Heat Extraction Test using a Miniature Horizontal U-Tube

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1. Introduction

Paying attention to the warm shallow ground heat inside a tunnel, a Horizontal U-Tube (HUT) road heating system[1)] 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. Heat extraction/injection performance of the HUT system has been analyzed through experiments in winter and summer since then. Indoor experiments were also carried out using a miniature HUT to evaluate the validity of our theoretical model and the HUT heat transfer coefficient.

This paper describes the behavior of soil temperature surrounding the HUT under system operation and the relations between the extracted heat with flow rate and the HUT heat transfer coefficient or Nusselt number with Reynolds number.

2. Outline of the indoor experiment

Fig. 1 shows the experimental equipment that consists of a miniature HUT, a wooden soil box (1.2m×0.405m×0.305m), 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 covered with a heat insulator (styrofoam). 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 U-shape is 45 mm and 1.0 m, respectively.

In this experiment, the soil 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 the right photograph of **Fig. 1**). The ambient air temperatures around the soil box were also measured. The data obtained from 90 thermocouples were automatically recorded into three data loggers at intervals of 30 seconds. The constant temperature bath controls the fluid temperature at the inlet of HUT i.e., temperature of the inflow fluid to the HUT.

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

Table 1 Indoor experimental conditions

Case No.	Room conditions T_a (^oC)	Room conditions RH_a (%)	HUT pitch (mm)	Flow rate (m^3/sec × 10^{-7})
1	25	50	45	7.0
2				12.4
3				20.8
4				25.7
5				47.6

3. Experimental results

3.1 Soil temperature profile

Fig. 2 shows the observed isothermal contours of the soil temperature in the upper part of the horizon which crosses the HUT (Case-5, section 1) after 1.5 hours system operation. The fall of soil temperature is concentrated around the HUT associated with the heat extraction and spread with elapsed

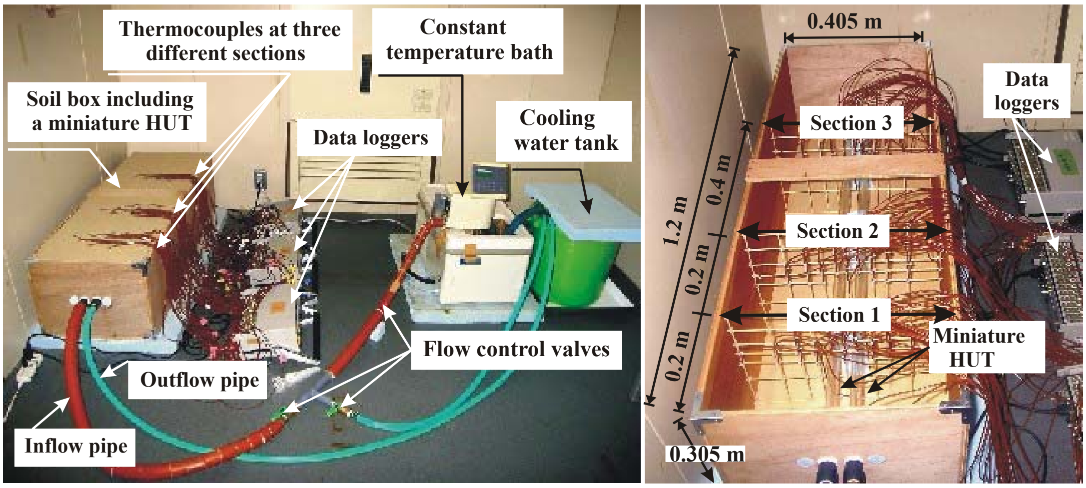

Fig. 1 Photograph of indoor experiment

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time, although not shown here. It is noted that the distribution of the observed soil temperature becomes nearly symmetric with respect to the vertical centre line, a-a.

3.2 Extracted heat

Fig. 3 shows the extracted heat flow, H_{ext} (W), with elapsed time, t, for Case-2 and Case-5, respectively. The inlet fluid temperature of HUT, T_{in}, for Case-2 and Case-5 were 10.4 °C and 8.6 °C, respectively. H_{ext} is calculated by the following equation,

$$H_{ext} = (\rho C)_w Q(T_{out} - T_{in}) \tag{1}$$

where, $(\rho C)_w$: the heat capacity of the HUT fluid (J/m^{3}K), Q: the flow rate (m^3/sec), T_{out} : outlet fluid temperature of HUT (°C).

The value of H_{ext} suddenly reached the maximum as soon as the inflow started. Subsequently, H_{ext} fell rapidly and then approached an equilibrium value. The maximum value is larger for Case-5 (large Q) than for Case-2 (small Q), but the equilibrium value is almost same for both the cases.

