

MODELING OF A HORIZONTAL U-TUBE ROAD HEATING SYSTEM AND ITS APPLICATION TO WADA TUNNEL

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ABSTRACT

Paying attention to the shallow ground heat inside a tunnel, a Horizontal U-Tube (HUT) road heating system was introduced for the first time in Japan in order to prevent winter traffic accidents associated with road freezing at the west side mouth of Nanaori-Toge tunnel, Aizu-bange, Fukushima Prefecture. Horizontal U-tubes were buried at a depth of 1.2 m in the ground of the central part of the tunnel. The ground heat extracted by the HUT is injected into the anti-freezing pavement at the tunnel mouth.

In this study, attempts were made to propose a simplified heat transfer model of HUT system. The proposed model consists of the energy balance equations of the fluid circulating in the HUT (HUT fluid) and the surrounding ground. Solving these two equations simultaneously, the extracted ground heat could be calculated as well as the fluid and ground temperatures. The model could also lead the overall heat transfer coefficient between the HUT fluid and the surrounding ground. The validity of the model was accepted from the comparison with indoor experimental results using a miniature HUT.

1. INTRODUCTION

Road heating has a significant requirement for reducing winter traffic accidents [1] at specific places such as intersections, bridges, tunnel mouths, etc. A slip accident at a tunnel mouth, for example, frequently occurs in winter and causes serious danger for human life and a heavy traffic jam [2], because the road surface condition remarkably changes inside and outside a tunnel mouth. A thermal map [3] in winter shows that the road surface temperature often falls below the freezing point near a tunnel mouth, although it keeps positive inside the tunnel.

In order to overcome the winter-traffic problems, a Horizontal U-Tube (HUT) road heating system, invented by Fukuhara [4], has been working at Nanaori-Toge tunnel, Aizu-bange, Fukushima Prefecture and Udodani tunnel [5], Tanba City, Hyogo Prefecture, Japan. We reported that the shallow ground heat extracted through the HUT from the central part of the tunnel is good enough for the road freezing prevention at a Nanaori-Toge tunnel mouth [6]~ [8].

Since the shallow ground heat has low energy density, a reliable HUT heat transfer model is required to calculate the extracted ground heat for different tunnel lengths and tunnel ground temperatures.

We propose a simplified model that can provide satisfactory outputs with less computational effort. The model is principally based on two dimensional heat transfer

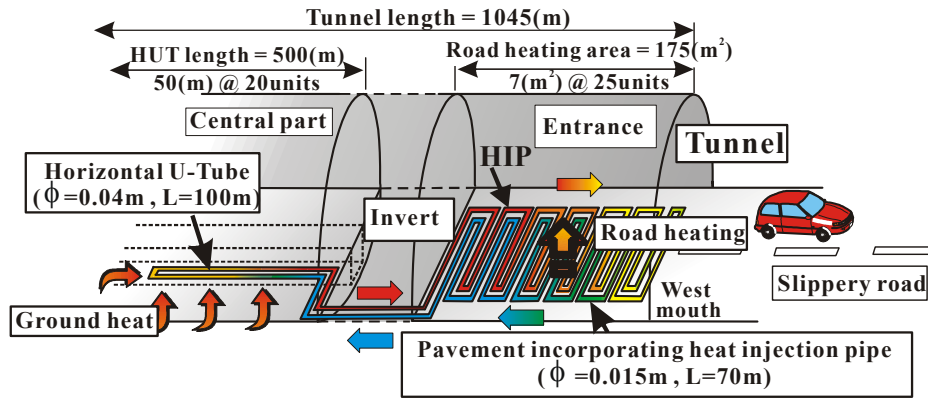


Figure 1 - Schematic view of the HUT system at Nanaori-Toge tunnel

theory taken account of the sensible heat due to the movement of fluid in the HUT (HUT fluid) and the heat transfer between the HUT fluid and the surrounding ground.

