EXPERIMENTAL STUDY METHODS OF THE PCCS CONTAINMENT WALL CONDENSATION WITH NON-CONDENSABLE GAS

Cheng Li*, Zhan Gao, Shan Zhou, Hongsen Li, Wangfang Du, Wei Zhao and Lin Yang
State Nuclear Power Technology Research & Development Center
South Park, Beijing Future Science &Technology City, 102209, Beijing, China
licheng1@snptc.com.cn, gaozhan@snptc.com.cn, zhoushan@snptc.com.cn
lihongsen@snptc.com.cn,duwangfang@snptc.com.cn
zhaowei@snptc.com.cn,yanglin@snptc.com.cn

ABSTRACT

To accomplish the innovating development of the 3rd advanced nuclear power technology, the ISCOE tests studying the containment inner wall condensation with non-condensable gas was performed. The present work gave and specified the research roadmap. It then considered the prototype and experiment factors, they were the prototype phenomenon and its corresponding experimental section, the primary heat losses for the experiment study, thermal analyses of the experimental section structure and the key local measurement technologies. These analyses effectively supported and then verified the reliability of the experimental facility and the identity of key phenomenon with the prototype. Besides, future experiment works about the local important phenomena studies for steam condensation with non-condensable gas were also specifically described.

KEYWORDS

passive containment, wall condensation, water film evaporation with counter-current air flow

1. INTRODUCTION

China introduced the 3rd advanced nuclear power technology, AP1000, from the Westinghouse in 2006. The safety related passive technology of AP1000 was firstly absorbed and then the further independence innovation was encouragingly started [1]. Lots of thermal-hydraulic facilities in China were gradually constructed and they are used to verify its engineering designs about the safety related cooling and heat removal technology. One of these is the ISCOE (containment inner wall steam condensation coupled outer evaporation) facility and it was built at the famous 200# experimental base of the Tsinghua University in China, which is one birthplace of the Chinese nuclear reactor and nuclear power applications.

The characteristics of the wall condensation and the evaporation on the containment wall could reveal the containment heat removal capacity during the long term depressurized stage. Thus, to avoid any radioactive leakage from the containment during accidents, the ISCOE experimental project was

*Male, Born in 1982, Ph. D, senior engineer, technical director of the ISCOE experimental subject supported and it should reliably verify the engineering designs by investigating the containment wall heat removal capacities and mass transfer characteristics due to the steam wall condensation and the water film evaporation. As the steam condensation with non-condensable gases and the water film evaporation with countercurrent air on the passive containment walls are different key phenomena and their experimental methods are different. Thus, the following will only make the analyses and discussions on the steam condensation on wall with non-condensable gas. The present work will discuss condensation heat transfer feature of the prototype condensation phenomenon and it then will provide the functional requirements for the ISCOE facility and the physical phenomena from the view of its boundary layers development by analyzing the physical model, flow pattern, heat losses and mainly measurement techniques. It will also guide the latter key data reduction and at last conclude the following investigations.

2. EXPERIMENTAL METHODS

The experimental methods were formed with its roadmap in Figure 1. The first step is to analyze the PCCS (passive containment cooling system) prototype key phenomena near the containment wall and then to obtain the prototype structure features and its operational parameters. By identifying the phenomenon and by scaling down, previous investigations corresponding with their conclusions are checked for their applicability. Their applicability factors include the same thermal-hydraulic phenomenon, operational parameters (temperature, pressure, and condensation heat flux), flow patterns, measurements uncertainties and so on. Finally, the ranges of the dimensionless number for further researches and verification are given and the test needs appear. By making the test matrix and by carrying out the tests, the condensation mass transfer characteristics are obtained and they are used to verify correlations and even to improve the empirical model, which is on the other hand guide the engineering designs.

