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The Development of the Thermohydraulic Analysis Code for the Passive Containment Cooling System : PCCSAC

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ABSTRACT

To estimate the performance of the passive containment cooling system(PCCS) of the AC—600 nuclear power plant, the PCCSAC code is developed currently by the jointed efforts between Tsinghua University and NPIC. Different featureson the passive behavior of the system and the main components of the containment are considered in the code which is needed by the further AC—600 R & D Program. With a brief description of the AC—600 passive containment cooling system and components, the main thermohydraulic models and numerical scheme used in thePCCSAC code are introduced and the selected results of the verification and the prediction for the performance of the AC—600 passive containment cooling system under LOCA and a steam line break accident are presented to preliminarily demanstrate the applicability and reliability of the PCCSAC model. The current PCCSAC model is conservative and a further 2—D PCCSAC version is under consideration in addition to provide the database for models from some tests associated with the components and systems unique to AC—600 nuclear power plant to meet the requirement of the more realistic modelization for the AC—600 passive containment cooling system.

1. INTRODUCTION

Under the sponsorship of the State Science and Technology Commission ofthe People' s Republic of China, the R & D Program of AC — 600 nuclear power plant, an advanced passive nuclear reactor design, is in progress to meet the need forsafe, dependable, and affordable electrical power in the near future.

The AC — 600 is based on the 600 MWe two — loop pressurized water reactor (PWRs) power plant designed by Nuclear Power Institue of China (NPIC). However, the AC — 600 uses safety systems that rely on predominantly on natural forces such as gravity, convection, and natural circulation. This combination provides increased reliability and public safety, as well as a significant reduction inequipment seismic building volume, resulting in reduced capital cost and ashortened construction schdule.

The Program is supported by developing some useful codes in addition tosome tests associated with components and systems unique to AC — 600 plant, especially where their performace and operation is essential to the natural safety concept upon which the AC — 600 plant is based. A major portion of the AC — 600 R & D Program is devoted to the study of the Passive Containment CoolingSystem (PCCS).

The Passive Containment Cooling System is designed to transfer core decay heat from the containment to the outside air, which then acts as the ultimate heat sink, as shown in Figure 1. The containment vessel is a cylindrical steel pressure vessel surrounded by a concrete shield building with an air baffle in between, supported off the cylindrical steel pressure vessel. Air is drawn through intakes at the tip of the cylindrical portion of the shield building. This air flows downward between the baffle and the shield building. It makes a 180 degrees turn and then flows upward between the steel shield and the baffle, thereby cooling the outside of the containment vessel. The heated air is exhausted through a chimney at the top of the shield building. Inside the containment, steam condenses on the vessel walls and drains back via a collection system to the sumps. The external cooling is enhanced by spraying water onto the dome of the containment vessel from a storage tank located at the top of the shield building.

To estimate the performance of the AC — 600 passive containment cooling system, the PCCSAC code is developed currently by the jointed efforts between Tsinghua University and NPIC. Different features on the passive behavior of the system and components, included as following :

- Saturated water inside sumps steaming to containment atmosphere and steam condensation in the presence of noncondensable gases on the inside of the steel containment vessel;
- The external cooling by spraying water onto the dome of the containment vessel from a storage tank located at the top of the shield building;
- The heat transfer from the outside of the steel containment vessel by evaporating a water film on the wetted outside area of the containment surface;
- And natural buoyancy driven forced convection heat transfer from the water film or containment surface to air;

are considered in the code which is needed by the further AC—600 R & D Program.

2. BASIC PCCSAC MODELS

PCCSAC is a transient thermohydraulic code for passive containment cooling analyses. The thermohydraulic model and the associated numerical scheme are based on the use of fluid control volumes and junctions to represent the spatial character of the flow. The basic PCCSAC models are constituted under assumptions and the modeling philosophy as briefly described below:

2. 1. Containment Space:

