Numerical Study on Indoor Fire of Leaked Gaseous Fuel

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ABSTRACT

The indoor fire of leaked gaseous fuel was numerical studied by using FLUENT software. A partially premixed combustion turbulent model was applied for the simulation. The results showed that the flame spreads faster in the flammable zone (a thin layer horizontal to the lower edge of the outlet) than other zones. The influence of the leak time and igniting position to fire spreading were studied It was found that the longer the leak time was, the lower the combustion intensity was, and the longer the fire would last. And the combustion intensity and the fire lasting time changed with the igniting position. Experiments were done to verify the results of the simulation, and the results of experiments tended to agree well with the simulation.

KEYWORDS: fire, liquefied petroleum gas, numerical simulation

INTRODUCTION

Gaseous fuel has been popular for most domestic applications recently. Accidents ascended with the gas consumption increasing. Safety of public and fireman is threatened by fire caused of gas leakage. Among the various kinds of fires, fires of gaseous fuel were infrequent. But once fire takes place, it will cause grave loss, especially for accidents that are difficult to prevent. Thus, it is necessary to research the behavior of the fire's engendering and spreading. Liquefied petroleum gas (LPG) was chose as the subject investigated in this study.

The simulations were conducted under some approximate conditions, including computational and experimental simulation. The premise was that the fire followed some certain law and the law only reappeared in simulation experiments, but also could be abstracted mathematics problems that control the process of fire [1].

However, the experimental simulations were carried out under some approximate conditions and the process of fire is complex, so it is difficult to establish rigorous criteria validation. The approximations included in the experimental simulations must also result in departures between experimental results and realities.

The advent of the computer provided new methods to study the behavior of fire. Computer simulation has been one of the most important contributions to fire research over nearly the last few decades period where mostly mathematical statistics and mathematical analysis methods were used in fire scientific research studies [2].We believe the results of CFD (Computational Fluid Dynamics) simulation is more creditable than those of empirical models that were obtained only from experiment [3].

FIRE SAFETY SCIENCE–PROCEEDINGS OF THE EIGHTH INTERNATIONAL SYMPOSIUM, pp. 681-691

In China, most numerical studies of gas burning in small space are static simulations. The documents on static numerical simulations were very few, and dynamic (time dependant) numerical simulations appeared in recent years [4,5].

Three-dimensional non-equilibrium simulation was used to simulate fires in the 1990's in Japan [6], involving solid or liquid fuels mostly. These studies emphasized on simulation for some specific cases to detect the problem concerned.

Fire caused by LPG leakage was simulated with a three-dimensional non-equilibrium method in this paper, some laws of fire occurrence and spread had been gained, which vary with the igniting positions and time changing, and the results were verified by experiments. The consequences of simulation agreed with the experiment well in tendency. Thus it was feasible to compare the experimental behavior of the fire with the results of the numerical simulation. Data which came from the computation, made it easier for us to analyze the mechanism of the fire's engendering and spreading. The behavior we obtained might contribute much to the work of forecasting, preventing and curing fire incidents.

NUMERICAL SIMULATION METHODS

Physical and numerical model

In order to predigest the problem, the cases of LPG leakage and combustion in buildings were abstracted and simplified in this paper. The room was considered as a cube, the leakage point was regard as a velocity entrance of LPG on the side of its wall, and the window was considered as a pressure exit of constant pressure. A combustion zone (ignition point) was defined to simulate the fire process in the combustible range after leakage lasted for a while.

LPG is inflammable and explosive, in addition the heat-producing capability and flame temperature is high, so the model should not be too big for security. Considering factors above, a box (750 mm×500 mm×250 mm) was used to simulated a room. Regard the center of the box as the origin and set up the system of coordinates (Fig. 1). Coordinates of the below observation surface is z = 0 mm, and the coordinates of the leak point (inlet), point A, point B, point C and point D are (375,0,0), (0,0,0), (0,-125,0),(-370,0,0) and (0,125,0) respectively. A combustion zone was defined with a radius of 10 mm as ignition point in the ignition positions after the leakage lasted for a moment, and ignited.

