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PCCS Analysis Model for the Passively Cooled Steel Containment

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Abstract

The containment pressure and temperature transient analysis computer code CONTEMPT4/MOD5 is modified to incorporate the passive containment cooling models. The correlations are selected from the existing experimental heat transfer correlations to model the natural and mixed convection in annular space between the containment shell and the shield building. The evaporative heat transfer of the water film on the outer shell of the containment is modeled using the correlations derived from the analogy between the heat and mass transfer. The modified code is applied to the AP600 containment transient analysis for the model verification and the results are compared to the results of GOTHIC calculation done by Westinghouse. Also, a series of parametric sensitivity studies of heat transfer correlations, water film ratio and delay time of the wet cooling on the containment peak pressure and temperature following LOCA are performed for the containment of 1000MWe passive plant, KP1000.

1. Introduction

The various concepts of the passive safety system including passive containment cooling system(PCCS) were investigated for the advanced light water reactors.[1] The passively cooled steel containment is one of the PCCS operating under the postulated accident conditions as shown in Figure 1. It provides a safety grade means by transferring heat from the inside of the containment to the environment following any postulated event that results in containment heat-up and pressurization. The passively cooled steel containment utilizes only natural phenomena such as steam condensation, conduction, natural convection, and the evaporation of the water film to remove the energy released from the reactor during the postulated accident.

For the evaluation of the PCCS performance of passively cooled steel containment, it is important to understand the thermal hydraulic behavior during the containment transients. Since the performance of PCCS is highly dependent upon the physical phenomena during the containment transients, the analysis models for PCCS performance should include those phenomena, such as steam condensation, evaporation of water film and the natural circulation of air.

This paper describes the PCCS analysis models specially developed for the passively cooled steel containment that are incorporated into the multi-compartment containment transient analysis computer code, CONTEMPT4/MOD5.[2] The modified code referred to as CONTEMPT4/MOD5/PCCS. For the verification of the PCCS models of the code, the containment transient analysis for AP600 is performed, and the results are compared with those of Westinghouse GOTHIC calculations. The modified code is then applied to the analysis of KP1000 - a 1000MWe capacity of passive reactor concept which was developed on the basis of AP600. Also, a series of sensitivity studies on the containment peak pressure and temperature following Loss of Coolant Accident (LOCA) for heat transfer correlations, water film ratio and delay time of the wet cooling were conducted to investigate the effects of PCCS modeling.

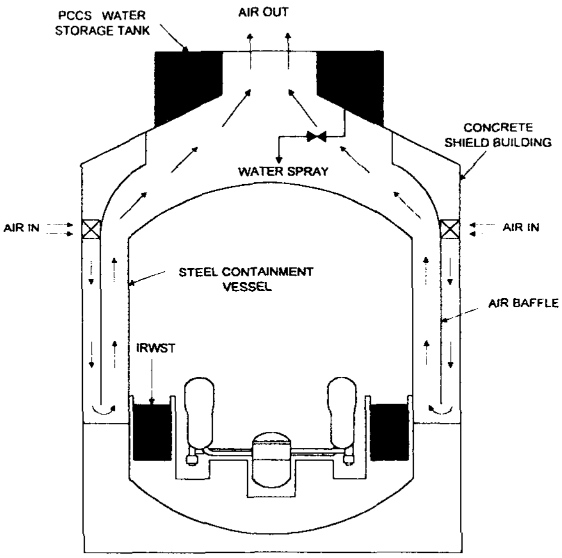

Fig. 1. Passive Containment Cooling System of AP600

2. The Passive Containment Cooling Model

2.1. Passive Cooling Mechanism

The passively cooled steel containment removes the energy released from the reactor system to the containment during the accidents through the conduction of the steel shell and the natural convection of air. The heat is transferred to the inside surface of the steel containment vessel by convection and condensation of steam and through the steel wall by conduction. Heat is then transferred from the outside containment surface to the environment by a natural convection of air and radiation heat transfer in annular space between the steel containment and the shield building.

The natural circulation of air flow is generated by the differences in temperature between the entrance of the containment annulus and the heated steel wall. The air entering through the inlet of the annulus is heated by the heat flux from the steel shell and transported to the upper part of the annulus due to the density difference. The air continuously flows into the inlet of the annulus and removes the energy out to the atmosphere. The physical properties of air and the temperature difference between the containment shell and ambient air are important parameters for air cooling(dry cooling).