The whole space inside containment is considered as a single control volume in which the kinetic and potential energy are disregared. Water, steam and gases exist in equilibrium condition. The set of conservation equations consist of the water and steam mass balance respectively and an overall energy balance as follows:

$$\frac{dM_{LC}}{dt} = W_{LB} - W_{LVD} + W_{SP} - \gamma M_{LC} - W_{LVC} \qquad (2-1)$$

$$\frac{dM_{VC}}{dt} = W_{VB} + W_{LVB} - W_{CSU} - W_{WC} + W_{LVC} \qquad (2-2)$$

$$\frac{d}{dt}(M_{LC}h_{LC} + M_{VC}h_{VC} + M_{ac}h_{ac})$$
$$= W_{LB}h_{LB} + W_{VB}h_{VB} + W_{SP}h_{sp} - W_{WC}h_{VC}$$
$$- W_{CSU}h_{VC} - \gamma M_{LC}h_{LC} - Q_{WC} - Q_{CSU} + V_C dP_C/dt \qquad (2-3)$$

2. 2. Sumps

PCCSAC uses a volume having the same pressure as that of atmosphere space inside containment to represent sumps filled with water and the effect on energy balance due to the change of pressure is neglected. Both mass and energy balance may be given below:

$$\frac{dM_{SU}}{dt} = \gamma M_{LC} + W_{CSU} + W_{WC} - W_{SU} \qquad (2-4)$$

$$\frac{d}{dt}(M_{SU}h_{SU}) = W_{WC}h_{LC} + W_{CSU}h_{VC} + \gamma M_{LC}h_{LC}$$
$$+ Q_{CSU} - W_{SU}h_{SU} - Q_{WSU} \qquad (2-5)$$

2. 3. Water Film

Water film formed by spraying water onto the dome of the steel containment vessel from a storage tank located at the top of the shield building is divided into control volumes along the direction of water film flow and its pressure is equal to that of its environment. The quasi—steady—state scheme is applied to determine the outlet flow from a volume when steady water film is established:

$$\frac{dM_{LF}}{dt} = W_{LFIN} - W_{LFEX} - W_{LFq} \qquad (2-6)$$

$$\frac{d}{dt}(M_{LF}h_{LF}) = W_{LFIN}h_{LFIN} - W_{LFEX}h_{LF} - W_{LFq}h_V + Q_{WLF} - Q_{LFq} \qquad (2-7)$$

2. 4. Air Natural Circulation

The concrete shielding building and baffle around the containment define the air flow path which is nodelized in PCCSAC by control volumes also along the direction of air natural circulation flow with a pressure identical to the surroundings. Dry air and lower partial pressure steam meet the state equations of ideal gases. A velocity of air natural circulation flow is predicted on the basis of the balance between air flow resistance and air density difference:

$$\frac{d\rho_v}{dt}=\frac{U_{gin}A_{in}\rho_{vin}-U_{gex}A_{ex}\rho_v}{V} \qquad (2-8)$$

$$\frac{dh_g}{dt}=\frac{U_{gin}A_{in}\rho_{vin}h_{gin}-U_{gex}A_{ex}\rho_v h_g+Q_{LFg}-Q_{Wg}}{V_{pg}} \qquad (2-9)$$

2.5. Numerical Scheme

The backward difference scheme known as Gear algorithm is basically applied to solve a stiff problem of ordinary differential equations derived from physical models. In addition, the methods of complete pivot Gauss—Jordon, Newton iterative, selected Lagrange and variable step Simpson are chosen for the solution of inverse matrix, nonliear eqution, interpolation function with the discrete points and numerical integration, respectively.

3. VERIFICATION AND APPLICATION

The PCCSAC verification is preliminary currently and a furthur concern will focus on comparing results with related test results as wind tunnel tests completed recently by the other department of NPIC that examined the performance of the natural circulation of the air on the outside of the containment shell, and the planned heat transfer tests on flat plates simulating water evaporation and steam condensation from the steel surfaces of the containment, as well as the further study of water distribution on the outside of the containment shell.

The results of the PCCSAC code indicates a good agreement with the COMMIX code for the prediction of the water film distribution of steam condensation onthe inside surface of the steel containment in the presence of noncondensable gases while the system became steady as shown in Figure 2 and 3 and also for the simulation of the transient spraying water film distribution on the outside of the containment shell as given by Figure 4 and 5 but an obviously different temperatures of the water film both on the inside and the outside containment shell shown in Figure 6 and 7 as COMMIX code uses 3—D model to describe the containment space.