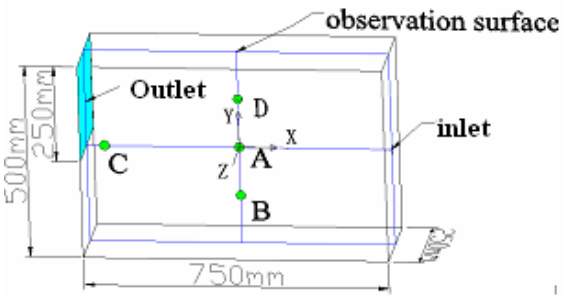


Fig. 1. Mathematical model.

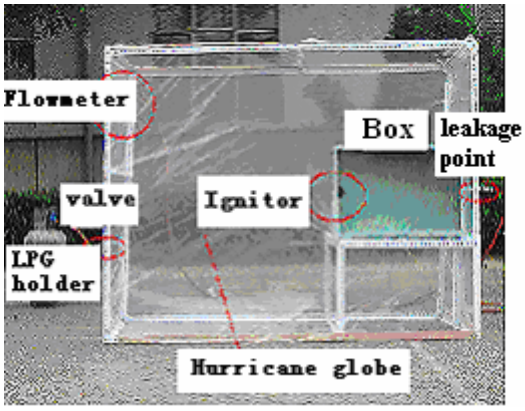


Fig. 2. Combustion simulation experiment platform.

According to the mathematics model, the experimental platform was set up as Fig. 2. The data collecting surface of the box was made of plexiglass, other three surfaces were welded with A3 steel. The electron gun was adopted to light a fire remotely, and the striking device can discharge and fire in the random position on observing surface. In order to guarantee security, the experiment was carried out in the open air. The windshield was used to prevent experimental error that caused by the air flow. The data were collected by digital camera. In order to observe conveniently the experiment was carried out at night.

Numerical Models

Mesh Division

The non-linear and non-uniform grid method was adopted for mesh division. There are 149629 nodes altogether, the smallest controlled volume is 7.24×10^{-9} m^3, the biggest one is $1.63\times10^{-7}m^3$.

Turbulent Model

LPG leakage was supposed that the gas flowed through nozzle. Because gas was influenced tremendously by buoyancy lift in the course of spreading, the turbulence model was adopted to simulate viscosity model of large eddy in this paper.

Combustion Model

Partially premixed combustion model, based on the theory of eddy dissipation combustion model and simplified PDF combustion model, was used to the simulation. The combustion was represented as reaction progress variable c. The reaction was proceeded complete in which $c = 1$, while it was not begin in which $c = 0$. Between them, the value of c was determined by linear difference. The progress variable is defined as $c = \sum_{i=1}^{n} Y_i \Big/ \sum_{i=1}^{n} Y_{i,ad}$. Where Y_i is the mass fraction of species i, $Y_{i,ad}$ is the mass fraction of species i after complete adiabatic combustion.

Partially premixed combustion model solves a transport equation for the mean reaction progress variable, $\bar{c}$ (to determine the position of the flame front), as well as the mixture fraction equations, $\overline{f}$ and $\overline{f'^2}$.

Reaction progress variable transport equation is,

$$\frac{\partial}{\partial t}(\rho c) + \nabla\cdot(\rho \vec{v} c) = \nabla\cdot\left(\frac{\mu_t}{Sc_t}\nabla c\right) + \rho S_c \tag{1}$$

where Sc_t is turbulent Schmidt number for the gradient turbulent flux, S_c is reaction progress source term(s^{-1}). For the adiabatic premixed combustion, the temperature is assumed to vary linearly between the temperature of the unburnt mixture, T_u, and the temperature of the burnt products under adiabatic conditions, T_{ad}. The pressure variations are neglected and the mean molecular weight is assumed to be constant. The density was calculated using the ideal gas law.

The mixture fraction equations are described as in Fluent help documents. Before numerical computation, a polling list was generated by fore-treatment software, prePDF**,** stores information about the streams in "look-up tables," which are then used by FLUENT to solve for the mixture fraction, enthalpy, and scalar quantities. The purpose of the polling list was to calculate the combustion parameters of gaseous mixture mixed by different ratios. During the computation, combustion parameters of the node were determined by look-up the polling list according to its *c* value.

