Dry Cooling System with Direct Contact Heat Transfer on the Falling Film along Vertical Straight String

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1. Introduction

The dry cooling systems commonly use extended surface, called fin, to increase surface area and heat transfer performance. The finned surfaces ideally have zero thermal resistance and show uniform temperature distribution. However, in reality, the temperature of the fin decreases along the fin due to thermal resistance of the fins, thus heat transfer performance decreases.

Direct contact heat transfer is getting interests as innovative solution in the dry cooling system. Hot fluid flows into the air and heat transfer occurs without physical barrier between the fluid and air, thus the heat transfer performance is high.

For getting large surface area in the direct contact heat transfer system, the hot fluid is emitted as small droplet shape or thin falling film. UCLA published the Direct Contact Liquid-on-String Heat Exchanger (DILSHE) that the hot fluid flows along strings, and is cooled by air. Drexel published Spray Freezing of Recirculating PCM system that the hot fluid is sprayed as droplet shape into air and the cooled fluid returns to the pool. The conceptual designs of the systems are shown in Fig. 1 and Fig. 2 [1,2].

In KAIST, dry cooled waste heat removal system that applies the direct contact heat transfer technology has been being designed. In case of falling film system, the hot fluid flows along strings. Thus, the string structure influences to the direct contact heat transfer and pressure drop of the air. In this research, vertical straight string structure is analyzed.

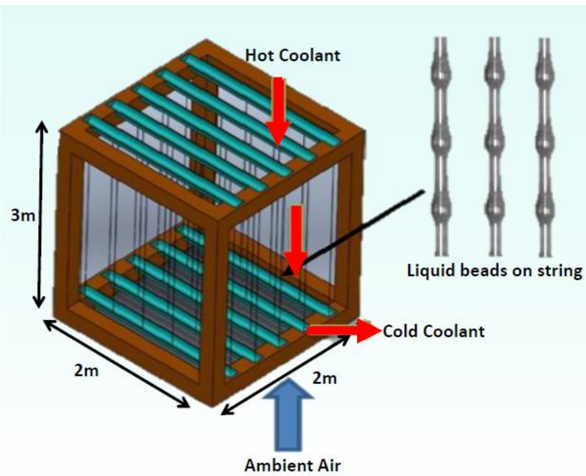

Fig. 1 DILSHE design (UCLA, USA)

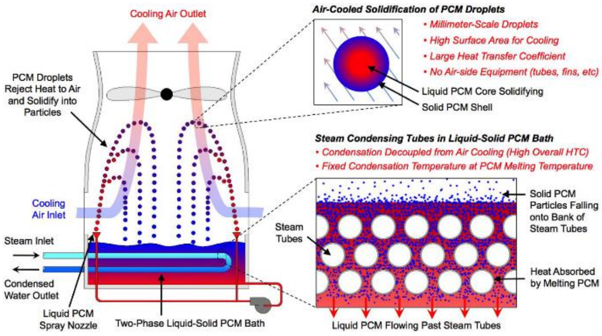

Fig. 2 Spray Freezing of Recirculating PCM (Drexel, USA)

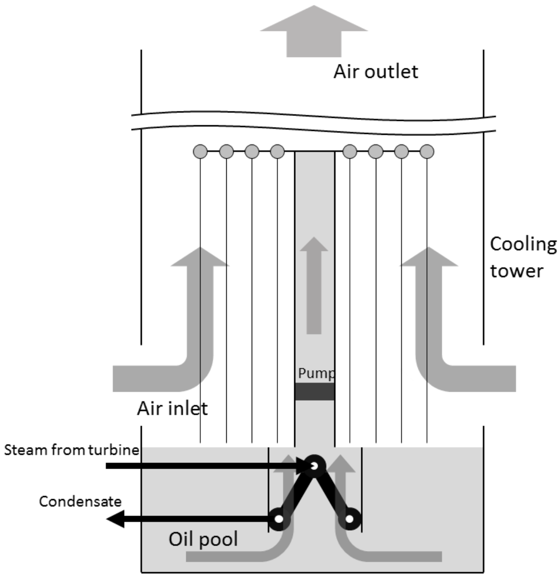

Fig. 3 Schematics of the dry cooled waste heat removal system

2. Methods and Results

The schematics of system is shown in Fig. 3. Steam from the turbine flows into heat exchanger submerged in the pool and condenses. The heated fluid is pumped and returns to the pool along the vertical strings. There is heat transfer between the falling film and air and the fluid is cooled. The air flow is caused by density difference caused by a cooling tower. Silicone oil 10 cst that has high flash point and is low evaporative is selected for the fluid of this system.

