# EVALUATION OF PASSIVE CONTAINMENT COOLING WITH AN ADVANCED WATER FILM MODEL IN A LUMPED-PARAMETER CODE

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#### ABSTRACT

In this paper the Lumped-Parameter containment code system COCOSYS has been applied to evaluate the performance of Passive Containment Cooling System (PCCS) during accidents. The original physical model describing water film behaviors in the code has been modified by taking into consideration the film breakup and subsequent phenomena as well as the effect of film interfacial shear stress created by countercurrent air flow. Moreover, the phenomenon of rivulet hysteresis and the effect of wave on the surface have also been taken into account. The results of simulation, which is conducted based on the geometry of AP1000, indicate that without the modification the original film model may overestimate the cooling performance of PCCS. Sensitivity analyses are carried out and discussed as well.

#### **KEYWORDS**

PCCS; Water film cooling; Lumped-Parameter code; COCOSYS; Liquid film behavior

# 1. INTRODUCTION

The Generation III nuclear reactor designs have incorporated evolutionary improvements characterized by upgraded cost effectiveness and safety standards. Passive safety or inherent safety features have been highlighted. One of the representative designs is AP1000, for which PCCS (Passive Containment Cooling System) plays a critical role in the nuclear reactor accidents and is the final barrier to radioactive release. It is designed to maintain containment pressure below the design limit for 72 hours without action by the operator [1]. During the accidents, steam comes in contact with the much cooler containment vessel wall, heat is transferred to the inside surface of the steel containment wall by convection and condensation of steam and through the containment steel wall by conduction. Heat is then transferred from the outside of the containment vessel dome. Air in the annular space is heated by both convection and injection of steam from the evaporating liquid film. [2] The heated air and vapor rise as a result of natural circulation and exit the shield building through the outlets above the containment shell.

The design of film cooling on the exterior surfaces of the containment is quite novel and determines the performance of PCCS. In order to evaluate its efficiency and reliability, it's necessary to systematically investigate the containment responses under accident scenarios with the activation of PCCS. Therefore the simulation tools should be capable of capturing different phenomena and covering different scenarios from the beginning of the accident and activation of safety facilities. Moreover, a relatively large time scale usually from hours up to days after the onset of the accident should be simulated with reasonable computational effort. Currently only so called Lumped-Parameter (L-P) codes meet the requirements of evaluating the long term transient and considering comprehensive phenomena during the whole process of accidents simultaneously. Different physical models considering various phenomena have been developed and integrated into these codes.

Lately several specialized physical models describing film behavior have been developed and implemented into different L-P codes, e.g. CDW model in COCOSYS [3] and Film Tracking model in MELCOR [4]. Studies with these models have been carried out to evaluate the performance of film cooling in PCCS. However in these liquid film models some notable film behaviors such as its breakup, the formation of dry patches on the surface and the change of velocity distribution under countercurrent shear are not considered or described in detail. This may bring about inaccuracies and therefore lack the reliability of the predictions. Accordingly behaviors of the film including its flow regime, development, transformation, and the resultant impacts on the PCCS cooling capability are of crucial significance to be investigated. The main objective of the present work is to introduce an integrated water film model considering the following phenomena: The change of the velocity distribution and film thickness due to the interfacial shear stress created by the countercurrent flow; The critical status of film breakup in the case of full coverage; The development and the shape change of rivulets; The connection between the fully covered liquid film at the critical state and the stabilized rivulet flow after the rupture. The development is processed based on the existing water film model in the L-P code COCOSYS. The new model can therefore help to define and optimize the flow rate of PCCS over time. Moreover, the methodology of the work can be introduced into other codes.

#### 2. THEORETICAL BASICS AND METHODOLOGY OF MODELLING

#### 2.1 Existing water film models in COCOSYS

The wall condensation model CDW has been developed for COCOSYS to capture condensation of steam and evaporation of liquid film on surfaces of structures and has been applied for investigating film cooling on the exterior surface of containment shell for AP1000 PCCS.

In CDW model, velocity distribution complies with Nusselt's theory and water film thickness is calculated with Eq. (1) with a prescribed mass flow rate.

$$\delta = \left[\frac{3\mu_l M}{\rho_l^2 g}\right]^{1/3} \tag{1}$$

Assuming condensation/evaporation rate  $m_z$  as constant in one cell, as indicated in Fig. 1.



