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Experiment study of water film/air counter-current flow heat transfer on a vertical plate for passive containment cooling system

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ABSTRACT

Passive containment cooling system (PCCS) is a key component of the passive safety system in the AP1000 type reactor design. The free falling water film spreading on the outer surface of containment helps to keep the temperature and pressure inside below safety limits. An experiment was setup to study the water film/air counter-current flow heat transfer on a vertical plate with back heating. There was a glass cover placed 0.3 m away from the plate surface forming an air flowing duct, and the heating plate was 5 m in length and 1.2 m in width. Water flowed down from the distribution box on the top of the plate, and then spread on it; while the air flowed in from the bottom of the plate. The inlet and outlet temperatures and flow rates of water and air, heat flux on the plate surface were measured or estimated under different water/air flow rates, water/air inlet temperatures, heating surface temperatures. A new correlation based on the experiment results was developed using heat and mass analogy and included effects from the entrance, plate temperature and gap height between the cover and the plate.

1. Introduction

The evaporation phenomenon encountered in a configuration of a free falling water film covering a heating surface interacting with a counter-current air flow is widely available in industrial applications, such as cooling towers, and the passive containment cooling system (PCCS) in AP600/AP1000 type nuclear reactors. A number of experiments have been setup to studied the phenomenon (Takahama et al., 1974, Ambrosini et al., 1995, Kang and Park 2001, Tan et al., 2002), while the scale of the apparatuses, shape and dimension of the air flow ducts, hydrodynamic and thermodynamic conditions of the water (liquid) and air (gas) inlet flows, and even the measuring methods varied in many ways. Noticeable discrepancies exist between the correlations based on these results. The current paper studied the evaporation heat transfer related to the PCCS of CAP1400 in a larger vertical duct with experiment and developed a more generalized correlation.

PCCS is one of the passive safety systems adopted by Westinghouse in their AP series nuclear reactor designs (Sha et al., 2004)˙ It uses the counter-current natural circulating air flow and gravity-driven water film to cool down the containment steel wall during accidents. The containment has a dual shell, where the inner one is made of steel and the outer of concrete. The gap located between the two shells forms a pathway for the air flow. Under accident scenarios, a water storage tank placed on top of the containment can release the water to the dome top of the steel shell, and a gravity-driven water flow will pass through two distribution weirs, forming an evenly distributed water film covering the heated shell wall. A natural circulating air flow flows upwards above the downwards flowing water film, therefore forming a counter-current water film/air flow configuration, which will cool down the containment, maintain its integrity and prevent the release of the radioactive materials. In most postulated scenarios the evaporation will dominate the heat transfer process.

Ambrosini et al. (1995) studied the water film/air counter-current flow heat transfer based on AP600 PCCS setup, the experiment duct was equipped with 2m × 0.5 m back-heating plate, and the gap height was 0.1 m. The evaporation heat flux was estimated based on electrical power, sensible heat raise for non-evaporated water flow, and convection heat from water to air and heat loss to environment, the results were compared with heat and mass analogy using a modified Dittus-Boelter equation, and a correlation was developed as following,

$$\mathrm{Sh} = 0.023\left[1 + \left(\frac{D_h}{L}\right)^{0.7}\right] Re_g^{0.8} Sc^{0.33} \tag{1}$$

Kang and Park (2001) also studied the water film/air counter-current flow heat transfer phenomena with an experiment duct equipped with 2m × 0.6 m back-heating plate, but with an adjustable gap height, and the heat flux was estimated similarly as Ambrosini. Based on their experiment results a new correlation was developed as showed in Eq.

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Nomenclature

C_i vapor concentration at interface (kg/m^3)
C_∞ vapor concentration in bulk air flow (kg/m^3)
D_h hydraulic diameter (m), defined as $\frac{4A}{P}$, in which A is the cross section area and P is the perimeter of the rectangular air flow duct (two sides lengths are 1.2 m and 0.3 m)
D_v steam vapor diffusion coefficient (m^2/s)
H gap height (m)
H_{ref} reference gap height (m), 0.05 m
L length of the duct (m)
$\dot{m}_{eva}$ averaged evaporated mass flow rate (kg/m^2-s)
P_{sat} saturated steam vapor pressure at water film temperature (Pa)
P_t total gas pressure (Pa)
q''_i heat flux measurement from i sensor (i from 1 to 15) (W/m^2)
q''_{el} average heat flux of the plate based on electrical power and heat loss as shown in Eq. (4) (W/m^2)
q''_{eva} average heat flux of the plate based on evaporation power and powers relates to sensible heat change in water flow and energy change in air flow as shown in Eq. (3) (W/m^2)
q''_s average heat flux of the plate based on heat flux sensor measurements as shown in Eq. (5) (W/m^2)
Q_{air} power for energy change of the air flow between inlet and outlet in which energy from evaporated water is excluded (W)
Q_{el} electrical power used in heating oil system (W) which includes oil heater power and partial pump heating power
Q_{loss} power loss on heating oil piping system, plate backside and sideboards, plate glass cover (W)
Q_{eva} power generating the evaporated water (W)
Q_{sen} power for sensible heat change in unevaporated water flow between inlet and outlet (W)
Re Reynolds number, and $Re_g = \frac{\rho_g V_g D_h}{\mu_g}$, and $D_h = \frac{4A}{P}$, as defined before
S heating surface area of the plate (m^2)
Sc Schmidt number, $\frac{\upsilon_g}{D_v}$, in which υ_g is viscosity of gas, and D_v is vapor diffusion coefficient
Sh Sherwood number
S_i the neighboring surface area assigned to i sensor, and $S = \sum_i S_i$ (m^2).