In addition to the air cooling, the water sprayed on the outer shell of the containment to enhance the cooling capability of the PCCS. The sprayed water from the PCCS pool forms the water film at the outer shell of the containment. The water film is heated and evaporated to the annulus(wet cooling). The evaporation rate is dependent upon the temperature difference of vapor between the water film and ambient air. The rate of evaporation is expressed as a function of the density difference of vapor between the saturated air at the water film surface and the ambient air.[3]

2.2. Computational Models for PCCS

2.2.1. Natural Convection

A number of experimental studies have been performed on the buoyancy induced air flow of a vertical surface with various boundary conditions. Sparrow[4] developed a correlation for the natural convection of laminar flow. He derived a laminar heat transfer correlation from the experiment of uniform temperature and symmetrical heating of both sides of the vertical wall. Hugot,[5] McAdams[6] and Miyamoto[7] conducted a series of experimental studies on the natural convection of turbulent flow. Hugot performed an experimental study on natural convection for the vertical channel of 3.3m height and channel width of 5cm to 60cm. He observed the transition region between the laminar and turbulent regime and found that the heat transfer rate increases in that transition region. The air flow inside the channel is turbulent except the entrance region. Miyamoto performed the experiment for the vertical channel of one side heated with constant heat flux. The channel was 5m height with the ranges of width, 4~20cm. He measured the various physical properties such as velocity, temperature profile, heat transfer coefficient and turbulent intensity.

Among the correlations derived from the above experimental data, the correlation for the turbulent natural convection channel flow of Hugot's is most close to the actual PCCS annulus flow.[8][9] Meanwhile, McAdams' correlation for the turbulent natural convection of the vertical wall calculates the largest heat transfer coefficient and Sparrow' s correlation for the laminar channel flow calculates the lowest heat transfer coefficient which limits the upper and lower bounds of the heat transfer by natural convection respectively.

Generally the heat transfer correlation for the natural convection of the vertical wall is expressed by the Nusselt number and Rayleigh number based on the height of the wall. The correlation is expressed;

$$Nu_H = \frac{hH}{k} = C\ Ra_H^n \tag{1}$$

where the coefficient C and the exponent n are determined from the experimental data. The exponent n has the value of 1/4 for laminar flow and 1/3 for turbulent flow.

Similarly, the correlations for the natural convection of vertical channel are expressed by the Nusselt number and Rayleigh number based on the channel width. The geometry effects of vertical channel such as the aspect ratio and the ratio of the channel width to height(s/H) are also included in the Sparrow' s correlation. The correlation for vertical channel is expressed as;

$$Nu_s = \frac{hs}{k} = C\ Ra_s^n \left\{ \left(\frac{s}{H}\right)^n \right\} \tag{2}$$

2.2.2. Mixed Convection

The mixed convection occurs when the geometry effects such as chimney effect is superimposed to the natural convection of the vertical channel. The computer code GOTHIC[10] which was developed by the Westinghouse (WGOTHIC) to analyze the AP600 passive containment employs the buoyancy induced air flow modeled by Churchill[11]' s correlation for the mixed convection. The correlation is represented;[4]

$$h = \max[(h^3_{forced} - h^3_{free})^{1/3}, \quad 0.75h_{forced}, 0.75h_{free}] \tag{3}$$

where the symbol h_{forced} is the forced convection heat transfer coefficient and h_{free} is the natural convection heat transfer coefficient. Churchill' s correlation utilized the Colburn' s correlation for forced convection and the McAdams' correlation for natural convection.

2.2.3. Wet Cooling

The correlation for the evaporative cooling of water film on the outer containment shell can be obtained from the analogy between the heat and mass transfer. The physical phenomena in each field have strong similarity and these phenomena can be expressed in the same form of the field equation.[12]

The mass transfer correlation was obtained from the heat transfer correlation through the transformation of the nondimensional parameters based on the similarity between the heat and mass transfer. The correlation for the mass transfer has the same form as the heat transfer. The Prandtl number in the heat transfer correlation is replaced by the Schmidt number for the mass transfer. As the Nusselt number represents the gradient of the nondimensional heat transfer quantity, the Scherwood number represents the gradient of the mass transfer quantity at the water film surface. The Grashoff number for mass transfer is also redefined. The temperature difference term of Grashoff number in the heat transfer correlation is replaced by the density difference between the saturated air at the surface of the water film and the ambient air in the mass transfer correlation. Thermal diffusivity in Prandtl number is replaced by the diffusion coefficient in Schmidt number which is used in the mass transfer correlation. The mass transfer correlations which deduced from the analogy for the natural and forced convection of vertical channel are as follows.[1]

1) Natural convection analogy

$$Sh = C \ (Gr_m Sc)^m \ \left\{(\frac{S}{H})^m\right\} \tag{4}$$

2) Forced convection analogy (from Colburn correlation)

$$Sh = 0.023 \ Re^{0.8} \ Sc^{1/3} \tag{5}$$

2.2.4. Radiation Heat Transfer

Additional heat transfer mechanism in the PCCS compartment is direct radiation heat transfer between the steel containment and the shield building. According to the Hugot' s experiment, the fraction of the radiative heat transfer in the heated vertical channel is about 10% of the total heat transfer in case of the surface emissivity of 0.7[5]. Direct radiation heat transfer model is available in the CONTEMPT4/MOD5 and the model can be used to model the radiation heat transfer.

