



## Full Length Article

## Pressure history in the explosion of moist syngas/air mixtures



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## HIGHLIGHTS

- Effect of syngas composition on pressure development in syngas explosion is studied.
- Explosion parameters are obtained from the experiment and analyzed.
- H<sub>2</sub>O addition has different effects on the explosion parameters for syngas with various CO/H<sub>2</sub> ratios.
- The effect of heat loss on the explosion propagation of syngas/air mixtures is estimated.

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## ABSTRACT

The pressure history in the explosion syngas/air mixtures with H<sub>2</sub>O 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<sub>2</sub>O 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<sub>2</sub> 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<sub>2</sub> ratio. The experimental determined normalized explosion pressure decreases but normalized adiabatic explosion pressure increases with the increase of CO/H<sub>2</sub> ratio in the syngas mixture. This is mainly because the heat loss is larger for the mixture with a higher CO/H<sub>2</sub> 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.

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## 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<sub>2</sub> emissions if combined with CCS (Carbon Capture and Storage) technology. However, control of NO<sub>x</sub> emissions is still a big challenge in IGCC system and IC engine since NO<sub>x</sub> mainly comes from the high-temperature reaction of N<sub>2</sub> [3]. Previously published research showed that addition of H<sub>2</sub>O was an effective way to reduce the NO<sub>x</sub> 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

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due to the presence of H<sub>2</sub> and CO. Although the hazard of H<sub>2</sub> for gas leakage in the atmosphere is relatively lower than that of higher-order hydrocarbons because of the extraordinary buoyancy of H<sub>2</sub>, 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<sub>2</sub>O 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<sub>2</sub>/air/H<sub>2</sub>O mixtures were recorded over a wide range of hydrogen fractions and H<sub>2</sub>O 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  $\pm 3$  K which was fixed in the inner wall of the chamber. In experiment, the combustion chamber was heated to a certain temperature and H<sub>2</sub>O 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<sub>2</sub> and 21% O<sub>2</sub> 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<sub>2</sub>O. Equivalence ratio ranges from 0.6 to 2.5. H<sub>2</sub>O addition ratios are 10%, 20% and 30%. Here, H<sub>2</sub>O addition ratio is defined as  $Z_{\text{H}_2\text{O}} = \frac{X_{\text{H}_2\text{O}}}{X_{\text{H}_2\text{O}} + X_{\text{CO}} + X_{\text{H}_2}}$ . 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 starts 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],

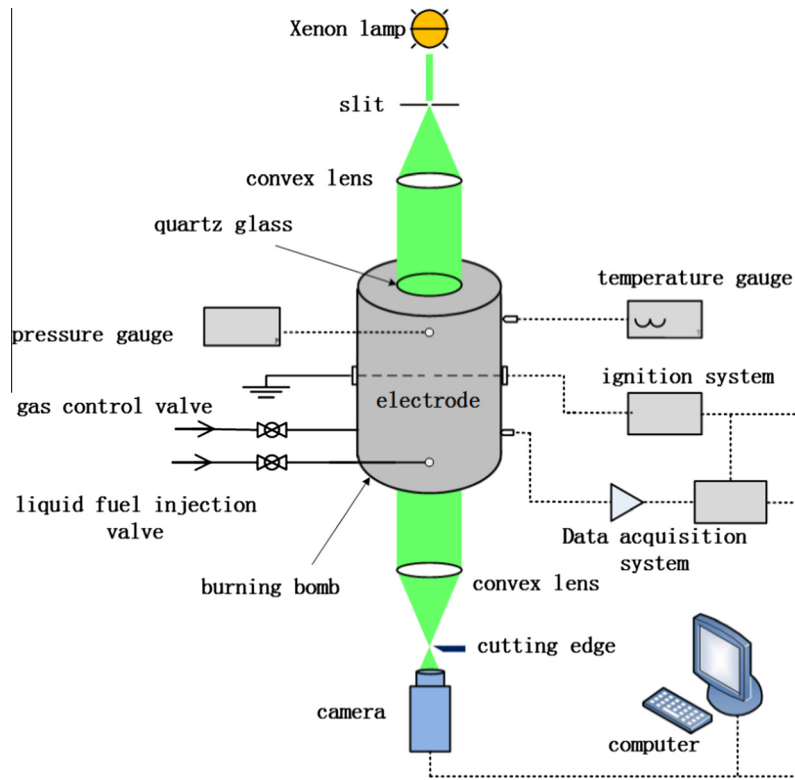


Fig. 1. Experimental apparatus.

