Assessment of RELAP5 code model to simulate U-shaped heat pipe performance for heat sink

Anhar R. Antariksawan, Mukhsinun Hadi Kusuma, Surip Widodo, Giarno, Mulya Juarsa, Hendro Tjahyono and Dedy Haryanto

Center for Nuclear Reactor Safety and Technology - BATAN, Puspiptek Area
Building 80, Serpong, Tangerang Selatan 15310
email: anhar@batan.go.id

Abstract. One of important component in a high temperature gas cooled reactor (HTGR) is reactor cavity cooling system (RCCS). The function of the RCCS is to remove the heat going out from the reactor pressure vessel. On the other hand, the use of passive system is highly considered in the nuclear reactor design, including in the HTGR design. The heat pipe is one of the passive apparatus. This current study deals with the research on the use of heat pipe to the RCCS design. As part of the study, the performance of U-shaped heat pipe will be assessed both through an experiment and numerical simulation methodology. The objective of this study is to assess the validity of the RELAP5 code model to simulate a U-shaped heat pipe performance. A small U-shaped heat pipe with fins in the condenser part is modelled using the RELAP5/SCDAP code. The result of simulation shows that the heat pipe could removed the heat received in the evaporator to the environment through the condenser of that heat pipe. The phenomena of evaporation and condensation are identified during heat removal. However, the steady state condition is not obtained until the end of the calculation. The calculated thermal resistance of the heat pipe is approx. 0.01258 °C/W. It is concluded that the model could simulate reasonably the heat pipe performance. The model needs to be improved, especially for the finned tube condenser.

1. Introduction

BATAN has decided to select the High Temperature Gas cooled Reactor (HTGR) type be developed in Indonesia in the future. As a starting point, a project is planned to built HTGR of 10 MWe, called Reaktor Daya Eksperimental (RDE-10). The project was started in 2014. Until 2016, several technical documents have been prepared, among other things, Front End Engineering Design (FEED) document, feasibility study document and document of RDE Construction Licensing [1].

The HTGR consists of helium cooled core, graphite moderated with ceramic coated fuel particles of capable handling temperature of 1600 °C [2]. The technology of HTGR is started from the advanced gas-cooled reactor in the 1960 and the high temperature reactor "Dragon" in 1964 [3]. China is one country that is continuously pursuing the development of HTGR technology. The construction of a pilot plant HTR-10 marked the development of HTGR technology in China [4]. After the successful construction and operation of HTR-10, the Chinese government decided to build a commercial-scale 200 MWe High Temperature gas-cooled Reactor Pebble-bed Module (HTR-PM) [4,5].
Reactor Cavity Cooling System (RCCS) is one of the most important components in a HTGR design. Its function is to remove the reactor heat, which is transmitted from the reactor vessel to the reactor cavity surrounding the reactor, to the environment. There are several designs of RCCS using water or air as a working fluid [6,7].

This paper deals with the idea to use a heat pipe in the RCCS. A U-shaped heat pipe with fins is proposed to transfer the residual heat from the reactor cavity to the air in the environment. Based on the HTGR RCCS’s design as described in [8], the heat pipe is used to replace the cooling tower allowing to maximize passive concept. In such concept, the heat pipe is put in the storage tank where only the evaporator of the heat pipe is submerged in the storage tank. While, the finned condenser is cooled by air. The use of heat pipe in a RCCS has been previously assessed, but some technical problem, such as small temperature difference between water and air, has been identified [9]. As long as the authors knowledge, there is no other study on the use of heat pipe for the RCCS. However, in a pressurized water nuclear reactor, the possibility to use a heat pipe technology for removing the decay heat in the emergency core cooling system (ECCS) has been proposed by several studies [10–12]. As a part of the work of R&D in the HTGR design in BATAN, this current work is dealing with the research on application of the heat pipe technology in the RCCS design. It might be an interesting alternative design for RDE’s RCCS beside the current design that utilizes an air cooling.

