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Rate of heat transfer in polypropylene tubes in solar water heaters

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Abstract

A heat transfer rate was determined for polypropylene tubes in solar water heaters for the Reynolds number range 800–5600. Experiments were conducted in ambient temperatures of 34 to 37 °C. Data were correlated in the form of Nusselt numbers as: $Nu = 0.0015\ Re^{0.75}\ Pr^{1/3}$ with correlation coefficient of 0.95. Such data can be used to predict heat transfer rates in a polypropylene solar heater in Tehran where the experiments were performed. An application of the results is shown in an example.

1. Introduction

In the past few decades water heating systems with natural circulation have been in use in many parts of the world and have been studied by some researchers (Close, 1962; Ong, 1976). Razavi and Riazi (1994) showed that polypropylene tubes can be used in thermosiphonic flow solar water heating systems. They also obtained an optimum condition for the best performance of the solar water heater. Later Riazi and Razavi (1997) compared the performance of polypropylene tubes with steel tubes through a set of experiments. It was found that polypropylene tubes may increase water temperature by 10 °C more than steel tubes, and as a result it was recommended that use of polypropylene tubes in solar water heating systems is preferable over steel tubes. Heat transfer rates can be calculated through heat transfer coefficients. In this study the same experimental set-up as in our previous studies was used to determine heat transfer in polypropylene tubes used for solar water heating systems. Heat transfer coefficient is correlated to flow rate and water properties through a generalized correlation in terms of Nusselt, Reynold and Prandtl numbers. The correlation can be used to predict the rate of heat transfer in such solar water heaters.

2. Experiments

A detailed description of the experimental set-up is shown in Fig. 1 which is similar to the one used in our previous studies (Razavi and Riazi, 1994; Riazi and Razavi, 1997). The apparatus is constructed by using one 180-l tank, 36 parallel polypropylene type tubes of 19 mm inside diameter, 1 mm thickness and 2 m length, thermometers and water-level floaters. A flow meter was also installed at the entrance of cold water to the collector. Tubes were connected to the 180-l tank and were fixed on a black board which could be tilted relative to the horizon. The tank, all tubes and fittings were painted black to maximize energy absorption and were completely insulated by fiber glass to prevent heat loss. However, the collector was not glazed. In our previous work (Razavi and Riazi, 1994) it was shown that the best performance for the polypropylene tubes can be obtained at a collector slope of 36° with respect to the horizon when the black board is facing south.

For the present study the experiments were performed

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Nomenclature

A_i	internal surface area of pipes, m^2 (or cm^2)
a, b, c	coefficients in Eq. (19)
C_p	heat capacity, J/kg K
d	tube diameter, m (or cm)
h	heat transfer coefficient, W/m^2 K
k_w	thermal conductivity of water, W/m K
ℓ	tube length, m (or cm)
$\dot{m}$	mass flow rate of water, kg/s
Nu	Nusselt number, dimensionless
Pr	Prandtl number, dimensionless
Q_r	heat transfer rate from solar radiation, W
Re	Reynold's number, dimensionless
T_{air}	air temperature, °C
T_{in}	inlet water temperature (city water temperature, °C)
T_o	outlet water temperature, °C
T_{so}	outside surface temperature of tubes, °C
$\dot{V}$	volumetric flow rate of water in tubes, ml/s (cm^3/s)

Greek letters

ϕ	angle between sun radiation and a plate normal to the collector board, degrees (°)
ρ_w	water density, kg/l
μ_w	water viscosity, kg/m s

on the roof of the Department of Chemical Engineering at Sharif University of Technology where it is located at the latitude of 36° north of the equator and 52° east of prime meridian. All the experiments were conducted during the summer season (July, 2002) when ambient temperatures varied from 34 to 37 °C. In each set of experiments, temperatures of the inlet and outlet water from the tubes were measured. The angle of solar radiation with respect to the plane normal to the black board (ϕ) and the air temperature were measured every hour. Surface temperature of polypropylene tubes were measured by a thermistor. The angle of solar radiation was measured using a rod of known length and measuring the length of its shade on the collector board. The city water used in all experiments had an average temperature of 19 °C during the period at which experiments were conducted. In each experiment the following parameters were measured:

