Fuel 234 (2018) 886–893

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Explosion characteristics of a methane/air mixture at low initial temperatures

Gan Cui*, Shun Wang, Jianguo Liu, Zhenxiao Bi, Zili Li*

College of Pipeline and Civil Engineering in China University of Petroleum (East China), Qingdao 266580, China
Shandong Provincial Key Laboratory of Oil & Gas Storage and Transportation Safety, Qingdao 266580, China
Qingdao Key Laboratory of Circle Sea Oil & Gas Storage and Transportation Technology, Qingdao 266580, China

ARTICLE INFO

Keywords:
Methane
Explosion characteristics
Low temperature
Combustion duration
Flame development duration

ABSTRACT

In this paper, the explosion characteristics of a methane-air mixture at low initial temperatures (up to 113 K) and elevated pressures were measured. Various parameters, such as explosion pressure, rate of the explosion pressure rise, combustion duration and flame development duration were obtained for the initial temperature range of 123–273 K. The results indicated that the maximum explosion pressure and the maximum rate of explosion pressure rise reached peak values at the equivalence ratio of 1.1. With the increase in initial pressure, the maximum explosion pressure increased significantly, and the maximum rate of explosion pressure rise increased linearly because of a larger density of the flammable mixture within the explosion vessel. With the decrease in the initial temperature the maximum explosion pressure increased monotonically, whereas the effect of initial temperature on the maximum rate of explosion pressure rise was negligible because of two opposing aspects: an increase in the amount of flammable mixture and a decrease in the flame propagation speed. Both the combustion duration and the flame development duration increased with the increase in initial pressure and decreased with the increase in initial temperature. Finally, at an equivalence ratio of 1.0, two empirical correlations were obtained to calculate the combustion duration and the flame development duration.

1. Introduction

With the increase in global energy demand, liquefied natural gas (LNG), which is a cleaner fuel compared to traditional fossil fuels, has started playing an important role in the energy sector [1–6]. LNG predominantly consists of methane and is stored at a temperature of 111 K. When LNG leaks, a liquid pool could build up at the low-lying terrain, and LNG vapors are formed via evaporation. When the flammable vapors come across a strong enough ignition source (such as electric sparks, mechanical sparks or open flames), an explosion may occur. In addition, to resolve the global energy crisis, the exploration and utilization of oxygen-bearing coal-bed methane (CBM) have important economic and environmental benefits [7–9]. Some researchers have found that, during the production of LNG using oxygen-bearing CBM liquefaction processes (in which the temperature is lower than 133 K), the methane concentration is within the flammable range that causes safety risks to the whole process [10,11].

Over the past few decades, many scholars have studied the explosion characteristics of combustible gases [12–17]. However, the initial conditions in their experiments were either room temperature or elevated temperatures. There are only a handful studies focusing on the characteristics of methane explosion at low temperatures. Karam et al. [18] used a cylindrical stainless-steel explosion vessel to test the lower flammability limits, hydrogen and carbon monoxide within the initial temperature (T_0) range of 140–298 K. The results showed that the lower flammability limits increased linearly with the decrease in T_0. Wierzba et al. [19] used the same experimental device and determined the upper flammability limits of flammable mixtures within the initial temperature range of 213–298 K and room pressure. Based on the experimental data, the equation for the prediction of the upper flammability limit at low temperatures was obtained. Later, Wierzba et al. [20] measured the flammability limits of some fuels within the initial temperature range of 173–298 K. The results showed that, at low temperatures, the existing Le Chatelier equation produced a large error in predicting the flammability limits of combustible gases. Li et al. [21] determined the flammability limits of methane with different nitrogen concentrations within the temperature range of 150–300 K. Another research group [22,23] constructed a gas explosion test device that was capable of withstanding a low temperature of 113 K and determined the flammability limits and the minimum ignition energy (MIE) of methane

* Corresponding authors at: The Yangtze River West Road no. 66 in Huangdao, Qingdao City, Shandong Province, China.
E-mail addresses: chennacuigan@163.com (G. Cui), zilimenhuzu@163.com (Z. Li).

https://doi.org/10.1016/j.fuel.2018.07.139
Received 2 May 2018; Received in revised form 22 July 2018; Accepted 30 July 2018

