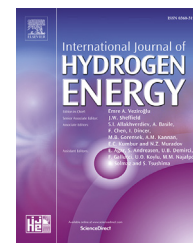


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Influence of hydrocarbon additions and dilutions on explosion behavior of syngas/air mixtures

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ABSTRACT

In this study, explosion behaviors of hydrocarbon-added and diluted syngas/air mixtures were investigated experimentally in a constant volume combustion chamber. Hydrocarbons such as methane and propane, and diluents, such as helium and nitrogen, were added to a syngas/air mixture to evaluate the effects of hydrocarbon and dilution on the explosion characteristics of flames. The results showed that for hydrocarbon additions, both the maximum explosion pressure and the explosion time increased linearly with the hydrocarbon concentration, while the maximum rate of pressure rise decreased non-linearly, which can be correlated to an exponential equation. It was observed that propane had a stronger effect on reducing the pressure rise rate than methane did. With dilutions, the maximum explosion pressure decreased linearly and the explosion time increased linearly, so the pressure rise rate was significantly reduced. An exponential correlation of pressure rise rate and dilution ratio was observed. Of the two diluents tested, nitrogen showed a stronger effect in reducing the pressure rise rate compared to helium. This indicated that the explosion hazard can be reduced by adding hydrocarbon or dilution to lower the pressure rise rate of syngas/air flame.

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Introduction

The world's primary energy source is conventional fossil fuels—oil, natural gas and coal—which are depleting, limited and unsustainable in the long term; therefore it is necessary to find alternatives to replace fossil fuels and reduce the

greenhouse effect. Due to its many significant advantages as a fuel in stationary power generation [1–3], syngas is a candidate among the alternatives being explored for energy conversion. Formed through a gasification process of coal, biomass, organic wastes and refinery residual, syngas primarily contains hydrogen and carbon monoxide. It may also include nitrogen, carbon dioxide, water, methane and other

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higher-order hydrocarbons [4–7]; its specific composition depends on the fuel source and processing technique.

Among the combustion characteristics being investigated, pressure rise during combustion in a closed system is one of the most important phenomena. In an explosion of a fuel/air mixture in a closed system, caused by high and rapidly rising pressure soon after ignition, the system could be damaged without proper venting or an explosion suppressing device [8–12]. It is necessary to understand the explosion behavior of the fuel in order to design efficient combustion devices, predict operation and emission of combustion systems and clarify safety issues for transportation, storage and fuel use, and to effectively utilize syngas.

The maximum rate of pressure rise during explosion in a closed chamber, $(dP/dt)_{\max}$, is defined as the highest value of pressure rise rate observed at a given fuel concentration under specific initial temperature and pressure conditions [13]. Because $(dP/dt)_{\max}$ depends on the size of the chamber, it is often normalized with respect to the chamber volume, V , according to the cubic root law [14–17],

$$K_G = (dP/dt)_{\max} \times V^{1/3} \quad (1)$$

Here, K_G is an explosion severity factor, the so-called deflagration index, used to evaluate the explosive consequence of a mixture [15]. It is assumed that K_G is a constant value, regardless of the chamber volume, depending only on mixture properties (mixture composition, initial pressure and initial temperature) [15,17]. Other fundamental phenomena which must be evaluated are maximum explosion pressure, P_{\max} (the highest pressure reached during the explosion at a given mixture property) and explosion time t_c , defined as the time interval between ignition and the moment maximum explosion pressure is reached.

