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Numerical Modeling of LOCA Accident in AP1000 Reactor Containment

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Abstract: In this paper, it has been modeled one of the most dangerous accidents in reactor containments known as Loss of Coolant Accident (LOCA) in its worst condition which is called large LOCA. The specific type of large LOCA is DECL (Double Ended Cold Leg) break which means totally guillotine type of break in cold leg pipe. When 'LOCA' occurs, the coolant itself is lost, then in this case that happens with pipe break or any kind of losing, the danger of core melting is possible. This modeling is performed in single volume method in AP1000 reactor which is one of the most sophisticated safe reactors that has ever been built. Its safety systems provide a large variety of safety margins. One of the most important safety features in AP1000 is its passivity. This advantage provides many simplifications to enhance the safety, reliability, construction, operation, maintenance, investment, protection and plant costs. Therefore, it is worthwhile and makes sense to perform the analysis of a most dangerous accident in one of the most secure reactors. The modeling software applied in our analysis is MATLAB, and the results are compared with the AP1000 safety, security and environmental reports.

Key words: Containment; LOCA; Two Phase; Heat Transfer

INTRODUCTION

During a severe accident, a large amount of radioactive fission products is generated and the goal of the containment system is to avoid or limit the release of these fission products to the external environment [1]. This goal is achieved through restriction of accidents or by using containment safety systems limiting the dangerous effects of the event. Therefore, the containment plays a basic role in safety. AP1000 is a two loop 1000 MWs pressurized water reactor (PWR) with passive safety features and extensive plant simplifications that enhances the construction, operation, maintenance, and safety [2]. First we look at the major advances of AP1000 design over conventional plant designs. AP1000 safety features rely on natural driving forces, such as pressurized gas, gravity flow, natural circulation flow, and convection. These features do not use active components, such as pumps, fans, chillers, or diesel generators. The features are designed to function without active safety support systems, such as AC power, component cooling water, service water and HVAC (Heating Ventilation and Air Conditioning) [3]. AP1000 safety features establish and maintain core cooling and containment integrity indefinitely, with no operator action or AC power following basic design faults. These systems contain significantly fewer components, reducing required tests, inspections, and maintenance, also their readiness is easily monitored [4]. The *Loss of coolant accident* (LOCA) is most likely to occur in 'water cooled reactors', where the stored energy content of the high pressure, high temperature coolant may be released to the containment by rupture of an exposed pipe. HTGR systems with their primary coolant loops contained entirely within the reactor vessel are not as readily susceptible to extensive coolant loss. The low pressure sodium coolant in LMFBRs is not also subject to such rapid removal.

Design basis LOCA analysis of LWR systems calls for the following scenario:

1) A double ended "guillotine" pipe break in a primary coolant line to allow free coolant flow from both ends.
2) Coolant flashes to steam under the influence of the stored energy and is discharged rapidly into the containment building.
3) Although the coolant loss, shuts down the system neutronically, reactor trip is initiated by an under-

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pressure reading to the protective system to assure continued sub-criticality.

4) The emergency core cooling systems (ECCS) (in AP1000 it is called PXS) operate to cool the core and prevent excessive decay heat driven damage.
5) Radioactivity in the coolant is retained by the containment structure with natural deposition processes and active removal systems, eventually reducing the overall levels of radioactivity.
6) Heat removal systems maintain ECCS effectiveness and reduce containment pressure.

In the LOCA, design features are expected to mitigate the consequences of the accident to minimize the amount of fuel failure and subsequent release of radioactivity for each of the reactor designs.

Figure.1 shows containment and the constitutive components of AP1000 containment cooling systems:

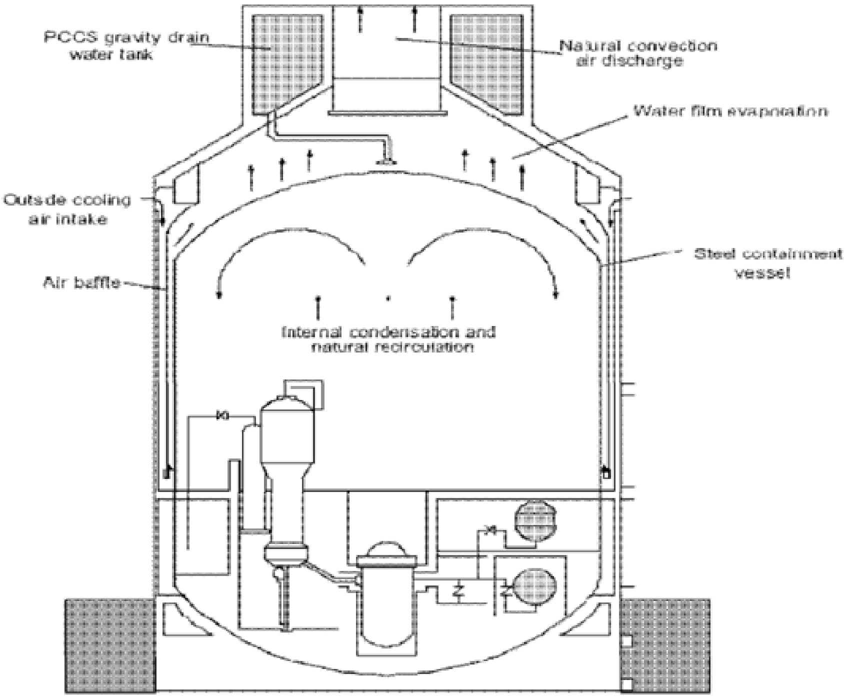

Fig. 1: AP1000 Passive Containment Cooling System [5].

