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AN ANALYTICAL MODEL FOR TRANSIENT FLUID MIXING IN UPPER OUTLET PLENUM OF AN LMFBR*

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ABSTRACT

A two-zone mixing model based on the lumped-parameter approach was developed for the analysis of transient thermal response in the outlet plenum of an LMFBR. The maximum penetration of core flow is used as the criterion for dividing the sodium region into two mixing zones. The model considers the transient sodium temperature affected by the thermal expansion of sodium, heat transfer with cover gas, heat capacity of different sections of metal and the addition of bypass flow into the plenum. The results of numerical calculations indicate that effects of flow stratification, chimney height, metal heat capacity and bypass flow are important for transient sodium temperature calculation. Thermal expansion of sodium and heat transfer with the cover gas do not play any significant role on sodium temperature.

INTRODUCTION

The current design of loop-type Liquid Metal Cooled Fast Breeder Reactor (LMFBR) plant contains a large volume of sodium stored in the upper outlet plenum. This large fluid volume can significantly attenuate the magnitude of transient temperature change issuing from the core prior to its impacting on the primary loop heat transport system. Thus, predicting the thermal response of the fluid in the upper plenum under various off-normal or accident conditions is important for the overall safety evaluation of the reactor system.

In the simplest mixing (perfect or complete mixing) model, the mixing process is characterized as that occurring in a well-stirred chamber. This model is satisfactory if the temperature of coolant entering the plenum is higher than the average temperature of the fluid in the plenum. It is believed that the momentum of the core flow aided by the positive buoyancy force is sufficient to provide a full penetration and results in complete mixing in the plenum. However, recent experiments have shown that this simplified model is inadequate under certain off-normal or accident conditions. The flow stratification within the plenum can occur if (a) the fluid entering the plenum is colder than that in

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DISCLAIMER

the plenum and (b) the fluid experiences a large decrease in momentum. Consequently, recent analytical models[1,2] have attempted to include the stratification effect by confining the mixing of fluids within the penetrating region only. The penetration distance is calculated from Bernoulli's equation.

In addition to the two aforementioned mixing models, the mixing process is further complicated by the interactions among the various components in the upper plenum. These interactions involve the metal heat capacity, bypass flow, thermal expansion of sodium and interface heat transfer between sodium and the cover gas, etc. A review of various analytical models shows that systematic study of the effects of these interactions on the two basic mixing processes has not been reported in literature.

This paper presents a detailed study of the mixing process in a general form. The maximum penetration distance of the core flow is determined from the analysis of one-dimensional turbulent jet equations.[3] The penetration distance is used to develop the two-zone mixing model. The model includes the interactions among the various components in the plenum. The purpose of this study is to determine the relative importance of different effects for the safety analysis of an LMFBR plant.

ANALYSIS

The physical model considered in this study is shown in Fig. 1. The upper

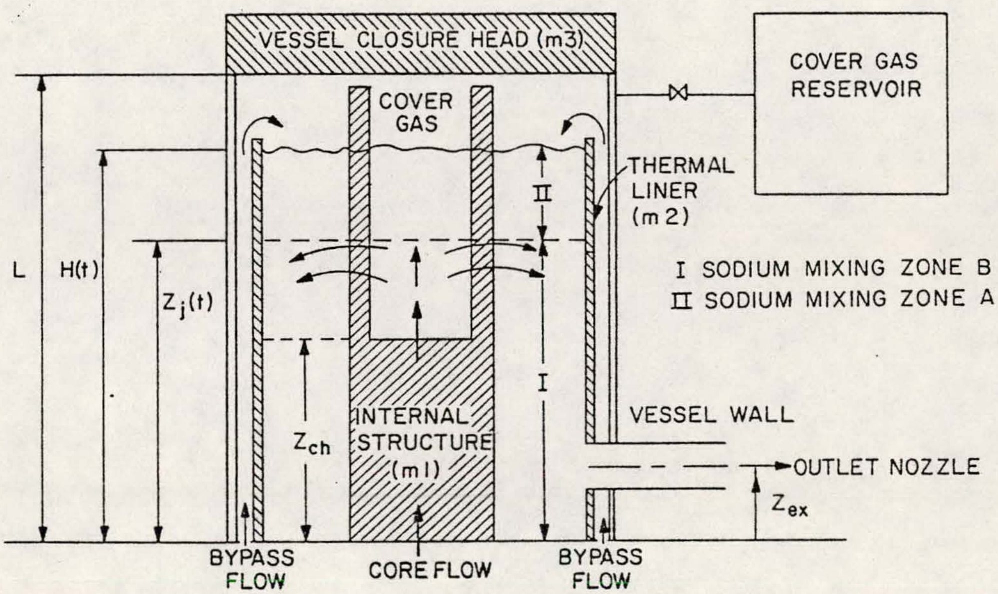

Figure 1. Schematic diagram for fluid mixing in the upper outlet plenum.