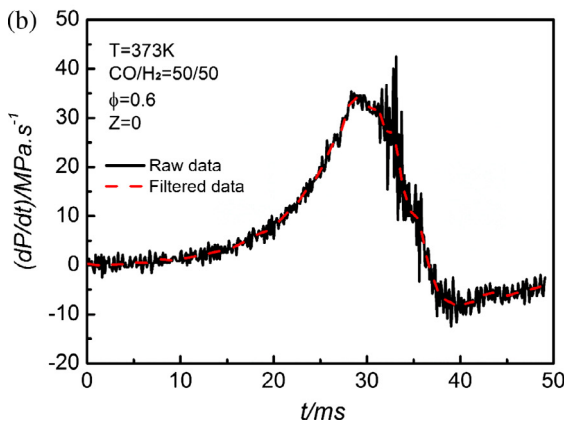
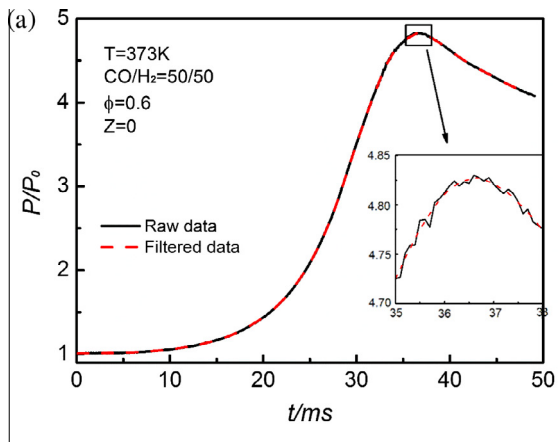


Fig. 2. An illustration of smoothing filter on the pressure-time curve and determination of the pressure rise.

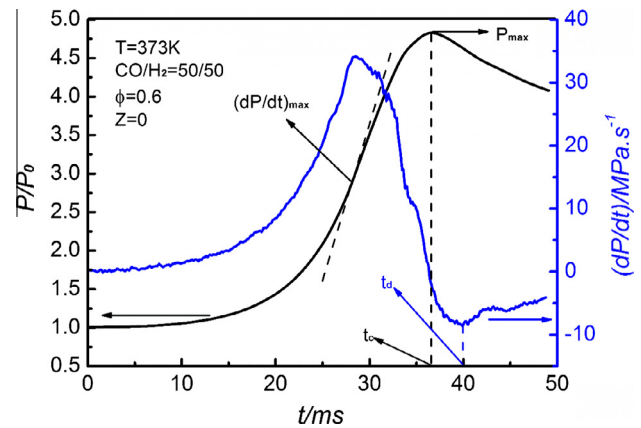


Fig. 3. Definition of the explosion parameters of the syngas/air mixtures.

$$K_G = \left( \frac{dp}{dt} \right)_{\max} V^{1/3} \quad (1)$$

The deflagration index,  $K_G$ , indicates the robustness of the explosion. If deflagration index is higher, the explosion will be more robust and consequences of the explosion will be more severe [24]. Since  $K_G$  is a constant regardless of vessel size and depends only on the combustible mixtures [8], it facilitates evaluating the explosions in such vessels for the practical purpose.

### 3. Results and discussions

The influence of equivalence ratio, syngas composition and initial temperature on pressure evolution is illustrated in Fig. 4. All pressures are normalized with respect to the initial pressure. For all pressure-time records during the explosion, the similar behav-

