Thermal Hydraulic Investigation of Sodium Fire and Hydrogen Production in Top Shield Enclosure of an FBR Following a Core Disruptive Accident

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Abstract.

During a Core Disruptive Accident (CDA), primary sodium from hot pool is expelled into the top enclosure, which is vented to reactor containment building (RCB). Sodium coming in contact with oxygen and moisture undergoes combustion and forms sodium oxide / sodium peroxide and hydrogen, releasing large amount of heat.

Sodium combustion in the enclosure has been analyzed using an in-house developed code. The rate of reaction is taken as a function of oxygen and moisture content in the air. Relative amounts of sodium reacting with moisture and oxygen are calculated based on its availability and stoichiometry. Energy conservation equation is solved to find out temperature of air and structural materials inside the enclosure. Due to high temperature during the reaction, natural circulation of air takes place and the flow rate is calculated by solving momentum equation. Continuity equation is solved to find out the concentration of various constituents of air, viz., hydrogen, oxygen, nitrogen and moisture in the enclosure. Pressure inside the enclosure is calculated using ideal gas equation.

A rapid increase in pressure is observed initially at the start of combustion but decreases afterwards when the natural circulation is established. Hydrogen concentration in the enclosure during the reaction is found to be out of deflagration range. The increase in temperature of structural materials is less than 10°C.

Parametric studies are carried out by varying humidity of incoming air and the fraction of sodium peroxide formation in the reaction. It is found that the concentration of hydrogen increases with increase in humidity and also with formation of sodium peroxide. By considering the reaction rate as a function of available sodium, the duration of combustion is increased and the maximum temperature in the enclosure decreased with the maximum hydrogen concentration in the enclosure remaining nearly same.

Key Words: CDA, hydrogen, sodium combustion

1. Introduction

Core Disruptive Accident (CDA) is a very low probability event, which can take place if there is a serious mismatch between heat generation and heat removal in the core. During a CDA, a large portion of the core in the fuel zone overheats, melts and flashes to vapour, forming a ‘core bubble’. The ‘core bubble’ pressure is more than that of the surrounding medium. The bubble expansion leads to movement of sodium mass in the upward direction. As the sodium moves upward, the pressure of cover gas increases. The cover gas pressure reaches a peak value at an instant when the sodium slug impacts the top shield. This slug impact leads to failure of seals and plastic elongation of the bolts in the top shield establishing leak paths. Thus, in the event of a CDA, 350 kg [1] of sodium is expelled into the enclosed space (‘the enclosure’) between Top Shield and Working Platform (FIG. 1). The sodium reacts with the oxygen and moisture present in the air and releases a large amount of heat. Reaction of sodium with moisture is accompanied by release of hydrogen. The products of reaction leave the enclosure at the top through holes in the working platform. A detailed analysis is carried out and various parameters in the enclosure, viz., pressure, temperature and concentration of hydrogen, oxygen and moisture in the enclosure are estimated. Parametric studies are carried out considering various factors, viz., sodium flame emissivity and Relative Humidity (RH) inside Reactor Containment Building (RCB); to understand their effects on the thermal hydraulic parameters during sodium burning period.

2. Description and Modelling Details

The sodium that was expelled into the enclosure reacts with oxygen and moisture present in the enclosure. The heat liberated by combustion increases the temperature of the internals and air present in the enclosure. The combustion of sodium is governed by the following equations:

$$2Na\ (l) + \frac{1}{2} O_2 \rightarrow Na_2O\ (s) \tag{1}$$

$$2Na\ (l) + H_2O\ (g) \rightarrow Na_2O\ (s) + H_2\ (g)\uparrow \tag{2}$$

The above reactions of sodium with oxygen and moisture are accompanied with release of 9460 kJ/kg [2] and 7742 kJ/kg [2] of energy respectively. The maximum burning rate of sodium is taken as 40 kg per m^2 of pool area per hour [3]. A linear dependence of burning rate on the oxygen and moisture concentration is assumed. The relative amounts of sodium reacting with moisture and oxygen are calculated based on their availability in the enclosure and the stoichiometry of reaction of sodium with oxygen and moisture. The burning rate of sodium (in kg/s) is given by:

$$\frac{dNa}{dt} = \frac{40A_{pool}}{3600}\left(r\frac{y_{H_2O}}{y_{H_2O,amb}} + (1-r)\frac{y_{O_2}}{y_{O_2,amb}} \right) \tag{3}$$

where

A_{pool}: pool area of sodium burning (m^2), y_{H_2O}: instantaneous moisture concentration (by mass) in the enclosure, y_{O_2}: instantaneous oxygen concentration (by mass) in the enclosure, $y_{H_2O,amb}$ & $y_{O_2,amb}$: moisture and oxygen concentration (by mass) in the enclosure at the time t =0, r: relative amount of moisture burnt

$$r = \frac{8y_{H_2O}}{8y_{H_2O} + 9y_{O_2}} \tag{4}$$

The heat generation rate (in Watt) is given by

$$\dot{H}_R = \frac{40A_{pool}}{3600}\left(7742r\frac{y_{H_2O}}{y_{H_2O,amb}} + 9460(1-r)\frac{y_{O_2}}{y_{O_2,amb}} \right)\times 10^3 \tag{5}$$

Energy Balance Equation

Heat released during combustion is absorbed by the air and structural components in the enclosure. Heat transfer to structural materials is through radiation and natural convection. A part of the heat is transported out with the outlet flow.