**Fig. 2 Formation of rivulets** 

**Fig. 1 Evaporation of water film** Then the local film thickness is expressed as:

$$\delta_z = \left[\frac{3\mu_l}{\rho_l^2 g} \left(M + m_z\right)\right]^{1/3} \tag{2}$$

Afterwards the average thickness of water film on a wall control volume is calculated:

$$\overline{\delta} = \frac{1}{z_{\max}} \int_{0}^{z_{\max}} \delta_z dz \tag{3}$$

Where the evaporation/condensation rate m is calculated with Stephan's law [5]:

$$m = A \cdot \beta \cdot \rho_{gas,bulk} \cdot \ln \frac{p_{tot} - p_{Sat}(I_{Film})}{p_{tot} - p_{Vapor}}$$
(4)

The equation takes the mass transfer coefficient  $\beta$  into account which depends on a diffusion coefficient, the saturation pressure at the film temperature  $P_{Sat}(T_{Film})$  and the partial pressures of vapor and gases,  $P_{Vapor}$ and  $P_{tot}$ , in the bulk with the density  $\rho_{gas,bulk}$ . Thus, it is obvious that this equation considers the evaporation at surface *A* as a diffusion problem. It is depending on the amount of non-condensable gases near the film surface. By applying the equivalence of heat and mass transfer,  $\beta$  is linked to heat transfer correlations. The temperature difference  $\varepsilon$  between the wall temperature  $T_{Wall}$  and the film temperature  $T_{Film}$  is given by Eq. (5) based on the assumption that the convective heat transfer between the wall and film is negligible compared to the heat conduction. Thus, the heat flow into the structure  $T_{Film}$  is only dependent on the heat conducted through the film of the thickness  $\overline{\delta}$  and the conduction coefficient  $\lambda_{Film}$ .

$$\varepsilon = \frac{\left(q_{evap} + q_{in} - q_{out}\right) \cdot \overline{\delta}}{\lambda_{Film}} \tag{5}$$

The average film thickness  $\overline{\delta}$  is dependent on the incoming water flow and the condensation/evaporation rate. Heat fluxes for evaporation  $q_{evap}$  and heat fluxes due to out-flowing water  $q_{out}$  are both dependent on the temperature difference  $\varepsilon$ . Therefore, an iteration of the film temperature, as indicated in Eq. (4) to (7), is performed to satisfy the energy balance.

$$T_{Wall} - T_{Film} - \varepsilon = DTN \tag{6}$$

$$T_{Film}^* = T_{Film} + DTN / 2 \tag{7}$$

#### 2.2 Modification of liquid film model

The improved liquid film model in COCOSYS, as an integrated film model, has involved the consideration of different scenarios of film progression which may occur during the operation of PCCS, e.g., the shear stress on the film sheet, which results in a change of film velocity distribution; the critical state of the film at which it splits up, with or without countercurrent shear stress; the configuration and the transformation of the film rivulets as well as the transition from the fully covered film sheet into the rivulets. The modified film model has introduced the parameter of film coverage rate, i.e., the effective fraction of the specific substrate coated with rivulets and film sheet. Different from arbitrarily specifying a coverage factor, which has been used in some containment codes, the improved approach can provide a more realistic prediction and this more universal and more theoretical based model is applicable for the users to predict the film behaviors with different geometries and under different operational conditions.

In the modified model the falling liquid film is presented on the substrate either in the form of film sheet or rivulet. The liquid flowing down a vertical or inclined surface forms a free surface between liquid and gas phase. The shape of the surface is a result of forces acting in the system. When the mass flow rate is large enough and the substrate is covered by the water film of a constant thickness, this flow pattern is regarded as film sheet. The velocity distribution in free falling film sheet is assumed to be one dimensional. Rivulet refers to the condition that the free surface come into contact with the solid surface when a small amount of liquid flows downward. The curve outlines the free surface at the rivulet cross section is the rivulet profile.

As the fully covered film sheet breaks up due to the reduction of mass flow rate, stabilized rivulets are formed after the expansions of dry patches as illustrated in Fig. 2. For COCOSYS, as a lumped parameter code, the scale of control volumes is large enough to omit the dry patch profile. Therefore in the new model the constricted stabilized rivulets are assumed directly connected to the fully covered water film of critical state.

#### 2.2.1 Effect of shear stress on film sheet

According to Nusselt's theory, at the film sheet surface, the partial derivative of velocity along the direction perpendicular to the substrate is 0.

$$y = \delta, \frac{du_z}{dy} = 0 \tag{8}$$

However when the shear stress acts on the film surface the boundary condition as well as velocity distribution on the cross section is changed, as denoted in Fig. 3. In order to predict the velocity profile,

several assumptions have been made. Firstly, it is assumed to have no pressure change in the film along the direction horizontal or perpendicular to the plate. Secondly, there is no slip at the solid-liquid interface. Interfacial boundary condition considering shear stress is expressed in Eq. (9), which implies the velocity gradient at the film surface is proportional to the shear stress.