The present paper aims at showing the validity of the model by the comparison between the computed outputs and the indoor experimental results using a miniature HUT. In addition, the applicability of the model is also discussed in this paper.

2. OUTLINE OF HUT ROAD HEATING SYSTEM

Figure 1 shows the schematic view of the HUT road heating system of Nanaori-Toge tunnel that consists of 20 HUTs installed in the shallow ground (1.2 m below the road surface) of the central part of the tunnel and an anti-freezing pavement incorporating a serpentine heat injection pipe (HIP) at the tunnel mouth. The HUT is made from acrylic resin with a diameter of 40 mm. The pitch and length of the U-shape is 0.3 m and 50 m, respectively. The HUT fluid (water) circulates between the HUT and the HIP as shown in Figure 1. In winter, the HUT fluid is warmed associated with the extraction of the shallow ground heat, while it passes through the HUT and then the extracted heat is supplied to the pavement surface via the HIP.

3. NUMERICAL MODEL AND HEAT TRANSFER EQUATIONS

Figure 2 shows the computation region and element discretization of the proposed HUT heat transfer model. The calculation is classified into the HUT and the surrounding ground. Especially, the ground element, which contains the HUT (a pair of going and return tubes), is called the HUT ground element in this paper. The HUT ground consists of 'n' HUT ground elements, arranged in the longitudinal (x) direction shown in Figure 2.

3.1. Model assumptions

The proposed model may be allowed by the following assumptions that would enhance a rapid and easy calculation for practical design of the HUT.

- i) The heat flux across the HUT (extracted heat flux) is proportional to the temperature difference between the HUT fluid and the HUT ground.