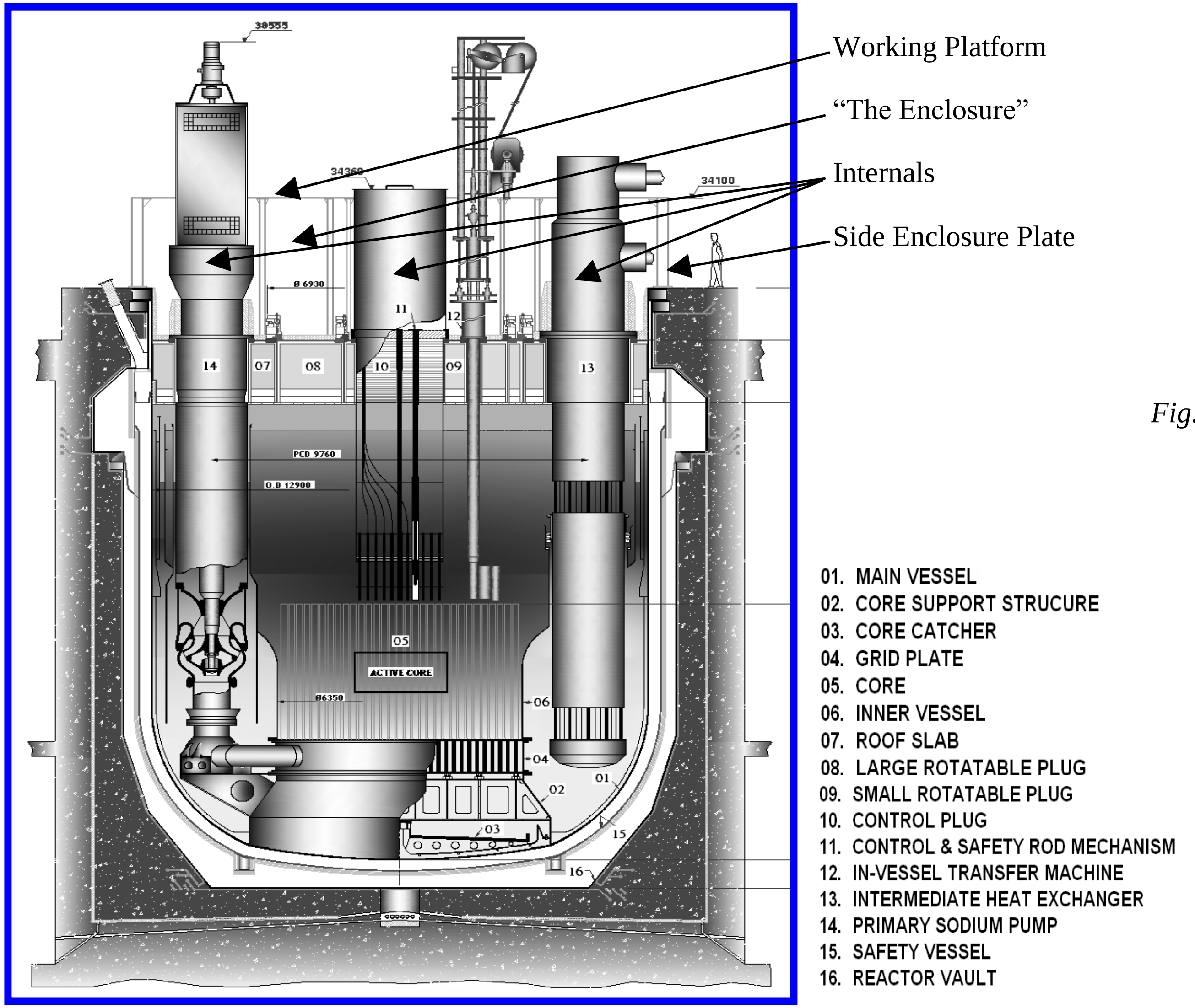

Fig. 1a: Vertical Section of Reactor Assembly

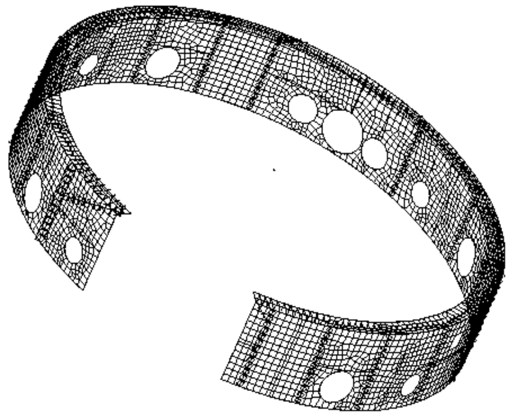

Fig. 1b: Side Enclosure Plate with the openings

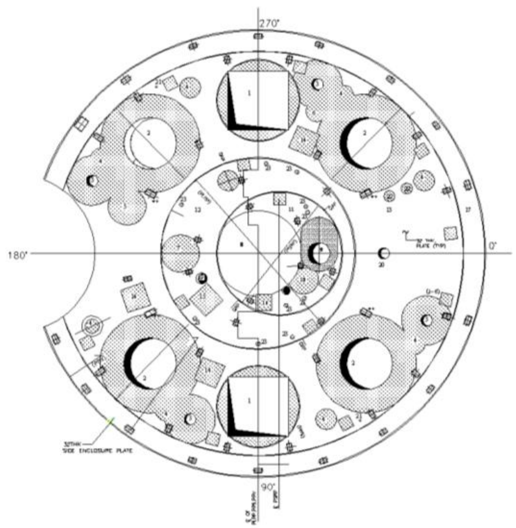

Fig. 1c: Top Shield Platform with the openings

The rise in temperature of air is calculated by solving energy balance equation as:

$$\frac{\partial}{\partial t}(\rho VcT) = \dot{m}_{in}cT_{in} - \dot{m}_{out}cT_{out} + \dot{H}_R - hA_{\text{int}}\left(T - T_{\text{int}}\right) - \varepsilon\sigma A_{pool}\left(T_f^4 - T_{\text{int}}^4\right) \quad (6)$$

Where

ρ: density of air in the enclosure (kg/m^3), V: volume of enclosure (m^3), c: specific heat of air (J/kg/K), T: Temperature of air in the enclosure (K), $\dot{m}_{in}$: inlet flow rate (kg/s), T_{in}: temperature of intake air (K), $\dot{m}_{out}$: outlet flow rate (kg/s), A_{int}: surface area of internals participating in the heat exchange (m^2), h: convective heat transfer coefficient between air and internals (W/m^{2}K), T_{int}: temperature of internals in the enclosure (K), ε: emissivity, σ: Stefan-Boltzman constant, T_f: flame temperature (K)

The temperature of structural materials is calculated by solving energy equation as:

$$(MC)_{\text{int}}\frac{\partial T_{\text{int}}}{\partial t} = hA_{\text{int}}\left(T - T_{\text{int}}\right) + \varepsilon\sigma A_{pool}\left(T_f^4 - T_{\text{int}}^4\right) \quad (7)$$

Where

M: mass of structural material in the enclosure (kg), C: specific heat of the material (J/kg/K)

The emissivity for internal structures is taken as 0.6. A parametric study is carried out by changing the emissivity from 0.3 to 0.7. Flame temperature is taken as 1000 K for stable burning of sodium [3].