Fig. 4 shows the relation between the hourly extracted heat, H_h (kJ), and the flow rate, Q. H_h is defined by the following equation,

$$H_h = \int_0^{1\,\text{hour}} H_{ext}(t)dt \tag{2}$$

The value of H_h is nonlinearly proportional to Q and may be given by the following equation, i.e.,

$$H_h = 38.07Q^{0.39} + 3.6 \quad \text{for} \quad 30 \le R_e \le 230 \tag{3}$$

In which, R_e: the HUT Reynolds number (=VD/ν, ν: the kinematic viscosity of the HUT fluid (m^2/sec), D: the diameter of HUT (m) and V: the fluid velocity (m/sec)).

3.3 Relation between Nusselt number and Reynolds number

Fig. 5 shows the relation between the HUT Nusselt number, N_u (= $\alpha D/\lambda_p$, α : the heat transfer coefficient between the HUT fluid and soil (W/m^{2}K) and λ_p : the thermal conductivity of the HUT[2] (W/mK)) and the Reynolds number, R_e.

N_u nonlinearly increases with the increase in R_e in the range from 30 to 230, and may be given by the following equation, i.e.,

$$N_u = 1.15R_e^{0.21} + 1.5 \quad \text{for} \quad 30 \le R_e \le 230 \tag{4}$$

4. Concluding remarks

Following the indoor experimental results, heat extraction performance of Horizontal U-Tube (HUT) was discussed in this paper. The conclusions were drawn as follows:

(1) When the pitch of HUT is small, the distribution of soil temperature surrounding the HUT is nearly symmetric with respect to the vertical centre line between the going tube and the return one.

(2) The extracted ground heat nonlinearly increases as the flow rate increases.

(3) The Nusselt number of the HUT nonlinearly increases with the increase in the HUT Reynolds number.

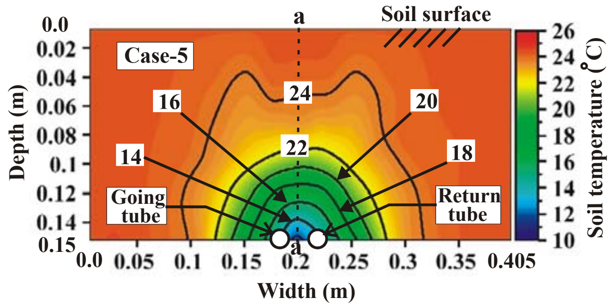

Fig. 2 Observed isothermal contours after 1.5 hrs.

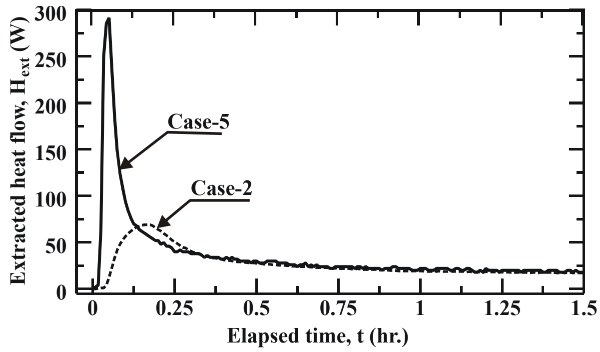

Fig. 3 Extracted heat flow with elapsed time

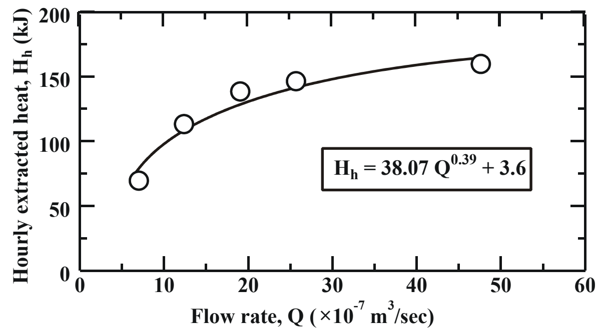

Fig. 4 Relation between hourly extracted heat and flow rate

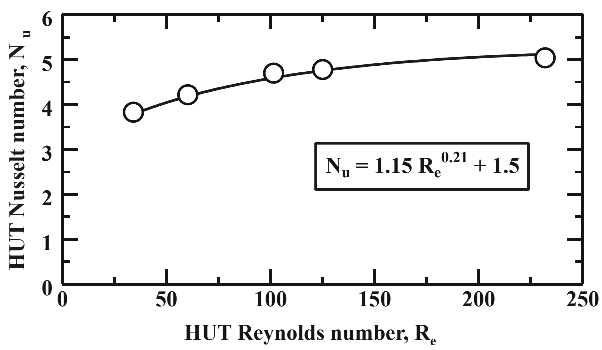

Fig. 5 Relation between HUT Nusselt number and Reynolds number

References

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