plenum contains a large volume of sodium, an annular bypass channel, a small region occupied by the cover gas and three sections of metal. Fluid leaving the reactor core enters the plenum from the bottom section, while a small percentage of cold bypass flow enters the plenum through the annular space formed by the thin thermal liner and the vessel wall. The outlet flow is represented by an exit nozzle. The support columns, chimney of the outlet module, control rod drive mechanism, vertex suppressor plate, control assembly, cellular flow collector, baffle, and all other structures are lumped together and represented by a section of mass (ml) immersed in fluids. The cylindrical thermal liner is indicated as m2. The vessel closure head and other metals above the cover gas region are considered as mass m3. The cover gas region is connected to a large reservoir which represents all its connections, such as the overflow tank, equalization line header and gas region of the loop pumps. The sodium region is divided into two zones according to the maximum penetration distance of the core flow. The upper mixing zone is denoted as zone A and the lower zone as zone B.

The basic assumptions are:

1) Core flows from different channels into the upper plenum are represented by a single equivalent flow. This flow is associated with the mass-average enthalpy of the different channel flows.

2) The maximum penetration distance, which is related to the initial Froude number, divides the upper plenum into two mixing zones. Full penetration is assumed for flow with positive buoyancy.

3) The mixing process in both zones is described by the lumped-parameter approach; i.e., perfect mixing in each zone is assumed.

4) The cover gas obeys perfect gas law, and it is initially in equilibrium with the gas in reservoir.

The governing equations which determine the instantaneous sodium level and various temperatures are given below:

Sodium level:

$$\frac{dH}{dt} = \frac{W_i - W_{ex}}{\bar{\rho} A_{g\ell}} + H \left[(1 - f)\, \alpha(T_B) \frac{dT_B}{dt} + f\, \alpha(T_A) \frac{dT_A}{dt} \right] \tag{1}$$

Sodium in upper mixing zone A:

$$\frac{dE_A}{dt} = \frac{1}{\rho_A A_{g\ell} H f} \left\{ W_{BP}(E_{BPE} - E_A) + \beta_1 W_C (E_B - E_A) + h A_{g\ell}(T_B - T_A) + U_g A_{g\ell}(T_g - T_A) + U_\ell f \left[A_{\ell m1}(T_{m1} - T_A) + A_{\ell m2}(T_{m2} - T_A) \right] \right\} \tag{2}$$

Sodium in lower mixing zone B:

$$\frac{dE_B}{dt} = \frac{1}{\rho_B A_{g\ell} H(1-f)} \left\{ W_C(E_C - E_B) + \beta_2 W_{BP}(E_A - E_B) + h A_{g\ell}(T_A - T_B) + U_\ell (1 - f) \left[A_{\ell m1}(T_{m1} - T_B) + A_{\ell m2}(T_{m2} - T_B) \right] \right\} \tag{3}$$

Cover gas:

$$\frac{dT_g}{dt} = \frac{U_g}{(mC)_g} \left[A_{g\ell}(T_A - T_g) + A_{gm1}(T_{m1} - T_g) + A_{gm2}(T_{m3} - T_g) \right] \tag{4}$$

Metal m1 (Internal structure):

$$\frac{dT_{m1}}{dt} = \frac{1}{(mC)_{m1}} \left\{ U_\ell \; A_{\ell m1} \left[f \; T_A + (1 - f) \; T_B - T_{m1} \right] + U_g \; A_{gm1} (T_g - T_{m1}) \right\} \tag{5}$$

Metal m2 (Thermal liner):

$$\frac{dT_{m2}}{dt} = \frac{1}{(mC)_{m2}} \left\{ U_\ell \; A_{\ell m2} \left[f \; (T_A - T_{m2}) + (1 - f) \; (T_B - T_{m2}) \right] \right.$$

$$\left. + U_g \; A_{gm2} (T_g - T_{m2}) + (UA)_{BP} \; (T_{BPM} - T_{m2}) \right\} \tag{6}$$