Momentum Equation

During sodium burning, temperature increases inside the enclosure. This high temperature increases the pressure and air comes out of the enclosure initially. Due to this high temperature and height of the enclosure, buoyancy head is developed. Air flows into the enclosure through side porous plate (FIG. 1) by natural circulation due to the buoyancy head. The flow rate is determined by the net effect of buoyancy head, pressure drop in the flow path and pressure difference between the enclosure and RCB using the following equation:

$$M\frac{dv_{in}}{dt} = \frac{\Delta\rho gHA_{en}}{2} - \left(P_{RCB} - P_{en}\right)A_{in} - \frac{k}{2\beta}A_{in}\rho v_{in}^{2} \quad (8)$$

$$\dot{m}_{in} = \rho A_{in}\frac{v_{in}}{\beta}$$

Where

M: mass of air inside enclosure (kg), v_{in}: velocity of incoming air into the enclosure (m/s), H: height of enclosure (m), A_{en}: cross-sectional area of enclosure (m^2), P_{RCB}: pressure in RCB (Pa), P_{en}: enclosure pressure (Pa), A_{in}: inlet area of enclosure (m^2)

The outlet flow of hot air from the enclosure is calculated in a way similar to that of inlet flow rate. The resistances offered by the porous enclosure surface are evaluated by the following correlations given by Ward Smith [4].

$$k = \left[\left\{\beta\left(0.872 - 0.015\frac{t}{d} - 0.08\frac{d}{t}\right)\left(1-\beta^{3.3}\right) + \beta^{4.3}\left(1 + 0.134\left(\frac{t}{d}\right)^{0.5}\right)^{-1}\right\}^{-1} - 1\right]^2 \quad (9)$$

0.98 < t/d < 7.1, 0 < β <0.48, 2.4 < k < 63400

Where

k: pressure drop coefficient across the porous surface with opening to RCB, β: porosity of the plate, t: thickness of the plate, d: equivalent diameter of the holes in the plate

Continuity Equation

The mass inside the enclosure at any time is calculated from:

$$\frac{\partial(m_{en})}{\partial t} = \dot{m}_{in} - \dot{m}_{out} + \dot{m}_{gen} - \dot{m}_{con} \tag{10}$$

Where

$\dot{m}_{gen}$: mass generation rate in the enclosure (kg/s), $\dot{m}_{con}$: mass consumption rate in the enclosure (kg/s)

Density of air inside the enclosure at any time is calculated based on the mass of gaseous substances inside the enclosure (m_{en}).

Hydrogen is generated due to reaction of sodium with moisture present in the enclosure. The rate of generation of hydrogen inside the enclosure is calculated from:

$$\dot{m}_{gen} = \frac{40A_{pool}}{3600}\left(r\frac{y_{H_2O}}{y_{H_2O,amb}} \times \frac{2}{46}\right) \tag{11}$$

Oxygen and water vapour react with sodium and form sodium oxide. Hence, they are considered to be consumed during the reaction and the consumption rate is given as:

$$\dot{m}_{con} = \dot{m}_{H_2O} + \dot{m}_{O_2} = \frac{40A_{pool}}{3600}\left(r\frac{y_{H_2O}}{y_{H_2O,amb}} \times \frac{18}{46} + (1-r)\frac{y_{O_2}}{y_{O_2,amb}} \times \frac{16}{46}\right) \tag{12}$$

The concentrations of various constituents, viz., oxygen, hydrogen, moisture and nitrogen are estimated separately using the continuity equation for each constituent as mentioned below. All other gases present in the RCB are included in the nitrogen concentration as they are non-reacting with sodium.