Fundamental Equation

As mentioned above, the combustion process of the leaked gaseous fuel can be modeled by a partially premixed combustion model in Fluent software. Other equations can be as following,

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \vec{v}) = 0 \tag{2}$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla\cdot(\rho \vec{v}\vec{v}) = -\nabla p + \nabla\cdot\left(\overline{\overline{T}}\right) + \rho \vec{g} \tag{3}$$

Component equation:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla\cdot(\rho \vec{v} Y_i) = -\nabla\cdot\vec{J}_i + R_i + S_i \tag{4}$$

Energy equation:

$$\frac{\partial}{\partial t}(\rho E)+(\vec{v}\cdot\nabla)(\rho E+p)=\nabla\cdot\left[k_{eff}\nabla T-\sum_j h_j\vec{J}_j+u_j\left(\overline{\overline{T}}\right)_{eff}\right]+S_k \quad (5)$$

Where, $\vec{J}_i=-\left(\rho D_{i,m}+\frac{\mu_t}{Sc_t}\right)\nabla Y_i$, R_i is the net rate of production of species *i* by chemical reaction and S_i is the rate of creation by addition from the dispersed phase plus any user-defined sources. The first three items of the right of energy equation described the energy transport caused by heat conductivity, component diffusion and viscous dissipation. S_k is chemical reaction heat.

Settlement of Boundary and Initial Condition

The velocity of flow of fuel velocity entrance is 1.5 m/s, the pressure of pressure exit is normal atmospheric pressure. The box wall was regarded as adiabatic, which had no heat exchange with external. The original temperature of wall, flow field, external and entry gas was 300 K. The temperature of external and entry gas was assumed to be constant.
Settlement of substance parameter

Because the composition of LPG is complicated, the LPG was regared as the mixture of C_3H_8 and C_4H_8 (mass rate is 1). Parameters of every gas composition were implied by the internal database of FLUENT software.

RESULTS AND ANALYSIS

Reference Case Analysis

To compare the influence of ignition position and ignition time to the fire, a case was selected as a reference, which means leak diameter was 5 mm, leak velocity was 1.5 m/s, window dimension was 250×250 mm, fire engendered in the point A, the leak time was 90 seconds.

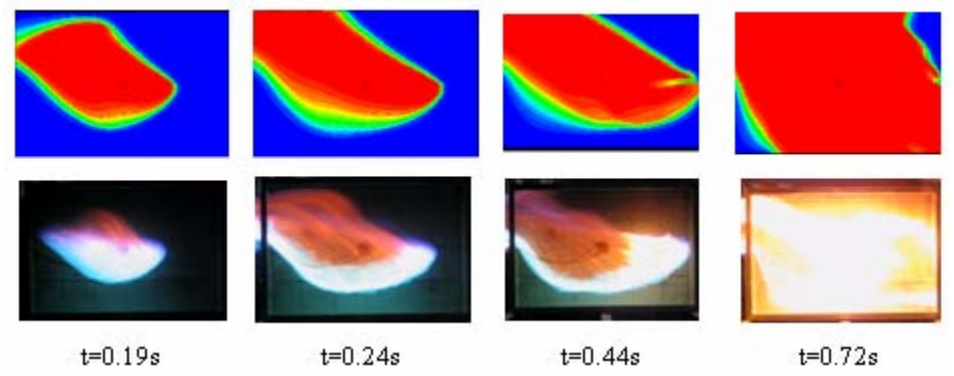


Fig. 3. The contrast of the combustion process comes from the computation to the experiment of the reference case.