Metal m3 (Vessel Closure head):

$$\frac{dT_{m3}}{dt} = \frac{U_g A_{gm3}}{(mC)_{m3}} \; (T_g - T_{m3}) \tag{7}$$

The auxiliary equations required by the above governing equations are

$$T_{BPE} = T_{m2} + (T_{BPI} - T_{m2}) \; \exp\left(- \frac{UA}{WC} \right)_{BP} \tag{8}$$

$$T_{BPM} = T_{m2} + (T_{BPI} - T_{BPE}) \left(\frac{WC}{UA} \right)_{BP} \tag{9}$$

$$W_i = W_C + W_{BP} \tag{10}$$

$$f = 1 - z_j(t) \; / \; H(t) \tag{11}$$

$$\overline{\rho} = (1 - f) \; \rho_B + f \; \rho_A \tag{12}$$

and the liquid sodium densities, ρ_A and ρ_B, are obtained from its constitutive relationships. The contact areas between the cover gas and liquid or metals ($A_{g\ell}$, A_{gm1}, A_{gm2} , A_{gm3}) and between liquid and metals ($A_{\ell m1}$, $A_{\ell m2}$) are obtained by assuming that the cross-sectional areas in direction perpendicular to the jet are constant during transients.

In the above equations, there are two control indices β_1 and β_2 which take values of either 0 or 1 depending upon the relative location of the outlet nozzle and the maximum jet penetration height, z_j. Their values are noted below:

$\beta_1 = 0$ and $\beta_2 = 1$ for $z_j \geq (z_{ex} + \frac{1}{2} D)$

$\beta_1 = 0$ and $\beta_2 = 0$ for $(z_{ex} - \frac{1}{2} D) < z_j < (z_{ex} + \frac{1}{2} D)$

and

$\beta_1 = 1$ and $\beta_2 = 0$ for $z_j \leq (z_{ex} - \frac{1}{2} D)$

The maximum penetration height is taken from a semi-empirical correlation.[3] It is given as

$$z_j = (1.0484\ Fr_o^{0.785})\ r_o + z_{ch} \tag{13}$$

where Fr_o is the local Froude number and is defined as

$$Fr_o = \left(\frac{W_C}{\pi r_o^2\ \rho_C}\right)^2 \left[\frac{\rho_B}{g r_o\ (\rho_C - \rho_B)}\right] \tag{14}$$

For the case of full penetration, i.e., for $z_j(t) = H(t)$, f becomes zero. Equations (2) and (3) are then replaced by the following equations:

$$\frac{dE_B}{dt} = \frac{1}{\rho_B A_{g\ell} H} \Big\{ W_C(E_C - E_B) + W_{BP}(E_{BPE} - T_B) + U_g A_{g\ell}(T_g - T_B) + U_\ell \left[A_{\ell m1}(T_{m1} - T_B) + A_{\ell m2}(T_{m2} - T_B)\right]\Big\} \tag{15}$$

$$E_A = E_B \tag{16}$$

The cover gas mass is determined by assuming that the temperature of the gas in the reservoir remains constant and its pressure equals that of the cover gas in the vessel at any instant. The cover gas mass is then given by

$$M_g(t) = \frac{M_t\ V_g(t)\ T_{res}}{V_{res}\ T_g(t) + V_g(t)\ T_{res}} \tag{17}$$

where

$$V_g(t) = [L - H(t)]\ A_{g\ell}$$

These equations when coupled with the boundary conditions ($W_C(t)$, $W_{BP}(t)$, $E_C(t)$, $T_{BPI}(t)$ and $W_{ex}(t)$) provide for a complete solution to the problem, i.e., the height of sodium, and coolant and other temperatures are obtained.[4] Using prototypical CRBR parameters actual computations were performed for two cases. Results are discussed in the following.

RESULTS AND CONCLUSIONS

A simplified boundary condition, which corresponds approximately to the case of normal scram and flow coastdown, was used so that our results can be compared with that obtained from the MIX code.[5] The average core exit temperature was assumed to decrease linearly from 834 K to 693 K in ten seconds and to 667 K in 110 seconds. The core flow rate was dropped exponentially to about 10% in 35 seconds and was assumed to remain constant beyond this time. The computed sodium temperature at outlet nozzle and mixing zone heights are shown in Fig. 2. Our computations were made by using perfect mixing (1-zone) as well as two-zone models. The flow stratification is illustrated by the instantaneous height of the two mixing zones. Initially, the core flow yields a full penetration and the entire plenum can be considered as a single mixing zone. As the momentum and temperature of the core flow are continuously decreasing, the penetration of the core flow is reduced and develops into a two-zone mixing.