Mathematical Formulation:

Containment modeling is performed in several ways. In single volume analysis, it is assumed that the containment has a single volume with single pressure and temperature.

Clear examples of time varying flow processes relevant to nuclear technology are such as: (1) pressurization of the containment due to postulated rupture of the primary or secondary coolant systems; (2) response of a PWR pressurizer to turbine load changes; and (3) BWR suppression pool heat up by addition of primary coolant.

Unlike the steady-flow analysis, the variable flow analysis can be performed with equal ease by either the mass control or the volume control approach [6].

Containment Pressurization Process, For the light water reactor, one postulated accident is the release of primary or secondary coolant within the containment. The magnitude of the peak pressure and the time to reach to peak pressure are of interest for structural considerations of the containment. The fluid released in the containment can be due to the rupture of either the primary or secondary coolant loops.

In both cases the assumed pipe rupture begins the blow down. The final state of the water/air mixture depends on several other factors: (1) the initial thermodynamic state and mass of water in the reactor and the air in the containment; (2) the rate of release of fluid into the containment and the possible heat sources or sinks involved; (3) the likelihood of exothermic chemical reactions; and (4) the core decay heat [6]. In the analysis of Transient Conditions, using the application of the first law of thermodynamics in three subsections including containment air, water vapor initially in the air of containment, and discharged water into the containment from primary system, and ultimately adding them up together, the following equation is obtained:

$$\frac{d}{dt}\left(m_a u_a + m_{wc}\, u_{wc} + m_{wpd} u_{wpd} + m_{wpr} u_{wpr}\right) = \dot{Q}_{n-wpr} - \sum_i \dot{Q}_{i-st} \quad (1)$$

Always derivative of free containment volume and the primary system volume is zero. Upon integration of from time t to a later time $t+\Delta t$ during the discharge process, equation below is obtained:

$$U^{t+\Delta t} - U^{t} = Q_{n-wpr}^{t+\Delta t} - \sum_i Q_{i-st}^{t+\Delta t} \quad (2)$$

Where

$$U^{t+\Delta t} = m_a u_a^{t+\Delta t} + \left(m_{wc}^{t} + m_{wpd}^{t+\Delta t}\right) u_{wc}^{t+\Delta t} + m_{wpr}^{t+\Delta t} u_{wp}^{t+\Delta t}$$

$$U^{t} = m_a u_a^{t} + m_{wc}^{t} u_{wc}^{t} + m_{wpr}^{t} u_{wp}^{t}$$

The discharged primary mass, $m_{wpd}^{t+\Delta t}$, is resulted by integrating the break flow rate, $\dot{m}(t)$ over the interval t to $t+\Delta t$:

$$m_{wpd}^{t+\Delta t} = m_{wpd}^{t} + \int_t^{t+\Delta t} \dot{m}(t)\,dt \quad (3)$$

Upon rupture, the system coolant flows into the control volume at the rate of $\dot{m}(t)$. The control volume shape remains constant with time, and there is no shaft work. Therefore the first law for a control volume is written as:

$$\dot{U}_{c.v.}^{t} = \dot{m}(t) h_p(t) + \dot{Q}_{wpr-c} - \dot{Q}_{c-st} \quad (4)$$

Integrating between times t and $t+\Delta t$, becomes:

$$U^{t+\Delta t} - U^{t} = +\int_t^{t+\Delta t} h_p(t)\dot{m}(t)\,dt + Q_{wpr-c}^{t+\Delta t} - Q_{c-st}^{t+\Delta t} \quad (5)$$

So for the control volume method we have:

$$U^{t+\Delta t} = m_a u_a^{t+\Delta t} + \left(m_{wc}^{t} + m_{wpd}^{t+\Delta t}\right) u_{wc}^{t+\Delta t}$$

$$U^{t} = m_a u_a^{t} + m_{wc}^{t} u_{wc}^{t}$$

Eq. 5 Becomes:

$$m_a u_a^{t+\Delta t} + \left(m_{wc}^t + m_{wpd}^{t+\Delta t}\right) u_{wc}^{t+\Delta t}$$

$$= m_a u_a^t + m_{wc}^t u_{wc}^t + \int_t^{t+\Delta t} h_p(t)\dot{m}(t)dt + Q_{wpr-c}^{t+\Delta t} - Q_{c-st}^{t+\Delta t} \tag{6}$$

Containment condition histories can be evaluated by in the following manner.

First obtain the break flow rate, $\dot{m}(t)$, and the heat transferred from the coolant remaining in the vessel to the containment and the heat transferred to the containment structures Q_{wpr-c} and Q_{c-st}, respectively, by applying transient thermal analysis (Q_{wpr-c} has been assumed zero in model and Q_{c-st} is evaluated in heat transfer). Primary system enthalpy is obtained similar to what described for primary system internal energy after Eq. 3[6]. Analysis of equilibrium pressure conditions with respect to time are achieved upon completion of the blow-down process and establishment of pressure equilibrium between the contents of the containment vessel and the primary system. Eq. 3 is still applicable, but the new state $t+\Delta t$ is the one after completion of blow-down and achievement of pressure equilibrium. Hence $u_{wc}^{t+\Delta t}$ and $u_{wp}^{t+\Delta t}$ are identical, and at the state t, the whole primary coolant is in the primary system. So that Eq. 2 becomes:

$$U^{t+\Delta t} - U^t = Q_{n-wpr}^{t+\Delta t} - \sum_i Q_{i-st}^{t+\Delta t} \tag{7}$$

