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# Study on Various Direct Contact Heat Exchanger Types for Dry Cooled Waste Heat Removal System in SMRs

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## 1. Introduction

Many types of SMRs with dry cooling systems for waste heat removal system and safety systems have been developed. The SMRs with the dry cooling systems get advantage on competition with old thermal power plants. These SMRs is able to be constructed in area without water resources and there is no time limit for the operation of safety system.

However, the dry cooling system requires larger volume and surface area of heat exchanger than the water cooling system due to low thermal conductivity and density of the air. The dry cooling system is large construction cost, thus optimization of the system is very important to reduce total cost of the SMRs. Especially the waste heat removal system requires very large volume and surface area due to required large amount of heat transfer rate within 10 K temperature difference.

To increase heat transfer performance of dry cooling system, direct contact heat exchangers were considered. There is no thermal resistance by wall structure and it is easy to get large surface area. On the other hand the conventional system uses fin structure and heat transfer performance is reduced due to thermal conduction in the fins.

In most cases, increasing heat transfer performance is able to be obtained by increasing Reynolds number. However the high Reynolds number also causes high pressure loss of the system. In this study, many types of direct contact heat exchangers were analyzed and the optimum heat exchanger type having high heat transfer performance and low pressure loss of the system was selected.

## 2. Methods and Results

Fig. 1 shows the concept of the dry cooled waste heat removal system [1]. The steam from turbine flows into an indirect heat exchanger submerged in the pool and the condensate flows out from the heat exchanger. There is oil in the pool and the heated oil is pumped to direct contact heat exchanger. The falling oil is cooled by air and returns to the oil pool. The air flows naturally by the cooling tower.

Four types of direct contact heat exchangers as shown in Fig. 2 were selected for this study. The heat exchanger types have been generally considered in many previous researches.

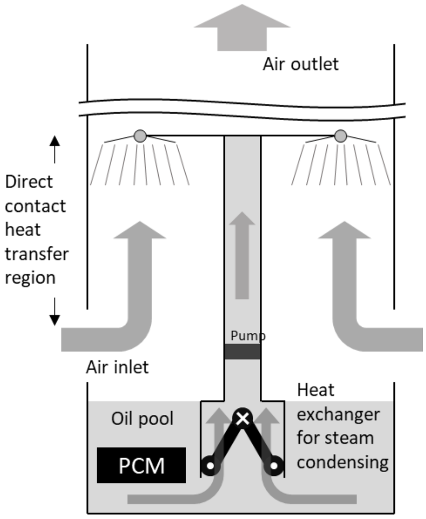


Fig. 1. Design concept of dry cooled waste heat removal system

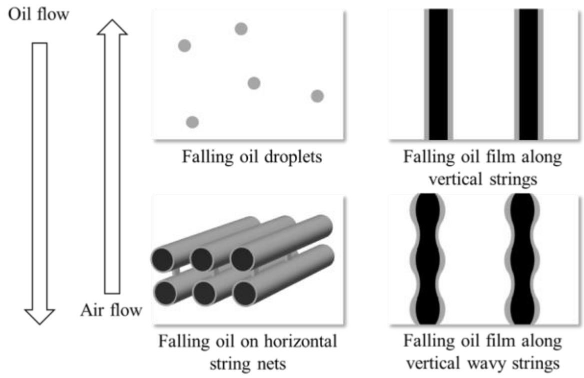


Fig. 2. General types of direct contact heat exchangers

### *2.1 Chilton-Colburn analogy*

Thermal resistance of air convection is the majority of the total thermal resistance of direct contact heat transfer between the air and the falling oil. The convective heat transfer increases as Reynolds number increases due to turbulence, but the turbulence also increases the frictional pressure loss. Chilton-Colburn analogy shows relation between friction factor and Nusselt number [2].

$$\left(\frac{f}{2}\right)\mathrm{Re} = \mathrm{Nu}\,\mathrm{Pr}^{-\frac{1}{3}}, \qquad j = \frac{\left(\frac{f}{2}\right)\mathrm{Re}}{\mathrm{Nu}\,\mathrm{Pr}^{-\frac{1}{3}}}$$

The Chilton-Colburn analogy is well known that the relation fits well for both of laminar and turbulent flow on the flat surface. Thus, j value which shows ratio between frictional pressure loss and heat transfer was named in this study and the j values on the non-flat surface were calculated. The low j value means that the system has relatively high heat transfer performance compared with frictional pressure loss.

Table I shows that correlations used for calculating j value in various types of direct contact heat exchangers [3 - 5].

Table I: Correlations for calculating j value

| Categories | Correlations |
|---|---|
| Falling oil droplets | $f=\frac{1}{4}\left\{\frac{24}{Re}+\frac{2.6\left(\frac{Re}{5}\right)}{1+\left(\frac{Re}{5}\right)^{1.52}}+\frac{0.411\left(\frac{Re}{263,000}\right)^{-7.94}}{1+\left(\frac{Re}{263,000}\right)^{-8}}+\frac{Re^{0.8}}{461,000}\right\}$ <br> $Nu = 2 + 0.6\, Re^{0.5}\, Pr^{0.33}$ |
| Falling oil film along vertical strings | Laminar: <br> $f=\frac{24}{Re}, \quad Nu = 7.54$ <br> Turbulent: <br> $f = 0.079\, Re^{-\frac{1}{4}}, \quad Nu = 0.023\, Re^{0.8} Pr^{0.3}$ |
| Falling oil on horizontal string nets | $f = 0.247 + \left(-\frac{0.595}{Re}\right)+\left(\frac{0.15}{Re^2}\right)+\left(-\frac{0.137}{Re^3}\right)+\left(\frac{0.396}{Re^4}\right)$ <br> $(800 < Re < 2\times10^6)$ <br> $= 0.188 + \left(\frac{566}{Re}\right)+\left(-\frac{6460}{Re^2}\right)+\left(\frac{60100}{Re^3}\right)+\left(-\frac{183000}{Re^4}\right)$ <br> $(7 < Re < 800)$ <br> $Nu = 0.27\, Re^{0.63} Pr^{0.36}\ (Re > 1000)$ <br> $= 0.52\, Re^{0.5} Pr^{0.36}\ (100 < Re < 1000)$ <br> $= 0.9\, Re^{0.4} Pr^{0.36}\ (Re < 100)$ |