Figure 3 shows the contrast of the combustion process of the computation and the experiment of the reference case. It was found that the results of simulation are in good

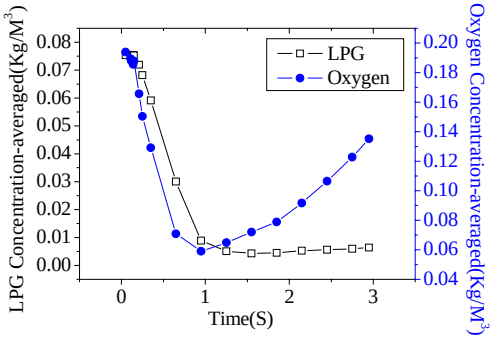
agreement with that of the experiment. The course that the flame spread is described as the following:

The flame is thick, and the flame spread speed is large. Early in its development the flame shape is like a lingua. The lingua becomes larger and longer then. When the lingua reaches the wall, the flame spreads downwards and upwards rapidly. It causes the whole box came into burn.

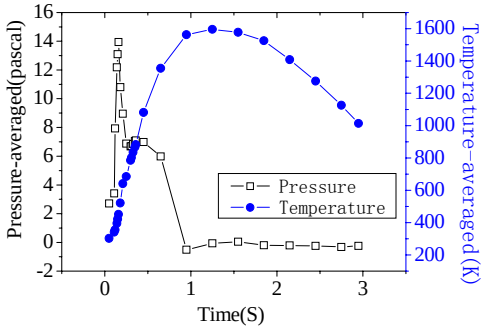
In the course of spreading upward, thin gas upside the box is burned and disappeared quickly, and the oxygen upside the box is pushed out or consumed. So the upside of the box is the hazardous area which is short of oxygen and in a high temperature.

At the end of the combustion, the flame is mainly located in the lower part, because the gas and oxygen, which have large density, deposited in the below of the box. At this time, the oxygen diffused from the window is an important factor to maintain the combustion.

Figure 4 shows the Curves of the parameters of reference case with the time after igniting.



(a) Curves of LPG concentration-averaged and oxygen concentration-averaged with time.



(b) Curves of pressure-averaged and temperature -averaged with time.

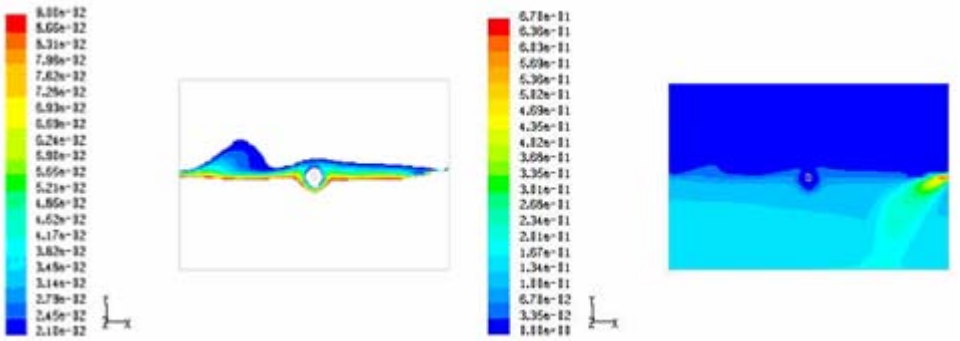
Fig. 4. Curves of the parameters of reference case with the time after igniting.

From above, several basic characteristics of the flame spread can been described as:

(1) It can be found from Fig. 3 that the flame is thick and the spread speed of flame is large because of the process belongs to premixed turbulent combustion.

(2) Area upside the box is a danger place with high temperature and thin oxygen. While the part under the window is a less hazardous area, where the fire is hard to reach, the temperature is lower and the oxygen, which is diffused from the window, reaches first.

(3) Figure 3 shows the beginning of the fire, the flame speeds are more rapid in the flammable zone, than other area. Flammable zone and LPG concentration distribution at the beginning of igniting are shown in Fig. 5.



(a) Flammable zone. (b) LPG concentration.

Fig. 5. Flammable zone and LPG concentration distribution of reference case when ignited.

Because the proportion of fuel and oxidant is approach Stoichiometric mass fraction in the flammable zone, the spread speed is large there. While the others zone is incombustible because there is too thick or thin fuel. If there is fuel diffuse off or to the zone, it will make the area can be burned. Thus the burning rate lies on the diffusion rate. It is similar to the diffusion flame. So the spread speed is small there.

