EXPERIMENTAL INVESTIGATION ON HELIUM JET RELEASE AND DISTRIBUTION IN A VENTED CYLINDRICAL ENCLOSURE – EFFECT OF WALL TEMPERATURE CONDITIONS

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ABSTRACT

Hydrogen generated during core meltdown accidents in nuclear reactors can cause serious threat to the structural integrity of the containment and safe operation of nuclear power plants. The study of hydrogen release and mixing within the containments is an important area of safety research as hydrogen released during such accidents in nuclear power plants can lead to hydrogen explosions and catastrophic consequences. A small scale experimental setup called the AERB-IIT Madras Hydrogen Mixing Studies (AIHMS) facility is setup at IIT Madras to study the distribution of hydrogen subsequent to release as a jet followed by its response to various wall thermal conditions. The present paper gives details of the design, fabrication and instrumentation of the AIHMS facility and a comparison of features of the facility with respect to other facilities existing for hydrogen mitigation studies. Then it gives details of the experiments conducted and the results of the preliminary experiments on concentration build-up as a result of injection of gases (air and helium) and effect of thermally induced natural convection on gas mixing performed in this experimental facility.

1. INTRODUCTION

All types of thermal nuclear reactors like boiling water reactors (BWR), pressurised water reactors (PWR) and pressurised heavy water reactors (PHWR) are prone to hydrogen generation during accident situations like Loss of Coolant accident (LOCA). The failure of mitigating systems such as the emergency core cooling systems can lead to overheating of the reactor core. Prolonged over heating of the reactor core can lead to core degradation, rupture of the fuel sheath and release of fission products. The loss of water due to blow down and boiling leads to rise in fuel sheath temperature, dryout and oxidation by steam to form large quantities of hydrogen within a short period of time. The exothermic zircolay oxidation reaction that leads to a runaway reaction releasing large quantities of hydrogen is given in Eqn. 1. A summary of the reaction rates for this reaction is given by Atomic Energy Regulatory Board (AERB) [1].

$$Zr(s) + 2H_2O(g) \rightarrow ZrO_2(s) + 2H_2(g) + 586.6 \text{ kJ/mole}$$
 (1)

The huge quantities of hydrogen released into the reactor containment following an accident situation can lead to hydrogen deflagration or detonation in the containment and the resulting pressure rise can cause serious threat to the structural integrity of the containment. The distribution of the released hydrogen depends on the prevailing flow and thermal conditions in the confined spaces within chambers of the containment.

Numerous experimental and numerical studies have been conducted subsequent to Three Miles Island Unit-2 accident to study the behaviour of hydrogen gas inside confined and unconfined spaces following unintended releases. These studies include those carried out within integral large scale facilities like the HDR containment (used to analyse large and small break LOCA experiments [2]) to small scale experimental facilities like GADIFFAN [3]. HYJET experimental program in BMC facility [4] investigated hydrogen mixing with air under different inlet conditions. Distributions of hydrogen in multi-compartment enclosures were carried out in experimental facilities like HEDL [5], SNU mixing chamber [6] and PANDA facility [7]. Experimental programs in single compartment

enclosures like the TOSQAN and MISTRA facilities and multi-compartmental enclosures like the ThAI facility were aimed to qualify various heat and mass transfer models in multidimensional CFD codes [8–10]. These three facilities were used for analysis of the capabilities of codes to predict gas distribution in small enclosures and the experimental data has been used for international benchmark problems like ISP-47 [11]. A detailed review of such experimental and numerical programs and the related heat and mass transfer issues were presented by Agrawal et al. [3]. The phenomenologies of hydrogen distribution were discussed and the gap areas in the study of hydrogen distribution in the nuclear reactor containment were identified. In order to address these issues in progressive manner, a small scale test facility named AIHMS (AERB-IIT Madras Hydrogen Mixing Studies) has been erected and commissioned at the Indian Institute of Technology Madras, Tamil Nadu, India.

In the present paper, three phenomena that influence hydrogen distribution, namely, jet induced mixing, natural convection and molecular diffusion are considered. During the release phase, jet induced mixing is very important. In the post-release phase, the effect of jet progressively decreases and the effect of natural convection and molecular diffusion become important. Thus, in the present paper, helium release as an isothermal jet is considered. After the release is over, different thermal conditions are considered and experimental studies are carried out on the effect of wall temperature on the rate of helium mixing within the AIHMS test chamber and the results obtained are presented.

2. EXPERIMENTAL STUDY

2.1 AIHMS test facility

The AIHMS test facility consists of (a) a cylindrical test chamber; (b) a steam generator unit; (c) a helium gas supply unit; (d) constant temperature bath; (e) process control unit; and (f) a data acquisition unit. The schematic layout and components of the test facility are shown in Fig. 1.



Figure 1. Layout and components of AIHMS test facility.