2.2.5. Condensation Model

The major heat transfer mechanism at the inner surface of the steel containment is the condensation of steam released from the reactor system to the containment during the postulated accident. Tagami and Uchida condensation models are already included in the CONTEMPT4/MOD5. The Tagami model was used for the blowdown phase and the Uchida model for the reflood phase. The conservatism of these models was shown by several studies, so these two models are incorporated into the containment transient analysis model of CONTEMPT4/MOD5.[8]

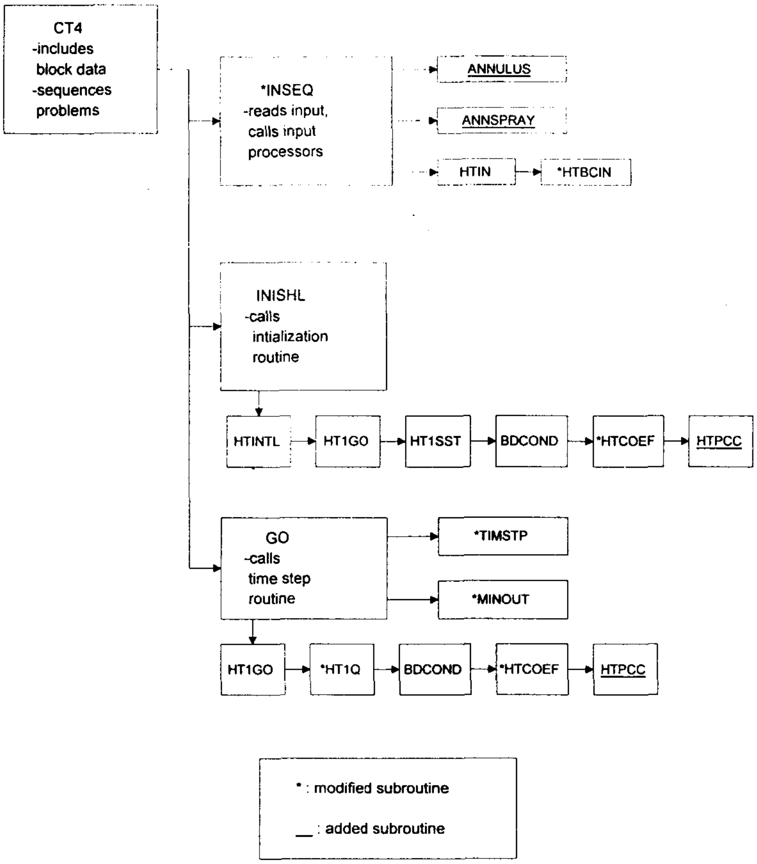

Fig. 2. Program Structure CONTEMPT/MOD5 and Subroutines Concerned

3. Improvement of CONTEMPT4/MOD5 Computer Code

3.1. Code Modification

CONTEMPT4/MOD5 is a containment pressure and temperature transient analysis code that describes the response of multi-compartment containment systems. It can be utilized to both of the pressurized water reactor(PWR) and the boiling water reactor(BWR). The program consists of 3 blocks as shown in Figure 2, for sequencing the input processing, problem initialization and time step calculations. The program calculates the containment pressures, temperatures and mass and energy inventories as a function of time. Analytical models available for describing the containment system include the models for engineering safety features(ESF), heat conducting structures and PWR ice condensers.

The PCCS utilized the heat structures such as the containment shell to remove the energy released from the reactor system into the containment. Since the passively cooled steel containment is cooled by the heat transfer through the containment shell, the correlation represented by the heat transfer phenomena at the containment shell is important for the containment transient analysis. Therefore, the CONTEMPT4/MOD5