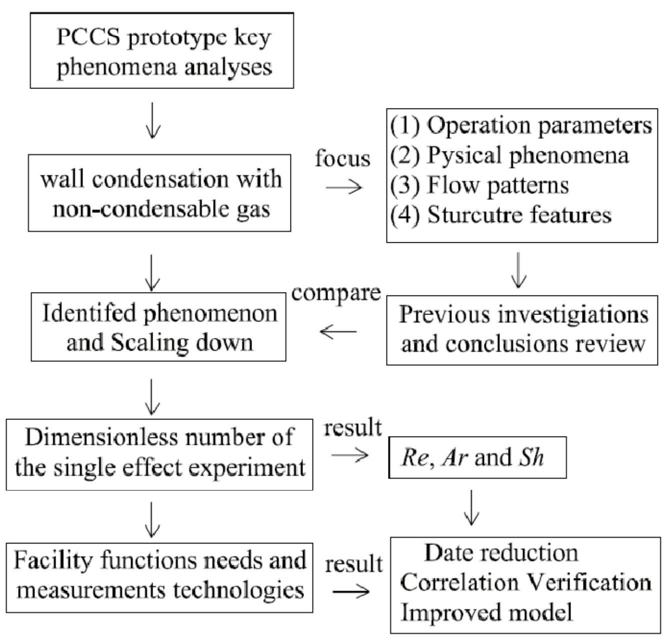


Figure 1. ISCOE investigation roadmap

The following will show and discuss the prototype condensation features and the physical model for experiments. The concluded parameters will help guide the experiment facility constructions and latter test verifications. These parameters are used to make sure that the experimental model can scale up to the prototype condensation phenomenon.

2.1. Prototype Phenomenon

The first objective of the ISCOE experimental project is to obtain the wall heat transfer characteristics, which are then used to evaluate the containment heat removal capacity and to verify the corresponding correlation used for the innovation engineering designs. Firstly, Figure 2 shows the steam mixture flow pattern and the wall heat removal model by Dehbi [2]. It indicates the basic heat transfer characteristics of condensation of mixed convection and the non-interrupted boundary layer, which cannot be freely developed in the prototype containment as equipments and components can easily interrupt the boundary layers. Even so, boundary layers from different wall meet. Secondly, the condensation should include the both the vertical wall and the dome section. Li et al [3] analyzed the importance and the necessities from the views of the mass fraction, condensation flux, condensate behavior, interfacial advective condensation convection [4] and space fog appearance.

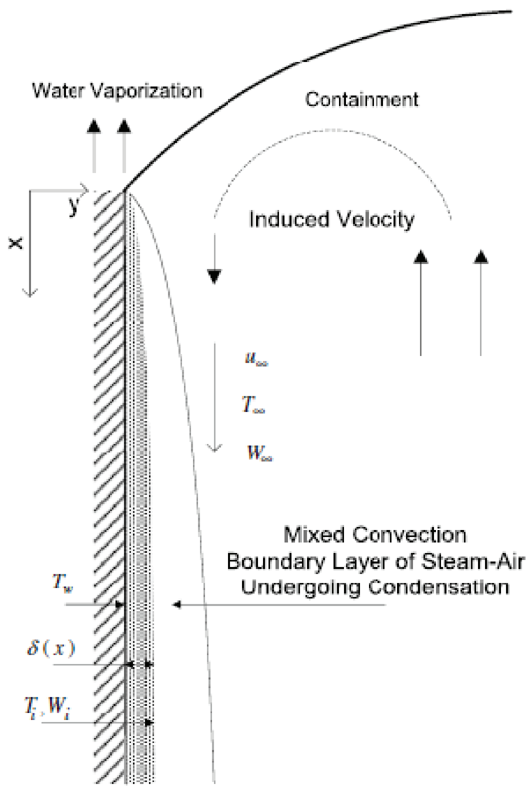


Figure2. Flow pattern and the wall heat removal model

The heat transfer modes on the containment inner wall include the wall convective condensation with non-condensable gas, the thermal radiation and the thermal convection. Of the three heat transfer modes, the wall condensation is the main one. Because the condensation heat flux takes 92% of the total wall heat flux while sum of the thermal radiation and thermal convection fluxes takes less than 8% [5]. So, previous correlations for radiation and convection can be used to predict their fluxes and their prediction uncertainties contribute relatively a little to the total wall heat flux.

2.2. Experimental Model

For the postulated PWR LOCA accident, the sprayed coolant rate at the broken pipe will become small and at the same time will be some stable during the long term depressurized stage [6]. Effects of the spray location, the sprayed coolant flashing and its kinetic energy on the wall neighboring flow become weak. The flow neighboring wall is mainly influenced by the fluid density difference due to the condensation and cooling. Thus, It is the mixed convection heat and mass transfer induced by natural convection. The wall neighboring bulk velocity is manly among 0.5-2.0 m/s. Take AP1000 Containment for example, its diameter is around 40 m and the boundary layers of the flow, the thermal and the concentration boundary layers can free develop. Thus, the boundary layers will not be disturbed for location higher than the operating platform. In order to accurately simulate the prototype containment condensation, the following factors should be carefully considered and analyzed. The first is the boundary layer of free development. The second is the turbulent flow and mixed convection. The third is that the turbulent disturbance and the concentration stratification at the entrance, which may happen if they are not well mixed during their supply. The last is the heat loss from the test plate boundary corner.

