Applied Thermal Engineering 118 (2017) 392–397

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Experimental study on the influence of wall heat effect on gas explosion and its propagation

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ARTICLE INFO

Article history:
Received 4 October 2016
Revised 27 December 2016
Accepted 15 February 2017
Available online 21 February 2017

Keywords:
Wall heat effect
Gas explosion
Heat transportation
Propagation velocity
Explosion wave pressure

ABSTRACT

In order to understand the mechanism and the influence degree of wall heat effect on gas explosion and its propagation, the influence of wall heat effect on gas explosion and its propagation is theoretically analyzed mainly from perspectives of the heat transportation and reaction process. Results show that the influence of wall heat loss on gas explosion strength is significant. In addition, the influences of wall heat effect on explosion wave and flame propagation velocity in the gas explosion process are experimentally investigated in the adiabatic condition and heat conduction. It is found that the wall heat effect can affect gas explosion strength, flame propagation velocity, peak overpressure and the peak flame propagation velocity, and their influence degree becomes more significant with the increase of the adiabatic degree. Therefore, it can be seen that the wall heat effect has an important influence on the gas explosion and its propagation. The influence of wall adiabatic condition on gas explosion with a higher combustion level is greater than the influence on gas explosion with low combustion levels.

1. Introduction

Gas explosion is a very complex physical-chemical reaction occurring in the gas-air mixture within a very transient time. As the behaviors of heat- mass transportation between unburned mixture and burned mixture are very complex, plus gas explosion happens in the limited space with the high temperature and high pressure, thus the changes of gaseous parameters are great, which brings a lot of difficulties to understand and study the gas explosion process. In general, in order to facilitate research or reach experimental goal, so some seemingly unimportant factors are artificially ignored, for example, the wall heat loss, etc.

In the gas explosion experiment, the energy supporting flame movement forward continuously is from chemical reaction caused by the violent heat-mass exchange between the unburned mixture and flame front, which is important for the initial gas combustion. If the heat loss consumes the released energy of some chemical reactions, the flame propagation velocity will be reduced and even the flame will be extinguished [1]. Gas explosion products have a high temperature, therefore, there is an inevitably considerable temperature difference between the products and experiment pipes. In this situation, part of the released heat in gas explosion process will be lost by means of heat conduction, convection and radiation, which will reduce heat transportation to the unburned mixture, affect the flame propagation velocity and weaken the explosion strength [2]. Yan et al. carried out the numerical study on influence of wall parameters on catalytic combustion characteristics of CH4/air in a heat recirculation micro-combustor, their results show that with the decrease in thermal conductivity of wall materials, the temperature of the reaction region increases and hot spots becomes more obvious [3]. The effect of thermal radiation on the dynamics of a thermal explosion of a flammable gas mixture was studied, it was pointed out that the effects of thermal radiation can be significant, especially at high temperatures, and cannot be ignored in the analysis of this phenomenon [4]. The material thermal characteristics also have influence on explosion parameters [5]. However, for safety reasons, the steel pipes with thickness wall withstanding a higher pressure have been frequently used in gas explosion experiments [6–8], but the good heat conductivity and high heat capacity of steel pipes make heat losses more obvious, and produce deviations. For example, the long-pipe experiments were employed in these experiments [9–13], the region behind the reflected shock wave can be considered isothermal prior to the main chemical reaction, but significant heat transfer to the walls of the shock tube brings observable deviations from the isothermal assumption. Actually, the heat conductivity of the

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http://dx.doi.org/10.1016/j.applthermaleng.2017.02.084
1359-4311/

underground roadway wall is poor [14], and the influence of wall heat loss on gas explosion is different from the influence in steel pipes. It can be obtained that there are still some differences between the laboratory experiment and the actual mine situation, To better apply the existing research outcomes to the actual mine's safety work, the influence degree of wall heat effect on gas explosion must be deeply studied, so the influence of wall heat effect on gas explosion and its parameters is studied in this paper. The study outcomes have an important practical significance for the gas explosion prevention during underground mining, safe and rational utilization of natural gas and other industrial energy.

2. Theoretical analysis on the influence of wall heat effect on gas explosion

It is obtained that thermal conductivity and convection on the surface of solid wall have an apparent influence on combustion in related literatures [15,16]. From the viewpoint of heat transportation, the pipe geometry size, pipe material and pipe wall structure commonly determine the heat losses caused by radiating propagation from hot products with high temperature to pipe wall. The wall heat effect was specially put forward in literatures [17,18], the concept of wall heat effect was formed and discussed in other disciplines, such as heat transfer. In the field of gas explosion, although it has been put forward, but so far, a detailed study and monographs about this issue have not yet seen. Normally, in order to facilitate the study and highlight the specific purpose of the experiment, the problems are often simplified as follows: the reaction region of unburned gas and the flame front is very thin, the contact surface between the pipe wall and reaction region is very small, plus the flame velocity is very fast. Therefore, it is considered that the heat transfer loss from hot products with high temperature to wall surface is very little in process of gas explosion, the influence of heat transfer loss on the flame propagation characteristics also is little, so as to ignore the influence of wall heat effects on gas explosion. With the further research, this view is not correct. The flame thickness in gas explosion is far more than the thickness of micron order of magnitude in the classical kinetic theory, so the radiating heat is large. In the initial stage of gas explosion, the flame wave is still in the low velocity stage, the heat- mass transportations between wave front and the unburned mixture are not severe, but the wall heat effect of pipe will inevitably affect the next flame acceleration [19]. In the transient process of continuous acceleration and eventual detonation formation, due to the increase in the internal turbulence and violent heat release of reaction, the heat exchange between the reactants and the pipe wall is bound to increase.