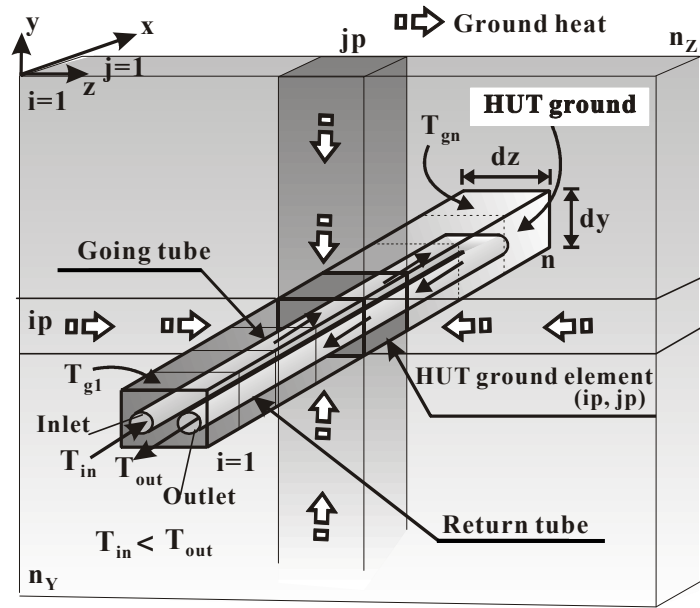


Figure 2 - Schematic view of two dimensional analysis

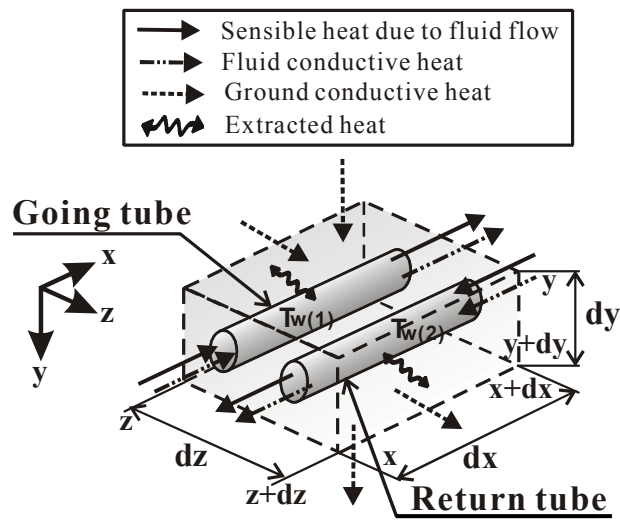


Figure 3 - HUT ground element with going and return tube

- ii) The temperature gradient of the HUT ground in the x direction is negligibly small in comparison with the ground temperature one in the vertical (y) or transversal (z) direction.
- iii) From the assumption ii), the HUT ground temperature, T_g , is assumed to be uniform in the x direction.
- iv) From the assumption iii), the heat transfer in ground is dominant in the y-z plane.

3.2. Energy balance equations

The energy balances of the HUT fluid and the surrounding ground may be formalized according to the heat transfer components shown in Figure 3.

3.2.1 Ground

Ignoring the ground heat conduction in the x direction, the time rate of the internal energy of the HUT ground element is given by Eq. (1).

$$(\rho C)_g \frac{\partial T_g}{\partial t} = \lambda_g \left(\frac{\partial^2 T_g}{\partial y^2} + \frac{\partial^2 T_g}{\partial z^2} \right) - E_{(m)} \cdot \eta_g \quad (1)$$

where T_g : the ground temperature, $(\rho C)_g$: the heat capacity of the ground, λ_g : the thermal conductivity of the ground, $E_{(m)}$: the extracted heat flux per unit circumference-surface area of HUT (subscript 'm' =1: for the going tube, subscript 'm' =2: for the return tube), η_g : the ratio of the circumference-surface area of HUT to the volume of HUT ground element. In this paper the ground temperature means the temperature of the soil in the sandy soil box.

In Eq. (1), the first and second terms of the right-hand side mean the heat conduction in the ground and the third term means the heat transfer between the HUT fluid and the HUT ground. Of course, the third term in Eq. (1) is excluded for every ground element except the HUT ground elements.

3.2.2 HUT fluid

The time rate of the internal energy of the HUT fluid is prescribed by the conductive heat, the sensible heat due to the movement of HUT fluid and the extracted heat flux, i.e.

$$(\rho C)_w \frac{\partial T_{w(m)}}{\partial t} = \lambda_w \left(\frac{\partial^2 T_{w(m)}}{\partial x^2} \right) - (\rho C)_w V \frac{\partial T_{w(m)}}{\partial x} + E_{(m)} \cdot \eta_p \quad [m = 1 \text{ or } 2] \quad (2)$$

where T_w : the HUT fluid temperature, $(\rho C)_w$: the heat capacity of the HUT fluid, λ_w : the thermal conductivity of the HUT fluid, V : the velocity of the HUT fluid, η_p : the ratio of the circumference-surface area to the volume of HUT.

3.2.3 Extracted heat flux

The extracted heat flux, $E_{(m)}$, in Eqs. (1) and (2) is calculated by Eq. (3) based on the assumption i) in 3.1.

$$E_{(m)} = \alpha (T_g - T_{w(m)}) \quad (3)$$

where α : the heat transfer coefficient between the HUT fluid and the HUT ground. In this paper, α is called the HUT heat transfer coefficient.

3.3. Initial and boundary conditions

The initial ground temperature is uniform in the whole region and equal to the ambient air temperature. The time variations of the boundary ground temperatures were interpolated from the observed data obtained from four thermocouples at intervals of 30 seconds. These thermocouples were placed 75 mm inside the central point of four boundary planes of the soil box.

The time variation of the inlet fluid temperature of the HUT was linearly interpolated from the observed data obtained at intervals of 30 seconds.