Where

$$U^{t+\Delta t} = m_a u_a^{t+\Delta t} + \left(m_{wc}^t + m_{wp}\right) u_{wc}^{t+\Delta t}$$

$$U^t = m_a u_a^t + m_{wc}^t u_{wc}^t + m_{wp} u_{wp}^t$$

In control volume approach the heat loss to the structures is re expressed as Q_{c-st}[6].

$$U^{t+\Delta t} - U^t = Q_{n-wpr}^{t+\Delta t} - Q_{c-st}^{t+\Delta t} \tag{8}$$

Interpreting the energy balance of Eq. 8 yields:

$$m_w\left(u_w^{t+\Delta t} - u_w^t\right) + m_a c_{va}\left(T^{t+\Delta t} - T_a^t\right) = Q_{n-wpr}^{t+\Delta t} - Q_{c-st}^{t+\Delta t} \tag{9}$$

And

$$m_w u_w^t \equiv m_{wa} u_{wa}^t + m_{wp} u_{wp}^t$$

$$m_w u_w^{t+\Delta t} \equiv \left(m_{wa} + m_{wp}\right) u_w^{t+\Delta t}$$

$$Q_{n-wpr} = Q_{wpr-c} + Q \quad Which \quad Q_{wpr-c} = 0$$

Eq. 9 can be rewritten to express the water conditions separately as primary water and water in air:

$$m_{wpd}^{t+\Delta t}\left(u_f^{t+\Delta t}+x_{st1}u_{fg}^{t+\Delta t}-u_{wp}^{t}\right)+m_{wa}^{t}\left(u_f^{t+\Delta t}+x_{st1}u_{fg}^{t+\Delta t}-u_{wa}^{t}\right)+m_aC_{va}\left(T^{t+\Delta t}-T_a^t\right)=Q^{t+\Delta t}-Q_{c-st}^{t+\Delta t} \tag{10}$$

$Q^{t+\Delta t}$ is produced by input mass flow to the containment, $Q^{t+\Delta t}=\dot{m}_{wpd}^{t+\Delta t}h^{t+\Delta t}\Delta t$ and $Q_{c-st}^{t+\Delta t}$ has been modeled in heat transfer section.

Whereas the water vapor and air are intermingled gases, each exerting its partial pressure, the liquid is agglomerated at a pressure equal to the total pressure. From Dalton's law of partial pressures:

$$p^{t+\Delta t}=p_w^{t+\Delta t}\left(T^{t+\Delta t}\right)+p_a^{t+\Delta t} \tag{11}$$

Where,

$p^{t+\Delta t}$ is the pressure of mixture, $p_w^{t+\Delta t}$ is partial pressure of the saturated water vapor corresponding to $T^{t+\Delta t}$, $p_a^{t+\Delta t}$ is partial pressure of air corresponding to $T^{t+\Delta t}$, and from the associated fact that each mixture component occupies the total volume, we get:

$$V_T^{t+\Delta t}=m_w^{t+\Delta t}v_w^{t+\Delta t}\left(T_{sat}^{t+\Delta t}\right)\simeq m_av_a\left(T^{t+\Delta t},p_a^{t+\Delta t}\right) \tag{12}$$

By introducing the definition of the steam static quality (x_{st}) in the containment and treating air as a perfect gas, Eq. 12 becomes:

$$V_T^{t+\Delta t}=m_w^{t+\Delta t}\left[v_f^{t+\Delta t}+x_{st2}v_{fg}^{t+\Delta t}\left(T_{sat}^{t+\Delta t}\right)\right]\simeq\frac{m_aR_aT^{t+\Delta t}}{p_a^{t+\Delta t}} \tag{13}$$

From Eq. 13:

$$x_{st2}=\frac{\dfrac{V_T^{t+\Delta t}}{m_w^{t+\Delta t}}-v_f^{t+\Delta t}}{v_{fg}^{t+\Delta t}} \tag{14}$$

Where

$$V_T^{t+\Delta t}=\sum_{t=1}^{t+\Delta t}\left(m_{wpd}^{t}v_{wpd}^{t}\right)+V_c \tag{15}$$

Establishment of the initial air pressure (p_a^t) in the containment should consider water vapor present. This correction on p_a^t is minor, but illustrates the use of Dalton's law of partial pressures. The initial conditions are characteristically stated in terms of a relative humidity (φ), the dry bulb temperature (T_a^t), and the total pressure (p^t).

According to the definition of relative humidity, the saturated water vapor pressure for the given initial condition (p_{wa}^{t}) is given by:

$$p_{wa}^{t} = \varphi^{t} p_{sat}(T_a^t) \tag{15}$$

Therefore by using Dalton's law of partial pressures, we obtain:

$$p_a^t = p^t - p_{wa}^t \tag{16}$$

And by the perfect gas law:

$$m_a = \frac{p_a^0 V_c}{R_a T_a^0} \tag{17}$$

Eq.18 shows the mass of initial water in the containment:

$$m_{wa}^0 = \frac{V_c}{v_{wa}^0} \tag{18}$$

And primary discharged water is:

$$V_{wpd}^t = m_{wpd}^t v_{wpd}^t \tag{19}$$

Where the total mass of water is:

$$m_w^{t+\Delta t} = \sum_{t=1}^{t+\Delta t} m_{wpd}^t + m_{wa}^0 \tag{20}$$

Now, all the unknown parameters depend on $T^{t+\Delta t}$ then with conjecture of this value and checking it, all of unknown variables can be determined. If the absolute difference of static qualities which are already denoted (x_{st1} in $Eq.10$ and x_{st2} in $Eq.14$) is less than an error function, then other parameters in subsequent conditions will be determined. These variables are:

$p_w^{t+\Delta t} = f_{sat.}(T^{t+\Delta t})$, which is obtained from saturation library, and $p_a^{t+\Delta t} = \frac{m_a R_a T^{t+\Delta t}}{V_T^{t+\Delta t}}$ and totally:

$$p^{t+\Delta t} = p_w^{t+\Delta t} + p_a^{t+\Delta t} \tag{21}$$

Else, if guessed value is not converged, then another value should be conjectured. This $T^{t+\Delta t}$ is the same as T_{sat} which is inserted to the $Q_{c\text{-}st}$ sub program which will be explained in the next section.

2.1 Heat Transfer:

In this section evaluations of $Q_{c\text{-}st}$ (heat transferred from inside of containment to outside) which is used in mathematical formulation, are presented. The heat transfer modeling is based on conjecture of temperature at outer surface of shield building, outer gap (down-comer, but in the initial condition it is presented as gap1), and inner gap (riser, which is presented as gap2 in modeling). But the correction of this process is achieved through comparison of the guessed value with the new one obtained for the same parameter from other thermal hydraulic parameters which are yielded from the estimated value based on the heat transfer relations. These relations are conduction in solid resistances (like shield building, air baffle, and carbon steel containment) in 1-D cylindrical coordinates (radial coordinate) and convection in fluid layers (like ambient, down-comer, riser, and inside of containment) also, in 1-D cylindrical coordinates (same as conduction). The absolute difference of values (guessed and produced values of each conjectured parameter like temperature of down-comer) should be less than an error function. If it is reached, estimated value is correct, otherwise another value for that parameter should be guessed again. With keep going on heat transfer toward the inside of containment and estimating the walls temperatures besides correction of each gap's temperature, inner surface of containment temperature is reached. This temperature and internal air/steam mixture temperature which is released in mathematical modeling are used in production of $h_{cont.}$ based on the following relation [20]:

$$h_{fg1} = h_{fg} + 0.68C_{pf}(T_{sat.} - T_{in.cont.}) \tag{22}$$

$$\Rightarrow h_{cont.} = \left\{ 0.943\left(\frac{9.8\frac{1}{v_f}\left(\frac{1}{v_f} - \frac{1}{v_g}\right)K_f^3 h_{fg1}}{\mu_f(T_{sat.} - T_{in.cont.})l} \right)^{0.25} \right\} \tag{23}$$

This coefficient produces another value of $T_{in.cont.}$ as below:

$$T_{in.cont.} = T_{sat.} - \left(\frac{Q_{c-st}}{2\pi l h_{cont.} r_{in.cont.}} \right) \tag{24}$$

When the absolute difference of this value and its prior value is less than the error function, estimated Q_{c-st} based on prime estimated temperature of outer surface of shield building is correct, otherwise the whole procedure should be repeated again with another guessed value of outer surface of shield building temperature. This repetition is maintained till a correct value (converged value) is obtained. All of the above procedures are just in one step. Each step is performed as long as each interior air/steam mixture temperature is produced from main modeling and entered to the heat transfer program. $H_{cont.}$ is just used inside of containment and is not used in gaps. In each gap h (convection heat transfer coefficient) is evaluated based on below correlations [8]:

$$\overline{Nu_\delta} = \left\{ 0.825 + \frac{0.387Ra_\delta^{\frac{1}{6}}}{[1 + (\frac{0.492}{\mathrm{Pr}})^{\frac{9}{16}}]^{\frac{8}{27}}} \right\}^2 \tag{25}$$

$$h = \frac{\overline{Nu_\delta}K}{l} \tag{26}$$

And convection heat transfer coefficient is obtained.

Results:

Modeling is performed by MATLAB R2009b software. Released mass flow and enthalpy (figures No. 3 & 4) are used as matrix from [9]. The main purpose is determination of temperature and pressure variations with respect to time (figures No. 5 & 6). In addition, the variations of heat, convection heat transfer coefficients in gaps and quality in containment are obtained (figures No. 7 & 8). In the following Table, initial conditions of modeling and containment geometry are presented.

Table 1: Containment Geometry and Initial Conditions

Parameter	Description	Value
$V_c^{(1)}$	Containment volume	5896.067(m^3)
$A_{out.cont.}^{(2)}$	Active area of outer surface of containment	5934.8567 (m^2)
$A_{in.cont.}^{(2)}$	Active area of inner surface of containment	5922.1553 (m^2)
$A_{conc.}^{(3)}$	Active area of concrete shield building	6552.1346 (m^2)
$A_{AirBaffle}^{(4)}$	Active area of air baffle	4258.6595 (m^2)
$A_{gap1}^{(5)}$	Active area of gap1 (downcomer)	6183.729 (m^2)
$A_{gap2}^{(5)}$	Active area of gap2 (riser)	5984.7455 (m^2)
$\delta_{cont.}^{(6)}$	Containment thickness	0.0444 (m)
$\delta_{gap2}^{(7)}$	Riser thickness	0.6561 (m)
$\delta_{AirBaffle}^{(7)}$	Air Baffle Thickness	0.015 (m)
$\delta_{gap1}^{(7)}$	Downcomer thickness	0.6561 (m)
$\delta_{conc.}^{(8)}$	Concrete shied building thickness	0.9144 (m)
$\Upsilon_{in.cont.}^{(9)}$	Internal radius of containment	19.812 (m)
$\Upsilon_{in.conc.}^{(10)}$	Internal radius of concrete shield building	21.132 (m)
$\Upsilon_{sat0.}^{(11)}$	Initial interior temperature of containment (Saturated)	50(°C)
$\varphi_0^{(12)}$	Initial relative humidity	0
$P_{0cont.}^{(12)}$	Initial containment pressure	0.1082(*MPa*)
$P_{ColdLeg}^{(13)}$	Cold leg pressure	15.9268(*MPa*)
$T_{ColdLeg}^{(13)}$	Cold leg temperature	280.66(°C)
$\dot{m}_{air}^{(14)}$	Inlet air mass flow rate	788.05(Kg/s)
$l^{(15)}$	Active height of heat transfer (common in each thermal layer)	47.8209 (m)