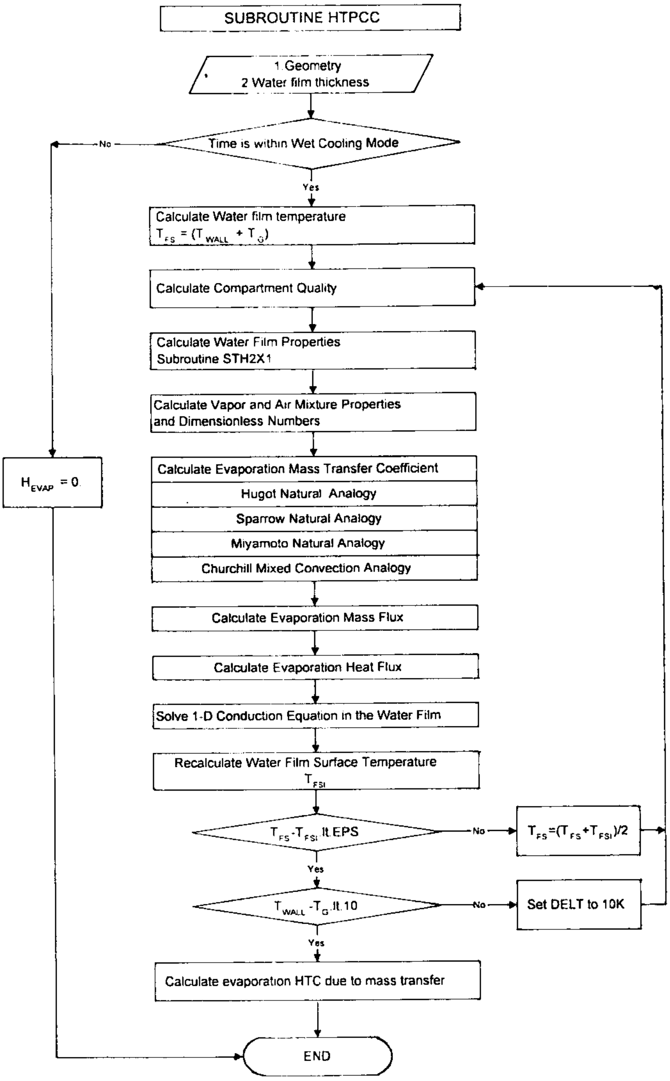

Fig. 3. Flow Chart of Subroutine HTPCC

needs modification by incorporating the passive containment cooling models to apply the code to the passive containment transient analysis.

The models for the buoyancy induced air cooling and the evaporation cooling of water film are incorporated into the CONTEMPT4/MOD5 code. The heat transfer correlations are selected from the existing correlations for the various conditions, and the correlations for the evaporation cooling of water film are derived from the analogy between the heat and mass transfer. The subroutine HTCOEF that calculates heat transfer coefficient is modified by adding new heat transfer models, and the subroutine INSEQ is extended to process the additional heat structure. The subroutine HTPCC is added to calculate heat transfer coefficient due to mass transfer. Several subroutines are additionally changed for I/O processing and conveniency of the calculation.

Table 1. Added Heat Transfer Correlation in Subroutine HTCOEF

Heat transfer coefficient		Correlation	Valid range
Natural convection	Hugot	$h = 0.108 \frac{k}{s} \left(\frac{g\beta(T_w - T_\infty)s^3}{\nu\alpha} \right)^{0.325}$	$6*10^6 \le Ra \le 3*10^9$
	Sparrow	$h = 0.667 \frac{k}{s} \left(\frac{g\beta(T_w - T_\infty)s^3}{\nu\alpha} (\frac{s}{H}) \right)^{0.229}$	$1*10^5 \le Ra \le 2*10^7$
	Miyamoto	$h = 0.0961 \frac{k}{s} \left(\frac{g\beta(T_w - T_\infty)s^3}{\nu\alpha} \right)^{0.344}$	$3*10^7 \le Ra \le 2*10^{10}$
Mixed convection	Colburn	$h_{forced} = 0.023 \frac{k}{D_h} Re^{0.8} Pr^{1/3}$	$0.5 \le Pr \le 100.$
	McAdams	$h_{free} = 0.13 \frac{k}{s} \left(\frac{g\beta(T_w - T_\infty)s^3}{\nu\alpha} \right)^{1/3}$	$1*10^7 \le Gr \le 1*10^{12}$

Table 2. Mass Transfer Correlation in Subroutine HTCC

Mass transfer coefficient	Correlation	Parameter	C	m
Natural convection analogy	$h_m = C(\frac{D}{D_h}) \left\{ \frac{gs^3}{\nu_m^2} \left(\frac{\rho_s - \rho_o}{\rho_o} \right) \frac{\nu}{D} \right\}^m$	Hugot	0.108	0.325
		Sparrow	$0.667(s/H)^{0.229}$	0.229
Forced convection analogy	$h_m = 0.023(\frac{D}{D_h}) Re^{0.8} (\frac{\nu}{D})^{1/3}$	Miyamoto	0.0961	0.344
		McAdams	0.13	1/3

Subroutine INSEQ

Subroutine ANNULUS and subroutine ANNSPRAY are added to process the PCCS input cards 200 and 300. Card 200 describes the PCCS geometry, the width and height of flow channel, and card 300 describes the starting and ending time of wet cooling, the mass flow rate of PCCS cooling water and the wetting fraction of the steel containment. Subroutine HTBCIN that processes the heat structure boundary condition is modified for extended heat transfer option flag.