The test enclosure of AIHMS is a vertical cylindrical stainless steel vessel of volume 2 m³ and is made up of five modular shells connected by flanges. There are three independent condensing sections at the top of the enclosure followed by one non-condensing injection section and condensate sump. Aluminium walled water jackets are used as the inner walls of the three independent condensing sections and are circulated with coolant water from a thermostatic wall temperature control unit and a constant temperature bath unit so as to maintain a well controlled wall boundary condition. The outer walls of the condensers are insulated with 30 mm thick synthetic foam to avoid heat loss and to fill the dead volume behind the condensers. Special windows are provided in the shells to provide access to concentration and temperature measurement units.

The internal diameter of enclosure (aluminium water jacket) is 1m and an overall height is 2.75 m. A photograph of the test enclosure installed at Heat Transfer and Thermal Power Laboratory, IIT Madras is shown in Fig. 2(a). Due to safety reasons helium is used as an inert surrogate for hydrogen in the experiment. The test enclosure is equipped with a dedicated mixing and injection arrangement for helium and steam release at different locations at vertical and horizontal orientations. The condensate formed will be collected in the bottom condensate sump and its quantity will be measured continuously. The modular construction enables parametric studies on hydrogen distribution and generation of large amount of experimental data.

The measurements provided at AIHMS are for pressure, temperature, gas composition, velocities, and condensate formation. The gas and condenser wall temperatures are monitored using calibrated thermocouples and resistance thermometric devices respectively. Local helium concentration is measured using thermal conductivity based helium concentration sensors located at seven places (H1-H7) as shown in Fig. 2(b) and Fig. 3. H1 is placed close to the jet exit so as to get the helium injection profile. H1, H2 and H6 are aligned with the centreline of the jet so as to measure the decay of helium concentration on the centreline of the jet. Sensors H4 and H5 were placed diametrically opposite on the plane of symmetry so as to confirm the axisymmetric nature of jet flow inside the test enclosure. H3, H4 and H5 lie in the recirculation zone of the jet and H7 is located below the point of injection.



Figure 2. (a) Photograph of AIHMS test enclosure and (b) Distribution of helium sensors.

Figure 3. Coordinates and locations of helium sensors inside AIHMS test enclosure.

2.2 Present study

The present study is aimed to understand the effect of wall thermal conditions on the mixing of light gas inside a confined enclosure. Non-isothermal condition leads to natural convection flow that can alter the flow patterns and influence the rate of mixing within the enclosure. Helium is released into the AIHMS test enclosure through a nozzle of 17 mm diameter as a round buoyant jet. The jet exit is placed at an axial location of 1.5 m from the ceiling and 1.25 m from the bottom cover of the enclosure. The helium release rate is kept constant at 7 LPM and the release time is kept as 857 s. The release duration is chosen such that the volume of helium released is 5% of the enclosure volume. The jet exit Reynolds number is around 100 and since the nozzle was located at the end of a long pipe (l/d \sim 120), the flow was fully developed. The system is isothermal at ambient temperature (\sim 37 °C) and helium is also released isothermally. After the end of release, the wall temperature is controlled by circulating water from the constant temperature bath at 10 LPM through the aluminium water jackets.

Three cases are considered as given in Table 1. In Case 1, the wall is at ambient temperature (\sim 37 °C). This acts as a control for the remaining two cases. In Case 2, chilled water at 27 °C is circulated after the end of helium release so that the wall temperature is slowly reduced to set value and in Case 3 heated water at 42 °C is circulated after the end of helium release so that the wall temperature is slowly increased to set value.

Table 1. Details of parameters for present study
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	Jet exit diameter	He release time	Wall temperature set
Case 1			NIL (Ambient temperature)
Case 2	17 mm	857 s	27 °C
Case 3			42 °C

3. RESULTS AND DISCUSSIONS

3.1 Helium dispersion and concentration build up under isothermal conditions

In Case 1, there is isothermal injection of helium into an air filled enclosure. The jet moves up due to combined effects of jet momentum and buoyancy. As it moves up, it spreads and entrains the gas mixture present in the vicinity. After hitting the ceiling the jet stagnates, spreads horizontally and moves down along the side walls.

The helium concentration build-up at the sensor locations H1, H2, H3, H4, H6 and H7 are shown in Fig. 4. Sensors H1, H2 and H6 are placed along the centreline of the test enclosure. It can be seen that as the jet progresses upwards there is significant reduction in concentration along the axial direction. Just after the beginning of release, the helium mole fraction at H1 is 57%. The helium mole fraction steadily increases at H2 and then at H3 and H4 showing that a stratified layer of helium is getting formed in the enclosure. By the end of release, the upper half of the test chamber is filled with helium air mixture with helium mole fraction nearly equal to 5%. The concentration values of H2, H3 and H4 reaches a maximum value at the end of helium release and then decreases gradually as the system tries to achieve uniform concentration by molecular diffusion as strong concentration gradient exits.