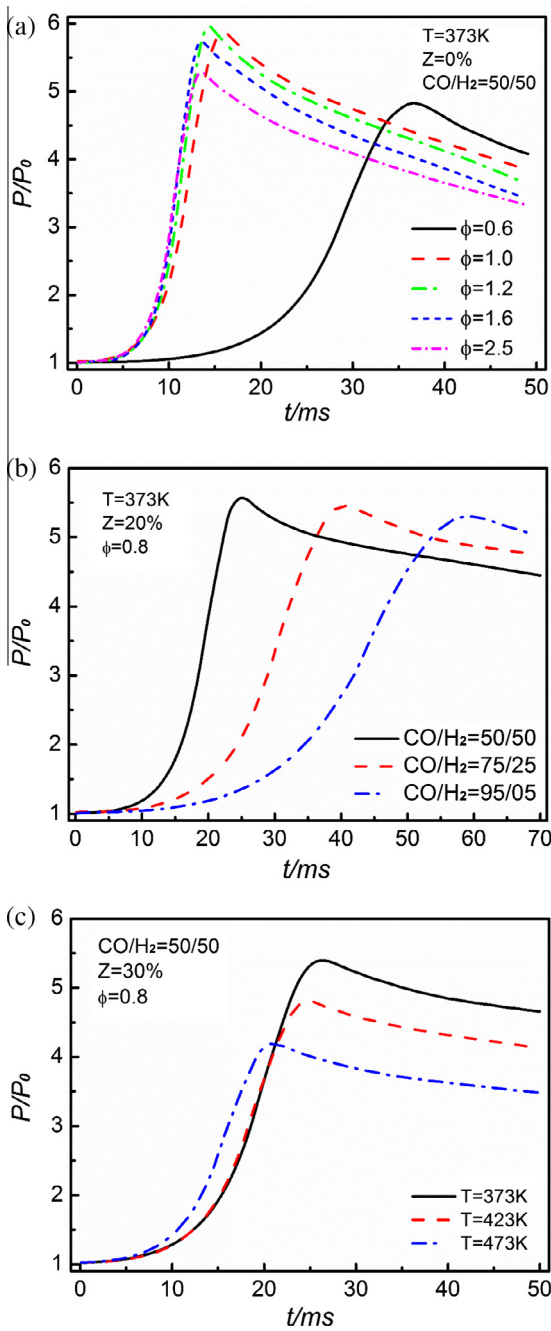


Fig. 4. Pressure evolution during explosions of CO/H<sub>2</sub>/air/H<sub>2</sub>O mixtures at various equivalence ratios, CO/H<sub>2</sub> ratios and temperatures.

ior could be observed. Upon the ignition of the mixtures, the pressure in the chamber increases gradually to its maximum value and then decreases due to heat loss. Fig. 4a gives the pressure-time curves of the syngas/air mixtures at different equivalence ratios. It is observed that the pressure-time curve of syngas/air mixtures is strongly affected by the equivalence ratio. Peak pressure increases to its maximum value and then decreases with the increase of equivalence ratio. For many hydrocarbons as well as H<sub>2</sub> and CO, the maximum value of the adiabatic flame temperature also occurs slightly on the rich side of the stoichiometric equivalence ratio [26]. This is mainly because the heat release reaches to its maximum value and this leads to a larger value of peak pressure at this equivalence ratio. As shown in Fig. 5, the adiabatic flame temperature, which is calculated with Davis mechanism

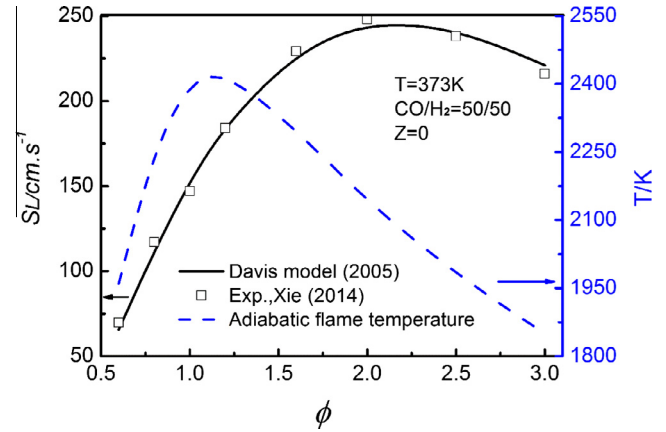


Fig. 5. Laminar flame speed and adiabatic flame temperature of CO/H<sub>2</sub>/air/H<sub>2</sub>O mixtures at various equivalence ratios.

[27] has the similar trend with the peak pressure and this indicates the correlation between them. In addition, the timing of the peak pressure decreases with the increase of equivalence ratio. Laminar flame speed increases with the increase of the equivalence ratio from 0.6 to 2.0. This indicates the dependence of the flame speed on the timing of the peak pressure. It is easy to understand since a higher burning velocity indicates that the mixture is exhausted more quickly and the timing of the peak pressure is shortened. Fig. 4b gives the pressure-time curves of the syngas/air mixtures at different CO/H<sub>2</sub> ratios. With the increase of CO/H<sub>2</sub> ratio, peak pressure changes slightly but the timing of the peak pressure increases greatly. The slight change in adiabatic flame temperature with the increase of CO fraction in syngas results in a slight change of the peak pressure. However, laminar burning velocity of syngas/air mixtures decreases greatly with the increase of CO/H<sub>2</sub> ratio [28], and the timing of the peak pressure is significantly increased. Fig. 4c shows the pressure-time curves of the syngas/air mixtures at different temperatures. Peak pressure is decreased with the increase of initial temperature and the same behavior also appears to the timing of the peak pressure. With the increase of initial temperature, laminar burning velocity of syngas/air mixture is increased and this leads to the decrease of the time to reach the peak pressure. In addition, mass of the combustible mixture in the chamber will be reduced when initial temperature increases and this leads to the decrease of peak pressure.

Fig. 6 presents the normalized explosion pressure,  $P_{max}/P_0$  of H<sub>2</sub>/air mixture at normal pressure. It is obvious that our experimental

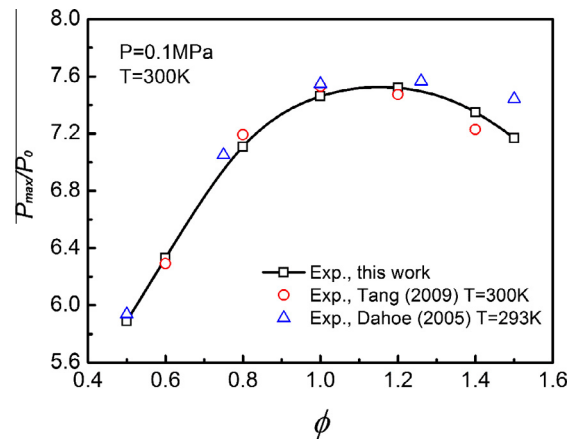


Fig. 6. Normalized explosion pressure,  $P_{max}/P_0$  of hydrogen/air mixtures.