For the first step, a small scale U-shaped heat pipe is modelled and simulated using a thermal-hydraulic system code RELAP5. The objective is to assess the applicability of the RELAP5 code model by simulating the performance of a small scale U-shaped heat pipe as function of the heat flux in the evaporator. In parallel, an experimental work is done and reported elsewhere. Previously, the model of RELAP5 has been used to simulate the performance of a straight wickless heat pipe and showed a good results [13,14].

2. Model and nodalization

Heat pipe is one of the heat transfer equipment that works based on the passive system, i.e. without any external mover. A heat pipe structure consists of a very high thermal conductivity tube filled with a working fluid in liquid and vapour phases enabling transport the heat from heat source to heat sink in a continuous cycle. The operation is as follows: the working fluid, which is located at the bottom of the pipe, evaporates when a heat source is applied (that section is called evaporator). Due to difference in densities between the vapour and fluid, allows the vapour to reach the cool condenser section. The cooling system in the condenser section causes the vapour to condensate, allowing the fluid to return to the liquid pool located in the evaporator, by the gravity force or by some sort of capillary wicking material [15]. There are several designs of heat pipe and wide spectrum of application area. The U-shaped heat pipe is commonly used in generated heat dissipation system in central processing unit of a computer [16].

Figure 1(a) shows the U-shaped heat pipe studied in the current work. That heat pipe is available in the market. Figure 1(b) depicts the scheme of the studied heat pipe geometry. The bottom part is the evaporator where the working fluid is located. The heat pipe tube is made of copper with 5.8 and 6 mm of inner and outer diameter, respectively. There are four U-shaped heat pipe tubes that are placed in a row. The upper part of the tube is condenser, which is added with the aluminium fins to enhance the heat transfer area. There are 57 fins of $116.3 \times 45.1 \times 0.4$ mm size. For cooling the condenser, the air is blown through the fins, allowing the vapour inside the condenser to release its latent heat to the air. The underneath of the condenser is the evaporator where the heat from the heat source is transmitted allowing the working fluid inside the tube evaporates.

The RELAP5 code is used one dimension thermal-hydraulic code, which is initially developed to analysis the loss of coolant accident and other transient conditions in a nuclear power plant. The RELAP5 code models the complex physical system into several simple components and nodes. In each component, the code equation set gives two-fluid simulation system using a non-equilibrium, non-homogeneous, six-equation representation. From its initial version, the RELAP5 is being developed in various version [17,18]. The use of RELAP5 is also broader, not only for a nuclear power plant, but also nuclear research reactor [19,20] and other thermal-hydraulic facilities [21,22].
The challenge is to make the model for the finned tube condenser because there is no specific model for finned tube in the RELAP5. As a first approach, the heat transfer coefficient boundary condition is determined. In that case the heat transfer coefficient of air flowing is assumed constant. Other assumption is that the temperature of the air is also kept constant. While, the heat source is applied at all part of the evaporator section of the heat pipe. The filling ratio of the evaporator is 100%.

Figure 1(c) shows the model and nodalization of RELAP5 for the studied U-shaped heat pipe. Table 1 shows the components of RELAP5’s model.

| No. | Component         | Nodalization            |
|-----|-------------------|-------------------------|
| 1.  | Evaporator        | SV-120, SV-130, SV-140, SV-150, SV-160 |
| 2.  | Adiabatic zone    | SV-110, SV-170          |
| 3.  | Condenser         | P-100, P-180            |
| 4.  | Fins              | SV-201 to SV-230        |
| 5.  | Heat structure    | HS-100, HS-120, HS-130, HS-140, HS-150, HS-160, HS-180 |

Figure 1. (a) The photography of the U-shaped heat pipe, (b). The scheme of U-shaped heat pipe, (c). The nodalization of the U-shaped heat pipe.

3. Results and discussion
For the base case, the calculation is done by determining the heat power of 100 watt at the horizontal part of evaporator. The initial pressure in the heat pipe is determined 29331 Pa. The outside boundary condition is determined with a constant heat transfer coefficient of $10^3 \text{ W/m}^2\cdot\text{C}$. This outside boundary condition of the condenser, which is constituted of the finned tube, shall be corrected in the further detailed study. On the other hand, the temperature of the environment is also assumed constant at 25°C.