Subroutine HT1GO

The subroutine HT1GO controls the heat structure calculations and it is called from the subroutine INISHL and subroutine GO. This routine calls HTCOEF which determines the boundary condition of heat transfer coefficient.

Subroutine HTCOEF

The heat transfer model for PCCS was implemented to the subroutine HTCOEF. The additional subroutine HTPCC that calculates the evaporation heat transfer coefficient of the water film also is added to the subroutine HTCOEF.

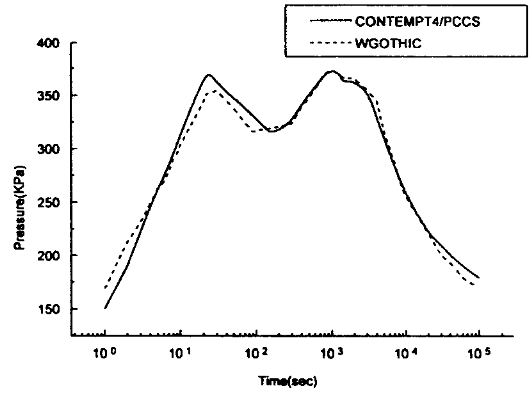

Fig. 4. Comparison of Containment Pressure of AP600 for LOCA (CONTEMPT4/MOD5/PCCS vs WGOTHIC)

The correlations of dry cooling and wet cooling models are implemented into the program. Each of the following heat transfer models can be used as an option.

Table 3. Design Parameters and Input Data of AP600 and KP1000 Plant

Compartment	PARAMETER	AP600	KP1000
containment	free volume (m^3)	48,139	75,040
	intial temperature (℃	48.89	48.89
	intial pressure (KPa)	108.25	108.25
	relative humidity	0.1	0.1
	liquid region surface area (m^2)	863.26	1,149.21(70% of radial area)
	inner diameter (m)	19.81	22.86
PCCS Annulus	total volume (m^3)	5,663	5,967
	channel height (m)	23.80	27.04
	channel width (m)	0.2762	0.2762
	channel area (m^2)	34.67	40.00
	initial temperature (℃)	46.11	46.11
	initial pressure (KPa)	101.36	101.36
	relative humidity	0.1	0.1
	wetting fraction	0.7	0.7
Number of passive heat sink type		19	19

Table 4. Result of the DECLB of AP600 Plant

Analysis code	Max. Pressure(KPa)	Max. Temperature(oC)
WGOTHIC	373.71	139.44
CONTEMPT4/MOD5/PCCS	372.33	128.04
Design Limit Value	411.61	137.78

- Buoyancy induced air cooling by natural convection
- Annulus air cooling by mixed convection
- Evaporation cooling in the surface water film by external water spray

The direct radiation heat transfer model also added to each heat transfer model as an option.

Subroutine HTPCC

In wet cooling mode, the mass transfer is governed by the density difference of the vapor between the saturated air at the water film surface and the ambient air of the compartment. The vapor density of the saturated air at the surface of water film is determined from the temperature at the water film surface, as shown in Figure 3. Since the conduction is the dominant heat transfer mechanism in the water film, the surface temperature of the water film is calculated by iteration of the conduction equation in the water film. Using the calculated surface temperature of the water film, the mass transfer coefficient and mass flux are calculated in sequence. The evaporation heat flux is calculated using the following equations.[9]

$$m'' = h_m(\rho_{Ps} - \rho_{Po}) \qquad q'' = h_{fg}m'' \tag{6}$$

The effect of evaporation cooling due to mass transfer is calculated by the following evaporation heat transfer coefficient.

$$h_{evap} = \frac{q''}{T_w - T_\infty} \tag{7}$$

3.2. Model Verification

In order to verify and check the applicability of the PCCS model of the modified code, the transient analysis of the containment following the LOCA was performed for AP600, and the results were compared with those of Westinghouse GOTHIC calculations. The input data were