data is lower than those of Dahoe [19], especially for the rich mixture. However, our results show good agreement with those of Tang et al. [22]. It should be noted that the experimental data strongly depends on the experimental setup [21] and Dahoe conducted the experiment with spherical chamber and we obtained the pressure data with the cylinder chamber, which is same with Tang et al. The comparison proves the accuracy the experimental setup and suitable for the study of the explosion of syngas. Fig. 7 illustrates the influence of equivalence ratio, CO/H<sub>2</sub> ratio, H<sub>2</sub>O addition and initial temperature on the normalized explosion pressure,  $P_{\max}/P_0$  and the normalized adiabatic explosion pressure,  $P_e/P_0$ . The adiabatic equilibrium pressure,  $P_e$ , can be calculated using EQUIL [29], assuming the flame propagation is a constant-volume and adiabatic process. For conducting the quantitative analysis on experimental phenomenon, the equation below will be used to calculate the adiabatic explosion pressure,

$$P_e = P_0 \frac{T_e}{T_0} \frac{n_e}{n_0} \quad (2)$$

$P_e$  and  $T_e$  indicates the adiabatic explosion pressure and flame temperature, separately.  $n_e$  and  $n_0$  indicates the number of molecules. It should be noted that the experimental explosion pressure  $P_{\max}$  is not only determined by adiabatic explosion pressure, but also the heat loss. Due to the heat loss to the combustion chamber, the experimental determined peak explosion pressure will be lower than the adiabatic explosion pressure. The discrepancy between them could be used to estimate the heat loss. Fig. 7a and b present that the normalized explosion pressure,  $P_{\max}/P_0$  and the normalized adiabatic explosion pressure  $P_e/P_0$  both reach its maximum at equivalence ratio around  $\phi = 1.1$ , regardless of CO/H<sub>2</sub> and H<sub>2</sub>O

addition ratio. The adiabatic flame temperature of the syngas/air mixtures also reaches to its maximum value at this equivalence ratio, as shown in Fig. 5. Chemical reactions between CO, H<sub>2</sub> and O<sub>2</sub> will decrease the number of molecules in the chamber and this decreasing effect will be enhanced by the equivalence ratio. This reflects the dominating effect of adiabatic flame temperature on the pressure evolution. Fig. 7b and c give the normalized explosion pressure,  $P_{\max}/P_0$ , it decreases with the increase of CO/H<sub>2</sub> ratio. However, it is noteworthy that the experimental determined normalized explosion pressure  $P_{\max}/P_0$  and the normalized adiabatic explosion pressure  $P_e/P_0$  show different trends with the increase of CO/H<sub>2</sub> ratio. Theoretically, the volumetric calorific value of H<sub>2</sub> is smaller than that of CO and the heat release and adiabatic flame temperature increase slightly with the increase of CO/H<sub>2</sub> ratio. The number of molecules in the chamber will not change with the increase of CO/H<sub>2</sub> ratio. Thus the normalized adiabatic explosion pressure  $P_e/P_0$  increases with the increase of CO/H<sub>2</sub> ratio in the syngas mixture. However, the laminar burning velocity of syngas mixture is decreased with the increase of CO/H<sub>2</sub> ratio [3]. Thus the combustion duration in the vessel is extended and heat loss transferred to the wall of the chamber is reduced greatly. In addition, CO<sub>2</sub>, the combustion product of CO has a stronger radiation effect than H<sub>2</sub>O. This results in the opposite effect of CO/H<sub>2</sub> ratio on the experimental determined normalized explosion pressure  $P_{\max}/P_0$  and the normalized adiabatic explosion pressure  $P_e/P_0$ . Fig. 7 shows that H<sub>2</sub>O addition lowers the normalized explosion pressure,  $P_{\max}/P_0$  and the normalized adiabatic explosion pressure  $P_e/P_0$  at different equivalence ratios, CO/H<sub>2</sub> ratios and temperatures. With H<sub>2</sub>O addition, the total heating value of the mixture remains unchanging but heat release and final adiabatic flame temperature are

