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Experimental Investigation of thermal hydraulic characteristic of water based thermosyphon under evacuated non-condensable and pressurized non-condensable gas

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1. Introduction

The accident of the Fukushima power plant that happened in 2011 has signified the importance of high-efficiency passive cooling in nuclear power-plant safety. Thermosyphon is a device that operates passively by utilizing phase-change and gravity as methods for heat and mass transfer. The feasibility of applying thermosyphon in nuclear powerplant cooling alternatives has been seriously considered [1-3]. To cope with a high-pressure and high-temperature environment inside a Pressurized Water Reactor (PWR), a non-condensable pressurized thermosyphon was proposed by Kim and Bang as a hybrid heat pipe that also functions as a control rod [4]. In order to develop more understanding of the behavior of non-condensable pressurized thermosyphon, an experimental set-up has been derived in this study by expanding the initial pressure range, such as vacuumed condition, non-condensable charged under near vacuum, and non-condensable charged above atmospheric pressure.

2. Methods and Results

2.1 Experimental set up and procedure.

The experiment was conducted on a stainless-steel tube with geometrical information mentioned in table.1. The experiment was done under 5 different initial pressure. Vacuum pressure was reached by using a vacuumed pump where all the non-condensable gas inside the thermosyphon was evacuated. The water then turned into vapor as a consequence. For the non-condensable pressurized condition, argon gas was selected due to its inert characteristic. The list of pressure value established in this experimental study was listed in detailed manner in Table. 1.

Table. 1Information of experimental detail

Material	Stainless steel pipe
EAC Ratio	1:1:1
Length	1 [m]
Inner Diameter	16.57 [mm]
Outer Diameter	19.05 [mm]
Working Fluid	DI water
Heat Load	50 – 1100 [W]
Non condensable gas	Argon
Initial system pressure	evacuated (2.8 kPa)
	pressurized (13, 25, 75, 75 kPa)
Coolant Inlet Temp.	20 °C
Coolant Flow rate	1.5 – 2.3 lpm
Insulation	Glass fiber, aluminum foil

The thermosyphon was operated by supplying a controlled amount of heat in the evaporator while measuring the released heat in the condenser. The evaporator section was made of Ni-Chrome wire connected with a direct current power supply. The amount of heat supplied to the evaporator was directly derived from Ohm's law by multiplying the current and the voltage. The heat will be released in the condenser section which was made as a close loop by utilizing water-temperature-controller to supply constant temperature water. The amount of heat released in the condenser is linear with temperature difference in the outlet and inlet of cooling jacket that was measured by putting an RTD sensor on both inlet side and outlet side. Temperature along the thermosyphon axial length was measured by attaching K-Type thermocouple on the surface. System pressure was measured by a pressure transducer on the top-end of the thermosyphon. The diagram of experimental set-up in this study can be seen in the Fig. 1.

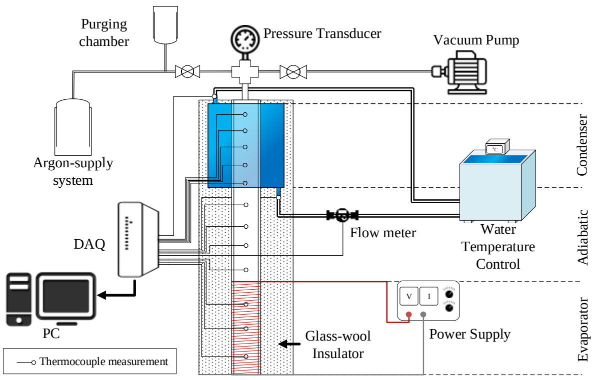


Fig. 1. Diagram of experimental set-up

2.2 2. 2 Modified condenser model for non-condensable presence

The condenser model in general was based on Kim and Bang hybrid heat pipe model [3]. However, in the detail, the assumption of sharp temperature change between the effective condenser and non-condensable occupied length was made in order to properly estimate the account of the non-condensable occupied length. In Fig. 2, on the left side is Kim and Bang model hybrid heat pipe, and the assumption added in this study is described on the right side.

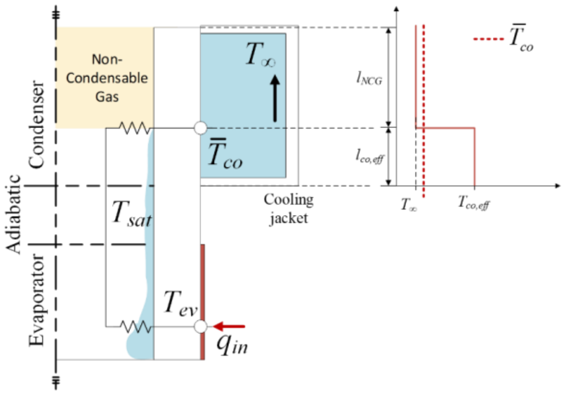


Fig. 2. Condenser model for non-condensable pressurized thermosyphon

An iterative form of calculation algorithm is shown in Fig 3 as an attempt to predict the performance of thermosyphon. Heat transfer formula being utilized in the condenser is Kim and Bang model which takes into account the effective length. The Kim and Bang heat transfer model is expressed in the eq. (1).

$$h = Re^{0.1} \exp(-0.0003 \frac{\rho_l}{\rho_v}) \times \left\{ 0.943 \left(\frac{\rho_l (\rho_l - \rho_v) g k_l^3 h_{fg}}{\mu_l \left(l_{co} - \frac{nRT}{PA_{cs}} \right) (T_{sat} - T_{co})} \right)^{1/4} \right\} \quad (1)$$

The equation was derived from Nusselt film condensation theory. Consideration of counter entrainment effect on the heat transfer was weighted by film Reynolds number which is calculated as $Re = 4Q / (\pi d h_{fg} \mu)$,as well as exponential of density ratio.

