Analysis of printed circuit heat exchanger (PCHE) for Small modular molten salt reactor (MSR)

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Abstract. Energy is the backbone of defense and essential for the effectiveness of operations. The archipelago country like Indonesia has a specific characteristic when deploy the army separated over the country will have deep complexity in energy distribution and security. The mobile nuclear power plant is interesting to evaluate, and we interested in heat transfer process in the heat exchanger. The paper presents the potential of the application of a printed circuit heat exchanger (PCHE) on small modular molten salt reactors (MSR) for the military. The Heat exchanger is played a crucial role in the nuclear reactor design where the size compaction and efficiency improvement two issues that must be solved. The PCHE promise some advantages such as high effectiveness, high surface area per volume, light and compact. We evaluate and compare the performance of the heat exchanger of the MSRE ORNL 8 MWT with PCHE's design where MSRE a benchmarking. The result shows that low-pressure drops, low-pumping power and high effectiveness and compactness (low-dimension). We recommended that PCHE is applied on MSR than conventional HX like a Shell tube heat exchanger (STHE) of MSRE ORNL.

1. Introduction

Energy is the backbone of defense and essential for the effectiveness of operations. An archipelago country like Indonesia has a specific characteristic when deploy the army separated over the country will have deep complexity in energy distribution and security. Currently, nuclear reactor grow vastly and now come to generation IV. The molten salt reactor (MSR) is one of nuclear gen IV, which has comparative values than another GEN-IV reactor type thermal-hydraulic characteristics and heat transfer performances [1]. The compact design, passive safety, low-pressure system, and genuinely sustainable (no fuel shortages “forever”) for fast reactor type. The mobile small modular nuclear power plant is interesting to evaluate. Small modular reactors (SMR) is reactor type that smaller than a conventional reactor. SMR offer greater scalability, and siting flexibility for locations unable to accommodate more traditional larger reactors. In contrast, the economic aspect offer competitive values compared to conventional plant coal, natural gas combined plants for some under certain conditions [2].

Scale down from the currently existing nuclear reactor plant are offering some challenging, one of them is in thermal-hydraulic component. The Heat exchanger is key component from the reactor where the heat transfer process occurs, and there are some technologies for it such as printed circuit heat exchanger [3][4], shell tube heat exchanger, and spiral tube heat exchanger [4].
Back to sixty years ago, [5] ORNL developed and operated the first molten salt reactor in the world. They used shell tube heat exchanger (SHTE as primary heat exchanger. In addition to significant dimension, during operation MSRE the shell tube heat exchanger (STHE) has inherent problem like a vibration [6]. It is attractive to evaluate the primary heat exchanger (PHX) from shell tube heat exchanger (SHTE) with a printed circuit heat exchanger (PCHE). Some studies show that the PCHE promise some advantages in space reduction and heat transfer performances. Also, other technical challenges must solve [3][4][7].

This paper will evaluate and compared the performance of a shell tube primary heat exchanger (PHX) from the MSRE ORNL 8 MWTh with PCHE’s design where the MSRE is benchmarking. The fuel salt (LiF-BeF$_2$-ThF$_4$-ZrF$_4$-UF$_4$), coolant salt (LiF-BeF$_2$) and material is the same, Hastelloy-N. The quantitative analysis used to evaluate PCHE, and some parameters will compare, such as pressure drop, dimensions, effectiveness, and heat transfer area [4][7].

2. Method

Some assumptions are used in this case, and we refer to the [4] [7] as based on quantitative analysis. For printed circuit heat exchanger, front area (A) for cold and hot as following where the mass flow and imposed by velocity (v) for specific density from hot and cold fluid:

$$A = \frac{\dot{m}}{\rho v} \quad (1)$$

Reynold number and Prandtl number for each side of fluid calculated as follow:

$$Re = \frac{\rho v D_h}{\mu} \quad (2)$$

$$Pr = \frac{\mu c_p}{k} \quad (3)$$

Nusselt number calculated to determine the heat transfer coefficient:

$$Nu = \frac{h D_h}{k} \quad (4)$$

And then, we find the overall heat transfer and total area of heat transfer:

$$U = \frac{1}{\frac{1}{h_h} + \frac{1}{k_w} + \frac{1}{h_c}} \quad (5)$$

$$UA = \frac{Q}{F \Delta T_{LMTD}} \quad (6)$$

From equation (1), the area front uses to determine the number of channels and number of channels imposed by diameter of the channel (D).