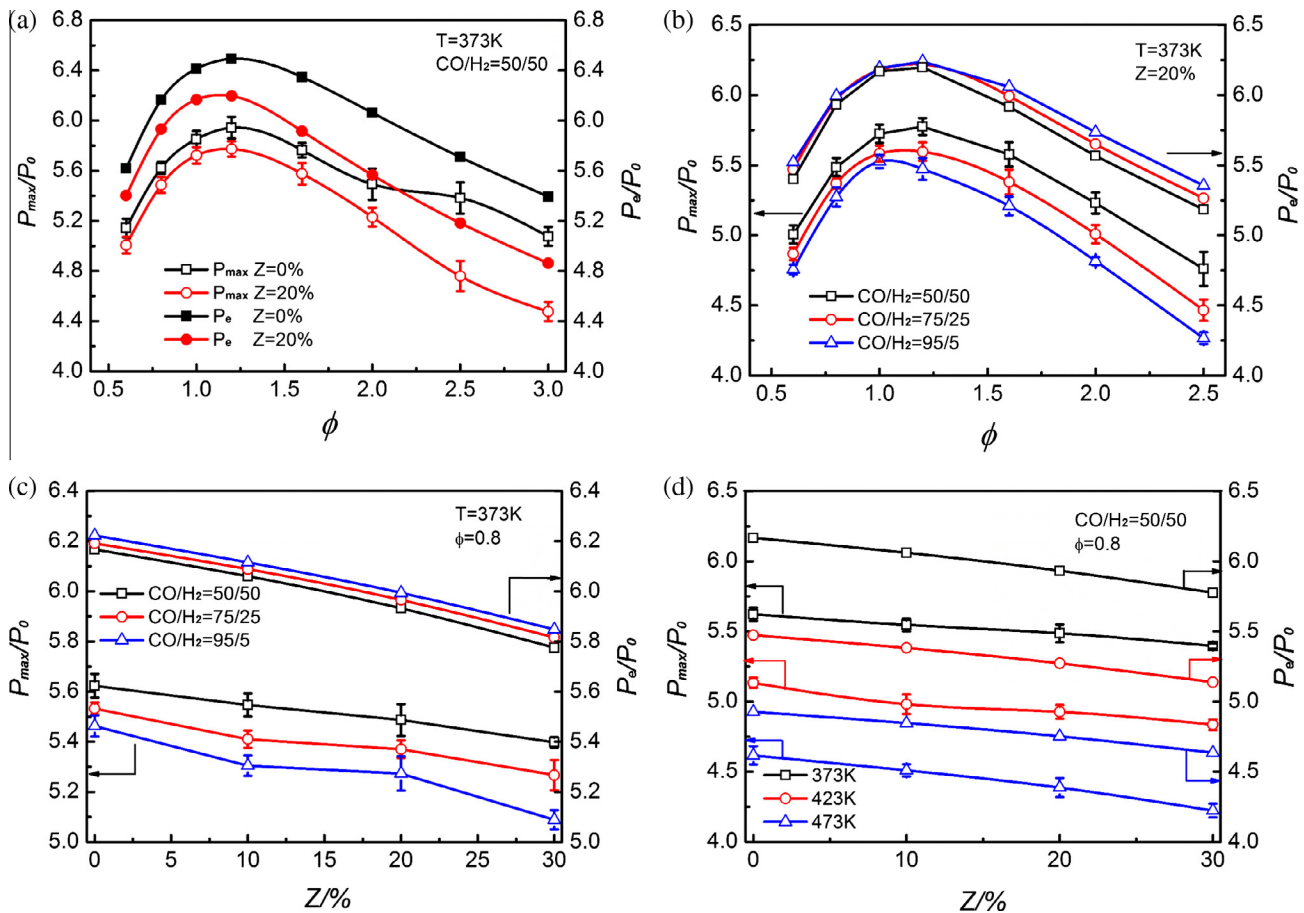


Fig. 7. Normalized explosion pressure,  $P_{\max}/P_0$  and normalized adiabatic explosion pressure,  $P_e/P_0$  under different initial conditions.

decreased. What is more, the addition of H<sub>2</sub>O will not change the number of molecules in the burned mixture. This results in a decrease of the normalized adiabatic explosion pressure. In addition, an increase in initial temperature decreases the normalized explosion pressure and normalized adiabatic explosion pressure as shown in Fig. 7d. Though the adiabatic flame temperature is increased with the increase of initial temperature, it should be noted that a higher initial temperature leads to a lower density of the mixture and hence the decrease of amount of unburned mixture in the combustion bomb. The ratio of the adiabatic flame temperature and initial temperature decreases and the increase of initial temperature will not change the number of molecules in the burned mixture. Thus, heat release and explosion pressure are decreased.