The sensor H7 is positioned 110 mm below the level of jet exit. It may be seen that there is practically no helium at this point during the release duration. Some helium concentration is detected only after 600 s. This is because, the downward moving gas mixture near the wall is sucked towards the centre due to the jet and the gas mixture is not able to easily move below the level of injection. After the release is stopped, helium starts moving below the level of jet release due to convection and diffusion.

Figure 4. Time history plots of helium concentration for Case 1.

In order to confirm the axisymmetric nature of the jet flow inside the test enclosure sensors H4 and H5 are positioned diametrically opposite locations at the same distance from the jet exit. The variation in helium volume fraction with time for sensors H4 and H5 are shown in Fig. 5. It may be observed that the concentration data from sensors H4 and H5 are identical. This clearly establishes that the jet flow follows an axisymmetric behaviour. This information is helpful because it enables one to analyze the problem using a two dimensional axisymmetric CFD model.

Figure 5. Time evolution of helium concentration at H4 and H5 for Case 1.

3.2 Helium dispersion and concentration build up under non-isothermal conditions

The time evolution of average wall temperature and the centreline gas temperature are shown in Fig. 6. For Case 2, the wall temperature is reduced from 37 °C to around 27 °C by circulating water from the constant temperature bath. The circulation of water starts at the end of the injection phase and the average wall temperature drops to ~ 27 °C in about 350 s causing a reduction in the centreline temperature as well but at a slower rate. At about 1500 s, the temperature profiles are observed as seen in Fig. 6(a). For Case 3, where wall heating is considered, the average wall temperature increases from 37 °C to 42 °C approx. and this result in the rise in gas temperatures as shown in Fig. 6(b). A small drop in the centreline gas temperature in the injection phase can be observed in all the cases as the temperature drops due to the gas expanding and spreading from the jet exit.

Figure 6. Time evolution of average wall temperature and centreline gas temperature for (a) Case 2 and (b) Case 3

Case 1 is considered as the base case for the analysis of thermally induced mixing for the three cases considered in the present study. The concentration values are normalised using V_{max} which is the volume fraction of helium measured at the particular sensor location at the end of helium release in Case 1. Time is normalised using the total helium release time (857 s). Fig. 7 shows the time evolution of normalised helium concentration for the cases considered in comparison with the base case (Case 1) where no thermal effects were considered. For Case 1, the concentration increases steadily as the

helium releases progresses and reaches a maximum at the end of injection and then diffuses down with time It can be clearly seen for Figs. 7 (a), (b) and (c) that when thermal effects are included, the evolution of helium volume fraction profiles at the three locations are similar.

Figure 6. Normalized time evolution of helium concentration at different locations (a) H2, (b) H3, (c) H4 and (d) H7.

For Case 2, the concentration of helium decreases rapidly after end of release because of the convection currents generated due to lowering of wall temperature. These convection currents enhance mixing and drag the helium towards the bottom region of the enclosure thereby reducing the concentration to 60% of that of Case 1. The effects of downward convection can also be confirmed by the steep rise in concentration at H7. The concentration at H7 keeps on increasing as time progresses until a uniform concentration of 3% is reached throughout the test enclosure as shown in Fig. 7(d). Thus for Case 2, thermally induced convection currents enhances mixing and help attainment of uniform conditions.

For Case 3, where the wall temperature is increased, the convection currents near the wall are towards the ceiling of the enclosure and this is against the concentration gradient prevailing inside the enclosure as a result of helium stratification. Towards the beginning of heating the concentrations above the level of jet exit is slightly increased and as the hot gases push the helium upwards. Later, as time progresses the concentrations are reduced at a faster rate than Case 1 but very similar trends as Case 1 as shown in Figs. 7 (a), (b) and (c). Sensor H7 also shows concentrations similar to Case 1 but at a slightly higher rate as shown in Fig. 7(d).

4. CONCLUSIONS

In the present paper, experimental studies on the effects of wall temperature induced natural convection on the mixing and distribution of helium inside the AIHMS enclosure has been presented.

The results show that even though the same amount of hydrogen is released into the enclosure, the distribution depends on the prevailing thermal and flow conditions inside the enclosure. A certain rate of mixing is attained because of the jet induced mixing. This rate can be enhanced if the walls are at different temperature as compared to the gas mixture in the enclosure. It was seen that when the wall temperature is less than the gas temperature in the enclosure, the convection currents drags the helium from the upper regions of the enclosure to the helium deficient lower regions and enhance the rate of mixing. When the wall temperature is more than the gas temperature in the enclosure, the wall temperature induced convection is in direction opposite to diffusion. The rate of mixing is only marginally enhanced when the walls are hotter than the gas in the enclosure.

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