2.1 Beads formation

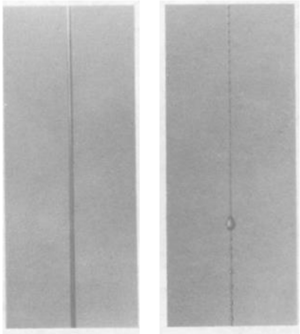

Fig. 4 Thin film and thick string (left), and thick film and thin string (right)

Falling film along the strings shows beads formation. The film breaks up into regularly spaced droplets due to surface tension. Film with the beads has smaller surface area than stable film, thus the film tends to be broken.

Kalliadasis & Chang published that the beads pulse is only shown when the film thickness is larger than a critical thickness. The critical thickness is calculated by following relation [3].

$$\delta_c = 1.68\frac{r^3}{\kappa^{-2}}$$

r is string radius and $\kappa^{-1} = \left(\frac{\sigma}{\rho g}\right)^{0.5}$ is capillary length. As the string radius increases, the critical thickness increases and the beads formation doesn't occur. Fig. 4 (D. Quere) shows The heat transfer and drag of the film with the beads are not sufficiently researched, thus this system aims to have stable film on the strings [4].

2.2 Physical modeling on the falling film

At the falling film along the strings gravity, viscous force and drag force by the air flow. The film is very thin and the oil has high viscosity, thus the film is assumed as laminar flow. Fully developed flow is assumed in vertical axis and the film thickness should be lower than the critical thickness. At the interface between film and string, no slip is assumed.

Volume element for getting force balance equation is shown in Fig. 5. At a volume element, the net force should be zero due to fully developed flow of the film. Then, the gravity should be balanced with sum of viscous force and drag force between air and the film.

$$\rho g dx \times [\pi(r+\delta)^2 - \pi(r+y)^2] = \mu\frac{du}{dy}\,2\pi(r+y)dx + f\frac{A_a}{n_{film}}\frac{dx}{d_h}\frac{\rho_a v_{rel}^2}{2}$$

LHS is gravity force on the volume and RHS is the summation of viscous force and drag force. The velocity in X axis at the interface is zero due to the assumption. Then, the following relation is resulted by integration.

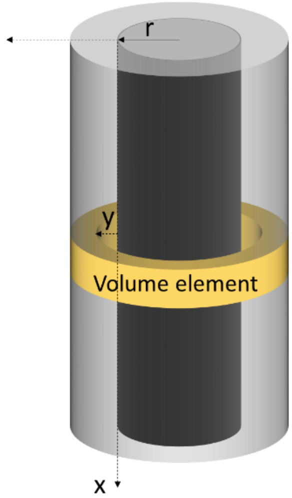

Fig. 5 Volume element of falling film along the string

$$u(y) = \frac{\rho g}{2\mu}\left[(r+\delta)^2\ln\frac{r+y}{r} - \frac{y(2r+y)}{2}\right] - \frac{fA_a\rho_a v_{rel}^2}{4\pi\mu d_h n_{film}}\ln\frac{r+y}{r}$$

And, the mass flow rate is calculated by following relation.

$$\begin{aligned}\dot{m} &= \int_0^\delta \rho u(y)\times 2\pi(r+y)dy \\ &= \frac{\pi\rho^2 g}{\mu}\left[\frac{(r+\delta)^4\ln\frac{r+\delta}{r}}{2} - \frac{\delta(2r+\delta)(2r\delta+\delta^2)}{4} - \frac{(r+\delta)^4 - r^4}{8}\right] \\ &\quad - \frac{fA_a\rho\rho_a v_{rel}^2}{2\mu d_h n_{film}}\left[-2r\delta + 2(r+\delta)^2\ln\frac{r+\delta}{r} - \delta^2\right]\end{aligned}$$

In the above equation, only δ is unknown variable, thus the film thickness, δ, is obtained.