Many studies related to explosion characteristics of different hydrocarbon/air mixtures have been investigated [16–33]. It was reported that explosion pressures changed with fuel concentration and reached maximum value at equivalence ratio $\phi = 1.1$ – 1.4 [16,26,28,29]; and the effects of initial pressure and temperature on explosion have been reported [17,26,28,30–32]. Maximum explosion pressure reportedly increased linearly with the initial pressure of fuel–air mixtures [26,28,31,32], while P_{\max} decreased slightly with increasing initial temperature [17,28,30,32]. However, it was observed that during simulation the linear relationship between $(dP/dt)_{\max}$ and initial pressure was not accurate for methane fuel, but instead, the simulated rate of pressure rise was proportional to the initial pressure to the power of 0.7 [17]. The explosion behavior of blends of alkanes with other fuels, such as hydrogen [17,22,23,33] and dimethyl ether [20] have been examined, and for a methane/hydrogen blend the deflagration index increased only slightly with the addition of hydrogen when its volumetric percentage in the mixture was less than 0.7. With a volumetric percentage of hydrogen higher than 0.7, K_G increased exponentially with the hydrogen blending level [17,22], due to the fact that K_G is strongly influenced by the laminar flame speed, which also increases slightly with a small hydrogen addition; but the laminar flame speed increases strongly with a large addition of hydrogen [34–36]. It was reported that P_{\max} and $(dP/dt)_{\max}$ increased with greater dimethyl ether content in the fuel blend [20].

The effects of ignition location and obstacles [9,10,12,16,25], water addition [37,38] and dilution [31,39–41] on the explosion of mixtures have also been discussed and it has been noted that the position of the ignition significantly affected P_{\max} and K_G of a mixture [16,25]. Compared to central ignition, the pressure reached maximum at a lower value, and a slower pressure rise rate occurred for top ignition, because of greater heat loss to the chamber wall and a reducing flame front area, which lowered laminar flame speed when the mixture was ignited at the side of the chamber [16]. It was reported that P_{\max} and K_G increased with the presence of obstacles in the chamber [25]. The severity of a fuel explosion can be drastically reduced [38] by lowering the heat release, leading to a reduction of adiabatic flame temperature with the addition of water. Dilution decreases the hazard potential of an explosion [31,39–41] because of decreased laminar flame speed [42]; and dust and exhaust gas can also be a diluent for mitigating fuel/air explosions [43–47].

The effects of chamber shape (spherical and cylindrical) on explosion have also been reported [16,41]. Because a flame is propagated spherically after ignition [5,42,48], using a spherical chamber causes the unburned mixture to be completely consumed; therefore the rate of rising pressure in the spherical chamber is much higher than in a cylindrical chamber [16,41]. Explosions of various liquid fuels and their blends have been examined, proving that the explosion behavior of liquid fuels is similar to alkane fuels [30,49,50]. The explosion characteristics of hydrogen [17,23,24,33,40,51], propylene [16,47], liquefied petroleum gas [46,52], dimethyl ether [53], epoxypropane [54], and ethylene [29,31,55] have also been investigated.

Recently, the influence of added H_2O on the explosion of syngas/air mixtures was studied experimentally [38]. Moreover, the explosion limits of $H_2/CO/O_2$ mixtures were analyzed computationally and theoretically, showing that limits changed dramatically with even a small amount of added hydrogen [56]. However, data on explosions of syngas/air mixtures with addition of hydrocarbon fuels and/or diluents are still scarce. In this regard, the objective of this study is to investigate the influence of hydrocarbon (methane and propane) additions and dilutions (nitrogen and helium) on the explosion characteristics of syngas/air premixed flames.

Experimental apparatus and setup

The experimental apparatus consisted of a constant volume cylindrical combustion chamber (CVCC), flow controllers, a pressure transducer, a pressure transmitter and an ignition system, as shown schematically in Fig. 1.

The CVCC, made from stainless steel, had an inner diameter of 200 mm and a length of 220 mm, and hence a volume of 6.91 L. Two tungsten electrodes, having a diameter of 0.5 mm, were connected to a high voltage source (8–10 kV) to ignite the combustible mixture at the center of the chamber. The electrodes were movable so that the spark gap was manually adjustable. A larger gap was used to ignite mixtures with small laminar burning velocities that require relatively large ignition energy, and vice versa. The reactant mixtures in the closed chamber were prepared by supplying individual component

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