Detonation of Hydrogen in a Partially Filled Interconnecting Vessel Following an Initial Period of Pressure Piling

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Introduction

The diffusivity properties of hydrogen have long been in contention regarding its ability to be stored safely and carried as a fuel. A common risk and observed problem comes from the possibility of leakage through improperly sealed flanges, openings or cracked pipes. This can be a problem even if detected early due to the wide flammability limits of hydrogen in air. In this paper, the dangers of even a small such leak becoming premixed is illustrated on a medium scale vessel where mixtures well below stoichiometric levels can produce detonation events in localised areas.

Interconnected or linked geometries are commonplace in a wide range of situations including reactor vessels, aircraft fuel tanks and even adjacent rooms or buildings connected by a corridor. In many situations, connected chambers house or carry hazardous materials such as hydrogen, which is an area which has attracted a great deal of interest from research regarding fully filled geometries (Phylaktou and Andrews, 1993; Maremonti, 1999; Razus, 2003; Singh, 1994). However, what has been little researched is the possibility of a leak being created in one chamber of an interconnected system and it is this area, which is to be addressed here.

Previous work focusing upon a fully filled geometry has shown that interconnected vessels display a phenomenon referred to as pressure piling, causing faster rates of pressure rise and maximum pressure in the second vessel when compared to an isolated vessel of the same size (Razus *et al*, 2003). Most literature reports a more severe explosion in the second vessel (Phylaktou and Andrews, 1993; Singh, 1994) and not as this research will show, in the ignition vessel. Other problems which can occur include the deflagration to detonation transition (DDT); this is a common occurrence in reactive systems such as hydrogen air mixtures (Bjerketvedt *et al*, 1997) and a very real risk.

The aim of the current work is to present a case where both of these mechanisms are occurring simultaneously, the pressure piling driving a detonation back in the test vessel long after the flame has entered the dump vessel and increasing the detonation peak pressure in accordance. This is a problem inherent in hydrogen-air mixtures providing both a case for the safety of storing hydrogen as a fuel under appropriate conditions, but also demonstrates the immense power which can be generated using the correct conditions increasing the attraction for hydrogen as a fuel.

Experimental Procedure

Figure 1 shows the schematic of the rig used, consisting of a cylindrical driver vessel (length (L)=0.5m, diameter (D)=0.5m), connected to a dump vessel (L=2.0m, D=0.5m) through a connecting pipe (L=1.0m, D=0.162m), a total volume of approximately $0.5m^3$ (see figure 1). The test vessel was independently pressure rated to 28bara (maximum 40bara). Measurements of flame-speed were made using an array of thermocouples along the centre-line of the entire vessel. Pressure measurements were taken in the test vessel, connecting pipe and dump vessel using piezoresistive pressure transducers and a 34 channel transient data recorder was used to collate the data generated.

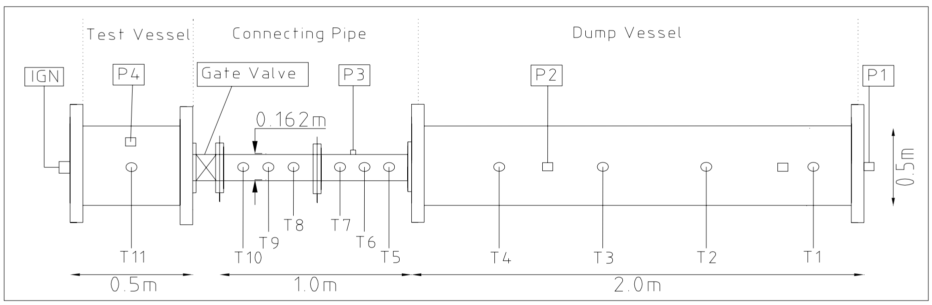

Figure 1. Vessel geometry.

Homogeneous hydrogen/air mixtures in the range 10% to 22% were prepared using the partial pressure method in the test vessel (smaller) only. Isolation of the test vessel from the rest of the rig was achieved using a 0.162m diameter gate valve positioned at the entrance to the connecting pipe. Pressures of the two separated areas were balanced to standard atmospheric pressure (approx 1013mbar) before ignition. The mixture was ignited immediately following the opening of the gate valve using a standard 16J combustion engine spark plug, positioned at the centre of the end flange of the test vessel, directly opposite the entrance to the connecting pipe. Repeatability was confirmed by conducting between 3 and 6 rests at each concentration.

Recent Experimental Progress

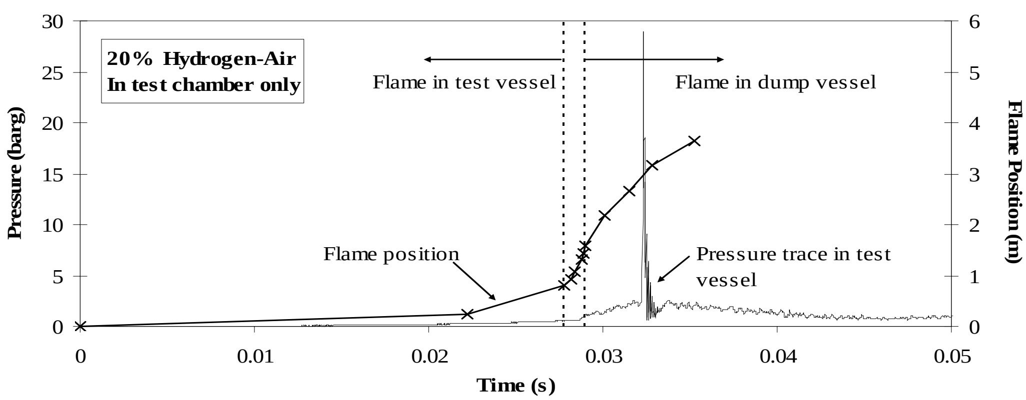

Figure 2. Detonation pressure in test chamber compared with respective flame position.