The PCCSAC nodalization for the PCCS is presented in Figure 8. The selected PCCSAC results estimating the performance of the AC—600 passive containment cooling system under LOCA and a steam line break accident are presented below. Figure 9 shows the transient pressure inside the containment following a double—ended hot leg LOCA. The pressure rises rapidly due to the blowdown mass and energy from the reactor coolant system and reaches a first peak of 0. 27 MPa at about 12 seconds and the highest temperature is about 118 C. Figure 10 shows a pressure transient fowllowing the main steam line break and the high pressure setpoint of 0. 24 MPa is reached at about 4. 4 seconds. These calculations are performed as part of the PCCSAC code development at present.

4. SUMMARY

The PCCSAC code is developed to estimate the safety performance of the AC — 600 passive containment cooling system and deep concern is focused on the different features on the passive behavior of the system. The code verification up to now is preliminary but satisfying and more comparison with the test results related to AC—600 is needed to perform. In addition, PCCSAC model is obviously conservative especially for the Containment Space description due to complicated natural convection and greater temperature gradient inside the containment space as cooling by means of natural forces, therefore a further improvement by using 2—D model for the containment space is under consideration to meet the requirement of the more realistic modelization for the AC—600 passive containment cooling system.

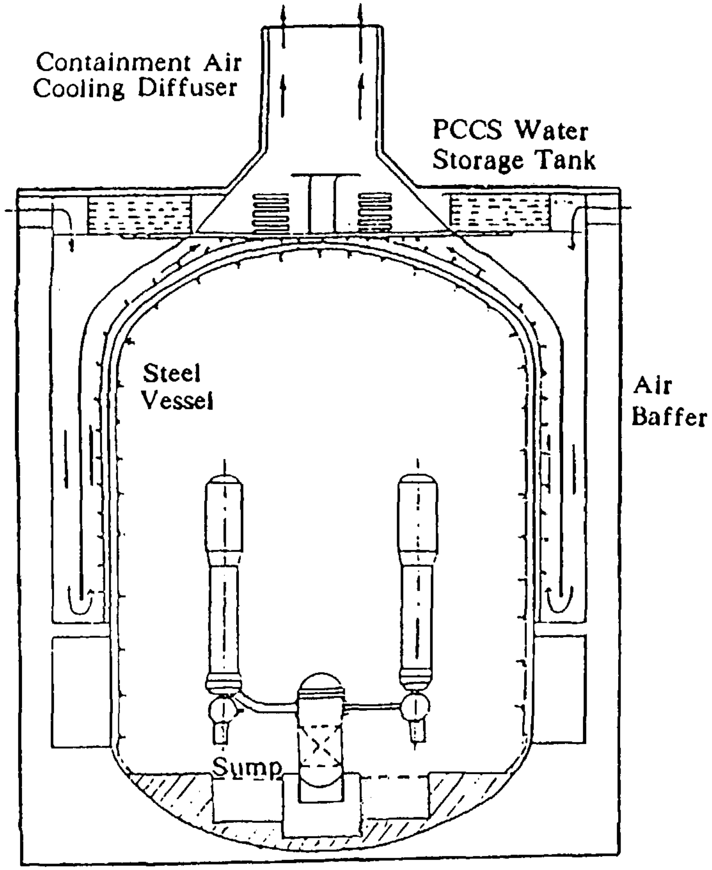

Figure 1. AC—600 Passive Containment Cooling System

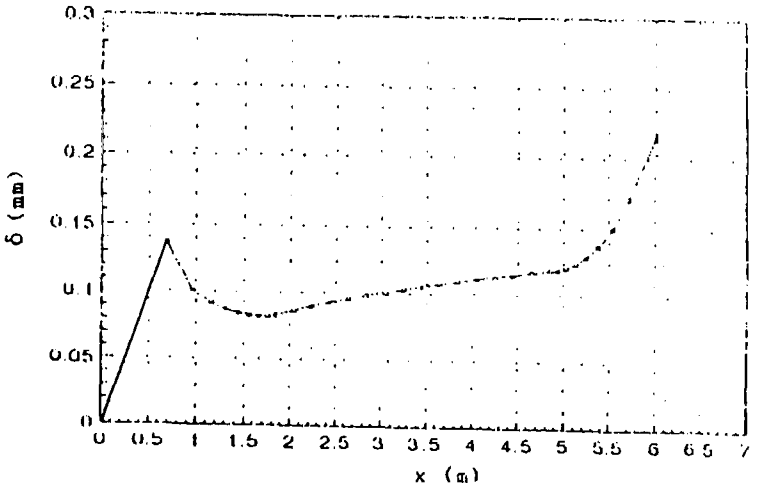

Figure 2. Distribution of Condensation Film Thickness (PCCSAC)