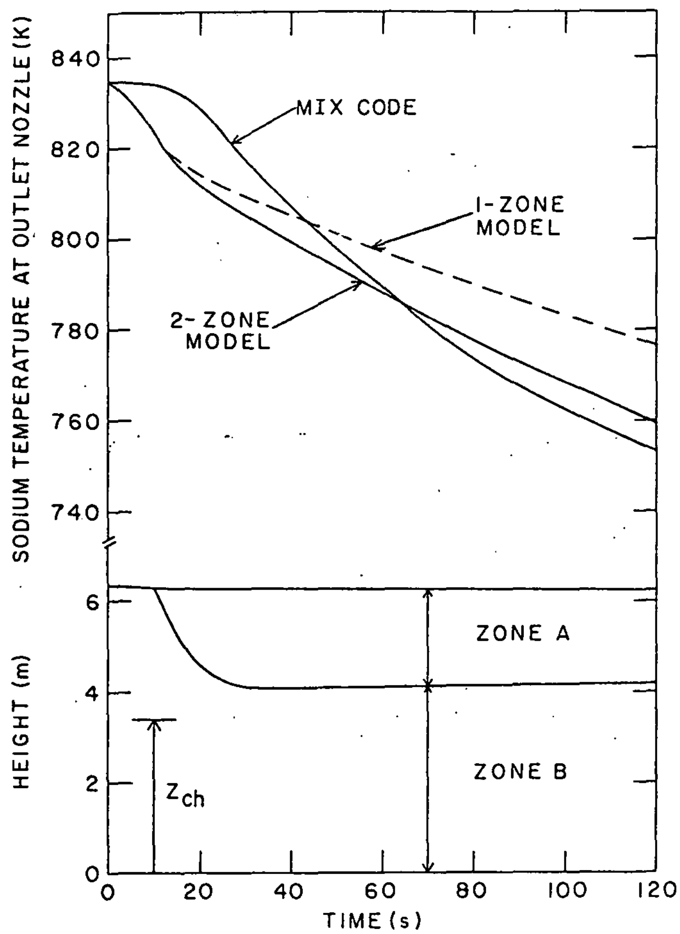

Figure 2. Comparison of the present mixing models with MIX code.

The present results were also compared with that obtained from a more detailed two-dimensional MIX code. As it can be seen from Fig. 2, MIX predicts a much slower change in sodium temperature during first twenty seconds. During this time, the MIX code prediction differs significantly (maximum difference of about 15 K) from either single-zone or two-zone mixing models of the current analysis. An inspection of comparison between MIX predictions and ANL experimental data[2,5] reveals that for most of the cases, MIX predicts a very slow response during the first 10 or 20 seconds. As the transient continues, the 2-zone mixing model (one-dimensional in space) exhibits a reasonably good agreement with the 2-D MIX code and is clearly better than the single-zone model.

An analysis of sodium mixing in the outlet plenum was also performed for the case of a double-ended pipe rupture. The boundary conditions (shown in Fig. 3) such as the core flowrate, upper plenum exit flow rate and core flow temperature were obtained from the preliminary computations with the DEMO code. The predicted sodium temperature in the lower mixing zone (zone B) is also included in this figure. It is seen that the core flow is characterized by negative buoyancy during the period between 11 to 52 seconds. Thus, it is expected to have one-zone and two-zone mixing occurring alternately during the transient.

Computed values for various temperatures are plotted in Fig. 4. The curves of two sodium temperatures reveal the short period (27 to 52 seconds) of two-zone mixing. Due to the large time constant associated with metals, the metal temperatures (T_{m1}, T_{m2} and T_{m3}) remain practically constant. The cover gas

