Effective Thermal Conductivity of a Screen Wick

By

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1. INTRODUCTION

Effective thermal conductivity of a screen wick filled with working fluid in the case that phase transformation is not considered has been calculated by the equation of Maxwell or the equation of Gorring and Churchill (Fig. 1). Both of the equations are described as a function of thermal conductivity of working fluid and wick materials, and porosity of the wick. Although, there is much difference for the same porosity, and it is difficult to estimate porosity itself on the other hand. In this paper, with consideration of diameter of a wire for a screen wick, mesh number, layer gap and coefficient of shrinkage, the equation to calculate effective thermal conductivity of a screen wick has been derived.

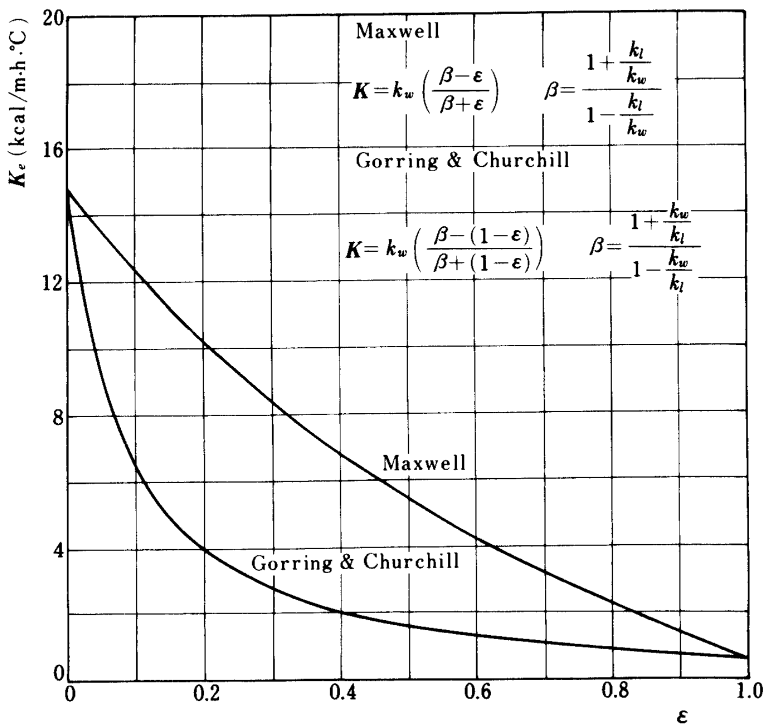

Fig. 1. Effective thermal conductivity by Maxwell and Gorring and Churchill.

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2. Model

Consider a model as represented in Fig. 2(a), like the former paper. Flatness of mesh plane cannot be realized perfectly even if the meshes contact each other with no gap. So, actual measured thickness of the wick is greater than twice of the wire diameter. Considering the gap between layers of mesh when a few layers of mesh are piled up more, h, the thickness per a layer, as shown in Fig. 2(b), is described as the following equation,

$$h=2d(1+\beta) \tag{1}$$

where

d: wire diameter, δ: layer gap, and $\beta=\delta/2d$

Therefore, we need to get effective thermal conductivity of the cell of 1 pitch square×height h.

When k_l is effective thermal conductivity of working fluid and K' is effective thermal conductivity of mesh filled with working fluid in which wires contact perfectly and these are arranged in series, total effective thermal conductivity K can be expressed as the following.

$$Q=\frac{p^2}{2d}K'\cdot\Delta T_1=\frac{p^2}{\delta}\cdot k_l\cdot\Delta T_2=\frac{p^2}{h}\cdot K\cdot\Delta T, \tag{2}$$

$$\Delta T=\Delta T_1+\Delta T_2, \tag{3}$$

where Q: heat passed through 1 pitch square
p: pitch length
ΔT: total temperature difference
ΔT_1: temperature difference of wick zone
ΔT_2: temperature difference of liquid layer