Fig. 3 Velocity distribution changed by shear stress

Fig. 4 Contact angle balance on the rivulet crosssection

$$-\phi'(x)\frac{\partial u(x,\phi)}{\partial x} + \frac{\partial u(x,\phi)}{\partial y} = -\frac{\tau_i(x)}{\mu}$$
(9)

Where  $\phi(x)$  describe the profile of the film. The one dimensional momentum equation for the film sheet:

$$\frac{\partial^2 u}{\partial y^2} = -\frac{\rho_l g \sin \alpha}{\mu_l} \tag{10}$$

Where  $\alpha$  indicates the inclination of the targeted structure and  $\alpha = 90^{\circ}$  when the structure is vertical. For the water film sheet as it can be regarded as one dimensional, the boundary condition Eq. (9) is written as:

$$\frac{\partial u(\delta)}{\partial y} = \frac{\tau_i}{\mu_i} \tag{11}$$

With these equations and non-slip boundary condition, the velocity distribution is expressed as:

$$u = \frac{\rho_l g \sin \alpha \delta^2}{\mu_l} \left[ \frac{y}{\delta} - \frac{1}{2} \left( \frac{y}{\delta} \right)^2 \right] + \frac{\tau_i}{\mu} y$$
(12)

The interfacial liquid velocity:

$$u_i = \frac{\rho_l g \sin \alpha}{2\mu_l} \delta^2 + \frac{\tau_i}{\mu_l} \delta$$
(13)

Where

$$\tau_i = -\frac{1}{2} f_i \rho_g \left( u_i - u_g \right)^2 \tag{14}$$

Then shear stress can be calculated:

$$\pi_{i} = -\frac{1}{2} f_{i} \rho_{g} \left( \sqrt{\left(\frac{\mu_{l}}{f_{i} \rho_{g} \delta}\right)^{2} - \frac{2\mu_{l} \mu_{g}}{f_{i} \rho_{g} \delta} + \frac{\rho_{l} g \delta}{f_{i} \rho_{g}} - \frac{\mu_{l}}{f_{i} \rho_{g} \delta} \right)^{2}$$
(15)

The mass flow rate per unit width,

$$\int_{0}^{\delta} \rho u(y) dy = M$$

$$= \int_{0}^{\delta} \rho \left( \frac{\rho g \sin \alpha \delta^{2}}{\mu_{i}} \left[ \frac{y}{\delta} - \frac{1}{2} \left( \frac{y}{\delta} \right)^{2} \right] + \frac{\tau_{i}}{\mu_{i}} y \right) dy \qquad (16)$$

$$= \frac{\rho^{2} g \sin \alpha}{3\mu} \delta^{3} + \frac{\rho \tau_{i}}{2\mu} \delta^{2}$$

By solving the cubic function, the real root gives the expression of film thickness. Lots of experiments have been conducted regarding liquid film behavior under countercurrent flow and corresponding empirical expressions regarding  $f_i$  are provided. However most of them are with respect to pipes or tubes and very few have been found focusing on water film on plates. Among these literatures, only Stephan

and Mayinger's research [6] has similar geometry and scale comparable with PCCS and drag force coefficient is correlated as:

$$f_i = 0.079 \,\mathrm{Re}_g^{-0.25} \left[ 1 + 115 \left( \frac{\delta}{L_L} \right)^N \right]$$
(17)

Therefore the factor  $f_i$  is dependent on film thickness. Then by iteration of the above expressions, with a given mass flow rate, the values of shear stress, film thickness and velocity distribution in a film sheet are all determined.

# 2.2.2 Breakup of fully covered film

To predict film breakup, typical ways including analyzing film stability by imposing a small disturbance on the laminar film, or force balance at the three-phase stagnation point of dry patch formed after film breakup are both flawed by comparison to the MTE principle. Therefore the current modification concerning film breakup is based on the work of Hartley et al., [7] who had obtained the critical thickness of one-dimensional film sheet by minimizing the sum of kinetic energy and surface energy per unit film width. According to this theory, when the total energy, or namely the sum of kinetic energy and surface energy per unit width, as indicated in Eq. (18), reaches its minimum, the critical state is reached.

$$d\left(\frac{E_{k}+E_{s}}{M}\right) = \frac{1}{M} \left[\int_{0}^{\delta} \frac{\rho u(y)}{2} u^{2}(y) dy + \sigma_{LV} u(\delta)\right]$$
  
$$= \frac{1}{M} \left[\frac{\rho}{2} \int_{0}^{\delta} u^{3}(y) dy + \sigma_{LV} u(\delta)\right]$$
  
$$= 0$$
 (18)