The Fig. 2 shows the temperature distribution inside the heat pipe, the evaporator, the adiabatic region and the condenser. It could be seen that the fluid temperature is continuing to increase until the end of calculation (i.e. 5000 s), and is similar in all part of the heat pipe. As the temperature, the pressure increases continuously up to about 3.5 bar as shown in Fig. 3. Yet the steady state condition
is not actually reached. However, by examining the value of the temperature and pressure, the fluid is at the saturation condition with its steam.

![Figure 2. Temperature distribution in heat pipe.](image)

![Figure 3. Pressure distribution in heat pipe.](image)

On the other hand, from the results of the calculation it could be known that the removal of heat from the evaporator to the condenser and to the environment could be established by the evaporation in the evaporator and the condensation in the condenser. Figure 4 shows the heat received in the evaporator and the heat removed from the condenser to the environment. The heat removed is still bit lower than the heat received in the evaporator that causes the pressure and temperature is still increasing continuously.

![Figure 4. Heat balance at the heat pipe.](image)

![Figure 5. Pressure at different heat power](image)

In order to know the effect of different heat power input to the evaporator, the simulation was done for 100 W, 50 W and 30 W heat power. Figure 5 shows the pressure distribution for three different heat powers. It is obvious that increasing heat power, the pressure in the heat pipe increases as well. As the fluid in the heat pipe is at the saturation condition, the temperature also higher at the higher heat power. In all three simulations, no one reached the steady state condition.

A parameter important to the heat pipe performance is thermal resistance. For a heat pipe, the thermal resistance, $R_T$, could be calculated using the below formula [22]:

$$R_T = \frac{T_e - T_c}{Q_o}$$  \hspace{1cm} (1)

where $T_e$ is the average of the evaporator temperature, $T_c$ is the condenser temperature and $Q_o$ is the heat transferred across the heat pipe. The calculation of the thermal resistance shall be calculated at the
steady state condition. As in the calculation done in this current study, the steady state calculation is not reached, the approximation is done using the data at the time calculation between 985 s to 1100 s where the temperature of the fluid in the evaporator and condenser are relatively constant at around 83 °C. The calculated thermal resistance is approx. 0.012585 °C/W. At some extent, the value of the thermal resistance is in the range of the thermal resistance obtained in the [22].

Based on the obtained results of the above simulation, the model could identify the overall performance of the heat pipe, but it still needs many improvement, especially for:

1. heat structure model for the finned tube
2. boundary conditions on the heat pipe (for example, convective air flow)
3. parameter of the cooling air, such as the temperature and the heat transfer coefficient

4. Conclusion
A model of RELAP5 code for U-shaped heat pipe with finned condenser tube has been developed. Several simulation of the heat pipe performance using the model have been done. The results show that the model could simulate the performance of the heat pipe, though the steady state condition could not be achieved yet. As a preliminary work, the model applicability is quite good. The improvement of the model has to be taken into account in the future study, especially to better model the finned tube condenser.

Acknowledgement
Authors gratefully thank PTKRN-BATAN for the support. This work is partly funded by Ministry of Research, Technology and Higher Education (Kementerian Ristekdikti) through Insinas Flagship Programme 2018.