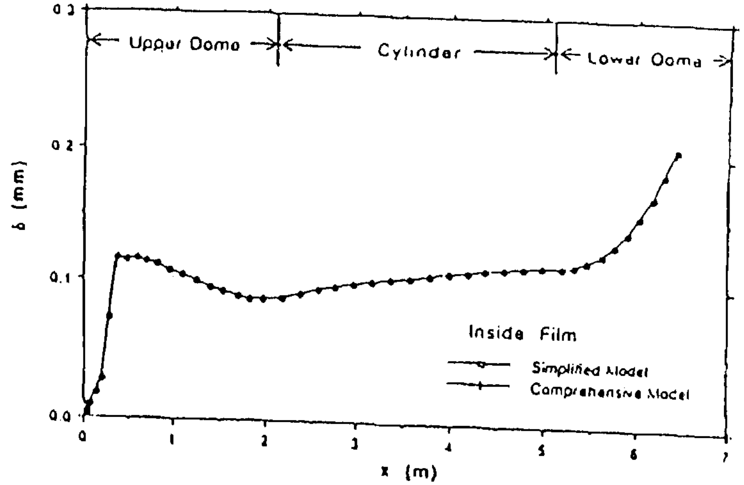

Figure 3. Distribution of Condensation Film Thickness (COMMIX)

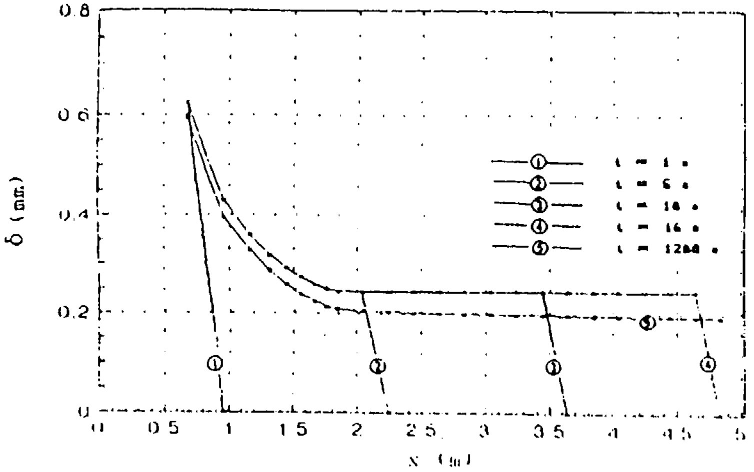

Figure 4. Distribution of Spraying Film Thickness (PCCSAC)

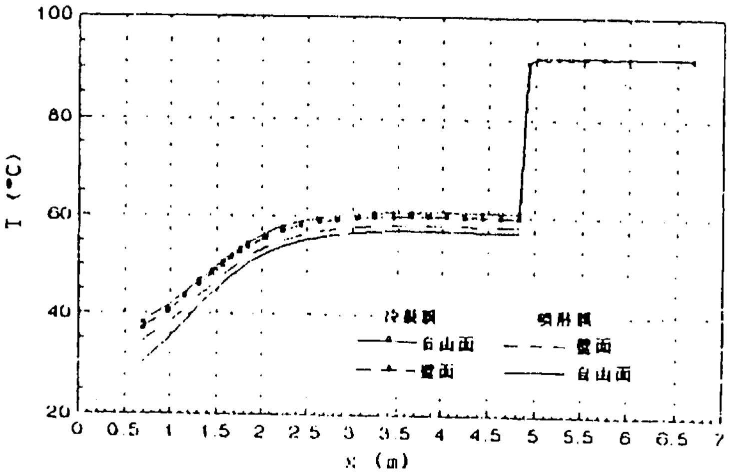

Figure 6. Film Temperature on Both Sides of the Containment Shell (PCCSAC)