Mass Conservation Equation for Hydrogen

$$\frac{\partial\left(m_{en}y_{H_2}\right)}{\partial t} = \frac{40A_{pool}}{3600}\left(r\frac{y_{H_2O}}{y_{H_2O,amb}} \times \frac{2}{46}\right) - \dot{m}_{out}y_{H_2} \tag{13}$$

Where y_{H_2}: instantaneous hydrogen concentration (by mass) in the enclosure

Mass Conservation Equation for Oxygen

$$\frac{\partial\left(m_{en}y_{O_2}\right)}{\partial t} = \dot{m}_{in}y_{O_2,amb} - \dot{m}_{out}y_{O_2} - \frac{40A_{pool}}{3600}\left((1-r)\frac{y_{O_2}}{y_{O_2,amb}} \times \frac{16}{46}\right) \tag{14}$$

Mass Conservation Equation for Water Vapour

$$\frac{\partial\left(m_{en}y_{H_2O}\right)}{\partial t} = \dot{m}_{in}y_{H_2O,amb} - \dot{m}_{out}y_{H_2O} - \frac{40A_{pool}}{3600}\left(r\frac{y_{H_2O}}{y_{H_2O,amb}} \times \frac{18}{46}\right) \tag{15}$$

Ideal Gas Equation

Pressure inside the enclosure is calculated using ideal gas equation as:

$P_{en}=\rho RT$ Where R: Characteristic Gas Constant

All the governing equations are discretized using finite difference method and the resulting equations are translated into a computer code. A suitable time step of magnitude 1 ms is taken for the computation.

3. Results and Discussions

The initial condition of enclosure is taken as 35°C and 27% RH. Initial flow rate of air into the enclosure is neglected. The amount of cumulative sodium burnt as a function of time in the enclosure is shown in FIG. 2. It is found that 350 kg of sodium is burnt in 368 s.

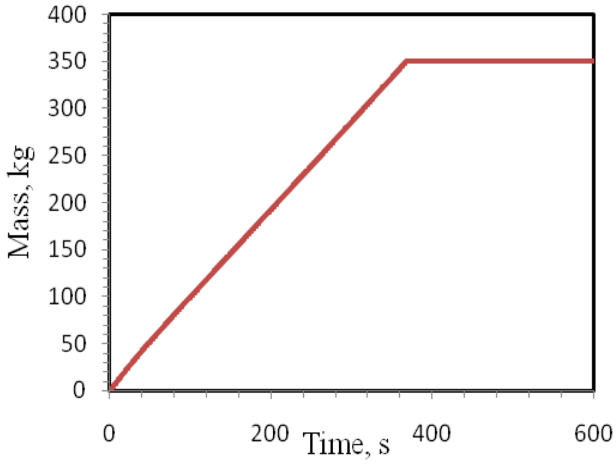

FIG. 2: Mass of sodium burnt inside the enclosure

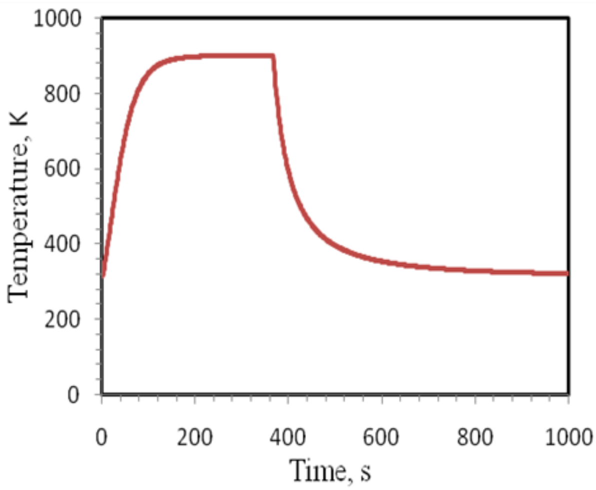

FIG. 3: evolution of air temperature inside the enclosure

Evolution of air temperature inside the enclosure is depicted in FIG. 3. A maximum air temperature of 899 K is attained during the burning. This temperature prevails only for a short duration of ~5 minute. From the figure it is found that temperature reaches the maximum in 120 s after which it remains nearly constant for rest of the burning period. Thus, a stable burning is observed during this period. Once the burning is completed, temperature falls rapidly. At the end of 15 minute the temperature of the enclosure is found to be 324 K. The temperature of enclosure remains higher than RCB temperature due to heat transfer from structures to the air in the enclosure.

Inlet and outlet air flow rates of the enclosure are shown in FIG. 4. Initially inlet flow rate is negative which implies the flow is going out of the enclosure. It can also be seen that the outlet flow rate is high at the beginning. This is due to high pressure in the enclosure which is generated by rapid rise of temperature due to sodium burning. After the initial phase, natural convection sets in and the flow rates are stabilized for rest of the burning period. At the completion of sodium burning, a sudden increase in inlet flow rate and fall in outlet flow rate are observed due to a rapid fall in enclosure pressure. After the peak, the inlet flow rate falls gradually. At the end of 1200 s, flow rate is not zero. This flow is due to the natural circulation in the enclosure due to release of heat from internal structures.