Then,

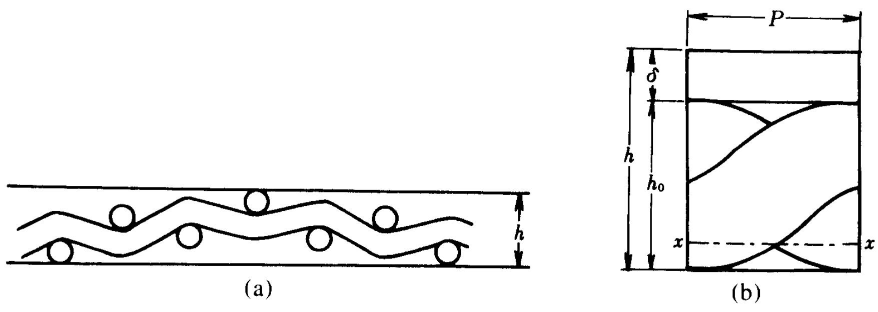

Fig. 2. Model.

$$\frac{1}{K}=\frac{1}{(1+\beta)}\left[\frac{1}{K'}+\frac{\beta}{k_l}\right], \tag{4}$$

Thus, if K' and β are given, K will be derived.

3. Effective Thermal Conductivity Per a Layer of Flat Mesh K'

Consider an arbitrary section $x-x$ in the wick as shown in Fig. 3. A wire and working fluid are in relation of pararell situation. Area ratio of them is a function of x. For dx, minute part of section $x-x$, S_w is section area of wire section and S_l is one of liquid section. Heat passed by is the following equation

$$Q=(k_w\cdot S_w+k_l\cdot S_l)\frac{dT}{dx}, \tag{5}$$

and

$$S_w+S_l=p^2, \quad S_w/p^2=\varepsilon', \quad S_l/p^2=1-\varepsilon'. \tag{6}$$

Then, temperature difference per a layer is

$$T=\int_0^{h_0} dT=\int_0^{h_0}\frac{Qdx}{p^2\{k_w\varepsilon'+k_l(1-\varepsilon')\}}. \tag{7}$$

It is evident from Fig. 3 that the sectional area of a wire is maximum in the central part and is 0 in top and bottom. So, approximately, since function is adopted for

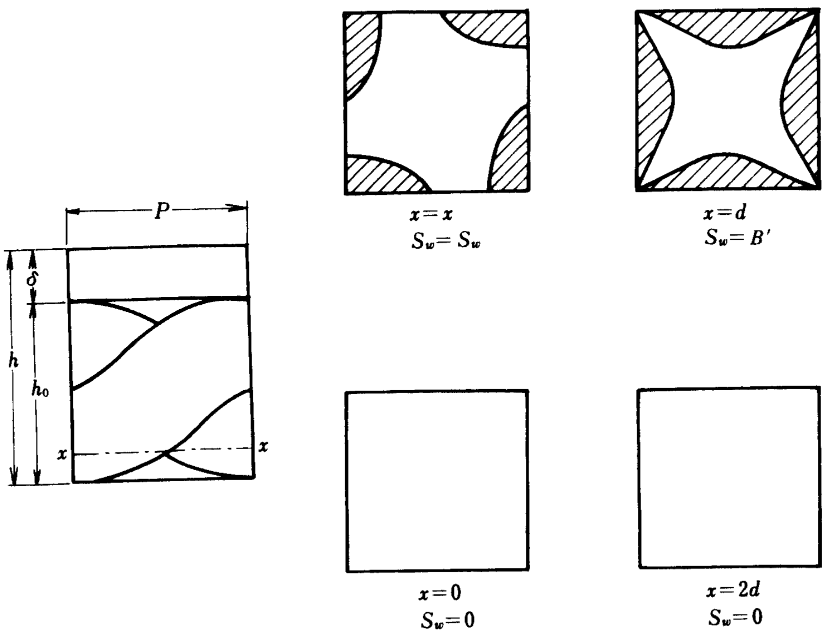

Fig. 3. Arbitrary section in the wick.

S as the following

$$S_w = B' \sin \frac{\pi}{h_0}, \quad h_0 = 2d. \tag{8}$$

Then, S_w is 0 at $x=0$, $2d$ and it has maximum value B' at $x=d$. Integrated value of this area from 0 to $2d$ is due to be as same as the volume of the wire. Thus, this is to be the volume of 2 wires.
Therefore,

$$\int_0^{2d} S_w d_x = \int_0^{2d} B' \sin \frac{\pi}{h_0} x dx = \frac{4B'd}{\pi} = \frac{\pi}{4} d^2 pS \times 2,$$

$$B' = \frac{\pi^2 dpS}{8}, \quad \varepsilon' = \frac{\pi^2 dS}{8p} \sin \frac{\pi}{2d} x, \quad B = \frac{\pi^2 dS}{8p}. \tag{9}$$