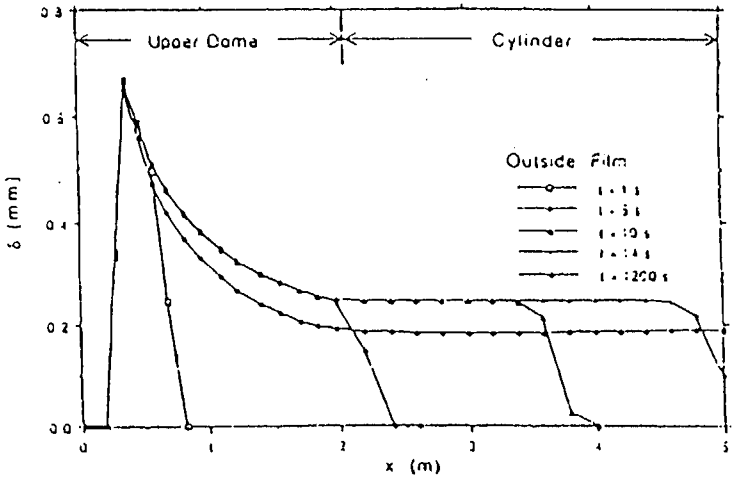

Figure 5. Distribution of Spraying Film Thickness (COMMIX)

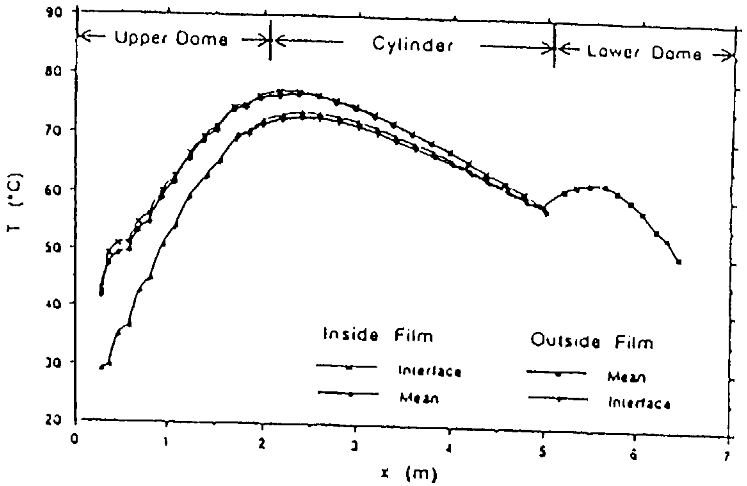

Figure 7. Film Temperature on Both Sides of the Containment Shell (COMMIX)