Density variation of air inside the enclosure is depicted in FIG. 5. The density of air falls gradually at the start of burning due to outflow of mass from the enclosure. It attains a near constant value of 0.4 kg/m^3 during stable burning period of sodium. During this time the inlet flow rate and generation rate balance outlet flow rate and consumption rate. Once the burning is completed, the sodium reaction with oxygen and moisture stops. The temperature and pressure in the enclosure come back to its initial state and inlet and outlet flow rates fall off and the density recovers to its initial value.

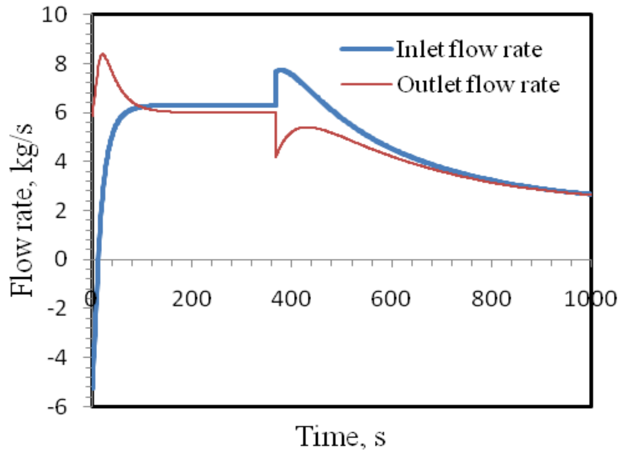

FIG. 4: Evolution of inlet and outlet air flow rate in the

FIG. 5: Evolution of density of air inside the enclosure

Pressure (gauge) evolution inside the enclosure is shown in FIG. 6. Initially the pressure increases rapidly due to sudden rise in temperature associated with sodium burning. Due to this pressure, air flows out of the enclosure through all the openings. As the air comes out suddenly, density falls which in turn reduces the pressure inside the enclosure which is shown as a small fall after the first peak. As the sodium is continuously burning, the pressure reaches another peak due to rise in temperature. The maximum pressure is found to be 281 Pa. Thereafter the pressure decreases due to fall in density inside the enclosure. Once the natural circulation sets in, the flow rate and pressure stabilize for rest of the burning period, where a stable burning is observed. After completion of burning, the pressure falls drastically which is shown in the figure as a sudden dip. This is due to the sudden fall in temperature after the completion of burning. After the dip, the pressure recovers gradually and reaches ambient pressure in 600 s.

Hydrogen is generated during sodium moisture reaction. Evolution of hydrogen concentration (volumetric) is shown in FIG. 7. The maximum concentration of hydrogen in the enclosure is found to be 0.34%. As the reaction starts, hydrogen concentration increases, remains fairly constant during stable burning period and falls to zero after the reaction is completed. The hydrogen generated during reaction comes out of the enclosure along with outlet flow. There is a remote chance of accumulation of hydrogen in the enclosure due to strong natural convection.