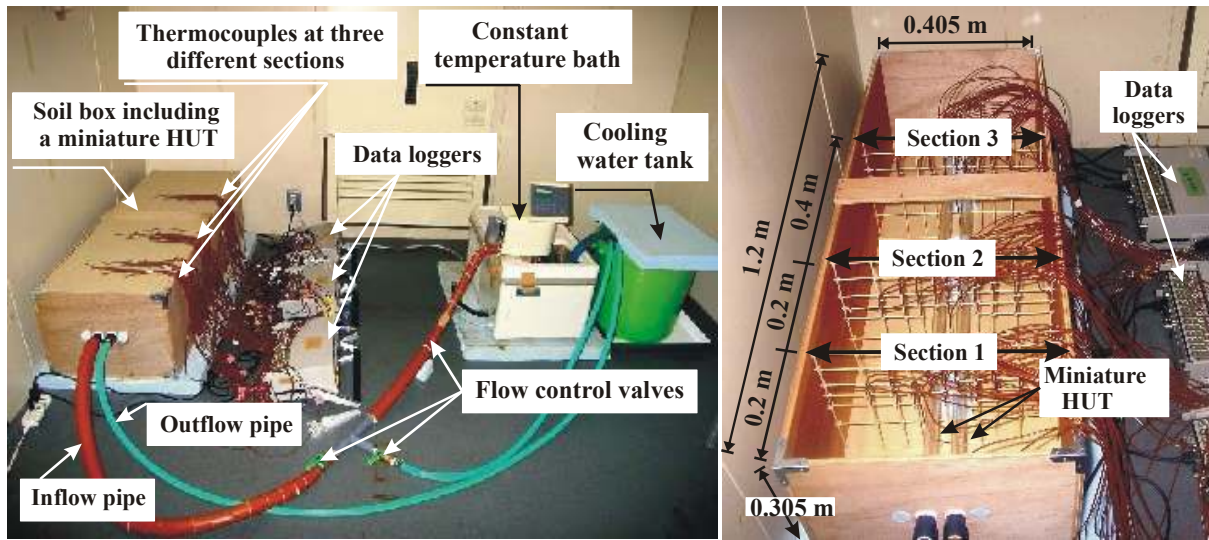


Figure 4 - Photograph of indoor experiment

Table 1 - Indoor experimental conditions

Case No.	Room conditions		HUT pitch (mm)	Flow rate $\times 10^{-7}$ (m ³ /sec)
	T _a (°C)	RH _a (%)		
1	25	50	45	7.0
2				12.4
3				20.8
4				25.7
5				47.6

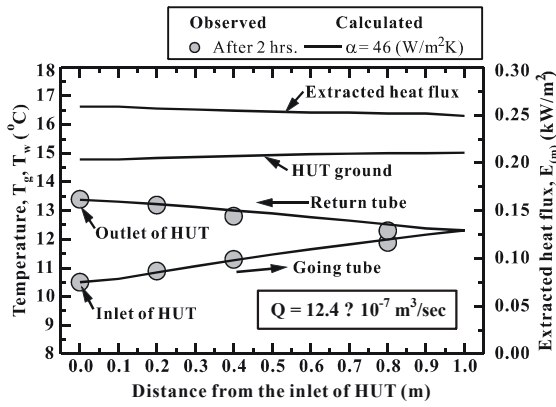
4. INDOOR EXPERIMENTS

To evaluate the extracted heat and the HUT heat transfer coefficient, indoor experiments were carried out in a constant temperature and humidity room at the University of Fukui.

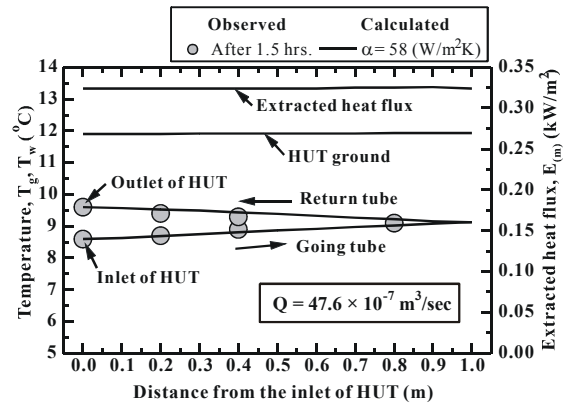
Figure 4 shows the experimental equipment that consists of a miniature HUT, a soil box (1.2 m \times 0.405 m \times 0.305 m), a constant temperature bath, a cooling water tank, three data loggers and an electric balance. Toyoura standard soil was uniformly packed in the soil box. The flow rate was controlled by the adjustment of the opening angles of the valves. A polycarbonate transparent pipe with an inner diameter of 20 mm and a thickness of 1.0 mm was used as the HUT and was buried 0.15 m below the soil surface. The pitch and length of the HUT is 45 mm and 1.0 m, respectively. The soil box was made of wood and covered with a heat insulator (styrofoam).