However in Hartley's model, the velocity distribution is assumed in accordance with Nusselt's theory and the influence of countercurrent air is not taken into account. When the shear stress is presented at the film surface, taking the velocity distribution considering interfacial shear as expressed in Eq. (12) into account, Eq. (18) can be simplified as a polynomial:

$$a_7 \delta_{Critical}^7 + a_6 \delta_{Critical}^6 + \dots + a_1 \delta_{Critical} + a_0 = 0 \tag{19}$$

Then the critical film thickness under shear stress created by countercurrent air is obtained.

### 2.2.3 Configuration of rivulets

After the breakup, the film coating goes to another stage that the fully film is transformed into numerous rivulets and dry patches are presented among these rivulets. According to the theory of Doniec, [8,9] the equilibrium, stationary free surface of the flowing rivulet is formed when the minimum total energy of the system is fulfilled. The study also indicates that for each specific contact angle between the attaching liquid and substrate, there is one corresponding equilibrium rivulet thickness and this thickness is also believed [10-14] to be the critical film thickness of a rivulet. This complicated pattern of rivulet flow is simplified in the improved model. It's assumed that all the rivulets have identical profiles and are distributed unanimously on the substrate. Thus several mean values of each rivulet including the contact angle and the profile should be specified.

The profile of the rivulet surface is a result of forces acting in the system and therefore the contact angle, defined geometrically as the angle formed by a liquid at the three phase boundary, is a significant factor which determines the profile of the rivulet, as shown in Fig. 4. The contact angle can be considered as the balance of three forces. Namely, the interfacial tensions between solid and liquid  $\sigma_{sL}$ , that between solid and vapor  $\sigma_{sV}$  and that between liquid and vapor  $\sigma_{LV}$  and given in Young equation:

$$\sigma_{SV} = \sigma_{SL} + \sigma_{LV} \cos\theta \tag{20}$$

As assumed in many previous studies on the critical profile of rivulets, in the modified model the profile of critical state of the rivulet is regarded as a circular segment, as demonstrated in Fig. 5, and expressed as:

$$\phi(\alpha) = R(\cos\alpha - \cos\theta) \tag{21}$$

Where  $0 < \alpha < \theta$ , the half width of the rivulet or

$$\phi = \delta - \frac{\delta}{1 - \cos\theta} \left[ 1 - \sqrt{1 - x^2 \left(\frac{1 - \cos\theta}{\delta}\right)^2} \right]$$
(22)





Fig. 5 Cross section profile of the rivulet at critical state



Based on the profile indicated in Eq. (22), El-Genk and Saber [13] have predicted the critical thickness of rivulet with a specified contact angle by using MTE principle. In the work, Ritz method, instead of zero order or first order approximation, is applied to approximate the velocity distribution in the rivulet. Then half empirical dimensionless correlations in a simple form are obtained to express the relationship of contact angle and minimum thickness and minimum mass flow rate.

$$\Delta_{Critical} = (1 - \cos\theta)^{0.22} \tag{23}$$

$$\Gamma_{Critical} = 0.67\Delta_{critical}^{2.83} + 0.26\Delta_{critical}^{9.51} \tag{24}$$

In the improved model the expressions proposed by El-Genk et al. are used to predict the height and mass flow rate of critical state of equilibrium, stationary rivulet.

Another question is how the geometry of rivulet changes, assuming that the contact angle stays as constant, when the flow rate is beyond the critical value. Doniec [8,9] proposed that "It was proved that in such a case the rivulet width would increase and its thickness would not change." This point of view is also supported by other studies e.g. El-Genk & Saber. Fig. 6 demonstrates the configuration of the rivulet with the flow rate beyond the critical value.

In this case the profile of the rivulet cross section is regarded as a circular segment and a rectangular film sheet in the middle, as indicated in Fig. 6, where a and b are the width of circular segment and width of rectangular part respectively. In contrast, when mass flow rate decreases to the critical value, which also means the rectangular part disappears by narrowing the width, the rivulet cross section profile is only a circular arc and at the same time the critical or minimum mass flow rate for a typical contact angle is reached. Afterwards, if the mass flow rate keeps reducing, according to the description of experiment results [15], all the stripes evaporated completely without changing their characteristic near the point of complete dry out. Thus for the surface test, the liquid film doesn't snap, or draw up into a thick film.