(1) From [10].
(2) Interior and exterior areas of containment are divided into two sections. First section which is cylindrical and being evaluated from operation floor elevation till top end of cylindrical portion elevation, and the second section is the dome portion that is calculated from top end of cylindrical portion elevation till the top of air baffle elevation [11]. Area calculations have been performed using the rotating curve formula.
(3) Cylindrical portion of the shield building is calculated in modeling. Heat transfers from conical portion and air exhaust are ignored.
(4) Total area of air baffle is evaluated in modeling [12], [13]. This area is based on references data and some calculations for knuckle portion, which has used rotating curve formula.
(5) From calculations based on measurements.
(6) From [14].
(7) Hypothetical values (based on some measurements and calculations).
(8) From [15].
(9) From [11].
(10) From [15].
(11) Near to the initial condition [10].
(12) From [10].
(13) From [16].

$$\dot{m}_{air} = \rho_{air} A_{AirInlets} = 1.16 \left({}^{kg}/_{m^3} \right) * (15 * 4.572 * 1.9812)(m^2) * 5 \ ({}^{m}/_{s}) = 788.05 \ ({}^{kg}/_{s}) \quad (17)$$

$A_{AirInlets}$ consists of 15 panels with 15 (ft) long (4.572 (m)) and 6.5 (ft) high (1.9812 (m)). The velocity of cooling air flow is assumed to be 5(*m/s*). The cooling air flow and PCCWST are participated in containment cooling system. But the effect of drained water from PCCWST is ignored in this model and the effect of air flow is just highlighted (Addition information is in reference [17] and Figure.1).

(15) This active length consists of two parts, one part is cylindrical (41.7703 (m) which is obtained from measurement between operation floor elevation and end of cylindrical portion elevation) [11], and the other part is knuckle (6.0506 (m)) which is achieved from calculations (These evaluations are made by curve length formula calculations from end of cylindrical portion elevation till the top of air baffle elevation).

The following figures are generated from modeling.

All materials which are used, has been derived from [18].

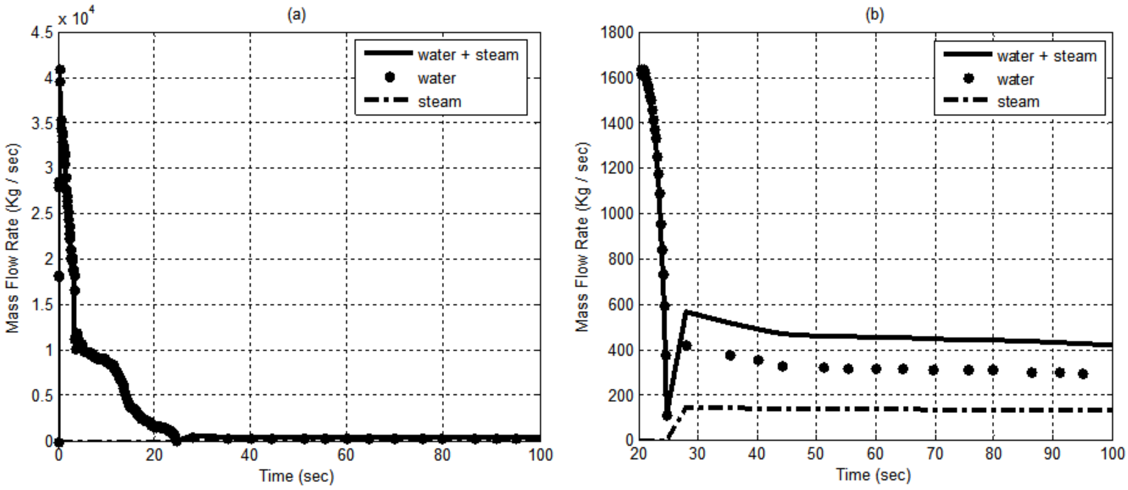

Fig. 2: Distribution of Mass Flow Rate with Time

From Figure.2 (a) and (b), it is clear that the maximum of flow rate is 0.4 (sec) and this is due to a big difference between pressure and temperature of water in cold leg and interior atmosphere of containment in the break moment. Till second 24 the water flow is released to the containment, but from this moment to the end of blow-down, steam is added to the flow.