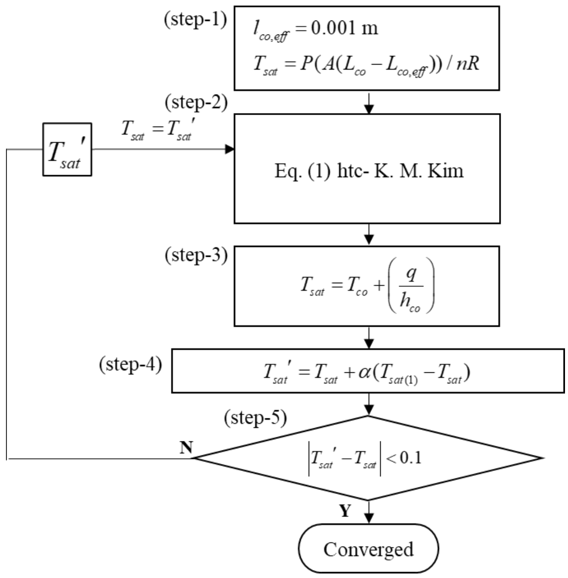


Fig. 3. Algorithm for predicting the performance of non-condensable pressurized thermosyphon.

Secondly is the calculation of effective length derived by the assumption of ideal gas substituting condenser length in the original Nusselt film condensation theory.

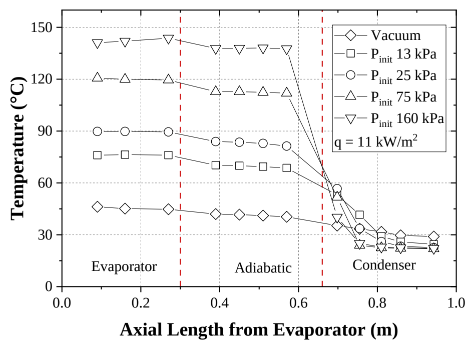
In the equation, subscript l, and v refer to properties of working fluid in the form of liquid and vapor respectively. Variable g refers to gravity acceleration, k is thermal conductivity, ρ is density, μ is viscosity, l is length, T is temperature and h_{fg} refers to enthalpy difference between vapor and liquid form of working fluid. The subscript *co* refers to value in the condenser, while addition of *co,eff* refer to the value in the effective length of condenser. The subscript *sat* refer to the value at saturation point. Variable α in the algorithm refers to under relaxation constant that being used to generate new saturation temperature value (marked with ‘) from particular iteration with the iteration before that.

By implementing the equation and algorithm into a MATLAB code, the prediction of system pressure is being compared with experimental data in the result and discussion section.

3. Result and Discussion

3.1 Temperature Data

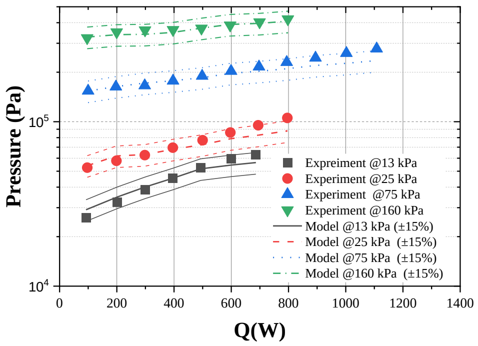
Temperature of thermosyphon along the axial length was measured at steady state. In fig.x the temperature difference between each initial pressure condition was presented under the same evaporator heat flux. The presence of pressurized non-condensable gas appeared to increase the saturation pressure of the working fluid and consequently increase the operating temperature. From the point of view of operating limitation, this is beneficial as operating limitation increases with the operating temperature.



3.2 Prediction of model and experimental validation

Validation for the design algorithm and physical model the being proposed in this study was done by comparing the system pressure. System pressure was directly measured in the experiment using pressure transducer. For model prediction, the system pressure was calculated inside the algorithm loop where saturation pressure is function of saturation temperature.

The result for validation work is being depicted in the fig. X. From the graph, it can be seen that the algorithm and the model succeed to predict experimental value with uncertainty less than 15 %.



4. Conclusions

In this study an experimental investigation of thermal hydraulic characteristic of water based thermosyphon under evacuated non-condensable and pressurized non-condensable gas was conducted. A model of non-condensable pressurized thermosyphon was proposed in this study. An algorithm based on the model also developed for designing a non-condensable pressurized thermosyphon. The prediction derived from the model and the algorithm was compared with experimental value. A good agreement was achieved, where the prediction of system pressure was less than 15%.

REFERENCES

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