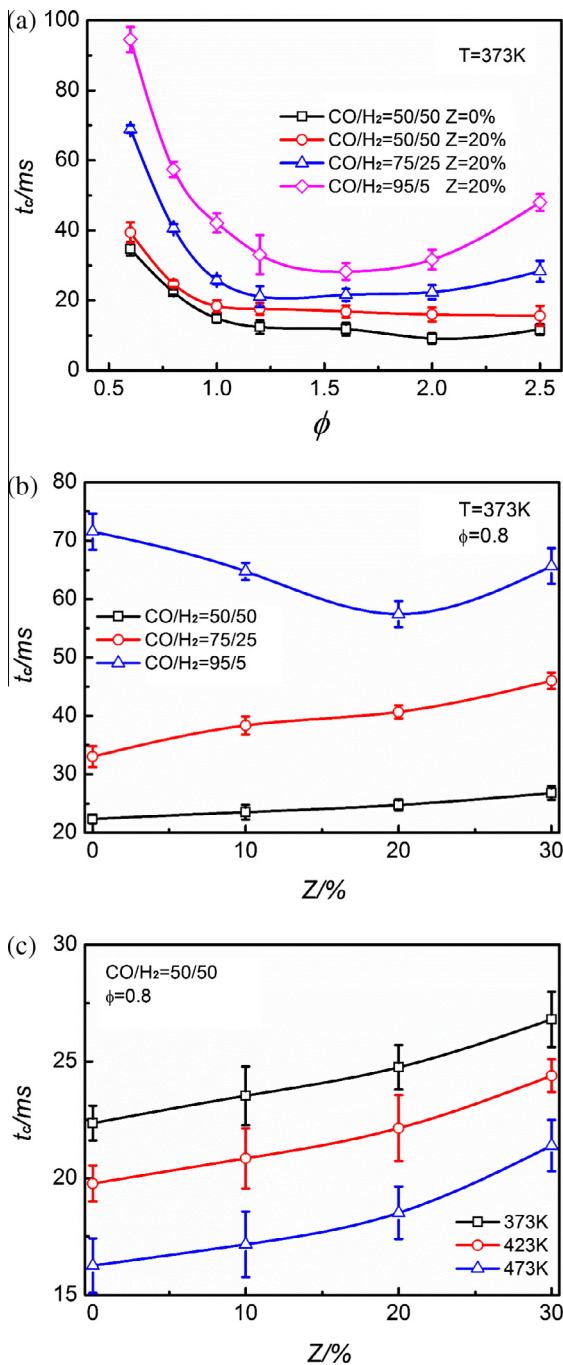


Fig. 8. Explosion time,  $t_c$ , under different initial conditions.

Fig. 8 gives the explosion time,  $t_c$ , at different equivalence ratios, CO/H<sub>2</sub> ratios, H<sub>2</sub>O additions and initial temperatures. The explosion time,  $t_c$ , which is strongly related with the moment when the maximum explosion pressure is attained, is also very important for the design of safety devices and ensuring the active protection of pressure vessels [30]. Fig. 8a illustrates the explosion time,  $t_c$  decreases until it reaches its minimum and then increases with the increase of equivalence ratio and this equivalence ratio at which the minimum explosion time occurs is between 1.6 and 2.0 under different conditions. The similar phenomenon also occurs at the equivalence ratio where laminar burning velocity reaches its maximum [3]. This is because the maximum laminar burning velocity of pure hydrogen [31] and pure CO with small traces of H<sub>2</sub> or moisture [32] occurs at  $\phi = 1.8$  and 2.6, respectively. In addition, the addition of H<sub>2</sub>O will lead to the equivalence ratio of maximum laminar burning velocity shifts towards the small value [3]. In the practical combustion chamber, the timing of peak pressure always occurs at the moment before the combustible mixture is depleted. At this timing, heat release rate is just equal to the heat loss rate by the thermal conduction, convection, and radiation. Thus, there exists a strong positive correlation between explosion time,  $t_c$ , and laminar burning velocity. A higher laminar burning velocity implies that the quick consumption of the combustible mixture and shorter explosion time. As shown in Fig. 8b, the explosion time,  $t_c$ , is decreased with the increase of initial temperature. This is mainly because of the higher laminar burning velocity at higher initial temperature. Fig. 8c illustrates the influence of H<sub>2</sub>O addition on the explosion time,  $t_c$ . It is obvious that the effect of H<sub>2</sub>O addition on the explosion time of syngas presents different trends at different CO/H<sub>2</sub> ratios. Explosion time increases monotonously with the increase of H<sub>2</sub>O addition ratio for the syngas with CO/H<sub>2</sub> ratio of 50/50 and 75/25. However, in the case of CO/H<sub>2</sub> ratio of 95/5, explosion time increases with the increase of H<sub>2</sub>O addition ratio and then decreases. This phenomenon can be explained by the competitiveness between thermal effect and chemical effect of H<sub>2</sub>O addition [32,33]. For the syngas with CO/H<sub>2</sub> ratio of 95/5, different from N<sub>2</sub> and CO<sub>2</sub>, H<sub>2</sub>O directly participates in and promotes the chemical reaction of syngas/air combustion. Meanwhile, the existence of H<sub>2</sub>O dilutes the flammable mixture and has a negative thermal effect on the chemical reaction. This leads to the non-monotonic behavior of laminar burning velocity and explosion time under this condition. In addition, explosion time increases remarkably with the increase of CO/H<sub>2</sub> ratio in the mixture.