2.3 Heat transfer and pressure loss analysis

In this study, the system is designed to remove 1 MW. The existing condenser in the nuclear industry is designed to perform sufficient heat removal in 10°C temperature difference, thus this system follows the design objective. Air temperature is assumed as 30°C and the steam after turbine temperature is 40°C. The oil pool temperature is assumed as 39°C and the returned oil is 37°C. The air temperature is designed to increases to 35°C which is the midpoint of the atmospheric temperature and steam temperature.

At the oil film surface air convection is dominant thermal resistance. The heat transfer coefficient is calculated by Dittus-Boelter correlation [5].

$$Nu = 0.023Re_d^{0.8}Pr^{0.3}, \qquad h_{conv} = \frac{Nu \times k_a}{d_h}$$

The Reynolds number and hydraulic diameter is calculated by following relation.

$$d_h = \frac{4A_a}{2\pi(r+\delta)\times n_{film}}, \qquad Re_d = \frac{\rho_a v_{rel} d_h}{\mu_a}$$

And, the frictional pressure loss on the air flow is calculated by following relation.

$$\Delta P_f = f\frac{L}{d_h}\frac{\rho_a v_{rel}^2}{2}$$

The friction factor $\left(f = 0.316\, Re_d^{-0.25}\right)$ follows Blasius equation. And, the gravitational pressure difference is calculated by following relation [5].

$$\Delta P_g = \int_0^L \rho_a g dx \cong \bar{\rho}_a g L$$

The heat transfer rate of the system can be expressed by following relation.

$$Q = \bar{h}_{conv} A \Delta T_{lm} = \bar{h}_{conv}\left[2\pi(r+\delta)\times n_{film} L\right]\Delta T_{lm}$$

Then, the string length, L, is calculated by following relation.

$$L = \frac{Q}{\bar{h}_{conv} 2\pi(r+\delta) n_{film} \Delta T_{lm}}$$

2.4 Cooling tower analysis

The cooling tower causes air flow by density difference between atmosphere and cooling tower inside. The pressure on the cooling tower is shown in Fig. 6. The atmospheric pressure at level H is calculated by barometric formula [6].

$$P_2 = P_1 \exp\frac{-gMH}{RT_1}$$

The pressure at top of the strings is calculated by following relation.

$$P_3 = P_1 - \Delta P_f - \Delta P_g$$

And, the cooling tower outlet pressure can be calculated by barometric formula.

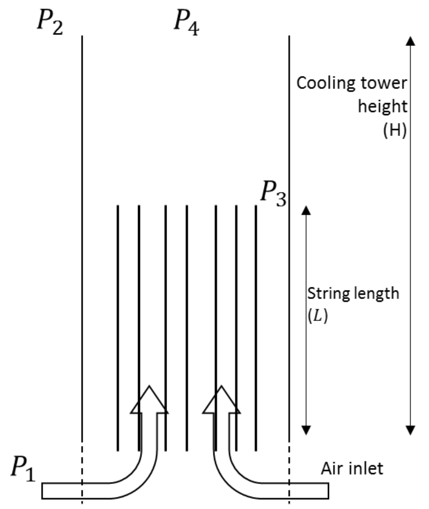

Fig. 6 Pressure points on the cooling tower

$$P_4 = P_3 \exp\frac{-gM(H-L)}{RT_3}$$

The atmospheric pressure at level H and outlet pressure of the tower should be balanced. Therefore the following relation is obtained.

$$H = \frac{1}{T_3 - T_1}\left(\ln\frac{P_1}{P_3}\frac{T_1 T_3 R}{gM} - T_1 L\right)$$

2.5 Analysis results

Control variables are footprint area of the cooling tower, string diameter, and total cross-sectional area of the strings. The footprint area is the sum of the air flow area and total cross-sectional area of the strings.

For optimizing the cooling tower cost function is constructed by following relation.

$$f(A,H) = A \times (c_1 H^2 + c_2 H + c_3)$$

The constants are following the Korean market price listed in Table I.