2.2.1. Boundary layer analyses

Figure 3 shows the crossing section of the condensation-evaporation test section (ISCOE facility includes both the outer water film condensation and the inner wall condensation). If the boundary layers from the test plate free develop, the flow pattern will belong to those outer flow, such as the flow along a flat plate. Thus, it is required that the boundary layers of the experimental surface should not meet. Traditionally, the flow boundary layer development of natural convection is faster than the forced convection one. The mixed convection boundary layer development is much complicated and it should consider both the natural and the forced effects.

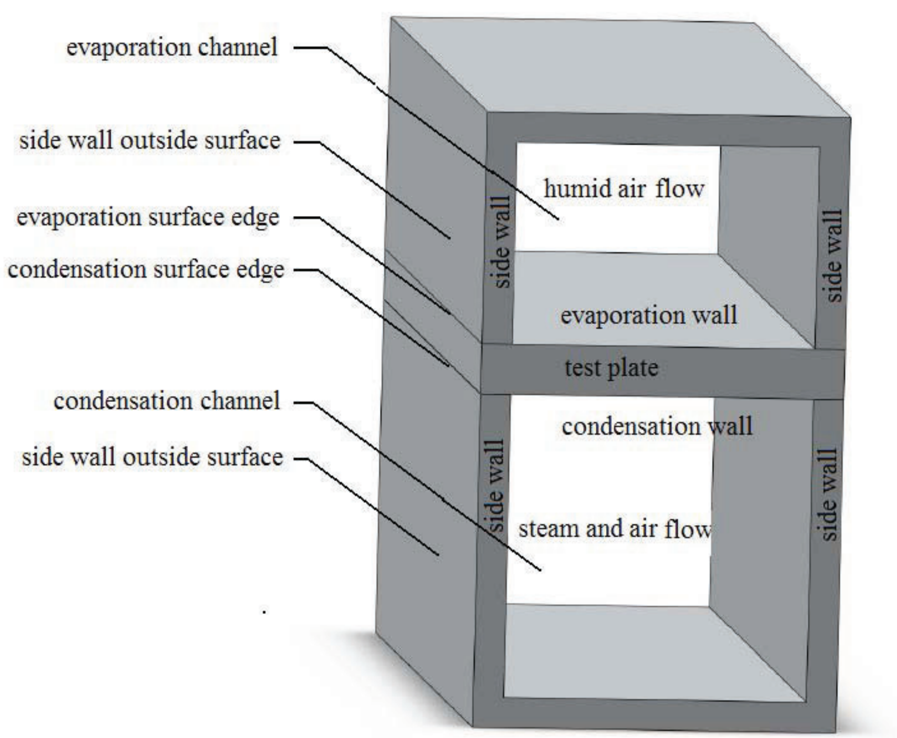


Figure 3. Crossing section of the condensation-evaporation test section

The numerical solution analysis is used to predict the flow boundary layer development for mixed convection, with its results used for the test section design. For example, the surface of 4.0 m in lengths and 0.3 m in width is chosen. The inlet velocity is 0.5 m/s and the vapor and air mass ratio of 2.47（corresponding to the temperature of 140 ℃）, with the cold wall temperature of 110 ℃. Boussinesq assumption is used to simulate the buoyancy effects. Figure 4 gives the velocities at different locations. It indicates that, for 0.5 m/s inlet velocity, the flow boundary layers between the test surface and the opposite surface tend to intersect at 2.0 m from inlet and thus, the downstream heat and mass transfer will be deviated from the prototype phenomena. Theoretically, the test data with 2.0 m in length from the test section inlet fit for the laminar and turbulent heat and mass transfer analyses, while the downstream are data is invalid. If we want all the data on the whole length to be valid, the width should enlarge so that the velocity boundary layers from two sides will not meet significantly.