Fig. 9 gives the maximum rate of pressure rise,  $(dp/dt)_{\max}$ , and the deflagration index,  $K_G$ , at different equivalence ratios, CO/H<sub>2</sub> ratios, H<sub>2</sub>O additions and initial temperatures. In all cases, the deflagration index,  $K_G$ , is smaller than 30 MPa m s<sup>-1</sup> and this indicates that syngas with CO/H<sub>2</sub> ratio larger than 50/50 is within a relatively safe level [8]. As shown in Fig. 9a, both maximum rate of pressure rise,  $(dp/dt)_{\max}$ , and deflagration index,  $K_G$ , reach their maximum at the equivalence ratio of 1.6 for the syngas with different CO/H<sub>2</sub> and dilution ratios. According to Bradley et al. [17,34] and Dahoe et al. [35], the rate of pressure rise and maximum deflagration index,  $K_{\max}$  in a confined vessel are closely correlated to the laminar burning velocity and the explosion pressure,

$$\frac{dp}{dt} = \frac{3S_u \rho_u}{R \rho_0} (p_e - p_0) \left[ 1 - \left( \frac{p_0}{p} \right)^{1/\gamma} \frac{p_e - p}{p_e - p_0} \right]^{2/3} \quad (3)$$

$$K_{\max} = (36\pi)^{1/3} (p_e - p_0) \left( \frac{p_0}{p} \right)^{1/\gamma} S_u \quad (4)$$

where  $S_u$  is laminar burning velocity,  $\rho_u$  and  $\rho_0$  are the densities of unburned and burned mixtures, respectively.  $p$ ,  $p_e$  and  $p_0$  are the real pressure, the adiabatic equilibrium pressure and initial pressure, respectively.  $\gamma$  is the adiabatic coefficient of burned mixtures.

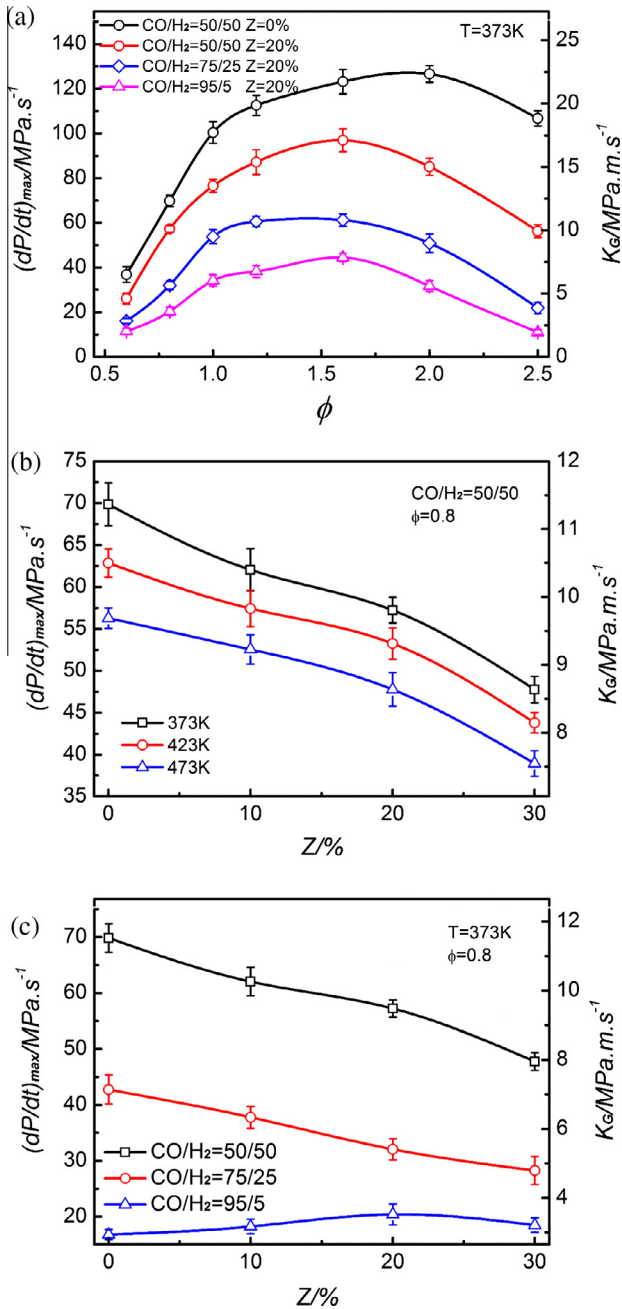


Fig. 9. Maximum rate of pressure rise,  $(dp/dt)_{max}$ , and deflagration index,  $K_G$ , under different initial conditions.