In this experiment, the ground temperatures were measured in the vertical plane at three different positions (section-1, 2 and 3), which were 0.2, 0.4 and 0.8 m away from the inlet of the HUT, respectively (see Figure 4). At the same time, the ambient air temperatures around the soil box were also measured. The constant temperature bath controls the fluid temperature at the inlet of HUT, T_{in}.

Table 1 shows the experiment cases and experimental conditions. The experiments were carried out for five different flow rates.

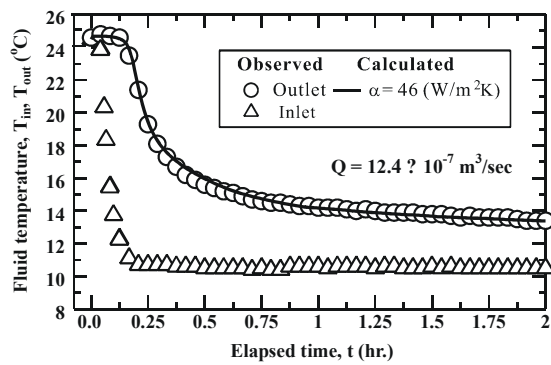


a) Case-2

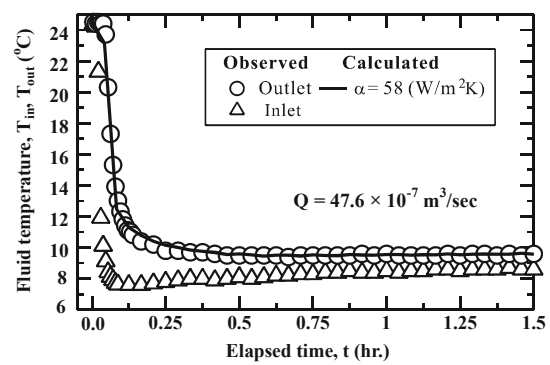


b) Case-5

Figure 5 - Longitudinal profiles of extracted heat flux, HUT ground temperature and HUT fluid temperature



a) Case-2



b) Case-5

Figure 6 - Comparison of calculated and observed outlet fluid temperatures of HUT with elapsed time

5. RESULTS AND DISCUSSIONS

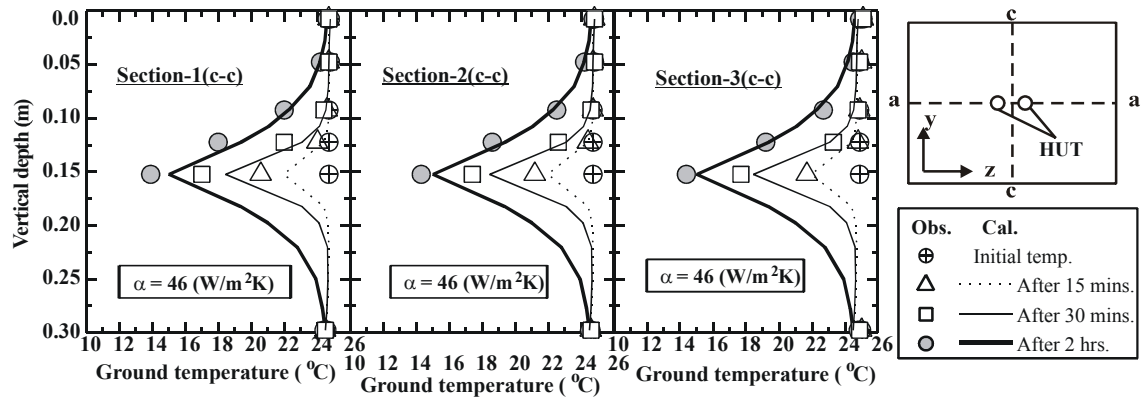
In order to verify the validity of the proposed model, the computed outputs were compared with the indoor experimental results.