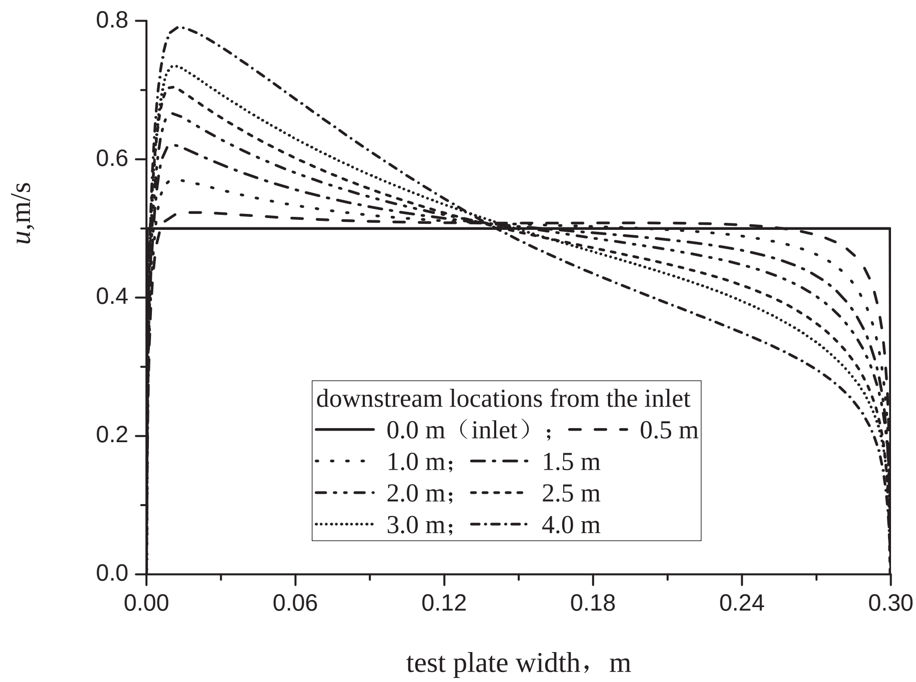


Figure 4. Velocities of different locations from the test plate entrance

2.2.2. Turbulent flow analyses

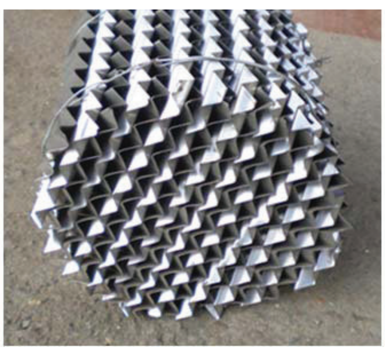
Turbulence appears earlier for natural convection than that of the forced convection, as the density difference between the cold wall and the fluid is large and the local *Ar* is three times of the local length. To realize the flow transition from laminar to turbulence, the maximum local *Ar* should be larger than 2.0×10^{10} for natural convection while the length-based maximum *Re* should be larger than 2.0×10^{5} for forced convection. The calculation indicates that the test plate length should be larger than 2.0 m, which could make sure that the turbulent flow appears for natural or the forced convection.

The existing vapor boiler with its power rating of the 1080 kW power is planned for the water vapor supply. Its maximum water vapor supply is also a limitation factor for the choice of the test section sizes. At last, the condensation plate surface dimension is 3.0 m in length and is 0.3 m in width with the channel height of 0.3 m, with the condensation channel shown in Figure 3.

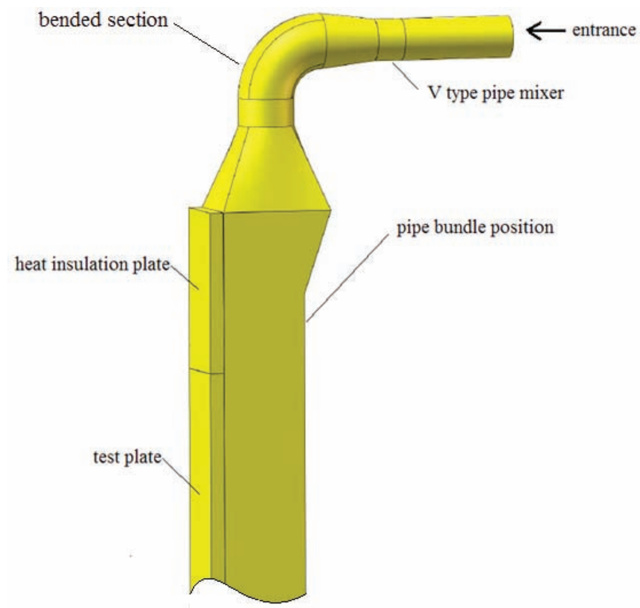
2.2.3. Concentration stratification and turbulence factors

To experimentally simulate the prototype containment wall condensation, if the water vapor supply and the air supply are not well mixed before they enter the test section, the concentration stratification will exist and it will influence the test quality and data availability. The V type piper mixer of 1 m in length is used to add into the pipe, which can make flow meet and mix more than 20 times so that they are mixed several times before they enter the test section.