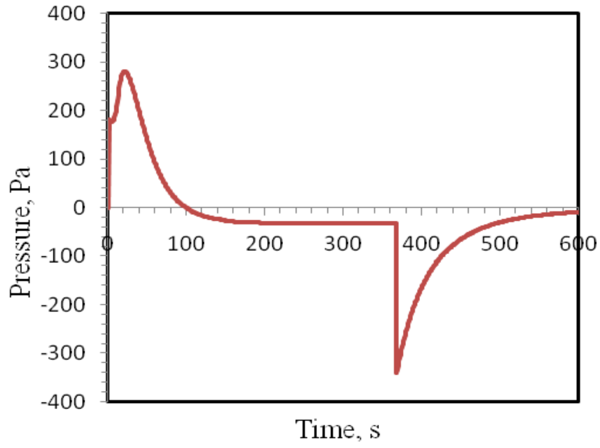

FIG. 6: Evolution of pressure inside the enclosure

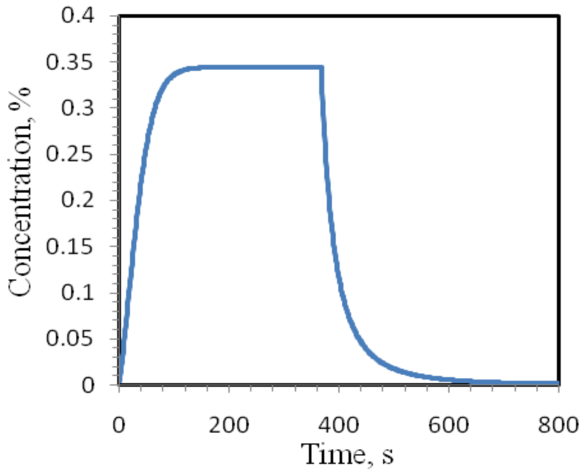

FIG. 7: Evolution of hydrogen concentration (volumetric) in air inside the enclosure

4. Parametric Study

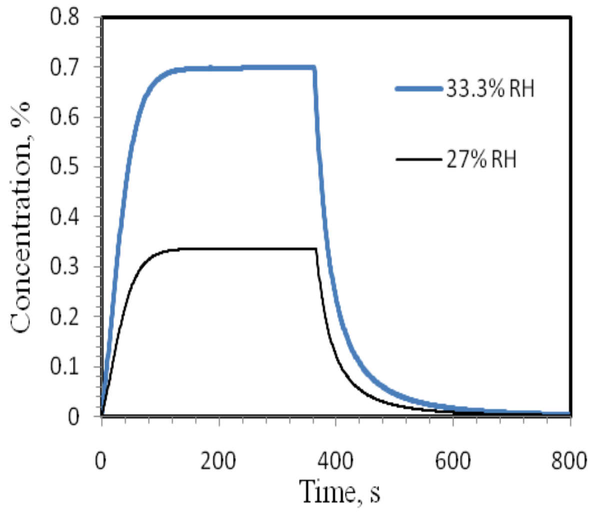

FIG. 8: Effect of relative humidity on hydrogen concentration of air inside enclosure

To study the effect of RH on various parameters of the enclosure during sodium burning, a parametric study is carried out taking RH of incoming air as a parameter. The RH values considered for the analysis are 27% and 33.3% (20.4 gm/kg specific humidity). The evolution of hydrogen concentration for various RH values is shown in FIG. 8. It is found that there is an appreciable change in hydrogen concentration in the enclosure. A maximum of 0.7% hydrogen concentration is found out during sodium burning for 33.3% RH. This increase is due to increase in specific humidity of air.

5. Formation of Sodium Peroxide during Sodium Reaction

The reaction of sodium with oxygen and moisture to form sodium peroxide is given below:

$2Na\ (l) + O_2 \rightarrow Na_2O_2\ (s)$

$2Na\ (l) + 2H_2O\ (g) \rightarrow Na_2O_2\ (s) + 2H_2\ (g)\uparrow$

Heat generation in this reaction is 11,280 kJ/kg of sodium [2]. It is found that complete burning of sodium takes 430 s. Thus, burning of sodium by this reaction takes more time as compared to the reaction where sodium oxide is formed. This is due to the reduction in burning rate of sodium which depends on oxygen concentration.

The evolution of hydrogen concentration is given in FIG. 9. The maximum concentration of hydrogen is found to be 0.6% during burning. Thus an increase in hydrogen concentration from 0.34% to 0.6% is observed due to formation of sodium peroxide.