Thermal properties of fluid and other parameters were derived from the hand books [9]-[11] and the reference [12]. On the other hand, the thermal conductivity of sand was measured with a thermal conductivity meter (Kemtherm QTM-D3). The porosity and specific heat of the sand used in the experiment were also measured from other tests.

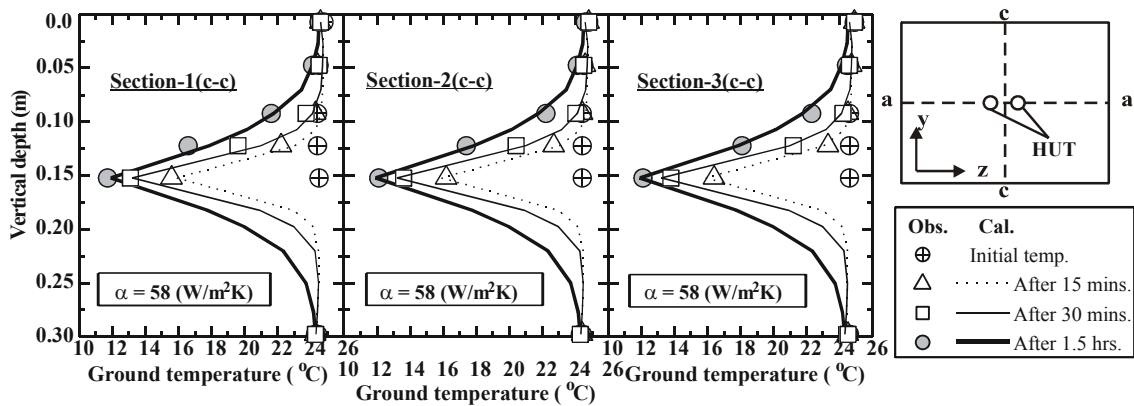
5.1. HUT ground and fluid temperatures and extracted heat flux

Figure 5 (a) and (b) show the longitudinal profiles of the extracted heat flux, $E_{(m)}$, the HUT fluid temperature, T_w , and the ground temperature, T_g , for Case-2 and Case-5, respectively. The circular symbol represents the observed HUT fluid temperature, while the solid line represents the calculated one. The measured HUT fluid temperatures were well in agreement with the calculated ones through the whole experiment period.

The spatial variations of the extracted heat flux and the HUT ground temperature in the x direction are negligibly small for both cases, especially for Case-5.



a) Case-2



b) Case-5

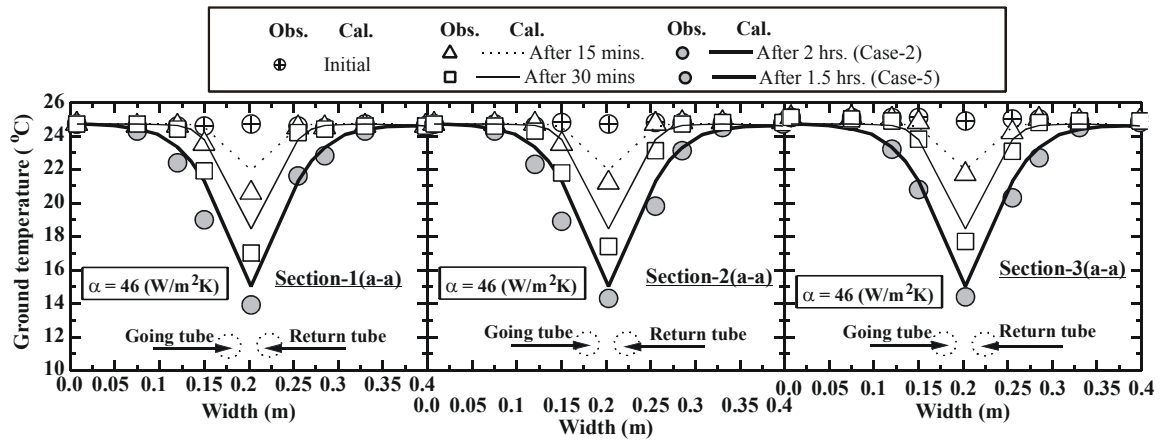
Figure 7 - Model verification based on vertical ground temperature profiles after system operation started