(4) Figure 4 b shows that the pressure-averaged increases rapidly, and high pressure last a short time. It's only 0.16 second from lighting to the pressure-averaged to reach supreme, and the time with a high pressure-averaged is short than 1 second.

(5) Figure 4 shows that the LPG concentration-averaged tends not to change, the temperature-averaged linear decreases and the oxygen-averaged linear increases.

Because the gas is nearly burned out after the critical time when the combustion area came to its maximum, there is only a torch at the leak in the end. Then the LPG concentration-averaged keeps invariant. Cold air diffuses into from the window, for the pressure-average in the box drops to negative pressure. Steady cold air pushes the temperature gas out, which makes the temperature-averaged decrease steadily and the oxygen concentration-averaged straight increase.

Effect of Igniting Time

In this paper, different igniting time was chosen to search how the igniting time affect the combustion. Two cases, igniting time were 70 seconds and 150 seconds after the leakage, were compared to the reference case.

Figure 6 shows the contrast of the combustion process of the computation and the experiment, with the igniting time 150 seconds after leakage. Figure 7 shows the contrast of parameter curves when ignited in different igniting time.

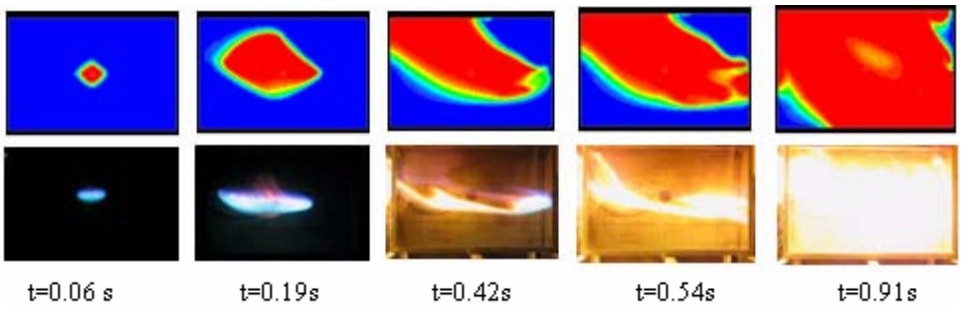
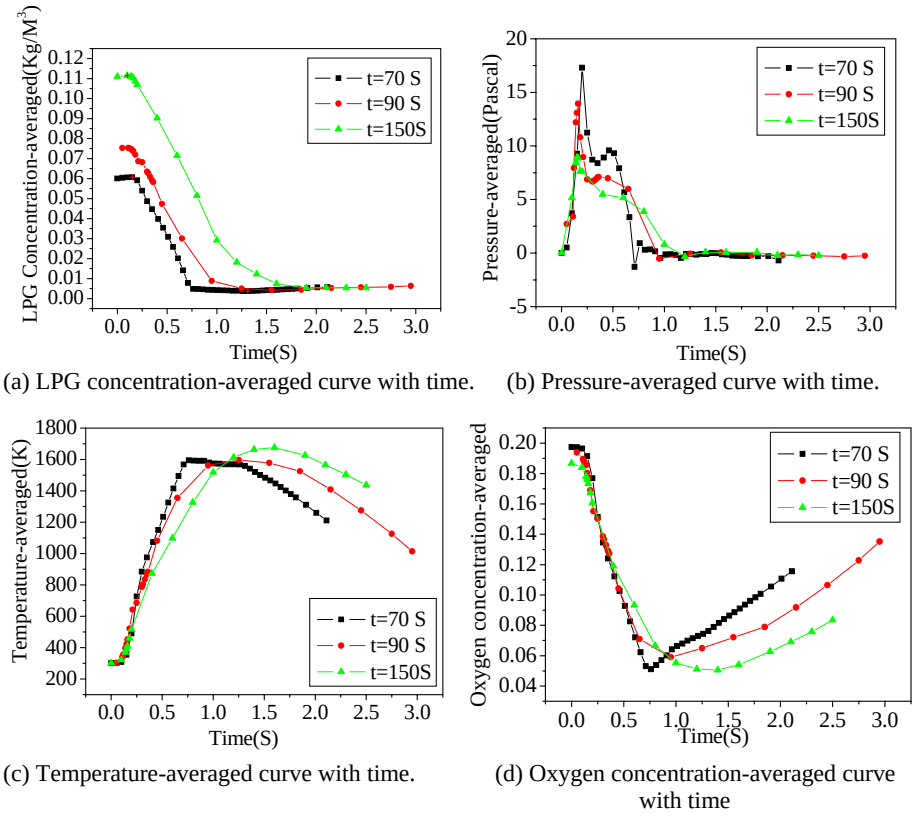


Fig. 6. The contrast of the combustion process comes from the computation to the experiment.