Analysis of this results gained from this research indicates that the pressure piling effect is present in this vessel even though initially it was only partially filled with the mixture. For example, the 10% H_2 concentration in the isolated chamber equates to a 1.9% if the same fuel volume were to be distributed throughout the whole vessel (outside the flammability range of hydrogen). Pressures traces from the leaner concentrations (10%, 12% and 14%) demonstrate maximum pressures in the second vessel, and also the flow interaction between the test vessel and the dump vessel were in concordance with that reported in literature for fully filled vessels (Phylaktou and Andrews, 1993; Razus *et al*, 2003).

As the concentration increases above this, a localized detonation mechanism is displayed. Between 18 and 22%, this configuration is providing flame-speeds and pressures synonymous with detonation (ranges of 17-36 bara and 900-1494 m/s for pressure and flame-speed respectively). Similar pressure traces to that shown in figure 2 are present at 16% however; the maximum is closer to 6 bara and flame-speeds indicating a fast deflagration are indicated. Pressure results from this test series indicate that there is an initial period of pressure piling present in this vessel, which appears to increase the maximum achievable detonation peak, occurring locally in the test chamber only. Pressure traces for the rest of the vessel remain relatively even indicating that the explosion is transmitting as a deflagration beyond the test chamber. Figure 2 displays a pressure trace obtained from the test vessel using 20% hydrogen/air (the trace is typical for concentrations above 16%). The flame position history indicates that the flame has passed through the connecting pipe (displayed as the area between the two dotted lines) and is approximately half way along the dump vessel when the detonation peak appears in the originating chamber. Flow analysis indicates that an oscillating flow is not set up here beyond the initial stages of the explosion, contributing to the initial pressure rise. Bjerketvedt *et al*, 1997 reported detonation pressures of typically 15-20 bar, however, at an elevated initial pressure (provided here by the pressure piling effect) this can effectively increase this expected maximum pressure, which as shown in Figure 2 seems to be the case.

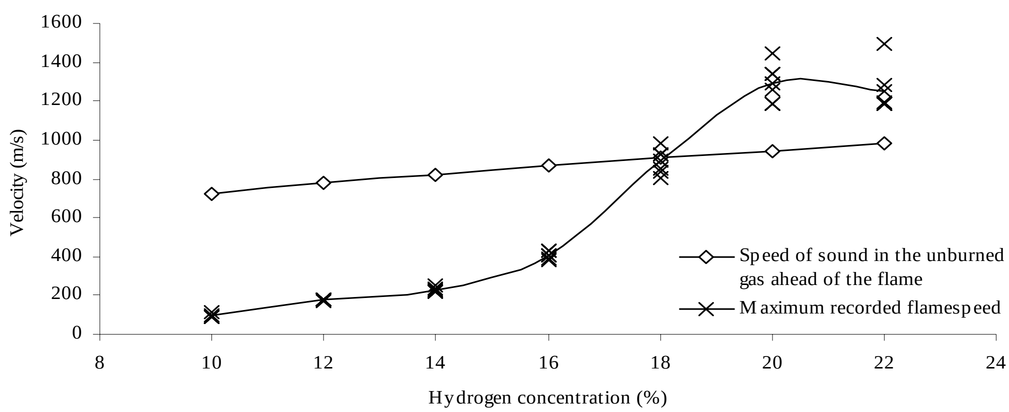

Figure 3. Maximum recorded flame-speed as a function of concentration.

Figure 3 shows the maximum flame-speed detected in the vessel, in each case this occurred at the last point in the connecting pipe (measured between T6 and T5). For lean concentration, flame-speed is generally quite consistent, providing low velocities through the vessel. For the higher concentrations investigated, the spread was much greater (see figure 3). There appears to be a direct relationship between the maximum pressure obtained at detonation and the maximum flame-speed recorded at this point at the end of the connecting pipe. These faster speeds are not only a function of concentration, but also of turbulence in the pipe created initially in the early stages of the explosion where the unburned gases are being pushed very rapidly ahead of the flame front.

Flame-speed measurements from this test series reinforce what is being shown in the pressure data; figure 3 shows an average flame-speed through the data points for each concentration (averaged over between 3 and 6 tests for each). An approximation for the speed of sound in the combustion products of hydrogen air mixtures ahead of the flame at the investigated concentrations has been obtained using GASEQ (assuming adiabatic combustion in a constant volume). Results indicate that at concentrations of 18% and above, detonations are present.

Conclusion

The results have shown the potential destructive severity of a partially filled interconnected vessel. At low hydrogen concentrations, the mechanisms involved are comparable to those reported in literature for fully filled vessels, and at higher concentrations, the detonation mechanism is displayed. The implications that stem from this research are that an ordinarily non-flammable H_2-air mixture when concentrated in a single chamber of a system, or even a gas pocket, within an interconnected vessel geometry, can produce overpressures sufficient to cause destruction to buildings and non-pressure rated equipment. It is also apparent that in a closed interconnected vessel environment, it is possible for the most severe damage to be caused back in the chamber of origin, and not necessarily always in the second or third vessel, and often after the initial flame-front has passed into the second vessel.

References

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