Gas explosion is a chemical reaction process with high temperature and high pressure. Hence experimental pipe of gas explosion should be the steel pipe with a good heat conductivity and high heat storage capacity, so that the heat loss caused by wall is bound to weaken the explosion strength and flame propagation velocity. On the contrary, the improvement of the wall's adiabatic condition can significantly accelerate gas explosion. Gas explosion energy is from the released heat of chemical reaction of gases, the energy loss is transferred to wall by method of convection, conduction and radiation, when the gases with high temperature and high pressure contact with the wall surface in process of fast flow. Because the shock wave does work to gas in front of wave, so there will be an upward jump change in the internal energy, enthalpy and kinetic energy of gas behind the shock wave, which is shown in Fig. 1. The shock wave does not have energy, but it creates condition for the chemical reaction. At the same time, the energy released from the chemical reaction continuously supports the shock wave propagation. According to the propagation structure

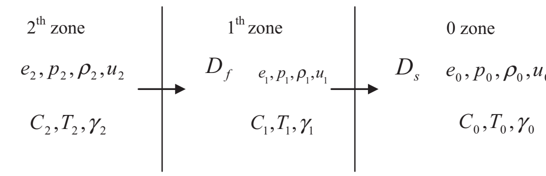

Fig. 1. Gas state distribution of combustion zone during gas explosion.

of detonation state, the energy conservation equation could be expressed as follows.

$$q + e_1 + \frac{p_1}{\rho_1} + \frac{1}{2}(D_f - u_1)^2 = e_2 + \frac{p_2}{\rho_2} + \frac{1}{2}(D_f - u_2)^2 \tag{1}$$

To facilitate the study on explosion energy conversion, the equation is rewritten as:

$$q + h_1 + \frac{1}{2}(D_f - u_1)^2 = h_2 + \frac{1}{2}(D_f - u_2)^2 \tag{2}$$

where e is the internal energy; p is the pressure; u is the particle velocity; C is the velocity of sound; T is the temperature; γ is the adiabatic index; ρ is the gas density; subscript 0,1and 2 denote 0 zone, 1th zone and 2th zone, respectively: 0 zone is the initial state of combustible gas mixture; 1th zone is the state behind shock wave front; 2th zone is the state behind detonation wave front (flame front).From the above formulas, it could be obtained that the reaction of combustible mixture per unit mass releases energy q. Part of the energy q supports the propagation of shock wave; another part of it is transformed into the internal energy and enthalpy of combustion products. At the same time, the volume of the combustion products is rapidly expanded, and the unit mass volume (m^3/kg) is about 5–15 times of volume of the unburned gases [20]. Combustion products do work by the expansion, the fundamental energy is transformed into pressure energy and kinetic energy. Because gas explosion experiments are done in the pipes and the gas explosion is completed instantly, the relative temperature rise of pipe wall is not large. Theoretically, there is a significant temperature difference between the high temperature combustion products and pipe wall. Meanwhile, there is also a great temperature difference between the burned products and the unburned gases. So the hot burned products transfer a part of the energy to the wall by method of convection and radiation; the hot burned products transfer the energy to the unburned gas by method of conduction, diffusion, etc.

Based on above analysis, more detailed combustion energy equation of the combustible mixture of per unit mass can be got [21].

$$q = q_1 + q_2 + W + F_K + L \tag{3}$$

where q_1, q_2 is the heat of combustion products radiating to the unburned gas and pipe, respectively, kJ/kg; W is the increased energy of shock wave, kJ/kg; F_K is the increase in kinetic energy of combustion products, kJ/kg; L is the energy loss, kJ/kg.

The above formula adequately reflects the combustion energy distribution of gas in the unit mass, i.e. under the condition of certain combustion energy, if the amount of radiating heat increases, the energy supporting shock wave propagation forward will reduce, the propagation velocity and overpressure of the shock wave will consequently be weakened. On the other hand, if the radiating heat reduces, the energy supporting shock wave propagation forward will increase, thus the propagation velocity and overpressure of the shock wave will increase, and the chemical reaction rate will increase, the explosion strength will be greatly enhanced. Therefore, the wall heat effect will reduce the explosion strength and temperature. The reduction of gas explosion strength and the