With substituting (9) to (7) and transforming it,

$$T = \frac{QAh_0}{p^2 k_l \pi} \int_0^{h_0} \frac{dx}{A + B \sin x}, \quad A = \frac{k_w - k_l}{k_l}. \tag{10}$$

This integration can be calculated easily by a formula, and from the relation of

$$T = \frac{Qh_0}{p^2 K'}, \tag{11}$$

effective thermal conductivity of flat mesh K' is given as the following

$$K' = \frac{\pi k_l \sqrt{B^2 - A^2}}{A \log \dfrac{B + \sqrt{B^2 - A^2}}{B - \sqrt{B^2 - A^2}}}. \quad [B^2 \text{ is much greater than } A^2]$$

By substituting this equation to (4), the total thermal conductivity is derived.

4. Comparison with the Equation of Maxwell and of Gorring & Churchill

A is influenced by thermal conductivity of wire materials and working fluid, and B is a function of diameter of wire, pitch (mesh number) and coefficient of shrinkage. Appropriate assumption of β, layer gap, will give effective thermal conductivity K. Fig. 4 shows the calculated results of K against porosity ϵ for the combination of stainless steel mesh and water. As shown in Fig. 4, in the case of $\beta=0$, when wires contact closely and mesh is flat and there is no gap between layers, the value by calculation using the equation (11) for mesh described in Table 1 is nearly in agreement with one by calculation using the Maxwell's equation.

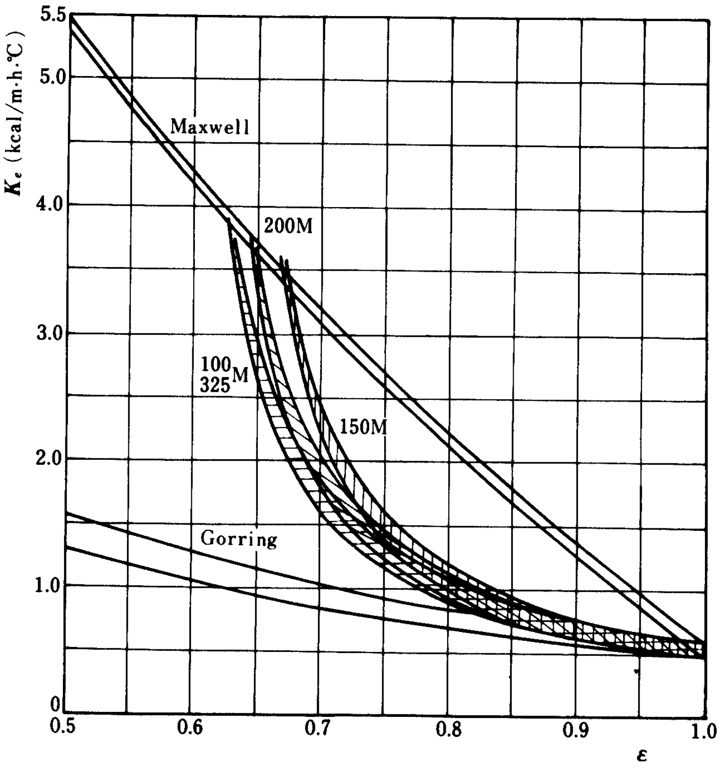

Fig. 4. Effective thermal conductivity.

With increasing of β, it approaches to the value by the equation of Gorring & Churchill. On the other hand, in the case of $\beta=\infty$, porosity $\epsilon=1$ and those three values are in agreement with each other and become to be the thermal conductivity of liquid.

Since the values of porosity about 100 mesh and 325 mesh are almost same, those are expressed by similar curves. But, in the case of 150 and 200 mesh, those curves differ from each other. Those are described about 100°C and 0°C and the thermal conductivity of working fluid depends upon temperature.

5. Discussion

Such experiments are not carried out so much. Results refered to data by Morooka[1] are represented in Fig. 5, 6, 7 and Table 1.

Fig. 5 shows the results calculated for the case of 100 mesh and 325 mesh. There are 5 drawed curves which are 100°C, 90°C, 60°C, 35°C, 0°C. In the case of 100°C and 90°C, those curves are on the same curve, since they have almost the same thermal conductivity. β and ϵ calculated from this figure using working temperature and experimental value K_e are represented in Table 1. The results of 150 mesh and 200 mesh are shown in Fig. 6 and 7. The relation between β and ϵ is shown in Fig. 8.