# 2.2.4 Rivulet hysteresis

Plenty of experiments have revealed that for any given solid-liquid interaction there exists a range of contact angles. When the three-phase boundary or known as contact line of the rivulet is in motion, the angle is referred to either as 'advancing' or 'retreating' angle when the wetting area is expanding or shrinking. The difference between the advancing and retreating contact angle values is called the contact angle hysteresis. Typically, better wetting occurs on surfaces with small contact angles. In practice, contact angles are measured for both advancing and receding films. Usually the two values are quite different, with the advancing contact angle being much larger than the receding contact angle. The relation between contact angle and velocity is qualitatively depicted in Fig. 7.



Fig. 7 Hysteresis of Contact angle



In the modified liquid film model, when the contact line of the rivulet is expanding or contracting, the contact angles are known as advancing contact angle  $\theta_A$  or retreating one  $\theta_R$  respectively. When the contact angle is between these values, the contact line is static even though the mass flow rate is changing. When rivulets are formed after breakup, the initially formed rivulets are presented with the equilibrium contact angle, which is within the range between advancing and retreating contact angles. These processes are shown in Fig. 8. In the modified film model of COCOSYS, it is possible to take the phenomenon of hysteresis into account. When this function is activated, the user needs to specify 3 different contact angles: the advancing one  $\theta_A$ ; retreating one  $\theta_R$  and equilibrium one  $\theta$ . The contact angle after breakup is considered as equilibrium status. Afterwards, as the rivulet is being evaporated, the thickness of the rivulet and the contact angle are reducing while the contact line, as well as the coverage rate are invariable. When the advancing or retreating contact angles are reached, the motion pattern of the rivulet is switched to the mode introduced in the last subsection.

# 2.2.5 Determination of the initial form after breakup

As a lumped parameter code simulating containment behaviors, control volumes in COCOSYS are of large size and film sheet is considered converted into stabilized and constricted rivulets directly. In the modified mode, mass balance as well as energy equilibrium are assumed for the connection between fully covered film and rivulets. The coverage rate, which determines the effective fraction of film coverage, is defined as:

$$x = \frac{2a+b}{2a+b+\lambda} \tag{25}$$

where  $\lambda$  indicates the width of the dry patch between two rivulets. As shown in Fig. 9, which depicts the profile of the cross section converting from fully covered film to stabilized rivulets, the rivulet is constricted and its height is increased as the dry patch has been presented.





Fig. 9 Conversion from fully covered film to rivulets.

The assumption of energy equilibrium is expressed as:

Fig. 10 Film thickness under

$$\frac{dE_{break}}{dx} = \frac{E_{arc} + E_{sheet'}}{2a + b + \lambda} = \frac{E_{arc} + b\left(\frac{dE_{sheet'}}{dx}\right)}{2a + b + \lambda}$$
(26)

#### 3. TEST AND CORRECTION OF THE MODEL

The previous chapter has introduced the theoretical basics and methodology to modify the liquid film model in COCOSYS. Some of the correlations need to be tested or compared to the experimental results. **3.1 Test of correlations introduced for the modified model** 

According to Eq. (15) to Eq. (17), the film thickness considering interfacial shear with Stephan and Mayinger's drag force model are calculated and compared respectively with Yu's experiment [16] and Roy's experiment [17] which have been conducted on vertical steel plates with countercurrent air flow. The calculated results agree well with experiment data as shown in these figures and only slight deviations are presented as shown in Fig. 10 and Fig. 11. Consequently Stephan & Mayinger's model is viable for the prediction of thickness of water film on the plates with countercurrent air flow.



Fig. 11 Film thickness under countercurrent flow (calculated results compared with Roy's experiment)



Fig. 12 Change of critical film thickness over gas/water relative velocity

As introduced in the previous chapter, in the modified water film model the MTE criterion has been applied to predict the critical thickness of water film under countercurrent air flow. Fig. 12 demonstrates the increase of critical thickness as air/liquid relative velocity increases. The physical properties of water and air are similar as the experimental condition of Xu's study. [18] This figure indicates that as the relative velocity increases, the critical film thickness is increased slightly. However during the PCCS operation, the velocity of countercurrent air is 3-4 m/s. [19]. Accordingly by considering only the change of velocity distribution due to interfacial shear, the change of critical thickness is not quite considerable based on MTE criterion. Square dots in Fig. 13 are captured from experimental study of Xu, [18] which show the coverage rate measured on a steel plate with 60° inclination and without countercurrent air flow. In this experiment the plate is perfectly coated with water film with large Re number, then when Re decreases the water flow rate on the plate cannot support a fully covered state and film starts to rupture so that coverage fraction decreases. The critical Re, as indicated in the Figure, is between 630 and 690 while with Hartley's correlation the predicted value of about 499 has under evaluated critical Re for roughly 24%.