Figure 6 (a) and (b) compare the calculated and observed outlet fluid temperatures of HUT, T_{out} , with elapsed time, t , for Case-2 and Case-5, respectively. The triangular and circular symbols represent the observed T_{in} and T_{out} , respectively. The calculated values are also shown as solid lines in Figure 6. It is seen that the calculation is satisfactory when the HUT heat transfer coefficient, α , is $46 \text{ W/m}^2\text{K}$ for Case-2 and $58 \text{ W/m}^2\text{K}$ for Case-5.

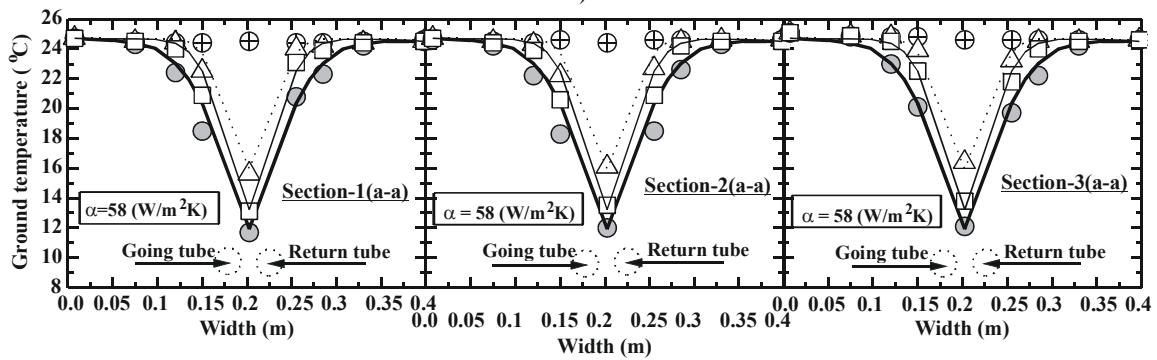
5.2. Ground temperature profiles

Figures 7 and 8 show the vertical and horizontal profiles of the ground temperatures along the centre lines (c-c and a-a, shown in Figure 7) in the three vertical planes (section-1, 2 and 3) at 15 minutes, 30 minutes, 1.5 hours and 2 hours after the operation start. The fall of the ground temperature is concentrated around the HUT associated with the heat extraction and spread with time. It is seen that the calculation satisfactorily reproduced the ground temperature profile with a best choice of α ($46 \text{ W/m}^2\text{K}$ for Case-2 and $58 \text{ W/m}^2\text{K}$ for Case-5).