Similarly, the entrance fluid direction will change when it flows through the bended pipe in Figure 5 (b), so the fluid turbulence may appear before it enter the test section. The turbulence and disturbance could easily make the turbulence transition earlier and the length-based *Re* or *Ar* will not well simulate the prototype characteristics. Thus, a pipe bundle was design and used to eliminate turbulence and disturbance at the entrance. Besides, the thermal insulation is adopted to avoid any significant heat and mass transfer upstream of the test plate. Figure 5 (a) and (b) respectively shows the mixer structure and the condensation section.



(a) V type static mixer



(b) condensation section

Figure 5. Entrance mixer and eliminating turbulent structure

2.2.4. Heat losses

The condensation channel is a pressured one, so the test plate should consider both the sealing and the heat insulation. If the heat insulation is not well considered, the heat from the high temperature wall will heat up the cold wall and the wall condensation characteristics will become necessarily different from the prototype. Furthermore, the local temperature distribution cannot be measured accurately. Thus, the ideal aim is to insulate the heat transfer from the side wall (see Figure 3) to the test section. The structure of Figure 6 is used and its design makes sure that the heat loss due to the boundary effects should be less than 1.0 %. There, a kind of heat insulating material, the aerogel, is used between the side wall and the test plate. The indirectly sealing method is used by the bolt fastening, which puts the stress act on the sealing material. The aerogel is typical of the porous material. The present measured average thermal conductivity on its pressured state is 0.033 W/m-K. The numerical simulation is used to predict the heat losses from the side wall to the test wall. In order to conservatively predict the heat loss, the thermal conductivities (test plate of 46 W/m-K, bolt of 17 W/m-K, side steel wall of 46 W/m-K, heat insulating material of 0.2 W/m-K) were used, with the thermal conductivity of the heat insulating material being larger than the aerogel. The bolt was also simplified to be a symmetrical structure in order to simplify the prediction. The third boundary condition is used with the thermal convection heat transfer coefficient of 400 W/m^2-K, which is equivalent to or larger than the total heat transfer coefficient from the condensation side. The temperature distribution within the structure is shown in Figure 7. The results indicated that the total heat loss percentage via heat insulating material was less than 0.8% and the heat transfer via the bolt was 3.85% [7]. The latter will contribute nothing to test plate heat loss. Thus, the heat loss from the condensation test plate edge can be neglected.

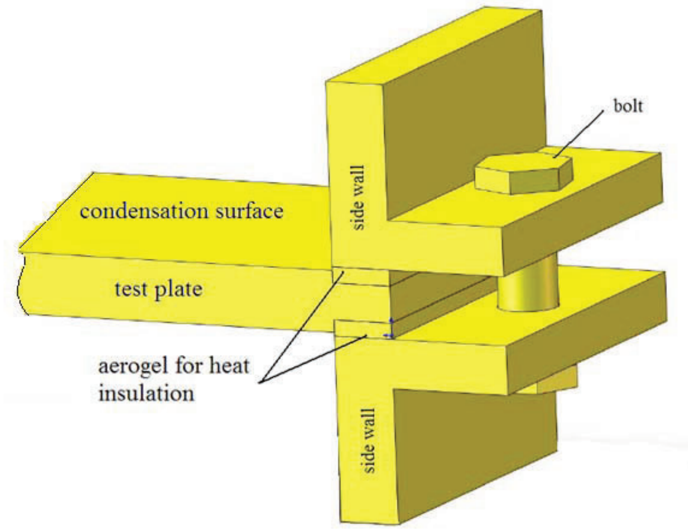


Figure 6. Test plate isothermal method

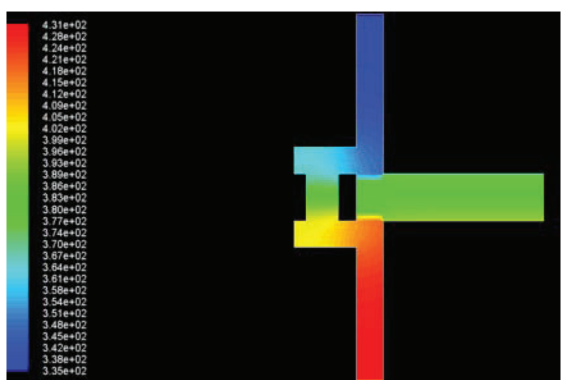


Figure 7. Temperature distributions of the connecting crossing-section

2.3. Key Measurement Techniques

During the data reduction, the important step is to connect the measure parameters with the mass transfer coefficient, based on these relations, the measurement techniques are arranged.

