Fuel 185 (2016) 18–25

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Pressure history in the explosion of moist syngas/air mixtures

Yongliang Xie, Jinhua Wang *, Xiao Cai, Zuohua Huang *

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China

HIGHLIGHTS

- Effect of syngas composition on pressure development in syngas explosion is studied.
- Explosion parameters are obtained from the experiment and analyzed.
- H_2O addition has different effects on the explosion parameters for syngas with various CO/H_2 ratios.
- The effect of heat loss on the explosion propagation of syngas/air mixtures is estimated.

ARTICLE INFO

Article history:
Received 17 May 2016
Received in revised form 18 July 2016
Accepted 18 July 2016

Keywords:
Syngas
Pressure history
Deflagration index
H_2O addition

ABSTRACT

The pressure history in the explosion syngas/air mixtures with H_2O addition over a wide range of equivalence ratios at elevated temperatures was recorded to study the explosion characteristics in a constant volume confined vessel. CO mole fractions in syngas are from 0.5 to 0.95, initial temperatures are from 373 K to 473 K, and H_2O addition ratios are from 0 to 30%. The explosion parameters such as explosion pressure, explosion time, maximum rate of pressure rise, and deflagration index are obtained from the experiment. Effects of the equivalence ratio, initial temperature, CO/H_2 ratio and dilution ratio on the explosion parameters are examined. These parameters are important input properties for evaluation of hazards of the explosion and the design the combustion vessel. In addition, the adiabatic explosion pressure is also calculated assuming the flame propagation is a constant-volume and adiabatic process. Results show the experimentally determined normalized explosion pressure and the normalized adiabatic explosion pressure show different trends with the increase of CO/H_2 ratio. The experimental determined normalized explosion pressure decreases but normalized adiabatic explosion pressure increases with the increase of CO/H_2 ratio in the syngas mixture. This is mainly because the heat loss is larger for the mixture with a higher CO/H_2 ratio. At last, the heat loss during the combustion process was calculated by the difference between experimental and adiabatic explosion pressure. With the addition of CO dilution ratio in the mixture, the amount of heat loss transferred to the wall heat loss to the unit area increases greatly.

1. Introduction

The growing demand of energy resources and continuously stringent restrictions on pollutant emissions have greatly promoted the study on reformed fuels in the past decade. Among these fuels, syngas is particularly promising in the future energy production and currently receives a tremendous interest in the areas such as power generation and internal combustion engines [1,2]. Syngas combustion in those applications is most attractive and promising research field with the development of IGCC (Integrated Gasification Combined Cycle) plants and alternative IC engine fuels. Syngas combustion can result in an improvement of the conversion efficiencies, a significant reduction in pollutant emissions and a potential reduction in CO_2 emissions if combined with CCS (Carbon Capture and Storage) technology. However, control of NOx emissions is still a big challenge in IGCC system and IC engine since NOx mainly comes from the high-temperature reaction of N_2 [3]. Previously published research showed that addition of H_2O was an effective way to reduce the NOx emission for the diesel engines [4], spark-ignition engine [5] and gas turbine [6]. In addition, the substantial variation in syngas composition due to different coal quality and origins, gasification and post-processing technique will cause a significant influence on the pressure history and explosion characteristics and is among the largest barriers to the design of combustion chamber and the prevention of fire hazards. For the syngas, safety problems persist constantly

* Corresponding authors.
E-mail addresses: jinhuawang@mail.xjtu.edu.cn (J. Wang), zhhuang@mail.xjtu.edu.cn (Z. Huang).

http://dx.doi.org/10.1016/j.fuel.2016.07.072
0016-2361/

due to the presence of H_2 and CO. Although the hazard of H_2 for gas leakage in the atmosphere is relatively lower than that of higher-order hydrocarbons because of the extraordinary buoyancy of H_2, hydrogen leakage inside an enclosed environment are extremely dangerous [7]. Explosion in enclosed environments is a well-recognized hazard due to the high explosion pressure and rate of pressure rise [8]. CO is a colorless and tasteless gas which is quite toxic to humans when encountered in higher concentrations. Therefore, it is of great importance to know explosion characteristics of syngas with various compositions to ensure the safety in industrial and domestic applications and undertake adequate risk assessment. Important and basic explosion parameters are needed as the necessary input for formulating safe working conditions and design of vents, aiming at reducing the damage due to the explosion in the chamber [9].

Explosion characteristics of hydrocarbon fuels in cylindrical and spherical chambers have been widely studied in the previous researches [8–15] but the experimental determined explosion parameters on the syngas explosion is quite limited [16]. In addition, previous studies have shown that addition of diluents can decrease the pressure rise and the maximum rate of pressure rise effectively and prevent damage from a deflagration in a closed chamber [17,18]. However, the effect of H_2O on the explosion characteristics is still unclear. The explosion pressure and parameters are strongly affected by initial pressure, temperature, composition, volume and shape of the chamber, ignition style and turbulence. But it is still hard to predicate the explosion parameters accurately with the knowledge of heat release and transfer for various moment of flame propagation [12] and necessary to provide the experimental input parameter for characterization of explosions propagating in chemical reactors, which is always cylindrical. The objective of this work is to study the explosion characteristics of the moist syngas. The experimental explosion pressure–time curves of $CO/H_2/air/H_2O$ mixtures were recorded over a wide range of hydrogen fractions and H_2O addition ratios at different temperatures. The explosion parameters such as explosion pressure, P_{max}, explosion time, t_c, maximum rate of pressure rise, $(dp/dt)_{max}$, and deflagration index, K_G, are obtained to evaluate the hazards of syngas explosion.