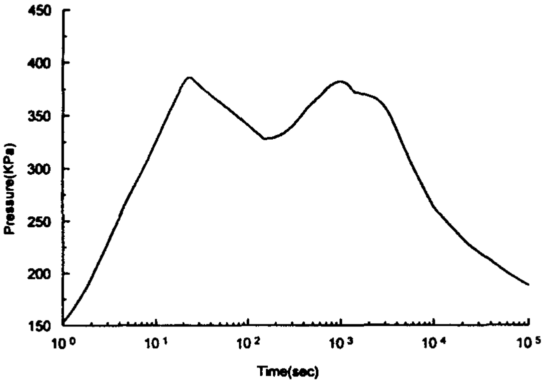

Fig. 5. Calculated Containment Pressure of KP1000 for LOCA

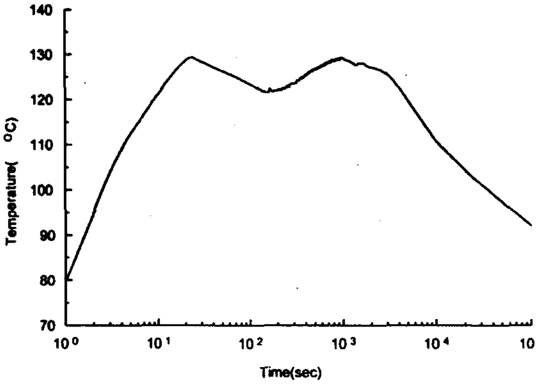

Fig. 6. Calculated Containment Temperature of KP1000 for LOCA

generated using the design data from the Safety Analysis Report of AP600.[8] The input data is presented in Table 3 and the calculated maximum pressure and temperature are in Table 4.

CONTEMPT4/MOD5/PCCS predicts the slightly lower containment peak pressure than that of the WGOTHIC calculation, but the calculated pressure and temperature response shows similar trends, as shown in Figure 4. The difference is caused by the heat transfer modeling of the PCCS channel. CONTEMPT4/MOD5/PCCS employs the correlation derived from the turbulent natural convection for PCCS modeling, but WGOTHIC uses about 75% of the calculated heat transfer coefficient derived from the turbulent forced convection and natural convection for conservatism as shown in equation (3). The conservative analysis of CONTEMPT4/MOD5/PCCS can be performed by using laminar or mixed convection model provided as an option. The difference of the maximum temperature of the containment is due to the compartment modeling. CONTEMPT4/MOD5/PCCS calculates the mixture temperature of inner containment while WGOTHIC calculates the localized temperature in break compartment.

4. Containment Transient Analysis for KP1000

4.1. Modeling for Containment Analysis

The PCCS concept of the KP1000 is modeled for the analysis of the containment pressure and temperature transient following LBLOCA. KP1000 is the 1000MWe passive reactor scaled up based on the Westinghouse AP600 design concepts. The containment pressure is reduced by PCCS features. The heat released into the containment is removed by the natural convection of air flow through the containment annulus, the evaporation of water sprayed to the external surface of the steel containment[1] and radiation heat transfer between the containment shell and the shield building. The increased core thermal power is reflected by increasing the free volume of the containment design. The upper part of PCCS annular space is enlarged due to the volume increase of the containment vessel.

For the containment transient analysis, the main parameters which affects the containment peak pressure and temperature during the transient are the free volume of the containment, the mass and

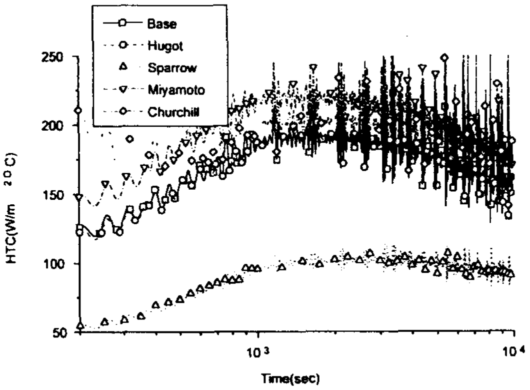

Fig. 7. Calculated Heat Transfer Coefficient of PCCS Models

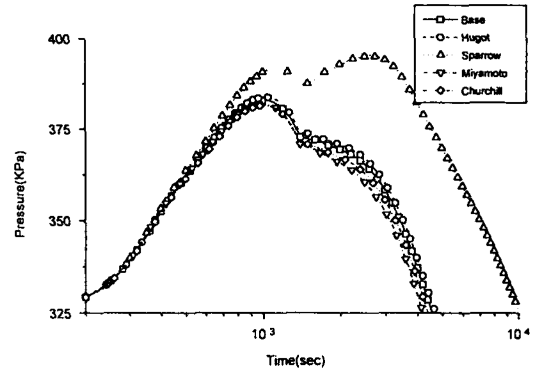

Fig. 8. Effect of the Transfer Models on Containment Pressure

Table 5. Result of the Sensitivity Study (Second Peak Pressure and Temperature)

