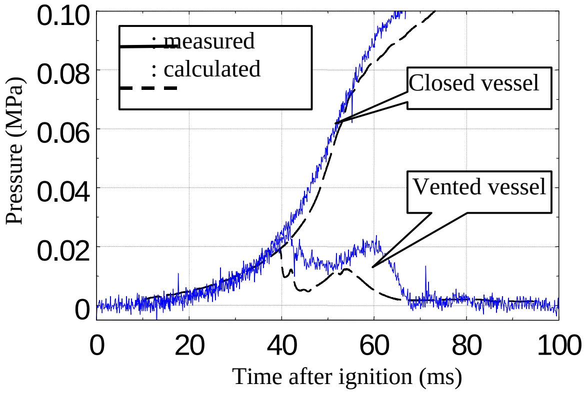

Fig.8. Comparison of measured and calculated pressure-time curves both in closed and vented vessels.

Numerical simulation was conducted for closed and venting vessel combustion. The simulation was based on the following assumptions: the system is axially symmetric; premixed mixture is used in experiments; the reaction is global one-step irreversible process; radiation is ignored; EBU-Arrhenius model and k-ε model are applicable for dealing with turbulent combustion problem. Fluent 5.0 CFD software is used for computation. About 12 hours is necessary to calculate flame propagation from the ignition to the end of the combustion process on personal computer. Figure 7 shows the comparison of computed and measured results of flame front evolution for a constant volume combustion process. The agreement between the computed and measured flame front position is satisfactory, especially during the first stage of flame propagation ($t<50ms$). Figure 8 shows the comparison of simulated and measured pressure-time curves in closed and vented vessels. It is seen that the computation succeeded in simulating the features of two pressure peaks on pressure-time curve. The predicted values of the maximum pressure in a closed and vented vessel are also comparable with the measured magnitudes. However the simulated pressure evolution is shifted in comparison with the measured one. The improvement of the numerical simulation is in progress.

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