2.3.1 Total local heat flux

As discussed in Section 2.1, heat fluxes from the thermal convection and the thermal radiation are relatively small and condensation flux and its characteristics are the measurement objectives. Thus, the Sherwood number is the important parameter for the convective condensation. Equation (1) gives its expression, which was used for the experimental data reduction.

$$Sh_x = \frac{q_{\mathrm{x,cond}}}{h_{\mathrm{fg}} M_{\mathrm{vapor}} (P_{\mathrm{bulk,vapor}} - P_{\mathrm{surface,vapor,i}})} \frac{k \cdot x \cdot \mathrm{R} \times t \cdot p_{bm}}{p_{\mathrm{t}} \cdot D} \qquad (1)$$

Equation (1) indicates that the Sherwood number is the function of temperature, pressure, heat flux and the thermal properties. Traditionally, the thermal properties are seen as the function of temperature and partial pressure. Thus, *Sh* can be directly related to the temperature, partial pressure and heat flux. The temperature and pressure can be accurately and directly measured, while no related instrument can be used to accurately measure either the heat flux or the partial pressure. The heat flux is often obtained according to the Fourier's law and its result produce the measurement uncertainties from the wall thickness, the temperature difference and the material thermal conductivity. Thus, the local heat flux should be carefully measured.

The ideal arrangement scheme for the thermocouple is that the path of its wire can be arranged along with the isotherm direction. If the temperature gradient is large enough, the thermal potential at the thermocouple junction will be badly influenced and additional error can appear. Presently, the smaller thermocouple of 1 mm diameter was used to measure the temperature difference along the plate thicknesses. Its wire arrangement makes sure that there is a low temperature gradient on its path within the length of the 50 times diameters from the thermocouple junction. Figure 8 shows the arrangements.

Based on the above thermocouple arrangement, the actual thermocouple junction and its connecting wire are buried at a micro-channel of 2 mm and filled up by tin material after the test plate was wholly heated to the tin melting temperature, avoiding air existing between materials. Finally, the flat plate surface was coated with the same material as the AP1000. The coated layer was checked by technicians and reports were made.

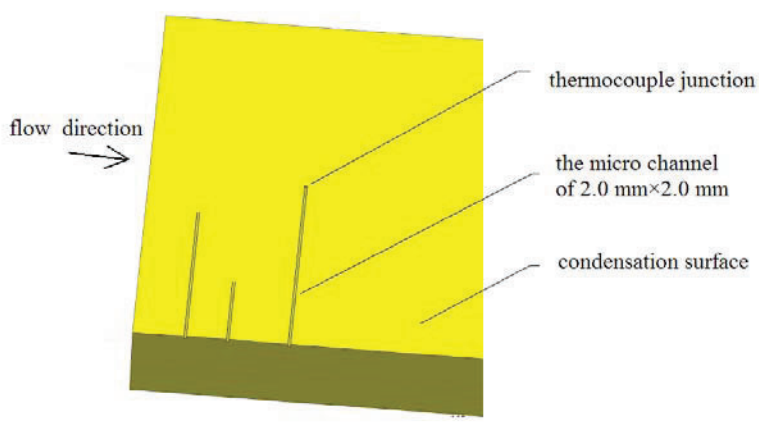


Figure 8.Thermocouple arrangements

Tin and test plate are different metal materials, so their thermal conductivities are different, which can bring measurement errors. A numerical simulation analysis was accomplished to evaluate the difference. Figure 9 gives the temperature distributions [8]. It shows that the temperature at the channel will increase

0.12 ℃. The errors were less than the thermocouple and data acquisition channel, so it was added into the latter data uncertainty assessment.