Sensitivity Study Items		Pressure(KPa)	Temperature(℃)
Base Case			
Heat transfer model	:Hugot(PCCS shell)		
	Churchill(PCCS dome)	382.95	128.92
Wetting fraction	:0.7	(1100 sec)	(1500 sec)
Wet cooling delay time	:0 min		
Time step size	:1.0 sec		
Heat Transfer model (Wet Cooling)	Sparrow	383.80	129.02
	Miyamoto	395.46	130.83
	Churchill	381.89	128.78
	Hugot	381.45	128.73
Wetting Fraction	0.0(dry cooling)	increasing	increasing
	0.1	476.90	139.00
	0.3	401.09	131.48
	0.5	387.16	129.41
	0.9	379.59	128.51
	1.0(totally wet)	378.19	128.33
Wet Cooling Delay Time	1min	382.96	128.92
	10min	391.42	129.94
	20min	405.39	131.57
	60min	476.37	139.38
Time Step Size	0.2sec	381.81	131.56
	0.5sec	382.09	128.81
	2.5sec	383.75	129.01

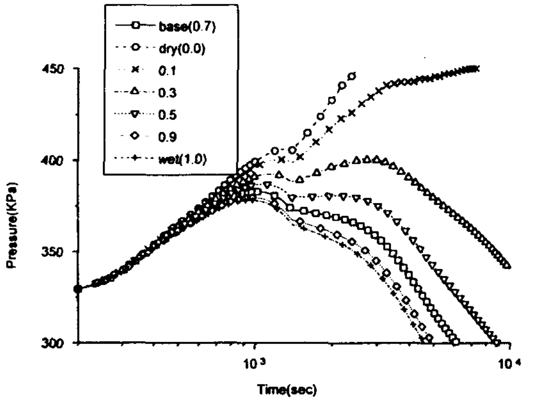

Fig. 9. Effect of Wetting Fraction on Containment Pressure

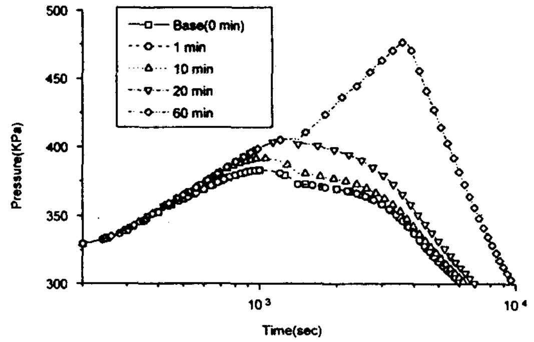

Fig. 10. Effect of Wet Cooling Delay Time on Containment Pressure

energy release rate from the RCS, the heat removal by the passive heat sink structures and the heat removal by the containment cooling system. The containment was modeled using 4 compartments - a dry compartment of inner part of steel containment, PCCS annulus between the steel containment and shield building, outside air compartment of PCCS inlet and the outside air compartment of PCCS outlet. The initial conditions and dimensions are listed in table 3. The input data were prepared to meet the conservatism required by the peak pressure calculation and the passive heat sink are modeled as 19 heat structures.

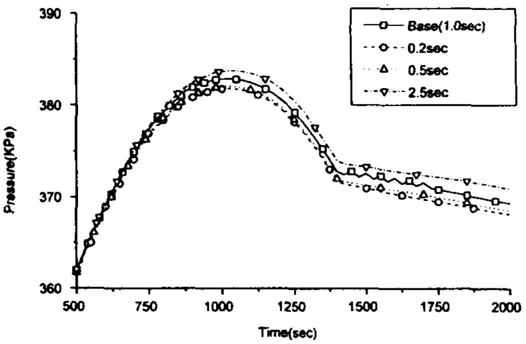

Fig. 11. Effect of Time Step Size on Containment Pressure

4.2. Sensitivity Analysis

The sensitivity analyses on the PCCS models and the computational parameters are performed for the Double Ended Cold Leg Break(DECLB) of KP1000. The mass and energy release data are taken from the result of RELAP5/MOD3.2. The results from the analysis are presented in Figures 5 and 6. The PCCS of KP1000 maintains the effective cooling of the containment by limiting the calculated pressure and temperature within the design limit as shown in the figures. The design limit values for KP1000 containment were assumed to be the same as AP600 in Table 4.

The sensitivity study was conducted to identify the major parameters affecting the containment cooling and to verify the various heat transfer models and the calculation conditions. The parameters of sensitivity studies are heat transfer models, wetting fraction of the outer shell of the steel containment, the delay time of the wet cooling(starting time) and the calculation time step. The results show that the first peak of the containment pressure and temperature which occurs in the earlier time scale(short time) is not influenced by the PCCS models, but the second peak is significantly affected by the heat transfer models of PCCS, as shown in the Figures 8, 9 and 10. The results of the sensitivity study of these parameters are summarized in Table 5.