The calculated profiles were, however, found to be somewhat lower than the observed ones near the HUT for Case-2. It is noted that the distribution of the observed ground temperature becomes nearly symmetrical with respect to the vertical center line (c-c) toward the section-3 from the section-1.



a) Case-2



b) Case-5

Figure 8 - Model verification based on horizontal ground temperature profiles after system operation started

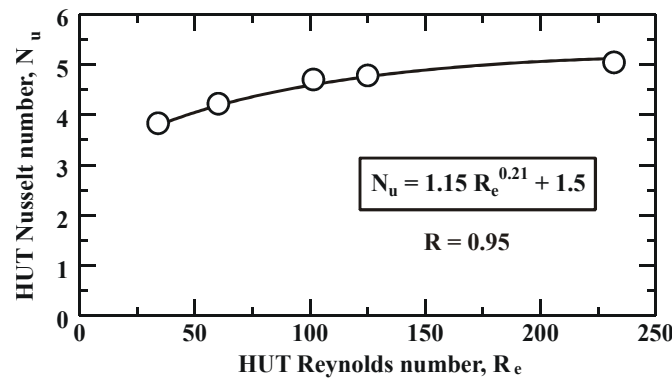


Figure 9 - Relation between HUT Nusselt number and Reynolds number

5.3. Relation between HUT Nusselt number and Reynolds number

Figure 9 shows the relation between the HUT Nusselt number, $N_u (= \alpha D / \lambda_p, \lambda_p$: the thermal conductivity of the HUT), and the HUT Reynolds number, $R_e (= VD / \nu, \nu$: the kinematic viscosity of the HUT fluid, D : the diameter of HUT). The value of N_u nonlinearly increases with the increase in R_e in the range from 30 to 230, and may be given by the following power function, i.e.,

$$N_u = 1.15 R_e^{0.21} + 1.5 \quad \text{for } 30 \leq R_e \leq 230 \quad (4)$$

The correlation coefficient, R , of Eq. (4) is also shown in Figure 9.

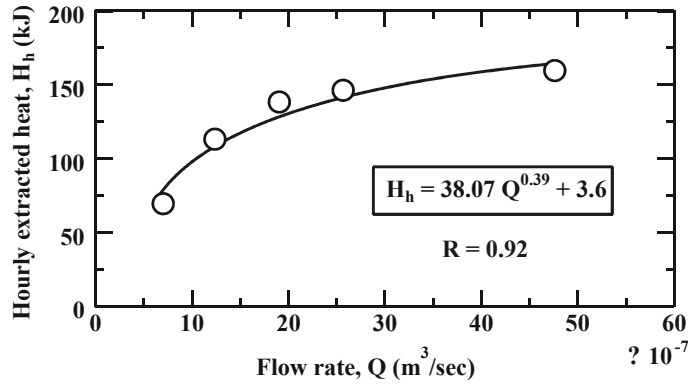


Figure 10 - Relation between hourly extracted heat and flow rate

5.4. Extracted heat

The extracted heat flow, H_{ext} , is calculated by the following equation,

$$H_{ext} = (\rho C)_w Q (T_{out} - T_{in}) \quad (5)$$

Figure 10 shows the relation between the hourly extracted heat, H_h , and the flow rate, Q . H_h is defined by the following equation,

$$H_h = \int_0^{1\text{hour}} H_{ext}(t) dt \quad (6)$$

H_h also becomes large as Q increases and this relation may be expressed by the following power function,

$$H_h = 38.07 Q^{0.39} + 3.6 \quad \text{for } 30 \leq R_e \leq 230 \quad (7)$$

The value of R of Eq. (7) is also shown in Figure 10. It is clear that the positive relation between H_h and Q may be attributed to the relation between N_u and R_e , shown in Figure 9.

CONCLUSIONS

In this paper, a simplified heat transfer theory of a Horizontal U-Tube (HUT) is proposed and the applicability of the proposed model was discussed in comparison with experimental results using a miniature HUT. The following conclusions were drawn:

1. It can be considered from the present experiment and the proposed model that the extracted ground heat and the HUT ground temperature is uniform, as long as the present HUT configuration and flow rate are concerned.
2. The relation between the HUT Nusselt number, N_u , and the HUT Reynolds number, R_e , is given by a power function and N_u increases with R_e . The extracted ground heat is also given by a power function of the flow rate.
3. The indoor experimental results allowed the proposed model to reasonably predict the extracted ground heat.

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