(2). Kang showed the influence of film wave on the heat transfer, and Huang et al. (2015) also showed the results on this effect. However, discrepancy exists between the predictions from Ambrosini's and Kang's correlations as shown in Fig. 5.

$$Sh = 0.015\left[1 + \left(\frac{D_h}{L}\right)^{0.4}\right] Re_g^{0.8}\left(\frac{1}{1-\frac{P_{sat}}{P_t}}\right)^3 \quad (2)$$

A new reactor design CAP1400 also adopts the PCCS in a larger dimension and presumptively has larger decay heat release during accident comparing to AP600 design, therefore experiments with extended test conditions focusing on the CAP1400′s scenario should be carried out (Li et al., 2016). The current study established a new experiment facility corresponding to these needs. A back-heated plate with enlarged size and power was used, and a glass cover on its surface formed a wind duct to provide counter-current flow path. The experiments were carried out with various water inlet temperatures, flow rates; inlet air temperatures and velocities; and plate temperatures. Current study also measured and estimated evaporation heat flux both locally and globally on the plate surface. The experimental results were used to develop a new correlation based on heat and mass analogy and includes effects from the entrance, plate temperature and gap height between the cover and the plate. A code validation work will be carried out based on the current experiment results and will be reported in a separate paper.

2. Experiment facility description

The experiment facility WAFT (WAter Film Test) for the current study consisted of a main plate, a glass cover, a rotating frame, a water heating equipment, a water supply and recovery system, air heating and supply system, heating oil supply system, as shown in Fig. 1.

The dimension of the main plate was 5m × 1.2m × 0.019 m. It was made of carbon steel and its front surface was polished and painted with nonorganic zinc paint as used in AP1000 containment (Carbozinc 11 HSN). Its manufacturing process followed precisely the direction of the AP1000 document. The back side of the plate was welded in 250 thin round copper tubes, and these tubes were parallel with the short side of plate (1.2 m) as shown in Fig. 2. The heating oil were pumped into the tubes, and the oil temperature can be regulated up to 350 °C. The power of heating oil supply equipment was up to 1 MW.

A glass cover, in the same size as the front side of plate, was placed 0.3 m away from the plate with side walls to form a rectangular air flow duct. The rotating frame supporting the plate and glass cover could be tilted at any angle between 0° to 90° to simulate the water film flowing down from the dome area to the side wall area of the containment. Water supply system could heat up the inlet water up to 95 °C at various flow rates from 0.01 to 1.08 kg/m-s, and use the water delivery box to spread the water on the plate. The delivery box had an adequate volume to stabilize the water flow and V-shaped outlets as in real containment weirs. A water recovery tank on top of a weighting platform was used to gather the outflowing water from the bottom of the plate to estimate the mass of evaporated water.

The WAFT air supply system could heat up the injected air up to 95 °C at various air velocities.

The WAFT experiment parameters are shown in Table 1. The heat flux is an average value crossing the heating plate. The water flow rate is the outlet flow rate per wetted perimeter which is the width of the plate in a water film fully-covered scenario, and the water temperature is the temperature of the outlet flow from the water delivery box as shown in Fig. 1. The air velocity and temperature are the inlet values at the air flow entrance of the rectangular duct.

During the evaporation tests, the air flowed in from the bottom of the gap using a wind blower, and the water spread on the plate surface from the distribution box at the top driven by gravity. The heat source was supplied by parallel heating oil tubes on the backside of the plate. The plate surface temperature was measured with K-type thermocouples mounted on the surface; the water flow rate was measured with two electromagnetic flowmeters operating at different ranges (0–0.6 m^3/hr, 0.6–6 m^3/hr), which were selected to better control the flow rate. Inlet and outlet water temperatures were measured with K-type thermocouples, and the air velocities and temperatures were measured at 15 positions with an anemometer right above the heat flux sensors. The heat flux film sensors (RDF27036) were directly attached to the surface at 15 positions to measure local heat flux as shown in Fig. 2. Three humidity sensors measured humidity at the inlet, the outlet and the middle position of the air flow duct. The errors of measurements were shown in Table 2.

3. Experiment procedure

After setting up the designated tilting angle, plate surface