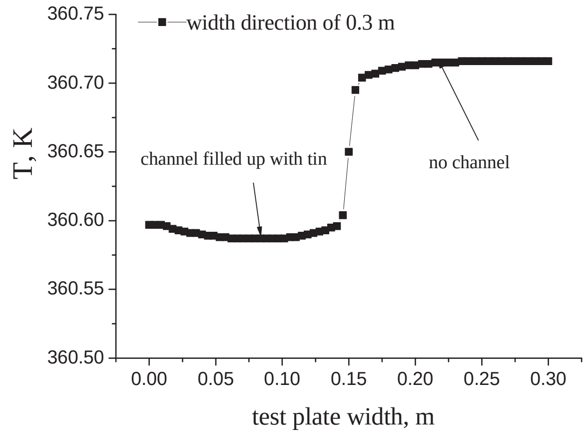


Figure 9. Temperature profiles by tin filler on condensation side

In Figure 10, L1 are at the center line and the thermocouples there are the important test data and are used for latter heat and mass transfer analyses. The thermocouples at L2 and L3 are used to check the boundary edge effects of heat loss and fluid retention on the temperature disturb of center line. Section2.2.4 has numerically made sure that the heat loss can be neglected. Thus, if the measured temperature at different lines exists significant different, the temperature at centre line will be affected due to the boundary heat loss and fluid stagnation. Then, the heat fluxes measured will be inaccurate and the tests will be failing. The latter test exercise indicated that the temperature at L3 was a little different from L1 and L2 while the temperature at L1 and L2 are almost the same value for the same location from the entrance. These results indicate that the effect of fluid retention on the L 1 temperature can be neglected.

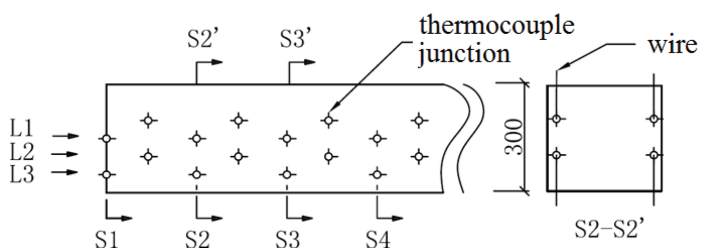


Figure 10. Thermocouple location and its wire

High performance 108 thermocouples from WIKA were used to measure the condensation wall temperature and the heat flux. Calibration results from the qualified testing institution indicated that the thermocouples were qualified but their performance of measurement uncertainties was shown different directions. Some are a little large while some are small. Thus, the two of the same direction deviation are paired to obtain the heat flux. Furthermore, the thermocouple system errors are analyzed and some are then offset. Finally, the residual errors are less than 0.15℃. Besides, an additional transient error value of 0.1 ℃ was also considered from the point of its conservative measurement. Besides, the systematic errors from the data acquisition and the thermocouple compensation wire were also included. The effect of the electromagnetic environment from the operating of the surrounding ACME and IVR facilities on the flow-meter's accuracy was also tested. These two facilities are in the same factory and they possibly works at the same time.

2.3.1 Partial pressure

The partial pressure or component concentration is another key parameter, which cannot be directly measured by instruments. Results from investigation on the humidity instrument indicates that the worldwide famous instruments for relative humidity measurement cannot be used for more than 100 ℃ of saturated fluid. On the other hand, Mixture gas temperature cannot be seen as water vapor at its saturation state, so there are no relations between temperature and the water vapor partial pressure.

On the other hand, when the steam and air mixed together before they come into the test section, they undergo the flow resistance and pipe wall condensation. Thus, it is unreasonable to recognize the water vapor to be saturated. Based on these analyses, the mass flow rates and the total pressure of the air, the water vapor and their mixture were measured and were used to deduce the water vapor partial pressure [9]. Effects of the pipe surface condensation loss [10] on the mass flow were measured and were also considered during the data reduction.

2.4. Local condensation heat flux

The steam and air mixture near the containment wall bring the natural convection, including the condensation induced mixed convection and condensation. The local parameters are used for the latter data analyses. Those data of invalid should be eliminated, or else the conclusion will be meaningless. Take the 0.5 m/s inlet velocity for example. The downstream data for 2.0 m should be neglected for analyses.

Presently, the local condensation heat flux is the important parameter for condensation analyses. However, the heat flux measured according to the Fourier’s law is the sum of the thermal convection, condensation convection and thermal radiation heat fluxes. How to obtain the condensation heat flux becomes the key. Li et al [5, 11] expounded these and they compared the numerical simulation with latter test data. Their argument related to the actual testing. That is taking the thermal radiation and the thermal convection fluxes away from the local total heat flux and the left is the condensation heat flux.

$$q_{\mathrm{cond}} = q_{\mathrm{t}} - q_{\mathrm{conv}} - q_{\mathrm{radi}} \tag{3}$$