Heat Transfer Model

New heat transfer models for PCCS implemented into the CONTEMPT5/MOD5/PCCS are applied to calculate the containment pressure and temperature transient of KP1000. Hugot, Sparrow, Miyamoto and Churchill' s correlations are used for dry cooling and the correlations derived from the heat and mass transfer analogy are used for wet cooling. Figure 7 shows the calculated heat transfer coefficient by these models. As shown on the Figure 7, Churchill' s correlation for turbulent mixed flow predicts the highest heat transfer coefficient for the earlier phase of transient and Miyamoto' s correlation for the vertical open channel predicts the highest heat transfer coefficient for the later period of transient. The Sparrow' s correlation for laminar channel flow predicts the lowest heat transfer coefficient throughout the whole transient. Figure 8 shows the calculated pressure histories of the containment on the heat transfer models of PCCS.

Wetting Fraction

The formation of water film on the outer shell of the containment is the most important parameter for long term cooling. In the reference case, the wetting fraction, the ratio of the water film area to the whole surface area of the outer shell, are set to be 70%. The sensitivity calculation of the wetting fraction is performed by changing the ratio from 0 to 100%. The calculated result shows that the wetting fraction of 30% is the minimum value to prevent the containment pressure from exceeding the design pressure and ensure the long term cooling. Below the 30% of wetting fraction, the time of the second peak pressure delayed and the peak pressure exceeds the design pressure as shown in Figure 9.

Delay Time of Wet Cooling

The initiation of wet cooling could be delayed depending on the design feature of containment. The effect of time delay of the water spray on the containment peak pressure is analyzed and the results are presented in Figure 10. The maximum allowable delay time to limit the containment pressure within the design pressure is calculated as 20 min which is sufficient time for operator action in case of spray failure. The delayed actuation of the spray system later than the maximum allowable time results in exceeding the containment design pressure.

Time Step Size

Sensitivity analysis of time step size is performed for the convergence check of the computer code. The time step size is chosen as 1.0 sec in the reference calculation and the sensitivity study is conducted by varying time step from 0.2 sec to 2.5 sec. As shown in Figure 11, the numerical solutions were converged according to the reduction of time step size and the higher pressure was calculated in a larger time step size, which shows the conservatism of code with respect to the time step size.

6. Conclusions

Multi-compartment analysis code for passive containment cooling system, CONTEMPT4/MOD5/PCCS, is developed by incorporating passive containment cooling models in the CONTEMPT4/MOD5. Various heat transfer models for dry and wet cooling can be selected as an input option depending on the containment geometry and flow pattern of annulus. Wetting fraction and the water spray time are also modeled as user inputs. The code models are verified through the comparison of AP600 analysis result with those of Westinghouse design code, GOTHIC. Sensitivity analysis for KP1000 is performed using CONTEMPT4/ MOD5/PCCS. The result shows that the code can be applied for the design calculation of passive containment cooling system.

Nomenclatures

C_p	specific heat
D	diffusion coefficient
D_h	hydraulic diameter
g	gravitational acceleration
Gr_S	Grashof number based on S, $(g\beta\Delta TS^3)/V^2$
Gr_H	Grashof number based on H, $(g\beta\Delta TS^3)/V^2$
Gr_m	Grashof number for mass transfer, $(gS^3(\rho_s-\rho_O)/\rho_O Vm^2)$
H	channel height
h	heat transfer coefficient
h_m	mass transfer coefficient
h_{fg}	latent heat of evaporation
k	thermal conductivity
m''	mass flux
Nu	Nusselt number, hD_h/k
Pr	Prandtl number, V/α
q''	heat flux
RaS	Rayleigh number based on S, $(g\beta\Delta TS^3)/\alpha$
Ra_H	Rayleigh number based on H, $(g\beta\Delta TH^3)/\alpha$
Re	Reynolds number, uD_h/V
s	channel width
S_c	Schmidt number, V/D
S_h	Sherwood number, h_mD_h/D
St	Stanton number for heat transfer, $h/\rho c_p u$
T_w	wall temperature
T_∞	ambient air temperature

Greek Letters

α	thermal diffusivity
β	thermal expansion coefficient
δ	film thickness
V	kinematic viscosity
ρ	density
ρ_{PS}	partial vapor density of saturated air at the water film surface temperature
ρ_{Po}	partial vapor density of ambient air
ρ_S	saturated air density at the water film surface temperature
ρ_O	ambient air density

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