Fig. 13 Change of coverage rate and the critical Re number predicted with minimum total energy criterions 3.2 Influence of wave on the film surface



One of the disadvantages of Nusselt's theory is the assumption of smooth surface. However the instability is one of the most significant characteristics of film flow, which results in the generation of surface wave. The small disturbance is produced on the film surface as it flows down and it gradually develops into big solitary waves. Thus the velocity distribution in the smooth film is deformed. Yu et al. [20] concluded that free falling film flow usually consists of film substrates, large solitary waves, and small capillary waves in front of solitary waves as shown in Fig. 14.

Moran et al. [21] had experimentally investigated instantaneous hydrodynamic characteristics of laminar falling films on an inclined plate with a photochromic dye activation technique and the Reynolds number ranges from 11 to 220. In the experiment the instantaneous velocity distribution on the laminar film is measured. The data indicated that the maximum velocity at the crest of the wave is over predicted by Nusselt's theory, while the time-averaged film thickness is only slightly under predicted. The instantaneous velocity profiles in different regions of the wavy film also indicated that the velocity profiles in the film substrate (the very thin layer of film attaching the structure) was in agreement with Nusselt's theory, as depicted in Fig. 15. Based on the velocity profiles, it's concluded that substantial liquid mass was transported by the waves.





# Fig. 15 Variations of instantaneous velocity profile and film thickness at Re = 220



Wave behavior on the film flow has been studied for several decades, but the fundamentals are still not fully understood. As a result of chaotic characteristic of film flow, wave behavior on the film flow is quite random. Therefore, it is reasonable and feasible to describe the film flow behavior statistically especially when the study focuses on the large scale surface such as containment film cooling.

Numerous studies have been conducted to statistically analyze the characteristics of falling liquid film such as the study of Ambrosini et al. [22], which investigated the behaviors of water film freely falling down a vertical and inclined flat plate. In the work, time-averaged, minimum and maximum film thickness and wave velocity are statistically analyzed with the Re number from 140 to 3200 and different water temperature. Yu et al. [20] had also experimentally studied the water film falling and spreading on a large vertical flat plate. The experiments aim at investigating the flow characteristics of a falling film. The Reynolds number of falling film ranges from 50 to 900. The water film thickness and wave velocity are measured in the study. Many of such studies had approximated the results of time averaged film thickness with empirical correlations, as listed in Table 1.

Tuble 1 Empirical correlations for averaged min thekness		
Author	Re range	Relations
Nusselt	0 < Re < 1000 ~ 2000	$\delta = 0.909 \mathrm{Re}^{1/3} \left( v^2 / g \right)^{1/3}$
Takahama [23]	Re > 1472	$\delta = 0.228 \mathrm{Re}^{0.526} \left( v^2 / g \right)^{1/3}$
Karapantsios [24]	500 < Re < 13000	$\delta = 0.214 \mathrm{Re}^{0.538} \left( v^2 / g \right)^{1/3}$
Yu [20]	80 < Re < 900	$\delta = 0.462 \mathrm{Re}^{0.422} \left( v^2 / g \right)^{1/3}$

Table 1 Empirical correlations for averaged film thickness

Based on Nusselt's correlation, other works all have introduced the film thickness empirical correlations in the similar:

$$\delta = a \operatorname{Re}^{b} \left( v^{2} / g \right)^{1/3} \tag{27}$$

It's believed that with different coefficients a and b, the influence of wave is reflected in the correlations. Assuming no slip exists at the solid - liquid interface and the velocity distribution in the film is parabolic:

$$u(y) = \alpha y^2 + \beta y \tag{28}$$

When no shear stress is imposed on the surface:

$$\frac{\partial u(\delta)}{\partial y} = 0 \tag{29}$$

Then the velocity distribution can be calculated and according to Eq. (18), the critical thickness is obtained:

$$\delta_{Critital} = \left(\frac{9}{140}\right)^{\frac{b}{b-2}} a^{\frac{2}{2-b}} \left(\frac{1}{b} - 1\right)^{\frac{b}{b-2}} \mu^{\left(\frac{6b-4}{3b-6}\right)} \rho^{\left(\frac{4-3b}{3b-6}\right)} g^{\frac{2}{3b-6}} (\sin\theta)^{\frac{2}{3b-6}} \sigma^{\frac{b}{2-b}}$$
(30)

And the critical mass flow rate:

$$M_{Critical} = \frac{1}{4}\mu a^{-\frac{1}{b}} \left(\frac{\mu^2}{\rho^2 g \sin\theta}\right)^{-\frac{1}{3b}} \delta_{Critical}^{\frac{1}{b}}$$
(31)

And among which the work of Yu is PCCS oriented and therefore is used in the present work to replace Nusselt's expression in predicting the critical film thickness. As shown in Fig. 16, compared to the prediction of Nusselt's theory, MTE approach with Yu's correlation gives a better prediction of the film critical state, and therefore applied in the modified film model.