Nomenclature

LNG	liquefied natural gas
MIE	minimum ignition energy
P_f	pressure in the final state, MPa
P_0	pressure in the initial state, MPa
T_0	temperature in the initial state, K
dP/dt	rate of explosion pressure rise, MPa/s
$(dP/dt)_{max}$	maximum rate of explosion pressure rise, MPa/s
n_f	mole fraction in the final state, mol
S_u	laminar flame speed of the unburnt gas, m/s
S_{uf}	laminar flame speed of the unburnt gas in the final state, m/s
ρ_u	density of the unburnt gas, kg/m^3
R	inner diameter of the explosion vessel, m
C	variable
t_R	combustion duration, ms
CBM	coal-bed methane
FS	full scale
P	explosion pressure, MPa
T_f	temperature in the final state, K
t	time after ignition, ms
n_0	mole fraction in the initial state, mol
$\rho_{u,0}$	density of the unburnt gas in the initial state, kg/m^3
ΔP	pressure rise, MPa
φ	equivalence ratio
t_d	flame development duration, ms

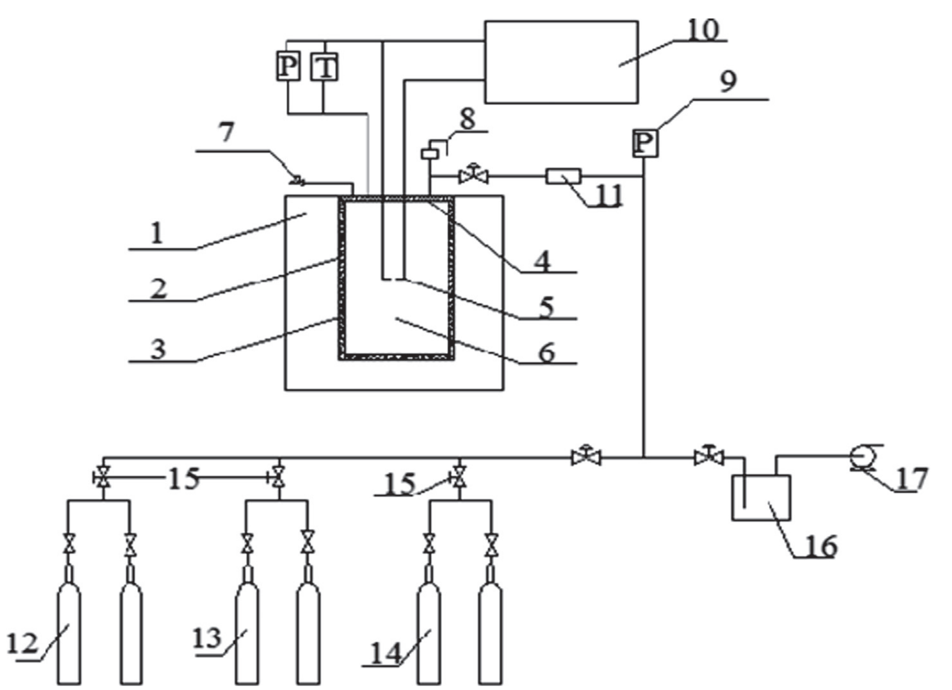
within the initial temperature range of 123–273 K and the initial pressure (P_0) range of 0.1–0.9 MPa.

In short, the research on the explosion characteristics of methane at low initial temperatures has been limited to the flammability limits and the MIE. To the best of our knowledge, there is no research on other explosion characteristics, such as explosion pressure (P), rate of explosion pressure rise (dP/dt) and duration of combustion at low temperatures. Therefore, in this paper, the explosion characteristics of methane were determined using an experimental setup within the initial temperature range of 123–273 K and different initial pressures. The relationships among combustion duration (t_R), flame development duration (t_d) and initial temperature and pressure were established.

2. Experimental section

2.1. Composition of the experimental device

Fig. 1 shows a schematic of the experimental setup, which mainly consisted of a gas distribution system, a refrigeration system, a vacuum system, an explosion vessel, an ignition system, a data collection system and some safety measures. The purities of methane, oxygen and nitrogen were greater than 99.999%. The refrigeration system consisted of a refrigeration box, and the refrigeration temperature ranged from 103 K to 313 K, with a temperature fluctuation of less than 2 K. The vacuum system consisted of a vacuum pump, a vacuum vessel, a vacuum gauge and the corresponding pipelines. The 2ZX-4 type vacuum pump used delivered at a flowrate of 4 L/s. The vacuum vessel was a 1 L stainless steel container that was placed between the vacuum pump and the explosion vessel to prevent water (generated during the explosion



1-Cooling box, 2-Inner wall of the cooling box, 3-Aluminium powder, 4-Insulating layer, 5-Ignition electrode, 6-Explosion vessel, 7-Sampling valve, 8-Safety valve, 9-Precision pressure gauge, 10-Data acquisition system, 11-Flame arrester, 12-Methane gas cylinders, 13-Oxygen gas cylinders, 14-Nitrogen gas cylinders, 15-Needle valve, 16-Vacuum vessel, 17-Vacuum pump

Fig. 1. Schematic of the experimental device.