2.5. Other studies

The experimental study of the PCCS wall condensation of steam with non-condensable gases is only the first task. Besides, the ISCOE test platform includes studies as follows: (1) The full coverage water film evaporation with countercurrent air, which is to simulate the PCCS outer up-comer evaporation heat and mass transfer. (2) The partially wetted surface water film evaporation coupled the 2-D heat transfer within the steel wall, which is the actual phenomenon when water from the containment top water storage tank flows along the containment outer wall. (3) Behaviors of the water film transient flow on extreme conditions, when the dry wall temperature is higher than 120 ℃. The scenario could appear when the trigger delay on the containment top water tank. (4) The heat transfer enhancement method after 72 h, typical of no water film evaporation. (5) Developing condensation correlations of mixture gas mixed convection, which can much accurately predict the PCCS heat removal. (6) Transient scenario condensation heat transfer characteristics. Traditionally, the steady heat and mass transfer correlations were often used to predict the transient heat transfer. However, heat transfer at transient scenario no longer obeys by Newton's law of cooling. (7) Model development of either the condensation or the evaporation used for special applications.

3. CONCLUSIONS

The current work generally described the experimental methods of the PCCS wall condensation win non-condensable gas by analyses. It started from the building of roadmap and it then made the discussion on the prototype phenomena and analyzed its flow and boundary layer development. The test section sketch was then given, combined with the existing steam boiler. The entrance structure and mixing technique were equipped on the ISCOE facility. Then, the heat loss at the boundary edge was numerically obtained and discussed. The data reduction and important parameter measurement were also discussed. Finally, the other future investigation aspects were given. The whole experimental methods and the corresponding technique analyses guide the design and the construction of the ISCOE test platform and the tests implement. The next work is to form and give the technical reports on mixed convection condensation heat transfer characteristics.

NOMENCLATURE

Ar	length from inlet based local Archimedes number,-
D	mass diffusivity coefficient, m^2/s.
h_{fg}	phase change heat, kJ/kg.
M	mean molecular weight, g/mol.
P	pressure, Pa.
q_{cond}	local condensation heat flux, W/m^2.
q_{conv}	local convection heat flux, W/m^2.
q_{rad}	local thermal radiation heat flux, W/m^2.
q_t	local total heat flux, W/m^2.
R	gas constant, J/mol-K.
Re	length from inlet based local Reynolds number, -,
Sh	local Sherwood number, -.
t	fluid temperature, ℃ or K
x	local distance from the entrance, m.

ACKNOWLEDGMENTS

The project was financially supported by the National Science and Technology Major Project of the Ministry of Science and Technology of China (No.2011ZX06002-005). We acknowledge the efforts from anonymous reviewers for the significant amount of edits and suggestions.

REFERENCES

1. http://www.snptrd.com/templates/news/index.aspx?nodeid=8
2. A. Dehbi, "On the Adequacy of Wall Functions to Predict Condensation Rates from Steam-noncondensable gas, " *Nucl.Eng. Des.* 265, pp.25-34 (2013)
3. C. Li, R. C. Zhao and H. J. Chang et al, "A brief of the ISCOE experimental platform research objectives and facility construction requirements," *The 23rd International Conference on Nuclear Engineering in Japan(ICONE23)*. Chiba. May 17th-21th (2015), Paper ID.1327
4. C. Li, "Study on Condensation Heat Transfer of humid Air without and with Alkane Added". *Doctorial thesis submitted to Tsinghua University*. Pp. 8-10 (2011)

5. C.Li, H. R. Fan and R. C. Zhao, “The outside transport phenomena of the passive containment cooling system,” *Proceedings of the ASME 2013 Summer Heat Transfer Conference ASME heat transfer conference in Ame*rican. Minneapolis. July 14 – 19 (2013) , Paper ID.17179
6. F. C. Rahim, M. Rahgoshay and S. K. Mousavian,” A study of large break LOCA in the AP1000 reactor containment, ” *Prog. Nucl. Energ.* 54 (1), pp.132-137 (2012)
7. C. Li, “Evaluation of the heat losses between the test plate and the side wall, ” *ISCOE group technical report*”. 2013.5.15
8. C. Li, “Numerical analyses of the effects of burying thermocouple on the wall temperature, “*ISCOE group technical report*. 2013.1.12
9. C. Li, “The method of the ISCOE facility mass balance prediction,” *ISCOE group technical report*. 2015.5.26
10. Z. Gao, “The method of the ISCOE heat losses calculation and prediction, “ *ISCOE group technical report*. 2015.5.26
11. C. Li, “The data reduction method for ISCOE test data, ” *ISCOE group technical report*.2014.7.16