# 4. APPLICATION OF THE MODIFIED MODEL

Prior to this work, analyses evaluating the performance of PCCS of AP1000 PWR in case of accidents had been carried out in different studies. In the work conducted by Sandia National Laboratories (SNL) [19], the pressure load inside containment predicted with different codes and geometry models during the double ended cold leg LOCA accident with activation of PCCS have been compared. Moreover, Broxtermann and Allelein [25] used COCOSYS with CDW water film model to simulate the same accident scenario with same boundary conditions of LOCA ejection as well as PCCS flow rate. The work has concluded that with the CDW water film model, COCOSYS can deliver valuable results considering different accident scenarios in AP1000 with evaporating water film on the exterior surface of containment.

In the current work the AP1000 containment is modeled with a simple geometrical model as displayed in Fig. 17 where the nodalization is established by referencing the research of SNL [19], and the geometry data are obtained from the literature which roughly described general features of AP1000 [26].



Fig. 17 Nodalization of AP1000 passive containment

Fig. 18 Pressure change in containment with different nodalizations

An accident scenario similar to SNL's analysis investigating AP1000 PCCS performance is calculated. Boundary conditions including water and steam injection as well as PCCS water film flow rate are roughly acquired from other literature [19,25].

The pressure response inside containment during the accident scenario of Double-Ended Cold Leg (DECL) LOCA is depicted in Fig. 18, where the red curve indicates the prediction with COCOSYS\_Cons nodalization while the blue one denotes the result of COCOSYS\_Plume nodalization [25]. The black curve, which is between these two curves, represents the pressure variation calculated with original film model of COCOSYS and current nodalization described in Fig. 17. Similar trends are observed between these curves. Since the data used for current input deck are roughly captured from the references [25, 26], this deviation of pressure responses may be due to the inevitable discrepancies of containment geometry as well as boundary conditions between the current case and others. Nevertheless, this input deck has already shown an acceptable deviation, thus confirms the availability of the containment nodalization.



Fig. 19 Pressure change with original film model and modified model of different contact angles



Fig. 19 presents the comparison of pressure variation between the simulation result with original version of COCOSYS and the predictions with modified model. Three different cases in terms of different sets of contact angles are performed with the modified model, i.e., advancing and retreating contact angles of  $90^{\circ}$  for case No. 1; advancing and retreating contact angles of  $30^{\circ}$  for case No. 2, and advancing contact angle of  $90^{\circ}$  and retreating contact angle of  $30^{\circ}$  for case No. 3. Compared with the result of original film model, pressure variation predicted with modified model tend to be higher. The figure also reveals that the advancing contact angle of the rivulets is a decisive factor for the peak pressure since higher advancing contact angle results in higher peak pressure as indicated in case No. 1 and case No. 3 while the retreating contact angle is influential in the long term cooling as denoted by case No. 2 and case No. 3.

Coverage rate of rivulets at different elevations is demonstrated in Fig. 20 and Fig. 21. In Fig. 20, the coverage rate of case No. 1 and case No. 3 are presented and for case No. 3, since the advancing contact angle is different from retreating one, the phenomenon of hysteresis is clearly visible. As shown by the full curves, shortly after the blowdown, the coverage rates at different elevations all increase rapidly. Then the coverage rates stay invariable during the long term cooling, even though the PCCS injection rate is gradually decreasing in the meantime. For this case, during the long term cooling, the contact lines between the rivulet and substrate are stagnated while the contact angle is ranging between advancing and retreating values. During the blowdown phase of case No. 1, the change of coverage rate is in accordance with that of case No. 3. However the coverage rates at different elevations start to vary as the PCCS injection rate and evaporation rate on the surface are changing. These discrepancies of coverage rate between each cases result in the discrepancies of pressure change. The peak pressure of case No. 3 is close to case No. 1 since the advancing contact angle of these two cases are the same and during the blowdown phase the rivulets are advancing due to the rapid increase of PCCS injection rate. This results in the same coverage rate at the beginning of the simulation. During the long term cooling the coverage rates of case No. 3 is generally larger than those of case No. 1, therefore the overall evaporation rate of case No. 3 is larger and the pressure is slightly lower than case No. 1 in the latter period.