$$N = \frac{8A_f}{\pi D^2} \quad (7)$$

The length dimension from the printed circuit heat exchanger calculated from equation (6) and (7):
\[
l = \frac{A}{\left(\frac{\pi}{2} D + D\right) N}
\]

After we found the dimension and number of channels for each fluid, we can use Equation (9) to calculate the distributed pressure drop for fuel salt and coolant salt, respectively.

\[
\Delta P = 4 f \rho \mu^2 \frac{l}{D_h}
\]

### 3. Results and discussions

#### 3.1. Printed circuit heat exchanger (PCHE)

Figure 1 shows the geometry shape of PCHE’s channel and semi-circular, chosen due to the possibility to manufacture. The primary manufacturer of PCHE use chemical etching to produce the PCHE channel. Even though we did not discuss in this paper, the manufacturing process decided on the channel shape, as shown in Figure 1. Detail arrangement and temperature requirement based ORNL 8 MWth also be shown.

![Figure 1 Channel geometry shape for fuel salt (hot) and coolant salt (cold)](image)

The channel shape for both of fluid is the same. The variation expects the number of channels and length from the channel, as a function of the fluid velocity. It represents with Reynold number values.

#### 3.2. Calculation result

Figure 4 shows the relation of the friction factor versus various Reynold number values. Reynold number influenced by velocity from working fluid in the case of fuel salt and coolant salt, respectively. From the figure can be seen that increasing the Reynold number value causes the pressure drop increase. The increasing pressure drops due to the Reynold number value effect on length from channel.
The same trend showed in Figure 5. The pressure drops affect pumping power based on equation (9). Therefore, in the design of heat exchanger the pressure drop value must be as small as possible.

Table 1 shows the best design from the calculation and focused on reducing dimension to meet the requirement for a small modular reactor. MSRE ORNL use as benchmarking due to this is a real molten salt reactor built. The calculation result shows that dimension can reduce 1/14 times. Besides, the performance increases due to the area of heat transfer also rise significantly. It can be understood, heat transfer mode forced convection, and increasing in thw area of heat transfer will effect on heat transfer enhancement.
Table 1 Best design of printed circuit heat exchanger for ONRL MSRE 8 MWth

| Parameter                  | Symbol | Unit | Fuel salt LiF-BeF$_2$, ThF$_4$, ZrF$_4$, UF$_4$ | Coolant salt LiF-BeF$_2$ |
|---------------------------|-------|------|-----------------------------------------------|--------------------------|
| Mass flow                 | $A_f$ | $m^2$| 75.6                                          | 52.392                   |
| Area-Front (WxH)          |       |      | 0.06                                         | 0.05                     |
| Plate thickness           | $t_p$ | mm   | 2.5                                          | 2.5                      |
| Channel diameter          | $d_{ch}$ | mm | 2                                            | 2                        |
| Number of channels        | $n_{ch}$ | -   | 48214                                        | 42870                    |
| Length                    | $L$   | m    | 0.299                                        | 0.34                     |
| Pressure drops            | $\Delta p_h$ | bar | 0.31                                         | 0.36                     |
| Effectiveness of HX       | $\varepsilon$ | -   | 0.58                                         |                          |
| Pumping power             | $P$   | kw   | 0.95                                         | 0.98                     |
| Material                  |       |      | Hastelloy-N                                  |                          |
| Area per volume           | $1/m$ |      | 1818                                         |                          |
| Volume of PHX             | $V$   | $m^3$| 0.037                                        |                          |

4. Conclusions
The preliminary analysis study of the printed circuit heat exchanger on small modular molten salt reactor has done, and the result shows that promising some advantages in scale down dimension as a primary goal without neglected heat transfer performance. Thermal-hydraulic is one aspect of the study to examine the printed circuit heat exchanger. Therefore, the comprehensive study must conduct further. Regarding the dimension of a channel in millimeter size, it was chosen because of some reasons. There are fission product sedimentations, the possibility of channel’s manufacturing on plate, and minimize the blockage on the channel’s path. The printed circuit heat exchanger is worthy to further study because it seizes a high efficiency and compactness in dimension.

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