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Effectiveness of diluent gases on hydrogen flame propagation in tee pipe (part II) – Influence of tee junction position

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HIGHLIGHTS

- The flame flow mechanism inside the symmetric and asymmetric tee pipe configurations.
- Effects of ignition position on flame acceleration of fuels.
- Dynamic of flame acceleration of hydrogen-inhibitors/air mixtures.
- Influence of obstacle location on flame development of hydrogen-inhibitors/air mixtures.

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ABSTRACT

Gas explosions in obstructed vessels have been investigated for many years. However, the flame acceleration mechanism of enriched-hydrogen fuels with diluents in the piping system has received little systematic study in the literature. This particular study aimed to analyse the flame front mechanism of hydrogen-diluents/air explosion inside the pipe by considering the influence of tee junction distance from the ignition points. The tests were performed using H_2/diluents-air at different concentrations and ignition positions, in two different tee junction pipe configurations. From the results, the worst case of explosion severity was found in 95% H_2–2.5% Ar–2.5% N_2/air for all ignition positions. In general, if ignition happened at the tee junction, the overpressure and rate of pressure rise profiles showed almost a similar trend on both configurations. Similar trend was also observed for the flame flow characteristic analysis. Overall, it was clearly demonstrated that a shorter distance between ignition point and obstacles resulted in higher explosion severity.

1. Introduction

Nowadays, the need for energy is soaring significantly in respect of conventional energies. Amongst all sources of energy, hydrogen is promising for the future due to its cleanliness, efficiency and renewable capability, while it is appropriate to characterize the combustion behaviour of hydrogen-air mixtures for the purpose of both safety and engineering applications of combustion [1]. However, incidents involving hydrogen fuels and pipeline explosions resulting in injuries, fatalities, destruction of equipment and downtime remain a significant problem in the process industry. As a consequence, there is a need in numerous synthetic procedures for assurance against proliferation of undesirable ignition marvels, for example, deflagration to detonation (DDT) in process equipment or piping and vent complex systems [2]. Among all precaution methods, inerting system has been considered as a suitable and reliable method for reducing the probability of flammable material combustion, especially hydrocarbon components, by using a chemically non-reactive gases (diluents) such as nitrogen, argon and carbon dioxide [3]. However, as far as authors' knowledge, only scarce and limited data available in literature on the effect of diluents on hydrogen explosion behaviour for different systems.

For instance, Kwon and Faeth [4] investigated the effects of N_2, Ar or He on the laminar burning velocities of H_2-O_2 flames, both experimentally and by computer modelling. Their results indicated

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that flames with corresponding Markstein numbers, in the range between ±3 and −7, were very sensitive to flame-stretching and, thus, exhibited ratios of unstretched to stretched laminar burning velocities in the range between 0.6 and 3.0. Moreover, Sabard et al. [5] showed that initial pressure and temperature, as well as initial nitrogen concentration, were in direct proportion to overpressure and laminar flame speed ratios of the H_2-O_2-N_2 mixture in the International Thermonuclear Experimental Reactor (ITER). On the other hand, an investigation into the H_2-O_2-N_2-CO_2 mixture showed that the effectiveness of CO_2 on burning velocity of this particular mixture is mainly based on kinetic mechanism [6]. A study of explosion behaviours of the H_2-O_2-N_2-CO_2 mixture found a significant stability in terms of the flame and, apparently, no ignition where there was a presence of CO_2 higher than 40% at normal temperature and pressure conditions [6]. Moreover, CO_2 has been shown to have a significant radiation and dilution effect on quenching and blow-off limits, respectively [7]. Based on authors' observation from the study, we reported that the blending of two diluents gave a lower severity to all investigated compositions of hydrogen/air mixtures containing CO_2 as compared to pure hydrogen/air mixtures [8].

Studies on flame propagation and blast components in pipes have been broadly examined and reported [9–15], yet, a large portion of theses are focused only on particular applications i.e., different diameter, effect of obstacles, bending pipes or straight pipes. Hence, comprehensive studies ought to be performed on flame propagation in various pipe designs that consider the unpredictable issues required in the interaction between fluid dynamics, heat transfer and turbulent combustion. Explosions in pipes and ducts, flame acceleration and the transition from DDT are well-researched subjects [16]. However, research in this area tends to concentrate on the effects of baffle-type obstacles or items in the path of the flow [17].