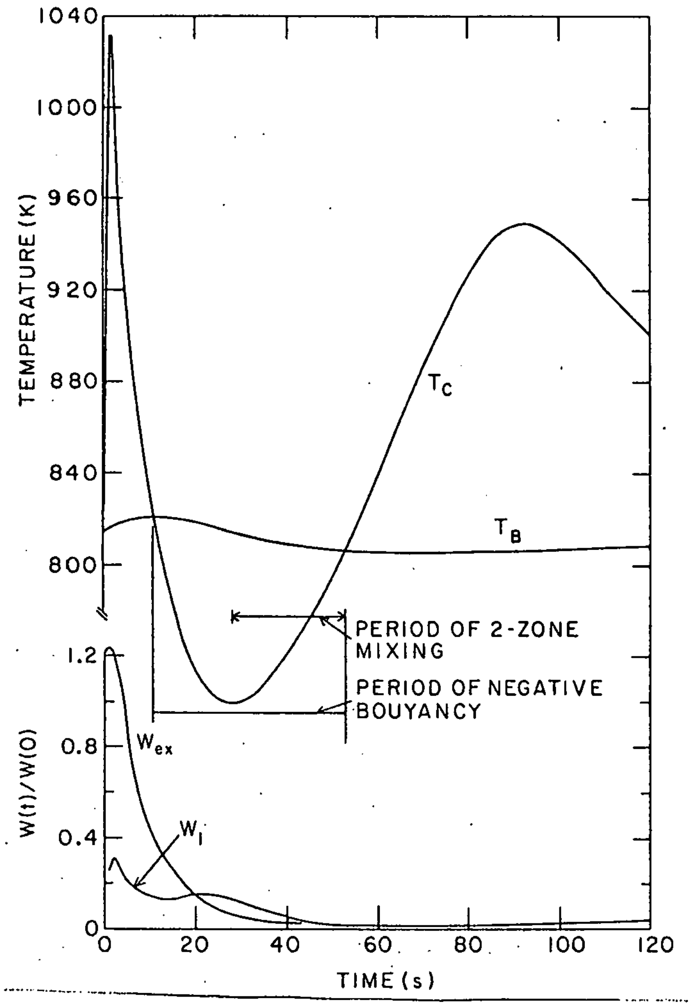

Figure 3. Transient boundary condition used for the case of a double-ended pipe rupture in the primary heat transport system.

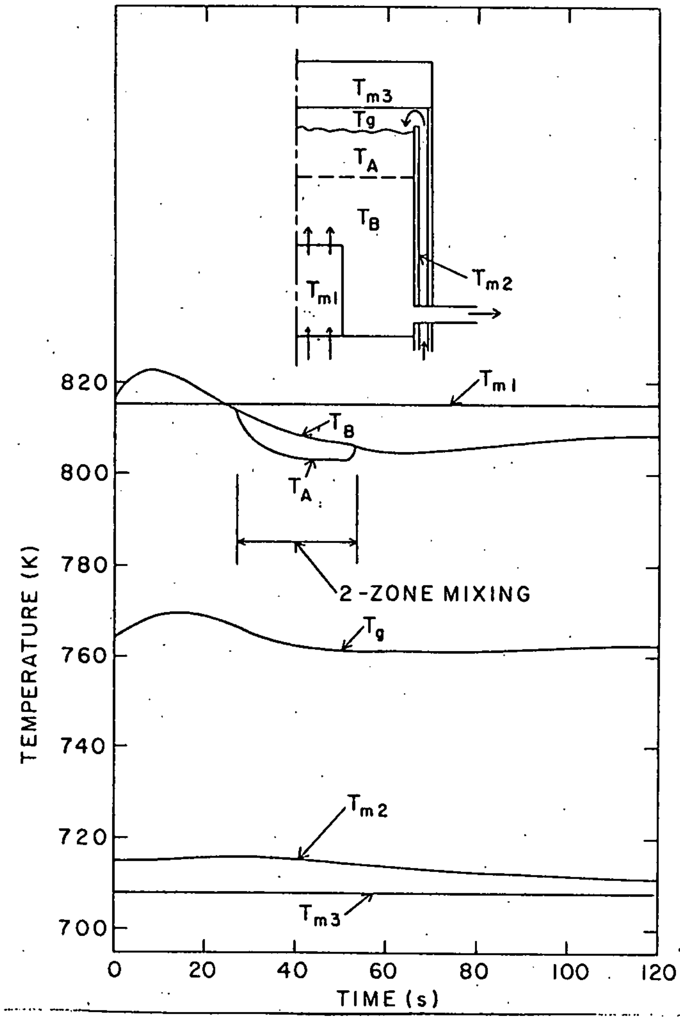

Figure 4. Computed transient temperatures for the double-ended pipe rupture case.

temperature, on the other hand, follows closely that of sodium in the upper zone since the cover gas was assumed to be isolated from the reservoir tank. The small discontinuity (∿ 1 K) in sodium temperature at 52 is caused by the sudden change from the two-zone mixing into single mixing as the buoyancy force of the core flow changes from negative to positive.