According to the equations the phenomenon about the maximum rate of pressure rise,  $(dp/dt)_{max}$ , can be explained by the explosion pressure and laminar burning velocity. Fig. 9b shows that both the maximum rate of pressure rise,  $(dp/dt)_{max}$ , and the deflagration index,  $K_G$ , decrease slightly with the increase of initial temperature. Increase in initial temperature increases the laminar burning velocity and shortens the explosion process, but the explosion pressure decreases greatly with the increase of initial temperature as shown in Fig. 7. Fig. 9c demonstrates that the effect of  $H_2O$  addition on the maximum rate of pressure rise,  $(dp/dt)_{max}$ , and the deflagration index,  $K_G$ , presents different trends at different  $CO/H_2$  ratios. For  $CO/H_2$  ratios of 50/50 and 75/25, both  $(dp/dt)_{max}$  and  $K_G$  decrease monotonously with the increase of  $H_2O$  addition ratio. For  $CO/H_2$  ratio of 95/5,  $(dp/dt)_{max}$  and  $K_G$  increase and then decrease with  $H_2O$  addition. This similar phenomenon was also reported in the

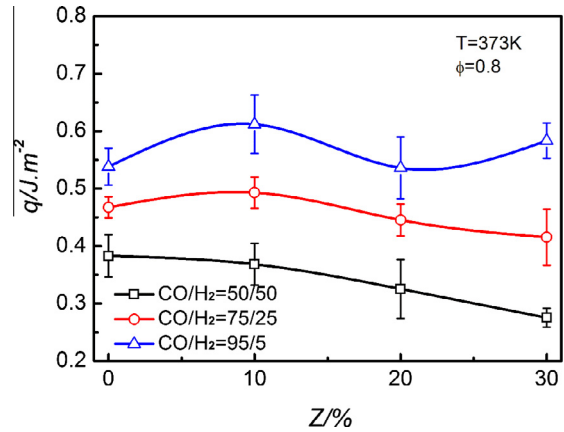


Fig. 10. Heat transferred to the unit area of walls during explosions of syngas under different conditions.

laminar burning velocity [33]. In addition, the explosion pressure and adiabatic flame temperature decrease linearly with the addition of  $H_2O$  in all cases, because of the change of thermo-physical properties of the flammable mixture. Experimental results indicate that the laminar burning velocity, rather than the explosion pressure, has more dominant effect on the change of  $(dp/dt)_{max}$  when  $H_2O$  is added into the mixture.

Fig. 10 calculates the effects of  $H_2O$  addition on the heat transferred to the wall of the chamber for the explosion propagation of syngas with various  $CO/H_2$  ratios. This calculation assists in the understanding of the difference of explosion parameters on actual combustors with the adiabatic ones and are very important for the design of the combustion devices. The heat loss can be estimated by the difference between the internal energy of burned mixtures in an adiabatic combustion chamber and that in an actual one in which energy loss can occur through the wall of the chamber. The heat loss was calculated with equations [9],

$$Q = mc_v(T_{max,ad} - T_{max,real}) \quad (5)$$

This equation could also be rewritten as,

$$q = \frac{V}{S} \frac{1}{\gamma - 1} (P_e - P_{max}) \quad (6)$$

where  $m$  and  $c_v$  are the mass and the average heat capacity of burned mixtures, respectively.  $T_{max,ad}$  and  $T_{max,real}$  are the maximum temperature of adiabatic condition and real condition.  $q$  is the heat loss of unit area of wall.  $P_e$  and  $P_{max}$  are the adiabatic equilibrium pressure and experimentally determined maximum explosion pressure.  $S$  is the surface of the closed vessel and  $V$  is the volume.  $\gamma$  is the adiabatic coefficient of the burned mixtures. Heat loss in the present work is estimated with Eq. (6) and the experimentally determined explosion pressure  $P_{max}$ . Fig. 10 indicates that the heat loss to the unit area increases greatly with the increase  $CO/H_2$  ratio. This could help to explain the phenomenon that  $P_{max}$  and  $P_e$  have different trend with the addition of  $CO$  in the mixture. What is more, heat loss is decreased with  $H_2O$  addition for the syngas mixture with  $CO/H_2$  ratios of 50/50 and 75/25 and changes little for mixture with  $CO/H_2$  ratios of 95/5.

#### 4. Conclusions

Explosion characteristics of syngas/air mixtures at different  $CO/H_2$  ratios and  $H_2O$  addition ratios were investigated at elevated temperatures using the outwardly spherical propagating flame. Main conclusions are summarized as following:

1. The experimentally determined explosion pressure, explosion time, maximum rate of pressure rise and deflagration index at different conditions are provided. Effects of the equivalence ratio, initial temperature, CO/H<sub>2</sub> 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.
2. The experimentally determined normalized explosion pressure  $P_{\max}/P_0$  and the normalized adiabatic explosion pressure  $P_e/P_0$  show different trends with the increase of CO/H<sub>2</sub> ratio. The experimental determined normalized explosion pressure  $P_{\max}/P_0$  decreases but normalized adiabatic explosion pressure  $P_e/P_0$  increases with the increase of CO/H<sub>2</sub> ratio in the syngas mixture. This is mainly due to the larger heat loss for the mixture with a higher CO/H<sub>2</sub> ratio.
3. 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.

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