By refering to Morooka, with decreasing of working temperature, K_e decreases. In one heat pipe, β is to be fixed, so difference of K_e depends upon only the difference of thermal conductivity of working fluid depended on temperature. Therefore, the thickness of liquid layer seems to be thick at low working temperature. The number of layers filled with liquid calculated from thermal conductivity per a layer at each

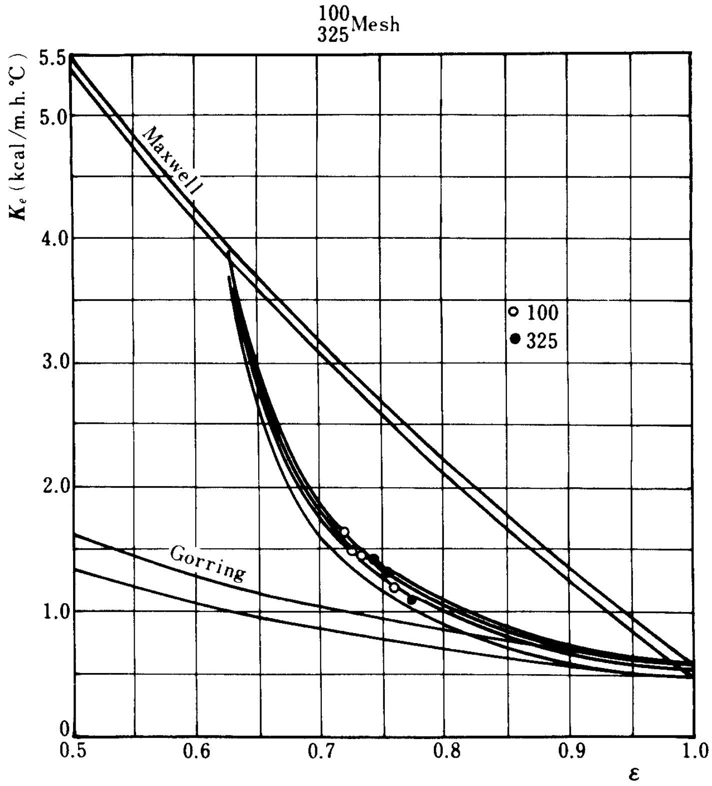

Fig. 5. Effective thermal conductivity (100325 mesh).

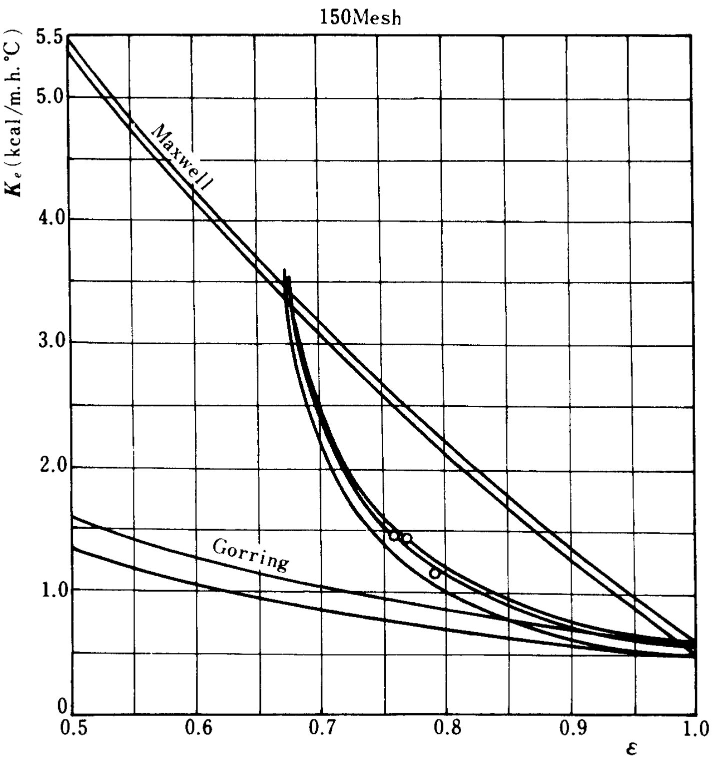

Fig. 6. Effective thermal conductivity (150 mesh).