Fig. 21 Film converage rate at different elevations (Comparison between case No. 2 and case No. 3)



Fig. 22 Change of contact angles at different elevations

Similarly, Fig. 21 implies the reason of smaller peak pressure of case No. 2. During the blowdown phase, the coverage rate of case No. 2 increases faster than that of case No. 1 or case No. 2 due to the smaller advancing contact angle, this results in a better film coating and a larger evaporation rate accordingly, especially at the upper part of the containment where the fully coverage is reached. In the long term cooling the fully coverage at the upper part of the containment is maintained and thus ensures better cooling effectiveness compared with other two cases.

Fig. 22 demonstrates the change of contact angles of case No. 3 at different elevations of the containment. At the beginning of PCCS injection, all rivulets are advancing and the contact angle reaches the maximum rapidly. When the PCCS injection rate starts to decrease slowly, the rivulets are undergoing the hysteresis and the contact angles decrease and vary according to the change of flow rate and the evaporation rate. It's noteworthy that at the upper part of the containment, the contact angle, as indicated with the green line in the figure, keeps as the advancing value. This is due to the fully coverage of the rivulets at the upper part of the containment and the breakup doesn't take place in the long term cooling.

#### 5. CONCLUSIONS

With the modified liquid film model in the L-P code COCOSYS, the effectiveness of film cooling on the exterior containment employed in PCCS is studied. Compared to the original liquid film model, which may overestimate the film cooling efficiency, the newly developed integrated film model has considered different film behaviors including the breakup; expansion/contraction of rivulets; hysteresis of rivulets; shear stress imposed on the film surface as well as the impact of wave generated on the film. The new model has been applied to evaluate the performance of film cooling based on the geometry of AP1000. The results indicate that in the simulated case, the pressure loads predicted with original water film model have been underestimated due to the absence of consideration of detailed film behavior. The sensitivity analysis regarding different sets of advancing/retreating contact angles reveals that the contact angle, which reflects the contact characteristic between the liquid and substrate, plays a significant role in film cooling. It's concluded for the simulated case that the advancing contact angle is decisive for the peak pressure since it determines the maximum coverage shortly after the release of PCCS cooling water while the retreating contact angle is more influential for the long term cooling as it determines the critical height of rivulets to constrict. Consequently, the contact characteristics between liquid and substrate are of crucial significance for PCCS cooling. Confirming the range of key factors such as advancing and contact angles would be helpful for optimizing the design of PCCS.

#### NOMENCLATURE (IF NEEDED)

- a semi width of circular arc part of rivulet (M)
- b width of film sheet part of rivulet (m)

- *E* energy per length (J/m)
- *M* mass flow rate per unit width  $(kg \cdot m^{-1} \cdot s^{-1})$
- *m* evaporation rate per unit width (kg/m/s)
- *p* pressure  $(N \cdot m^{-2})$
- T temperature (K)

$$U^*$$
 dimensionless velocity  $(=uv_l/|g(15\mu_l^2\sigma_{LV}/(\rho_l^3g^2))^{0.4}|)$ 

#### $\mathcal{U}$ velocity (m/s)

# **Greek symbols**

- $\beta$  mass transfer coefficient
- $\gamma$  inclination of the substrate
- $\delta$  liquid film thickness (m)
- $\mu$  dynamic viscosity ( $N \cdot s \cdot m^{-2}$ )
- $\rho$  density  $(kg \cdot m^{-3})$
- $\phi$  rivulet height describing the profile of rivulet (*M*)
- $\tau$  shear stress (*Pa*)
- $\delta^*$  dimensionless film thickness  $\left(\delta^* = \delta \left(\rho^2 g \sin \gamma / \mu^2\right)^{1/3}\right)$
- $\Delta$  dimensionless film thickness for predicting critical state  $\left(=\delta / \left[15\mu_l^2 \sigma_{LV} / (\rho_l^3 g^2)\right]^{0.2}\right)$
- $\Gamma$  dimensionless flow rate per unit width(= $M / \left[\rho_{\mu}\mu_{\sigma}_{LV}^{3} / g\right]^{0.2}$ )
- $\theta$  contact angle between liquid and substrate
- $\sigma$  surface tension (*N* / *m*)
- $\lambda$  width of dry match (*m*)

#### Subscripts

- *l* liquid
- g gas
- *i* interface between liquid and gas

#### Abbreviations

COCOSYS	German COntainment COde SYStem	
MTE	Minimum Total Energy	
PCCS	Passive Containment Cooling System	
SG	Steam Generator	

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