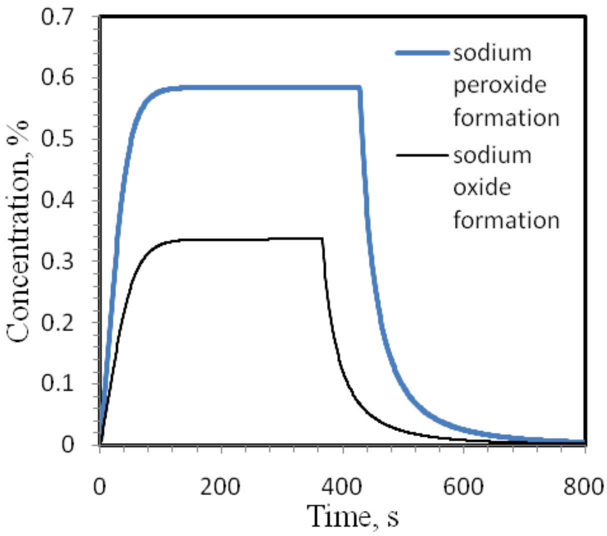

FIG. 9: Evolution of hydrogen concentration in the enclosure

6. Reduction of burning rate with available sodium

With the consumption of sodium during the reaction, the amount of sodium reduces with time and the burning rate is expected to reduce. The effect of such reduction on thermal hydraulic parameters is studied by varying the burning rate with available sodium. Thus the rate of burning of sodium depends on oxygen, moisture concentration and the amount of sodium remaining. The total burning time is found to be 556 s. This is due to the reduced rate of sodium burning. It is found that the rate of burning is 14 $kg/m^2/h$ just before the completion of sodium burning.
The evolution of pressure inside the enclosure is depicted in Fig. 10. A peak is observed at the beginning and then pressure falls and remains nearly constant for the rest of the burning period. The pressure recovery of enclosure is also smooth at the end of burning. The maximum pressure is found to be 264 Pa.

FIG. 11 shows the evolution of hydrogen concentration inside the enclosure. The maximum concentration is found to be 0.3 %. Thus a marginal reduction in concentration of hydrogen is observed due to reduced burning rate of sodium.

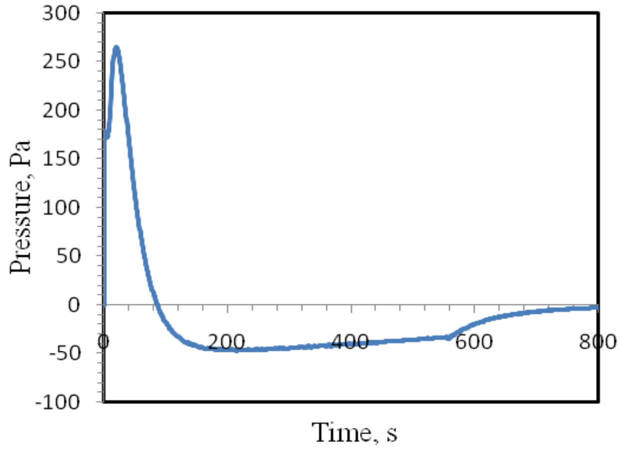

FIG. 10: Evolution of Pressure inside the enclosure

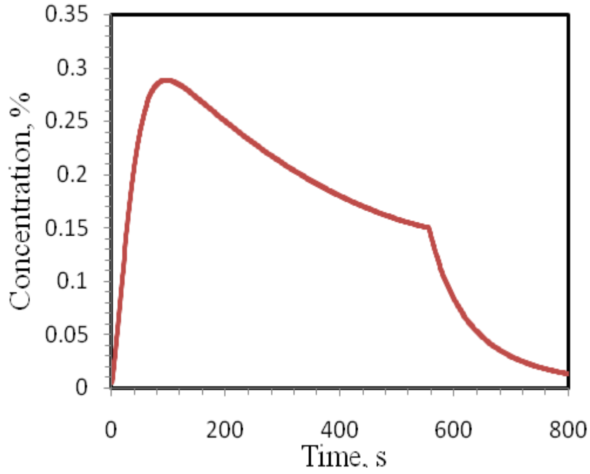

FIG. 11: Evolution of hydrogen concentration in the enclosure

7. Conclusion

The phenomenon of sodium burning in the space between top shield and working platform during a CDA is analyzed using an in house developed code. Various parameters, viz., temperature, pressure, inlet and outlet flow rates, density, concentrations of hydrogen, oxygen, moisture and nitrogen in the enclosed space are estimated. Hydrogen concentration (volumetric) in the enclosed space during CDA is found to be 0.34% which is much less than the deflagration limit of 4 %. Thus there is no need of hydrogen recombiners. Parametric studies are carried out for various values of relative humidity to investigate their effect on various parameters during burning. An increase in hydrogen concentration in the enclosed space is seen with increase in humidity and with formation of sodium peroxide as a product during combustion. A marginal increase in air temperature (20 K) is found due to sodium peroxide formation.

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