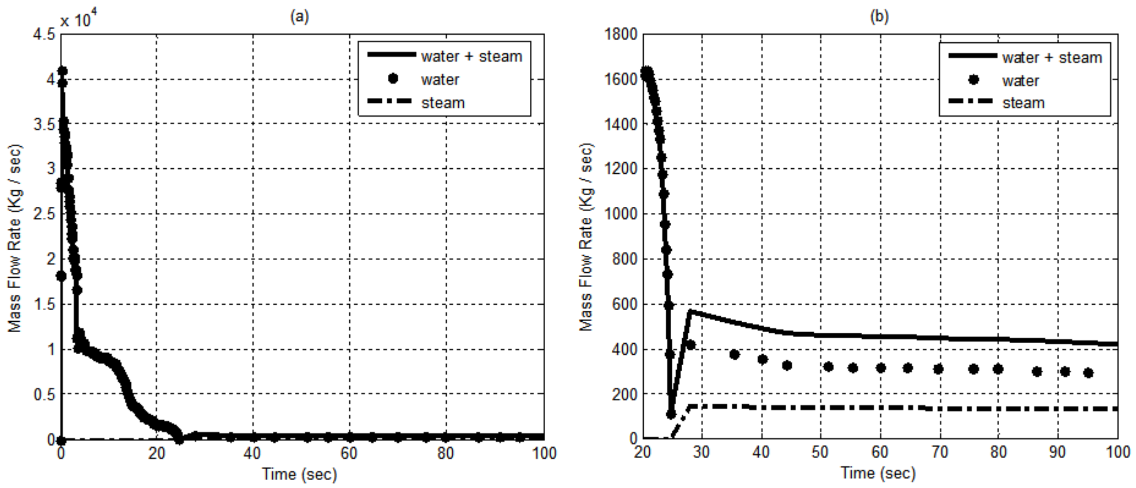

Fig. 3: Distribution of Integrated Mass Flow Released with Time

In Figure.3 distribution of integrated mass flow that released to the containment is represented in several modes. As shown in this figure, it is clear that water plus steam flow result matches with the report [7].

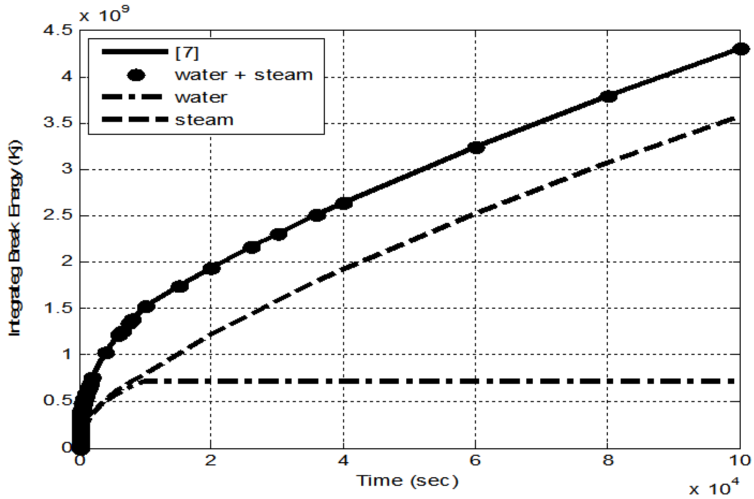

Fig. 4: Distribution of Integrated Energy Released with Time

Total integrated energy that released is combined with water plus steam flow (Like Figure.4). Because this summation of flows constitutes the total flow which is compatible with report [7] (All of integrated mass and energy plots are modeled with trapezoidal integration method).

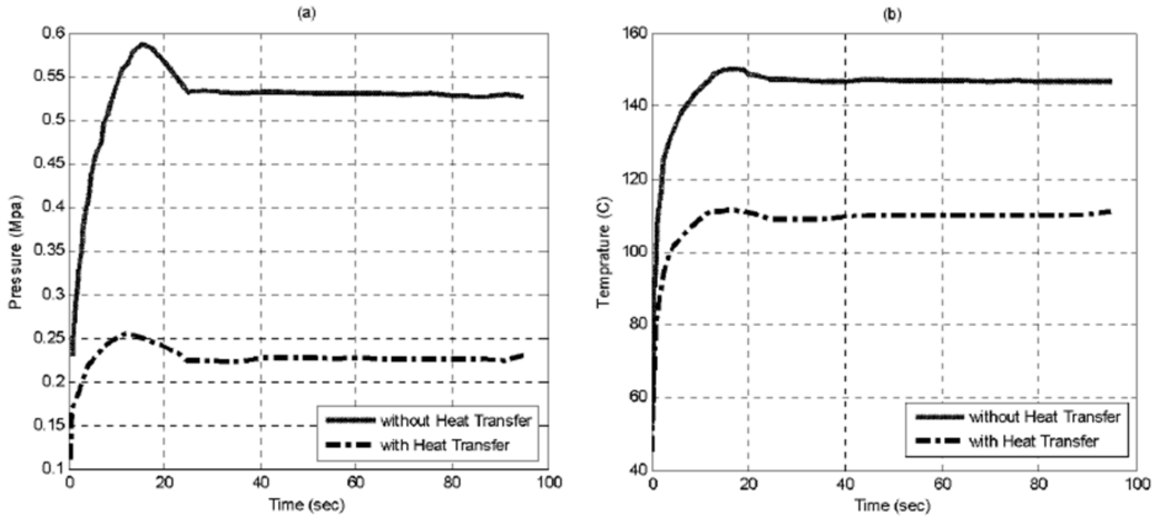

Fig. 5: Pressure and Temperature Variations with respect to time in Short Term

Influence of heat transfer is denoted prominently. As shown in Figure.5 (a) and (b), each plot peaks between 15 to 20 seconds, and this is because of variations of input flow.