2. Experimental setup and procedures

The sketch of the experimental system is shown in Fig. 1. It consists of a cylindrical stainless steel combustion chamber, the heating system, the ignition system, and the data acquisition system. The inner diameter and length of the cylindrical chamber are 180 mm and 210 mm (L/D = 1.16). On the two sides of the combustion bomb, two pressure-resisting quartz windows with diameter of 80 mm are installed to allow the combustion process optically accessible. Two electrodes, located along a diameter of the circle, are mounted with the ignition electrodes to produce the spark ignition. Thus, ignition could be produced at the center of the chamber. The combustion bomb is wrapped by heating tapes to heat the mixture in the chamber and the temperature of gas in the chamber can be measured and monitored by a thermocouple with an uncertainty of ±3 K which was fixed in the inner wall of the chamber. In experiment, the combustion chamber was heated to a certain temperature and H_2O was firstly injected into the chamber via micro syringes. Then hydrogen, carbon monoxide, oxygen and nitrogen were sequentially introduced into the chamber to required partial pressures. Ten minutes were awaited to make sure attainment of quiescent condition and the complete mixing. Then mixtures were ignited and the explosion pressure evolutions were recorded by a pressure transducer (Kistler 7001) at a sample rate of 100 kHz, combined with a Charge Amplifier (Kistler 5011). After combustion, the combustion chamber was vacuumed and flushed with dry air to avoid the influence of residual gas. For each experimental condition, at least 3 times repeated tests were done to verify the repeatability and ensure the data accuracy.

In this study, air was substituted by a mixture with 79% N_2 and 21% O_2 by volume. Purities of hydrogen, carbon monoxide, oxygen and nitrogen were 99.995%, 99.9%, 99.995% and 99.995%, respectively. Initial temperatures were set as 373 K, 423 K and 473 K, considering the evaporation of H_2O. Equivalence ratio ranges from 0.6 to 2.5. H_2O addition ratios are 10%, 20% and 30%. Here, H_2O addition ratio is defined as $Z_{H_2O} = \frac{X_{H_2O}}{X_{H_2O}+X_{CO}+X_{H_2}}$. Here X refers to mole fraction of the specific species in mixtures.

For the explosion experiments, the important explosion parameters such as peak explosion pressure, P_{max}, explosion time, t_c, and maximum rate of pressure rise, $(dp/dt)_{max}$, can be derived directly from the explosion pressure evolutions recorded by a data acquisition system. Pressure oscillation due to the combustion in the closed chamber has a great influence on the pressure-time curve, a smoothing filter is needed to determine pressure-time curve and its derivative [8,19]. Fig. 2 shows the comparison between the raw data and the smoothed one which is accomplished by Savitzky–Golay method [20], using ORIGIN Software by applying a second order polynomial and 21 points data window. Pressure-time curve changes little after the smoothing process but the maximum rate of pressure rise, dp/dt changes greatly. The raw pressure rise so heavily scattered around the mean value and this smoothed pressure rise is usually used as an important parameter. As shown in Fig. 3, the explosion pressure is defined as the peak pressure during the explosion in a closed chamber [21]. Due to the heat loss caused by thermal conduction, convection, and radiation, the experimental explosion pressure measured in the confined vessel is significantly lower than the adiabatic equilibrium pressure, P_e, the maximum value that the system can thermodynamically achieve [22]. The explosion time, t_c, is the time interval between ignition and the moment at which the explosion pressure is attained [8,21]. Maximum rate of pressure rise, together with explosion pressure are the most important explosion parameters to evaluate the risk of combustion process in the vessel and to design the vent used as the relief device of enclosure against the damage from gaseous explosion [12]. In addition, it is very important for the storage of the fuel.

It should be noted that the explosion time, t_c, is the moment that when the heat release rate due to the combustion equals to the heat loss. For spherical flame, it indicates the moment when the combustion process is completed and the flame front stats to be in collision with the combustion chamber. Before this, the pressure continues to increase and the heat release rate is always larger than the heat radiation. For cylinder chamber, however, t_c is not associated to the moment when no extra fuel is left in the chamber [9,23]. The pressure increases with the propagation of the flame front and reaches the maximum value at the time between the flame front reaches the wall and the fuel is run out. The moment when the combustion process is completed in cylinder chamber is the time (t_d) when the pressure curve has its second inflection point and pressure rise, dp/dt, reaches its minimum value, as shown in Fig. 3.

The deflagration index, K_G, is an explosion severity factor and can be determined from the maximum rate of pressure rise during the combustion. It should be noted that definition of the deflagration index is not strictly limited to spherical chambers but the cylindrical ones with a low asymmetry ratio [11]. Since $(dp/dt)_{max}$ is expected to be very sensitive to the size of the vessel [17], K_G is often introduced to exclude the influence of the vessel according to the formula in the following [12,24,25],