The j value was calculated by the correlations and the results of calculation are shown in **Fig. 3**. Generally, the direct contact heat exchanger has the Reynolds number of 100 to 10,000. The results show that direct contact heat exchanger with falling oil film along vertical strings has the lowest j value in laminar and turbulent flow region. This means that the type is the best for the direct contact heat exchanger.

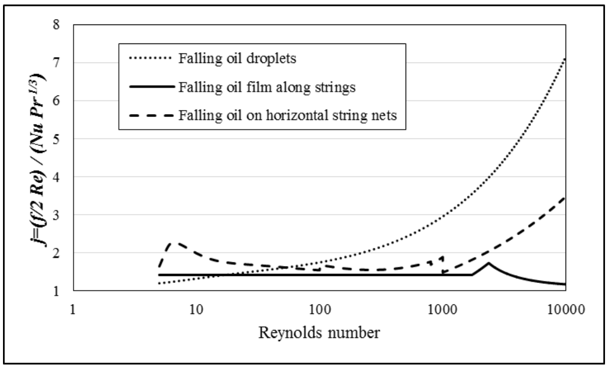


Fig. 3. The calculated j value

*2.2 Wavy structure*

At the wavy surface, air convection heat transfer and frictional pressure loss increase due to turbulence. A previous research that dealt with convection on the wavy surface was studied [6].

The research controlled ratio between wave length and wave amplitude ($L^* = \lambda/a$) and got a correlation for friction factor. The Nusselt number on the wavy surface was obtained as shown in Fig. 5.

$$f = \frac{C}{Re^m}, \qquad C, m\text{: function of } L^*$$

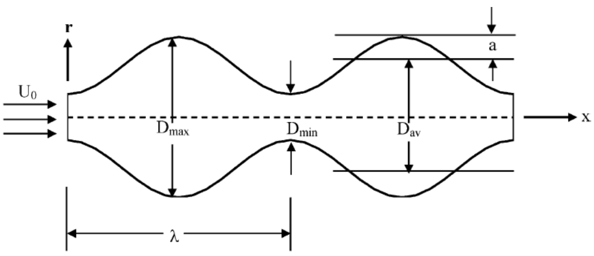


Fig. 4. Wavy length and amplitude of wavy structure

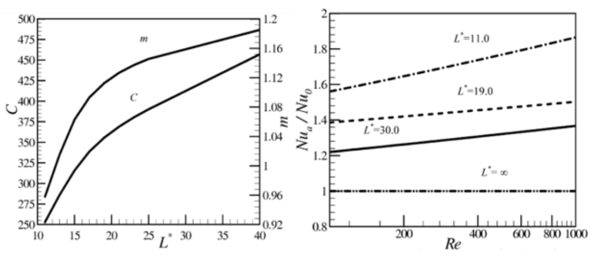


Fig. 5. Constants for friction factor equation and Nusselt number as $L^*$ changes

The constants C and m, and Nusselt number were used for calculating the j value on the wavy surface. The results of calculation are shown in Fig. 6. The lowest j value was obtained on the flat surface. The wave on the surface increases convection heat transfer, but increases more friction pressure loss than the convection.

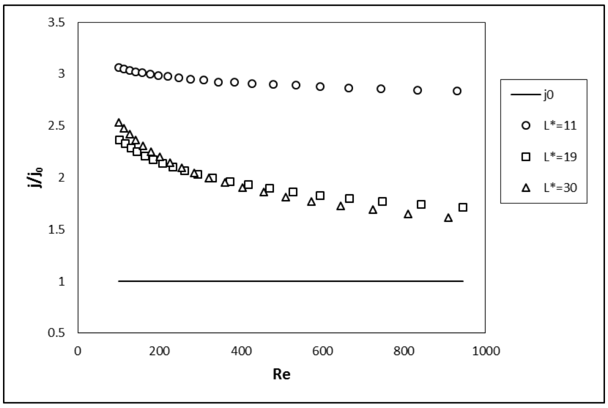


Fig. 6 The j values for flat surface and wavy surface

## 3. Conclusions

In summary, the best type for direct contact heat exchanger is falling oil film along vertical strings. It is important to consider not only heat transfer performance of the heat exchanger but also frictional pressure loss. The non-dimensional j value that shows ratio between frictional pressure loss and heat transfer performance was suggested. The j value on the falling oil film along vertical strings is the lowest. The range of Reynolds number in the direct contact heat exchangers are generally 100 to 10,000. Within this range, whole correlations used for this study are proven, thus the results are reliable.

This study shows that straight flow of air on the flat surface is the best option for direct contact heat exchanger. The heat transfer performance on the wavy surface is high due to turbulence, but the frictional pressure loss is much large.

## ACKNOWLEDGMENTS

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