Figure.6 plots (a) and (b) are similar to short term condition, but with great shifts in peak times. The influence of heat transfer is more prominent in long term and this, embosses the effects of heat transfer in accidents. In this model the effects of drained water are ignored. Containment faces overpressure if there is rupture in entrance of fresh air to the gaps.

The shapes of all plots are influenced by the variations of mass flow rate, even heat transfer and convection heat transfer coefficients in Figure.7 (a) and (b). The temperature of riser is greater than the down-comer and ambient, and the convection coefficient of riser is bigger than all. Also down-comer convection coefficient is bigger than ambient and it is influenced by higher temperature of down-comer with respect to ambient.

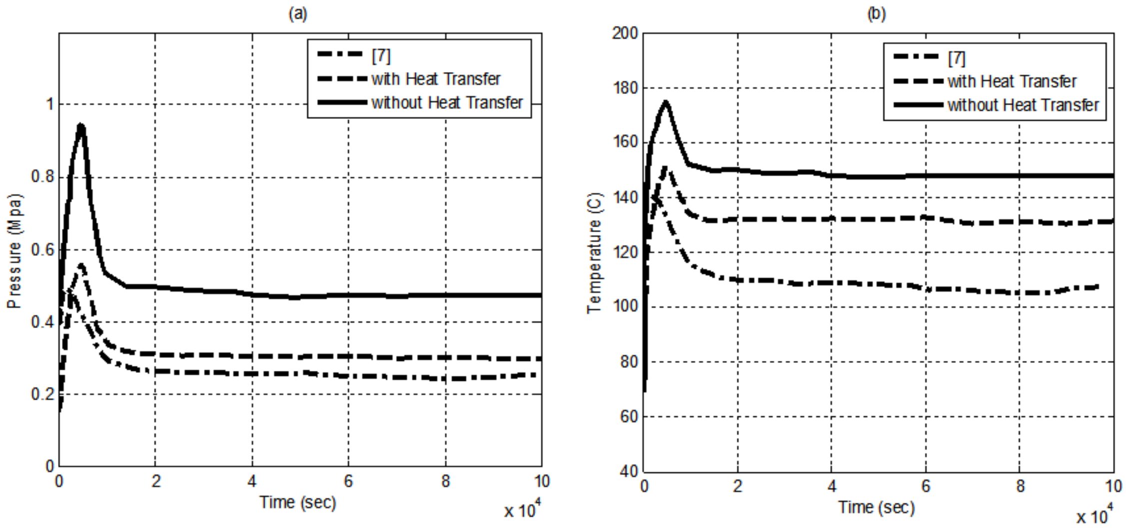

Fig. 6: Time variations of Pressure and Temperature in Long Term

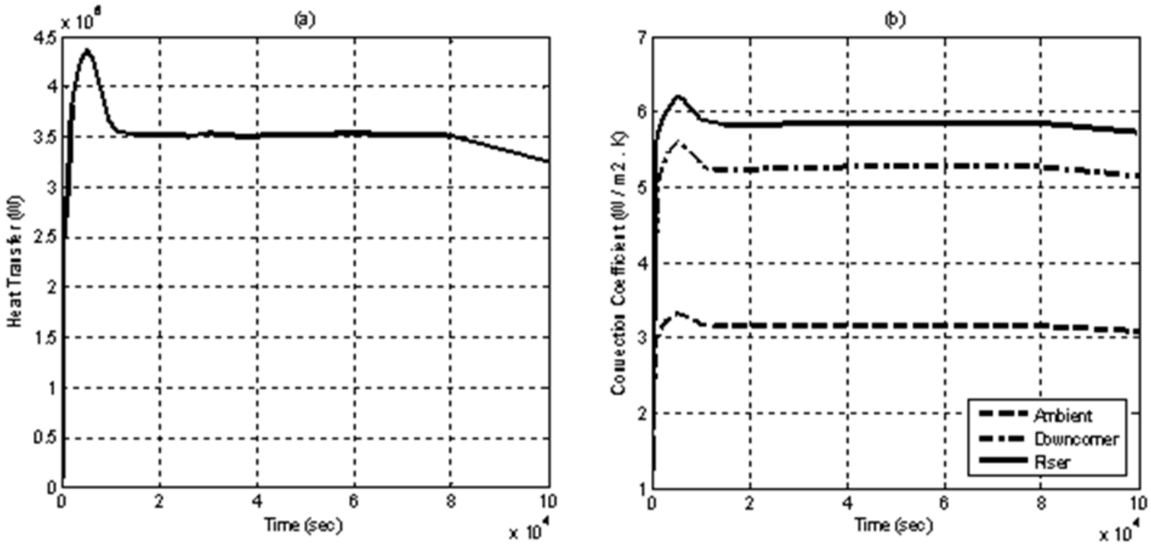

Fig. 7: Heat Transfer and Convection Heat Transfer Coefficient Variations

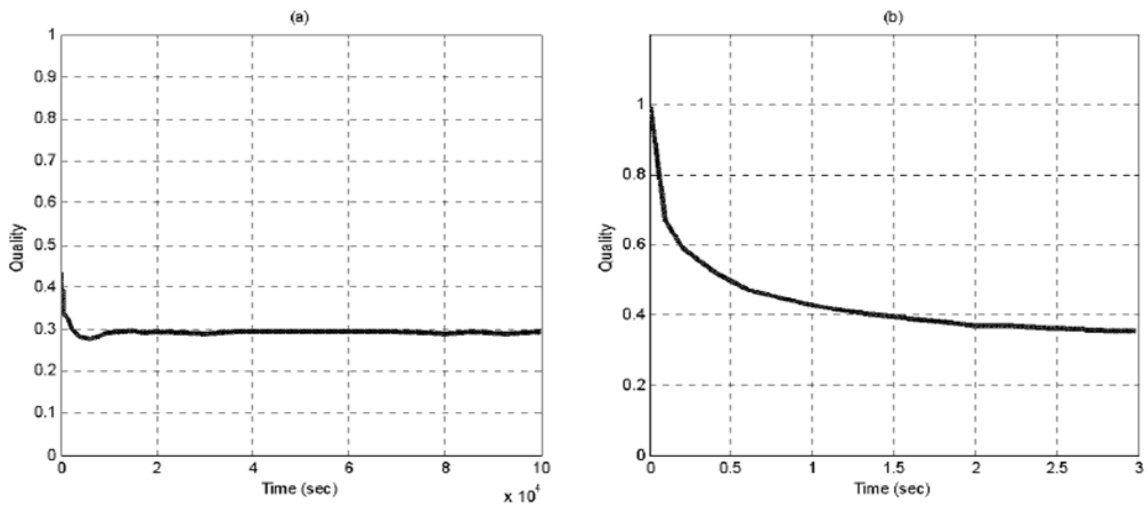

Fig. 8: Variations of Quality.

This model is based on two phase (water plus steam) condition (except for the integrated mass and energy released).

The quality changes in containment have been shown in Figure.8 (a) and (b).

In Table.2 brief results have been shown with differences between model and report [7].

Table 2: Summary of results with differences between model and report [7].

Break	Pressure Peak (Mpa)	Temperature Peak	Difference Between Model Pressure and [7] (Mpa)	Difference Between Model Temperature and [7]
[7] Results for Long Term	0.49	140.5	---	---
Short Term without Heat Transfer	0.5865	150	0.0965	9.5
Short Term with Heat Transfer	0.2544	111	0.2356	29.5
Long Term without Heat Transfer	0.9411	174	0.4511	33.5
Long Term with Heat Transfer	0.5531	151	0.0631	10.5

Conclusions:

By comparing the results from the model and report [7] it is seen that the two phase simulation of LOCA accident in AP1000 with single volume method is acceptable, also due to little differences observed between the consequences of modeling and report [7], it can be inferred that mathematical procedures and conjectures in transients, equilibrium conditions and heat transfer, with receivable assumptions are useful approximations for AP1000 systems. In both short and long term conditions without heat transfer, pressure peaks are over designed pressures (0.5013MPa) [19]. This verity is clear that without any heat transferring, safety is not possible. But in short term with heat transfer, pressure peak is under designed pressure. Therefore, air flow without any help of PCCWST is sufficient for cooling the containment. And finally in most important conditions, in long term with heat transfer, peak of pressure is over the design, hence, it is obvious that natural air flow is not sufficient for long term for cooling, and Passive Containment Cooling Water Storage Tank is a necessity for cooling the containment and suppression of reaching to design pressure.