T_{in}, inlet water temperature (city water temperature, °C);
T_o, outlet water temperature, °C;
ϕ, angle between sun radiation and a plate normal to the collector board, degrees (°);
$\dot{V}$, volumetric flow rate of water in tubes, ml/s (cm^3/s);
T_{air}, air temperature, °C

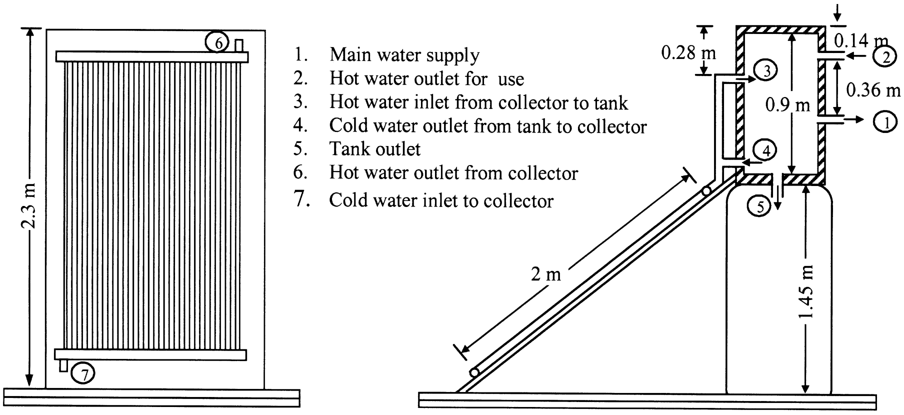

Fig. 1. Schematic of experimental apparatus.

Table 1
Set of experimental data

Experiment	$\dot{V}$ (ml/s)	ϕ	T_{in} (°C)	T_o (°C)	T_{air} (°C)	T_{so} (°C)
1	80	44.8	19	25.7	34	38
2	70	39.6	19	27.4	35	37
3	33	35.3	19	31.1	36	55.7
4	42	31.6	19	32.0	36.3	44.5
5	22	27.8	19	38.2	37.5	59.7
6	15	23.8	19	44.4	36.6	63.5
7	9.4	21	19	50	37	72.6

T_{so}, outside surface temperature of tubes, °C.

During each experiment T_{in} was constant, however, T_o is the average of measured temperatures at the beginning, middle and end of each set of experiments. T_{so}, the outside surface temperature, is the average temperature of several locations to represent all areas. Further details of experimental measurements are given in our previous publications (Razavi and Riazi, 1994; Riazi and Razavi, 1997). Measured values for these parameters are given in Table 1.

3. Analysis and correlation of data

The amount of heat transfer due to solar radiation (Q_r) depends on the angle of radiation (ϕ) as:

$$Q_r = Q_{max} \cos \phi \tag{1}$$

where Q_{max} is the maximum rate of heat transfer from the sun when the radiation angle is zero (normal radiation). Q_{max} can be calculated from maximum water flow rate and temperature difference. The apparatus can handle a maximum flow rate of $\dot{V}_{max} = 500$ ml/s. Before the system reaches steady state when there is no water outlet flow, the outside surface temperature of tubes reaches a value called maximum water temperature and is shown by $T_{so(max)}$. In a particular experiment when $T_{air} = 35$ °C we found that $T_{so(max)} = 98$ °C. Under maximum water flow (500 ml/s), T_{so} becomes minimum and it was 35.9 °C. The inlet water temperature during this specific experiment was 19 °C and the average outlet water temperature was the lowest among all the experiments ($T_o = 20.55$ °C). As mentioned earlier, this outlet water temperature is the average of three measurements at the beginning, middle and end of the experiment