Figure 6 indicates that the flame shape becomes thin and long when the igniting time is put off. The longer the leakage time is, the larger the concentration gradient is near the horizontal line flush to the window sill. So the flammable zone becomes narrow. This attests to the law that the flame spreads along the flammable zone.



(a) LPG concentration-averaged curve with time. (b) Pressure-averaged curve with time.

(c) Temperature-averaged curve with time. (d) Oxygen concentration-averaged curve with time

Fig. 7. Contrast of parameter curves in different igniting time.

Figure 7 indicates that the combustion speed becomes slow as the igniting time being postponed. The LPG concentration-averaged decreases slower gradually, the largest pressure-averaged drops and the time of critical time is postponed. Because the

concentration gradient decreases with the igniting time increase, the range, where LPG concentration is in flammable zone or similar to flammable zone, becomes larger with the igniting time increase. And the amount of gas participated in combustion tends to be great in a given time. It accelerates the reaction.

As a result of LPG concentration increases and there is more LPG participates in combustion, the maximum of temperature-averaged in the box increases with the igniting time being postponed. As have been shown by Figure 7c.

With the igniting time postponing, the speed of temperature decreases and the oxygen concentration increases after critical time. Since the longer the leakage time is, the more the LPG deposits in the bottom of the box, the gas, after the critical time, will burn in longer time, which heightens the temperature and consumes oxygen diffused from the window.

Effect of Igniting Position

In this paper, different igniting positions were chosen to search how the igniting position affects the combustion. Two cases, igniting positions of point B and C, were compared to the reference case (point A).

Figure 8 shows the contrast of the combustion process came from the computation to the experiment when the igniting position is point B. Figure 9 shows the contrast of the combustion process came from the computation to the experiment when the igniting position is point C. Figure 10 shows the contrast of parameter curves of different igniting position.

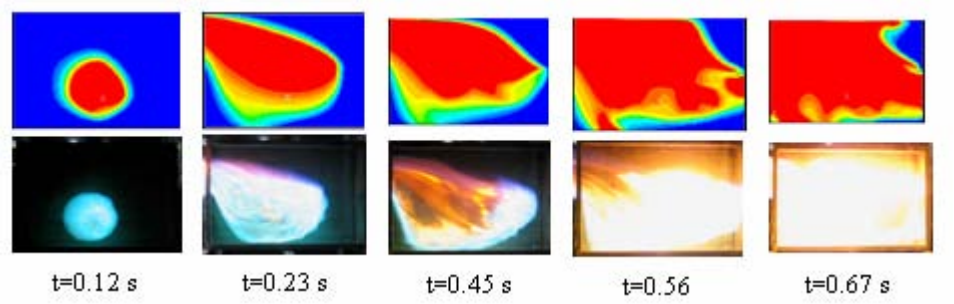


Fig. 8. The contrast of the combustion process (igniting position is point B) comes from the computation to the experiment.

Figure 8 shows that the flame shape igniting in point B is different from reference case. In this case, the shape of the flame is approximate to sphere, and the spread is faster than the reference case. But from the Fig. 9, the flame shape and the spread trend of the case of igniting point C are similar to those of the reference case, for they share the same flammable zone. Figure 10b shows the pressure-averaged in the case of igniting in point B is much more high than the others cases. This phenomenon had also been found in the experiment. Explosion tended to occur in this case.

For the concentration gradient is small in the lower part of the box, where LPG concentration is in flammable zone or similar to flammable zone, the amount of gas participated in combustion tends to be greater in a given time. Thus the reaction is strenuous.