References
[1] Taryo T, Bakhri S and Sunaryo G R 2017 The On-going Progress of Indonesia’s Experimental Power Reactor 10 MW and Its National Research Activities SENTEN 2017 pp 57–67
[2] IAEA 2001 Current status and future development of modular high temperature gas cooled reactor technology
[3] Zhang Z, Wu Z, Sun Y and Li F 2006 Design aspects of the Chinese modular high-temperature gas-cooled reactor HTR-PM Nucl. Eng. Des. 236 485–90
[4] Zhang Z and Yu S 2002 Future HTGR developments in China after the criticality of the HTR-10 Nucl. Eng. Des. 218 249–57
[5] Zheng Y, Shi L and Dong Y 2009 Thermohydraulic transient studies of the Chinese modular high-temperature gas-cooled reactor HTR-PM for loss of forced cooling accidents Ann. Nucl. Energy 36 742–51
[6] Capone L, Hassan Y A and Vaghetto R 2011 Reactor cavity cooling system (Rccs) experimental characterization Nucl. Eng. Des. 241 4775–82
[7] Park G, Cho Y and Cho H K Y U 2006 Assessment of a New Design for a Reactor Cavity Cooling System in a Very High Temperature Gas-Cooled Reactor Nucl. Eng. Technol. 38 45–60
[8] Tjahjono H 2017 Investigation of RDE Thermal Parameters Changes in Response to Long-Term Station Black Out Tri Dasa Mega 19 83–92
[9] Takamatsu K and Hu R 2015 New reactor cavity cooling system having passive safety features using novel shape for HTGRs and VHTRs Ann. Nucl. Energy 77 165–71
[10] Mochizuki H and Yano T 2015 A passive decay heat removal system for LWRs based on air cooling Nucl. Eng. Des. 286 139–49
[11] Kusuma M H, Putra N, Antariksawan A R, Susyadi and Imawan F A 2017 Investigation of the thermal performance of a vertical two-phase closed thermosyphon as a passive cooling system for a nuclear reactor spent fuel storage Nucl. Eng. Technol. 49 476–83
[12] Xiong Z, Wang M, Gu H and Ye C 2015 Experimental study on heat pipe heat removal capacity for passive cooling of spent fuel pool Ann. Nucl. Energy 83 258–63
[13] Kusuma M H, Putra N, Ismarwanti S and Widodo S 2017 Simulation of Wickless-Heat Pipe as
Passive Cooling System in Nuclear Spent Fuel Pool Using RELAP5/MOD3.2 *Int. J. Adv. Sci., Eng.* 7 836–42

[14] Kusuma M H, Putra N, Widodo S and Antariksawan A R 2016 Simulation of Heat Flux Effect in Straight Heat Pipe as Passive Residual Heat Removal System in Light Water Reactor using RELAP5 Mod 3.2 *Applied Mechanics and Materials*, Vol. 819 pp 122–6

[15] Jouhara H, Chauhan A, Nannou T, Almahmoud S, Delpech B and Wrobel L C 2017 Heat pipe based systems - Advances and applications *Energy* 128 729–54

[16] Wang J C 2014 U- and L-shaped heat pipes heat sinks for cooling electronic components employed a least square smoothing method *Microelectron. Reliab.* 54 1344–54

[17] Mesina G L 2016 A History of RELAP Computer Codes *Nucl. Sci. Eng.* 182v–ix

[18] Allison C M and Hohorst J K 2010 Role of RELAP / SCDAPSIM in Nuclear Safety *Sci. Technol. Nucl. Install.* 2010

[19] Antariksawan A R, Umar E, Widodo S, Juarsa M and Kusuma M H 2017 TRIGA-2000 research reactor thermal-hydraulic analysis using RELAP/SCDAPSIM/MOD3.4 *Int. J. Technol.* 8 989–99

[20] Antariksawan A R, Wahyono P I and Taxwim 2017 Steady state and LOCA analysis of Kartini reactor using RELAP5/SCDAP code: The role of passive system *ICONETS 2017* (Makassar)

[21] Antariksawan A R, Widodo S, Juarsa M, Haryanto D, Kusuma M H and Putra N 2018 Numerical study on natural circulation characteristics in FASSIP-02 experimental facility using RELAP5 code Numerical study on natural circulation characteristics in FASSIP-02 experimental facility using RELAP5 code *2nd international Tropical Renewable Energy Conference (i-TREC) 2017* (Bali, Indonesia: IOP)

[22] Kusuma M H, Putra N, Antariksawan A R, Koestoer R A, Widodo S, Ismarwanti S and Verlambang B T 2018 Passive cooling system in a nuclear spent fuel pool using a vertical straight wickless-heat pipe *Int. J. Therm. Sci.* 126 162–71