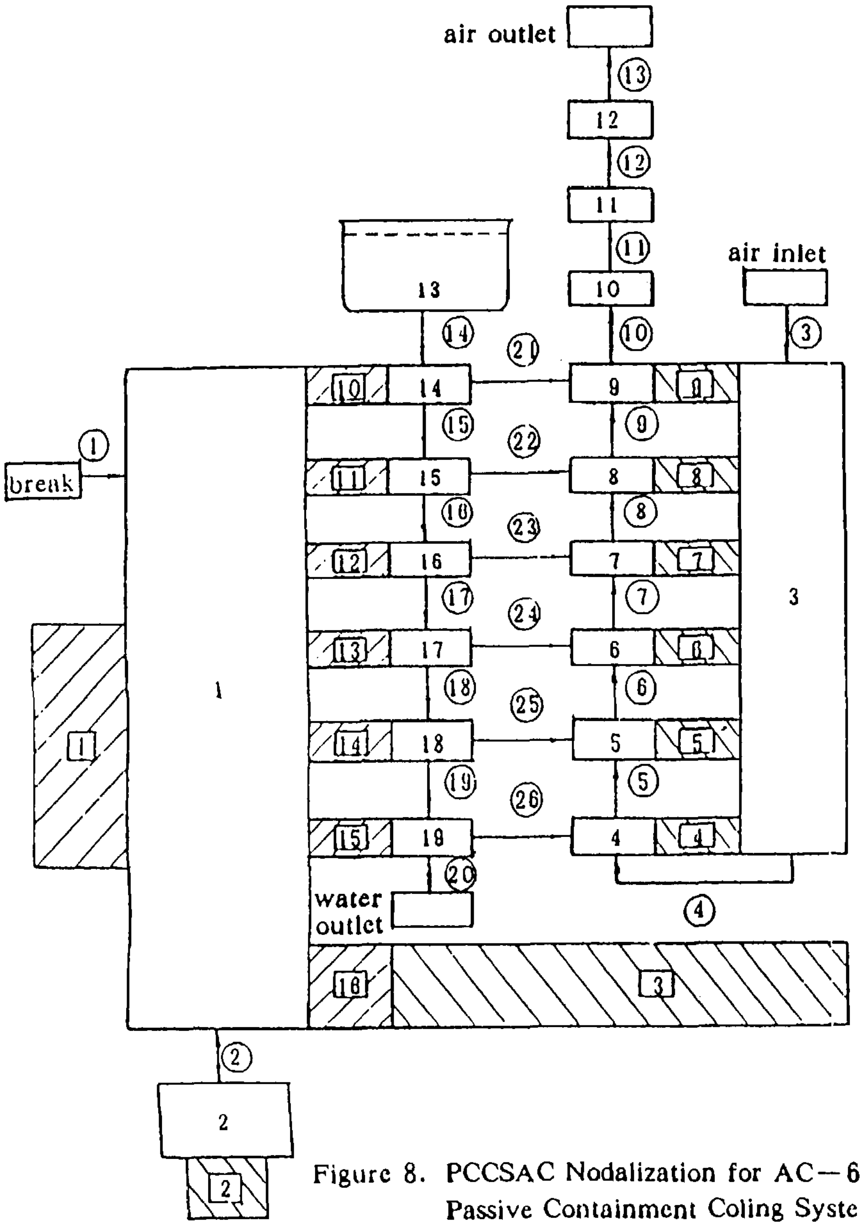

Figure 8. PCCSAC Nodalization for AC—600
Passive Containment Coling System

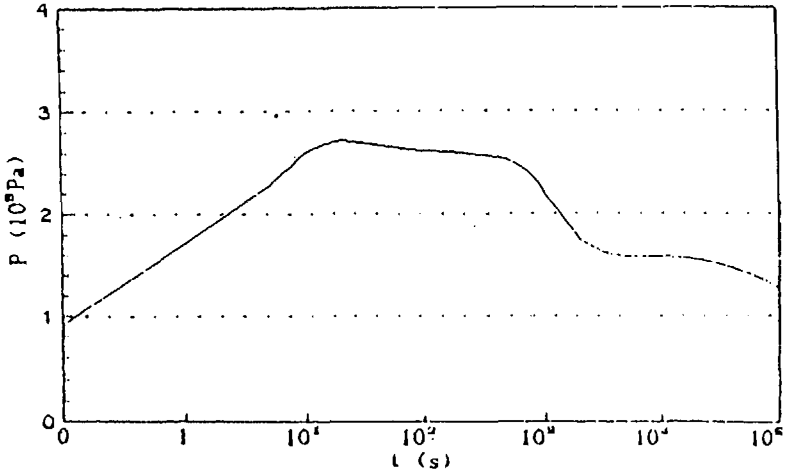

Figure 9. Inside Containment Pressure under LOCA

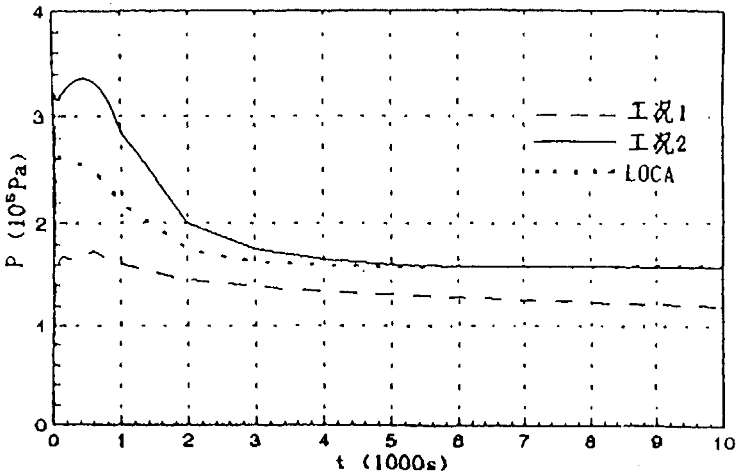

Figure 10. Inside Containment Pressure under SLB Accident

NOMENCLATURE

A = area
h = specific enthalpy
M = mass
P = pressure
T = temperature
t = time
u = velocity
V = volume
W = mass flowrate
γ = descending factor of liquid droplet
δ = thickness
ρ = density

Subscripts

a = dry air
B = break
C = containment or condensition
EX = outlet
g = wetted air
IN = inside or inlet
L = liquid phase
LF = liquid film
LV = liquid to vapor
SP = containment spray
SU = containment sump
V = vapor
w = wall

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