As showed in the Fig. 10, the maximum pressure-averaged of the case of igniting point C appears later and is smaller than that of the reference case. The maximums of the temperature-averaged and the oxygen concentration-averaged are nearly equal in these cases, for they share the same concentration field and ventilating standard. The trend of the parameter curves is similar, wherever the igniting point is, after the critical time.

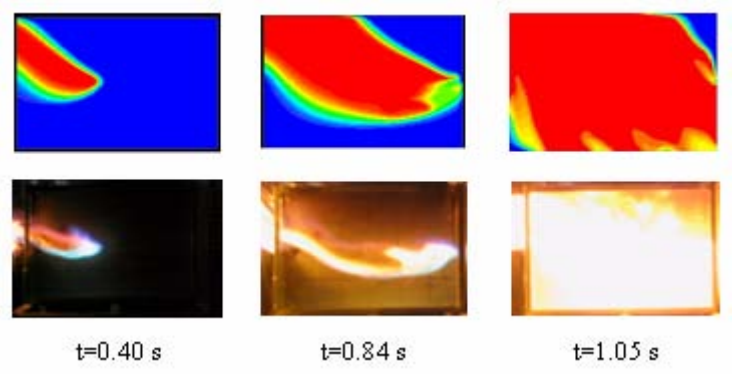
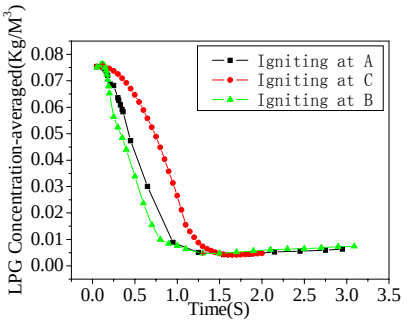
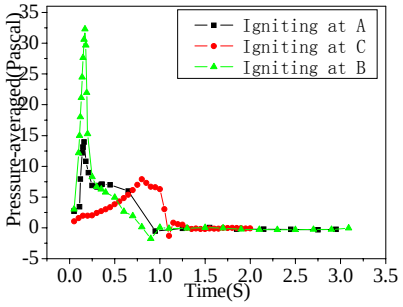


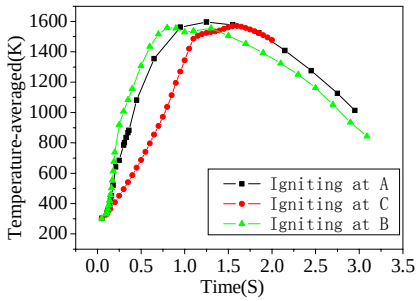
Fig. 9. The contrast of the combustion process (igniting position is point C) comes from the computation to the experiment.



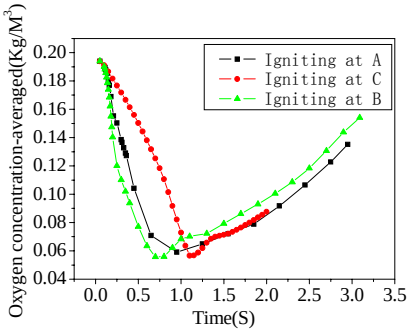
(a) LPG concentration-averaged curve with time.



(b) Pressure-averaged curve with time.



(c) Temperature-averaged curve with time.



(d) Oxygen concentration-averaged curve with time

Fig. 10. Contrast of parameter curves in different igniting position.

CONCLUSION

In sum, the main conclusion found in this paper described as the following:

(1) The simulation result agrees well with that of the experiment in trends, which testifies the feasibility to study the gaseous fuel fire with this method.

(2) At the beginning of the igniting, the flame spreads faster in the flammable zone than the others.

(3) When the leakage time last longer, the flame speed will become slow, the maximum of pressure-averaged will reduce; but the combustion will last longer, and the maximum of the temperature-averaged will increase.

(4) The time, when the maximum of pressure-averaged disappears, is determined by the x coordinates of the igniting point, rather than the leak time

(5) The case, which is ignited in the lower place, is strenuous and explosive. But the time of combustion is short-lived. After the critical time, the trend of the parameter curves is similar, wherever the igniting point is.

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