Nomenclature of Mathematical Formulation and Heat Transfer Is Shown Below:

m_a is the mass of containment air,
m_{wc} is water vapor in the containment air,
m_{wp} is water initially in the primary (or secondary) system depending on rupture assumption,
m_{wpd} at any given time, of the mass m_{wp}, has discharged into the containment,
m_{wpr} is remained portion of m_{wp} in the primary system,
V_c is the net free volume of containment,
V_p is the volume of primary system,
V_T is the total volume (V_c+V_p),
m_{wa} is the mass of water initially in the containment air,
m_w is the mass of water, which is composed of water vapor initially in the air and water or water and steam initially in the failed system, i.e., m_{wa}+m_{wp},
$u = u\ (T,v)$ is the internal energy per unit mass defined with respect to a reference internal energy $u_0\ (T_0,\ v_0)$ per unit mass,
u_w is the internal energy of the water in the containment air and the water in the failed system, i.e., u_{wa} and u_{wp},
c_{pa} is specific heat of air at constant volume,
$Q_{n\text{-}wpr}$ is heat transferred from fuel to water remaining of primary cycle,
$Q_{wpr\text{-}c}$ is heat transferred from water remaining of primary cycle to control volume,
$Q_{c\text{-}st}$ is heat transferred from control volume to structures (which is modeled in heat transfer),

T_a is air temperature,
T is temperature for the air/steam mixture in the containment,
$T_{sat.}$ is the internal air/steam mixture temperature in the containment (it is equal to T),
p is the pressure of mixture,
p_w is partial pressure of the saturated water vapor corresponding to T,
p_a is partial pressure of air corresponding to T,
$T_{in.cont.}$ is the interior surface of containment temperature,
R is universal gas constant,
u is specific internal energy and U is internal energy,
v is specific volume,
h is specific enthalpy,
μ is absolute viscosity,
δ is thickness of gaps,
K is thermal conductivity coefficient,

$\dot{m}$ is mass flow rate,

x_{st} is static mass quality,
$r_{in.cont.}$ is the interior radius of containment,
l is the active height of heat transfer which is common in all thermal layers,
$h_{cont.}$ containment convection heat transfer coefficient,

Indices:

Subscripts w and f refer to water, g refers to vapor, fg refers to evaporation, a refers to air, sat refers to saturation condition, and superscripts t refers to time t, and $t+\Delta t$ is one time step beyond the time t.

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