Fig. 7 shows the film thickness along the strings when the string radius is 0.5 mm. The critical thickness is 0.1 mm, thus there is beads formation and unstable film along the strings. Thus string radius should be larger than 0.5 mm.

Table I: Constants for cost function

Parameter	Value
c_1	$0.925\ \$/m^4$
c_2	$23.1\ \$/m^3$
c_3	$11{,}600\ \$/m^2$

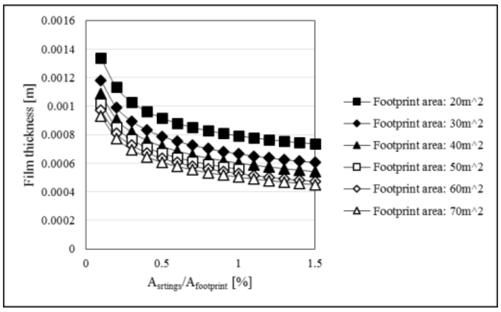

Fig. 7 Thickness of film along the strings (r=0.5mm)

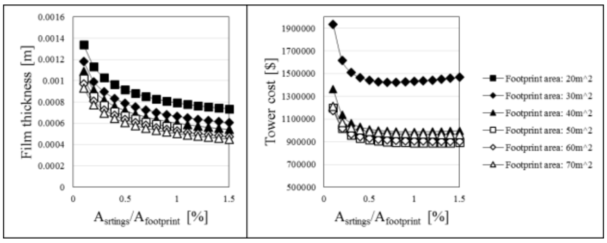

Fig. 8 Film thickness and cost analysis (r=1 mm)

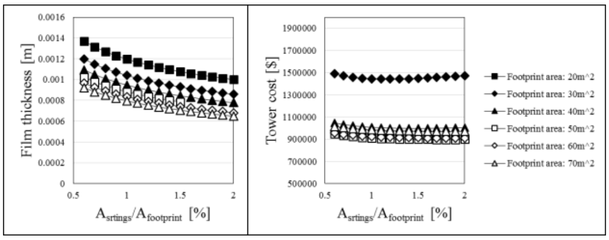

Fig. 9 Film thickness and cost analysis (r=1.5 mm)

The critical thickness is 0.8 mm at the string radius of 1 mm. When the footprint area and total cross-sectional area of the strings are large, the film thickness is smaller than the critical thickness as shown in Fig. 8. At the optimum point that the cost is minimized, the film thickness is smaller than the critical thickness.

At the string radius of 1.5mm, the critical thickness is 2.6 mm and the film thickness along the strings is smaller than it. At the optimum point, the cooling tower height is larger than case of the string radius of 0.5 mm. The optimum point is listed in the Table II.

Table II Optimum point of the system

String radius: 1 mm	
Tower cost	890,000 $
Footprint area	50 m^2
Number of strings	1.91×10^5
String length	5.06 m
Cooling tower height	70.4 m
String radius: 1.5 mm	
Tower cost	893,000 $
Footprint area	50 m^2
Number of strings	1.13×10^5
String length	3.74 m
Cooling tower height	70.7 m

3. Conclusions

This study conducted analysis for direct contact heat transfer on the film along vertical straight string. Physical modeling on the film, heat transfer analysis and pressure loss, and cooling tower analysis were conducted. When the string radius is larger than 1 mm, the film along the string doesn't break and stable film forms. As the string radius increases, the required cooling tower height is increased but the increase is very small.

Nomenclature

A: area $[m^2]$	σ: surface tension [N/m]
g: gravitational acceleration $[m^2/s]$	δ: film thickness [m]
k: thermal conductivity [W/m]	Nu: Nusselt number
L: string length [m]	Re: Reynolds number
M: molar mass of air [kg/mol]	v_{rel}: relative velocity [m/s]
P: pressure [Pa]	ρ: density $[kg/m^3]$
Q: heat transfer rate [W]	μ: viscosity [Pa.s]
R: gas constant [J/K.mol]	n_{film}: number of film
r: radius [m]	a(subscript): air
T: temperature [°C]	conv(subscript): convection

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