Pure gas explosions in obstructed vessels have been investigated for many years. Ibrahim and Masri [17] showed that the presence of obstacles in a cylinder, with both ends open, increases the flame speed to about 24 times higher than those without obstacles. The results in a small square cross-section combustion chamber also demonstrated that the explosion overpressure increased in line with the increasing blockage ratio and amongst all applied obstacles, with the square obstacle resulting in the highest overpressure and the circular obstacle yielding the lowest overpressure [17]. Recently, more experiments have been performed in small chambers [17–20] and in long closed pipes [10,21–23]. From the reported results, it has been agreed that, when the flame passes through obstacles, the rate of pressure rises and the flame speed increases due to the turbulence generation and the flame structure's irregularity.

Tube bends, for example, are obstacles used extensively in industrial applications. Little is known, however, about their effects on flame acceleration, overpressure enhancement and their contribution to DDT, thereby resulting in a complex problem involving the interaction between fluid dynamics, heat transfers and turbulent burning. Phylaktou et al. [15] reported that, with a short tube, a 90-degree bend could enhance both flame speed and overpressure for methane–air explosions, giving a factor of approximately five, which was equal to the effects of a baffle with a blockage ratio of 20% in a similar position. Observations of the flame front when travelling through a rectangular 90-degree bend were made by Zhou et al. [24]. They showed that, after initially propagating as a flat flame, the flame front took on a tulip configuration [25]. As the flame reached the bend, the upper tongue (the one propagating towards the outside of the bend) of the tulip began to slow down, whereas the lower tongue (the one propagating towards the inside of the bend) started to propagate more quickly around the inside of the bend, which is an effect named "flame shedding". The 3-D particle modelling of the flow around the bend showed that large vortices were created just downstream of the inside wall of the bend, while flow outside of the bend showed a more streamlined pattern. Lohrer et al. [26] demonstrated that a bend induced a significant increase in turbulence within the first 30% of the inner diameter of the pipe immediately after the bend, whereas only a relatively small amount of turbulence was induced around the outer side [11].

By reviewing the previous research studies, some questions have not been answered: (1) What would happen on flame acceleration if the diluent gases are added into hydrogen? (2) Do the diluent gases significantly reduce the explosion severity of hydrogen as much as hydrocarbon fuels?. Our previous investigation into the effectiveness of argon, nitrogen and carbon dioxide on hydrogen/air flame acceleration in an asymmetric tee pipe configuration showed the strong influence of ignition position and initial fuel composition on overpressure, flame speed and the rate of pressure rise [8]. From this study, it was found that, if the ignition point were closed to an obstacle (in this case, a tee point), this would immediately trigger the transition of the flames that had been deformed into detonation mode. However, when the ignition was initiated about two times further away from the obstacle, the recorded maximum overpressure and flame speed were caused by a strong interaction of a reflective wave at the end pipe. Considering the peculiar behaviour of enriched hydrogen/air mixture at the presence of diluent gases, particularly argon and nitrogen, at each ignition position in our previous work [8], a comprehensive analyse on the flame flow mechanism of hydrogen-diluents/air explosion inside the symmetric and asymmetric tee pipe configurations were applied in the current study. Due to the undeniable effects of ignition position on flame acceleration of fuels, the presence of ignition at the obstacle area (tee point) was also explored.

2. Methodology

The symmetric and asymmetric tee pipes rig configuration used in this study consisted of a 4.32 m horizontal length with 1.375 m on the junction length and a 0.1 m diameter (see Fig. 1). The pipes were included different sectors (ranging from 0.5 to 1 m in length), fastened together with a gasket seal in the middle of the connections and with blind flanges at ends. The flammable mixture was initiated by an electrical spark, which gave 16 J in energy at three ignition positions, C, E and F, for the gas explosion tests. It should be noted that ignition positions at A, B and D had been investigated in our previous study [8].

Type-k thermocouples were positioned along the centre line of the pipe to record the flame speed. It was logged from thermocouple flame arrival times (set apart as an unexpected change in the thermocouple yield). The thermocouple flame arrival time in the pipe was taken to be the main time when the perusing began to rise. The thermocouples were delayed by a pre-pressure wave in front of the flame and the associated high flow velocity around the thermocouple, giving rise to two different gradients on the thermocouple trace. Therefore, the latter (steeper) gradient got to be outward was taken as the flame arrival time. An array of piezoresistive pressure transducers was used within the pipe to monitor pressure at points around the outer wall in every segment, showed as P in Fig. 1. All data were gathered with a 34-channel transient data recorder (made by NI Compact DAQ). The ignition and sensor positions are presented in Table 1.

H_2-Ar/air, H_2-CO_2/air, H_2-N_2/air, H_2-Ar-CO_2/air, H_2-Ar-N_2/air and H_2-N_2-CO_2/air mixtures with a constant ratio (95:5 = H_2:diluents) were applied at a stoichiometric equivalence ratio ($\phi = 1$) by considering hydrogen as the primary gas. Meanwhile, the partial pressure technique was engaged for fuel-air blends arrange-