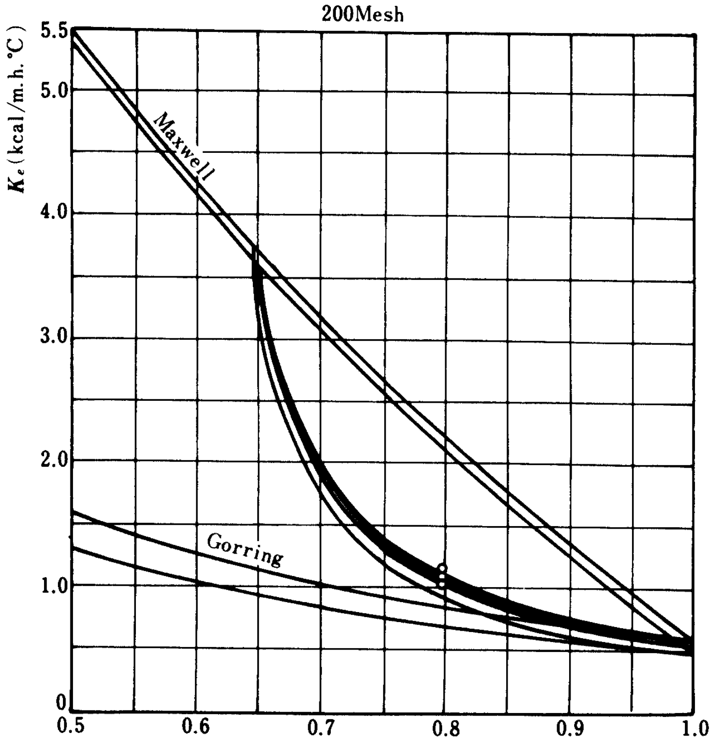

Fig. 7. Effective thermal conductivity (200 mesh).

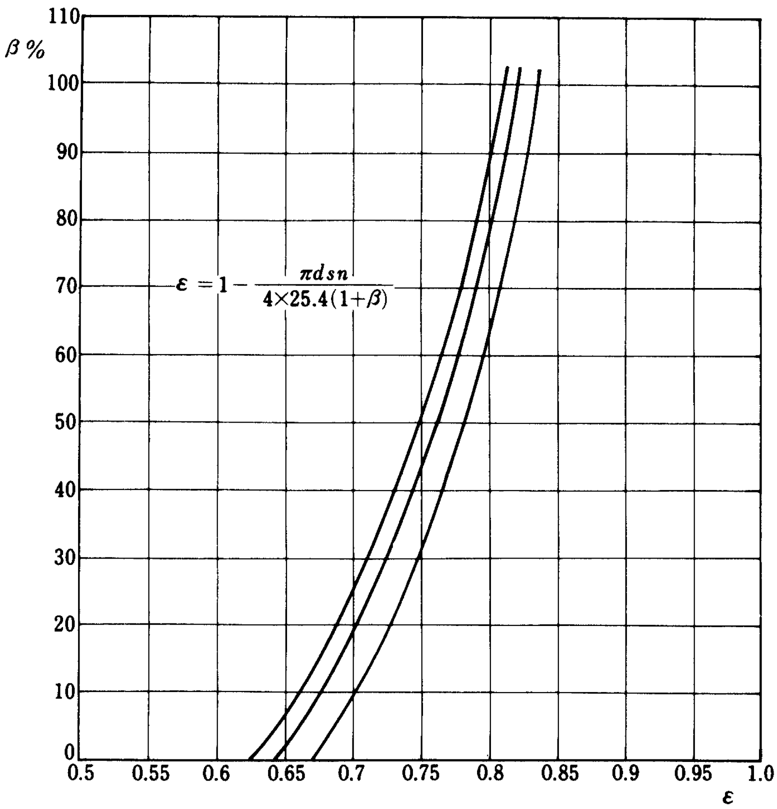

Fig. 8. β and ϵ.

temperature is shown in Table 1.

After consideration of gap between layers, the equation to calculate the effective thermal conductivity of a screen wick is derived. When diameter of wire and mesh number are given, it can be calculated by estimation of appropriate gap. Estimation of β from several experimental data would be possible.

Reference

[1] Morooka: Trans Jpn. Soc. Mech. Eng., Vol. 47, No. 414, S56-2.