ACCEPtANCE CRITERION FOR HYDROGEN MANAGEMENT IN NUCLEAR REACTOR CONTAINMENT

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INTRODUCTION

During the recent accident at Fukushima, the release of hydrogen and its subsequent ignition in one of the reactors substantially damaged the reactor systems and the surrounding containment structure. In most of the nuclear reactors, under postulated Design Basis Accidents (DBAs)/ Beyond Design Basis Accidents (BDBAs), large amounts of hydrogen may be produced in the core due to zirconium-steam reaction. Hydrogen generated in the core will be released into the containment which is generally a concrete structure that separates the nuclear core from the surrounding atmosphere. As hydrogen is a highly flammable gas, any small ignition source is sufficient to cause a global deflagration which will lead to significant pressure rise in the containment. For a safe reactor operation, it is imperative to maintain the post deflagration pressures to within the design limit of the containment. In this study, a CFD based methodology has been presented to predict the pressure rise caused due to deflagration for dry hydrogen air mixtures. A systematic parametric study has been conducted to evaluate the impact of initial conditions such as hydrogen mol fraction and initial temperature in the containment. Based on the results obtained, a new acceptance criterion for the limiting hydrogen mol fraction has been proposed. Such a criterion can be used in conjunction with various hydrogen management schemes to limit the hydrogen concentration to within the specified limit during accident scenarios.

METHODOLOGY

Combustion is described by solving a transport equation for the reaction progress variable, c. A value of zero for c corresponds to unburned mixture and a value of one corresponds to completely burned mixture. The heat released due to chemical reactions is imbibed in the source term for the reaction progress transport equations which is modelled using the Weller combustion model and Zimont turbulent flame speed closure [1]. In the low Mach number limit such as a deflagration, the reaction progress variable corresponds to the reduced temperature and fuel species mass fraction across the flame. The open source C++ library OpenFOAM [2] has been utilized as the CFD framework. The model has been run in the constant volume and adiabatic mode to be consistent with the non-moving walls of a representative reactor containment. The parameters considered are the initial hydrogen mol fraction (varied in the range of 6% to 15%) and the initial temperature (20°C and 180°C). Hydrogen mol fractions higher than 15% typically result in a transition from deflagration to detonation and such effects are not captured within the present modeling approach. Therefore the studies have been limited to hydrogen mol fractions less than 15%.

RESULTS AND DISCUSSION

Figure 1a shows a variation of the pressure magnification (ratio of final pressure to initial pressure) with hydrogen mol fraction at two different initial temperatures. As the hydrogen mol fraction increases, a larger amount of chemical energy is released on oxidation with air thereby leading to a higher pressure rise. Also, at a given hydrogen mol fraction, a higher initial temperature leads to a lower pressure magnification. This is consistent with a constant volume adiabatic heat release process where pressure and temperature are inversely proportional. Finally, it can be observed that the pressure magnification drops linearly with hydrogen mol fraction up to 7% after which the drop is much steeper. This ultimately leads to a nearly identical pressure magnification factors of 2.10 at 293K and 2.11 at 453K at the hydrogen mol fraction of 6% as shown in the boxed region. Further insight can be drawn by observing the trends in the Extent of Combustion (EoC). In CFD, the EoC has been calculated as the volume weighted average of the progress variable and represents the fraction of hydrogen which has burnt. Figure 1b shows a variation of EoC at the same initial temperatures considered previously. Clearly, as the hydrogen mol fraction is increased, the EoC tends to unity indicating complete combustion. Also, a higher initial temperature leads to a higher extent of combustion. However, irrespective of the initial temperature of the mixture, a hydrogen mol fraction of 9.5% leads to an EoC of ~97% (nearly complete combustion).
Figures 1a and 1b bring about the relative importance of two opposing effects. At the lower initial temperature of 293K, pressure magnification decreases as the hydrogen mol fraction decreases. At a higher initial temperature of 453K, similar trend is observed but the rate of decrease of pressure magnification with mol fraction is lower. Therefore, a balance between the hydrogen mol fraction, EoC and the initial temperature establishes the final pressure magnification. This balance is better represented in Figure 2 which shows the pressure-temperature region for different hydrogen mol fractions.

Figure 2 indicates that for mol fractions higher than 6%, a decrease in the initial temperature leads to an increase in the pressure magnification. However, at 6% the pressure magnification becomes independent of the initial temperature in the domain. Thus a balance between the opposing effects of EoC and initial temperature is attained at a mol fraction of 6%. Yielding to the fact that 6% hydrogen mol fraction leads to the lowest pressure magnification of about 2 and it also independent of the initial temperature in the domain, we recommend that the limiting hydrogen concentration should correspond to ~6% of mol fraction. This criterion is more conservative than the international regulatory requirement of ~10%.

CONCLUSIONS

An open source CFD methodology has been implemented to predict deflagration pressure rise in hydrogen air environment. The effects of initial conditions in the mixture have been clearly highlighted. Considering the combined effect of all the factors, a criterion of maintaining the hydrogen mol fraction to ~6% has been proposed.

REFERENCES