Figure 5 shows (a) sodium temperature at the outlet nozzle and (b) the maximum jet penetration distance for three different chimney heights. This figure illustrates the importance of chimney on the coolant mixing in the plenum. For Curves 1 and 2, the top of the chimney is higher than the height of the outlet nozzle and the nozzle is completely located within the lower mixing zone. Hence, the sodium temperature at the outlet nozzle does not differ much for the two cases. In contrast to Curves 1 and 2, a large variation of the temperature is predicted (see Curve 3) when chimney height is reduced below the outlet nozzle. In this case, the nozzle is exposed to both upper and lower mixing zones. A large temperature variation occurs when the interface of the two zones passes through the outlet nozzle. Further calculations show, as expected, that the temperature variation is even more pronounced when the chimney is completely removed.

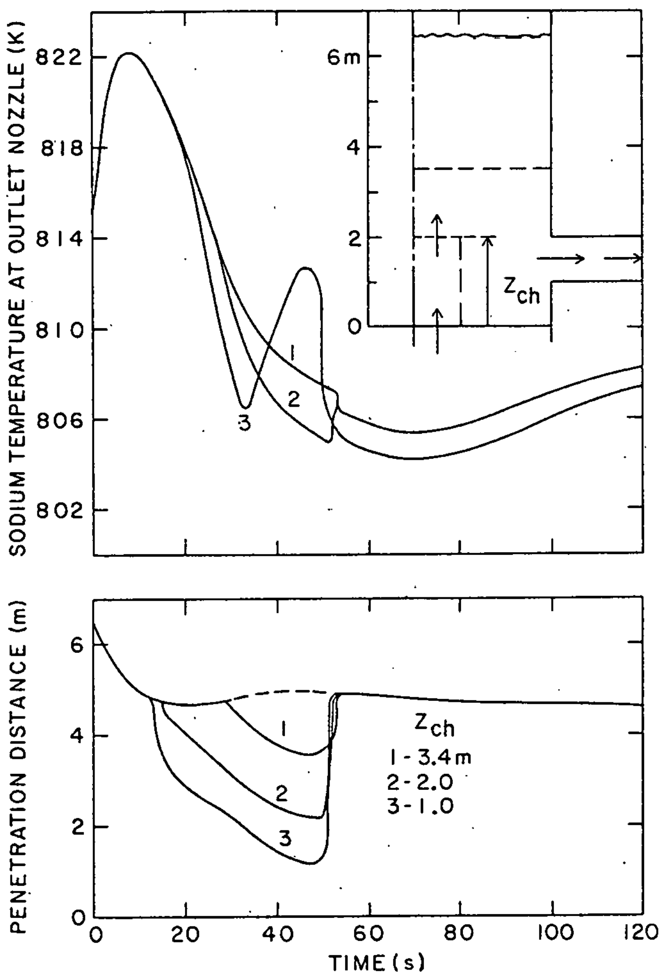

Figure 5. Effect of chimney height in sodium temperature at outlet nozzle.

The effects of metal heat capacity, bypass flow, the thermal expansion of sodium and heat transfer with the cover gas on the upper plenum were also investigated. The details are given in Ref. [4].

Based on these studies the following conclusions have been arrived at:

1. The transient mixing process in the upper plenum can be characterized by the present 2-zone, one-dimension in space mixing model.

2. Stratification effect is important when the exiting core flow is characterized by negative buoyancy. Perfect mixing model is inadequate for this situation.

3. Metal heat capacity and bypass flow are not negligible for calculation of transient sodium temperature.

4. Thermal expansion of sodium and heat transfer to cover gas have no significant effect on transient sodium temperature.

5. Chimney structure attached to the core is important in promoting complete mixing. Height of the chimney has an important effect on sodium temperature at the outlet nozzle.

NOMENCLATURE

Symbol	Description	Subscript	Description
C	Heat Capacity	BP	Bypass flow
D	Diameter of outlet nozzle	BPE	Exit of bypass flow
E	Enthalpy	BPI	Inlet of bypass flow
h	Heat transfer coefficient	BPM	Mean value of bypass flow
t	Time	C	Core flow
T	Temperature	ch	Chimney
U	Overall heat transfer coefficient	ex	Exit of outlet nozzle
V	Volume	g	Cover gas
z_j	Maximum penetration distance of jet flow	i	Inlet end of upper plenum
		ℓ	Liquid sodium
α	Thermal expansion coefficient	res	Cover gas reservoir
		t	Total

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