$$Q_w = \dot{m} C_p \Delta T_w \tag{2}$$

$$\Delta T_w = T_o - T_{in} \tag{3}$$

$$\dot{m} = \rho_w \dot{V} \tag{4}$$

where ρ_w is density of water and it may be assumed as 1 kg/l. C_p is the heat capacity of water which may be taken as 4.18 J/g °C. During maximum water flow rate the heat transfer coefficient is h_{max} and we have

$$(Q_r)_{max} = (\dot{m})_{max} C_p (\Delta T_w)_{max} + (Q_{loss})_{max} \tag{5}$$

$$(Q_r)_{max} = (h_{max} A_o) \times (\Delta T_2)_{max} \tag{6}$$

$$(Q_{loss})_{max} = (h_{max} A_o) \Delta T_1 \tag{7}$$

where

$$\Delta T_1 = T_{so} - T_{air} \text{ when } \dot{V} = 500 \text{ ml/s} \tag{8}$$

$$(\Delta T_2)_{max} = T_{so(max)} - T_{air} \text{ when } \dot{V} = 0. \tag{9}$$

When $\dot{V} = 0$, there is no flow and T_{so} reaches its maximum value of $T_{so(max)}$. By simultaneous solution of Eqs. (5)–(7) one can determine: ($h_{max} A_o$) and Q_{max}. For the case of $T_{air} = 35$ °C, $T_{so(max)} = 98$ °C we get $\Delta T_{so(max)} = 63$ °C and at the maximum flow rate ($\dot{V} = 500$ ml/s), $T_{so} = 35.9$ which gives $\Delta T_1 = 0.9$ °C. From water inlet and outlet temperatures at the maximum flow rate we have $\Delta T_w = 1.55$ °C. Substituting these values into Eq. (5) and combining with Eqs. (6) and (7) we get $h_{max} A_o = 52.2$ W/°C and $Q_{max} = 3310$ W. The energy loss, Q_{loss}, is then calculated as:

$$Q_{loss} = Q_{max} \cos \phi - \dot{m} C_p (T_o - T_{in}) \tag{10}$$

$$Q_{loss} = h_o A_o (T_{so} - T_{air}) \tag{11}$$

where h_o is the heat transfer coefficient for the external surface.

From the above two equations we have

$$h_o = \frac{Q_{max} \cos \phi - \dot{m} C_p (T_o - T_{in})}{A_o (T_{so} - T_{air})}. \tag{12}$$

Based on the thickness and thermal conductivity of polypropylene tubes the temperature difference between outside (T_{so}) and inside (T_{si}) surface temperatures is about 3 °C. As the thickness of the tube increases this temperature difference also increases

$$T_{si} = T_{so} - 3. \tag{13}$$

Now we define inside heat transfer coefficient, h_i, in the following form:

$$Q_w = h_i A_i \Delta T \tag{14}$$

where ΔT is defined as:

$$\Delta T = T_{si} - T_{water}$$

$$T_{water} = \frac{T_{in} + T_o}{2} \tag{15}$$

A_i is the total internal surface area of all tubes and it is given as:

$$A_i = n \pi \ell d \tag{16}$$

where n is the number of tubes, ℓ and d are the length and inside diameter of tubes. In our calculations $n=36$, $d=1.9$ cm and $\ell=200$ cm ($A_i=42{,}955$ cm^2).

Reynolds and Nusselt numbers are calculated as:

$$Re = \frac{4\rho_w \dot{V}}{\pi d \mu_w} \tag{17}$$

$$Nu = \frac{h_i d}{k_w} \tag{18}$$

where μ_w and k_w are the viscosity and thermal conductivity of water, respectively. Physical properties of water were taken from Holman (1997). Calculated values of Q_r, Q_w, h_i, Re and Nu are given in Table 2.

The general relation between Nu and Re is in the following form:

$$Nu = a\, Re^b\, Pr^c \tag{19}$$

where Pr is the Prandtl number ($C_p\ \mu/k$).

The value of c when $Re<5000$ is given as 1/3 (Holman, 1997). In this study Pr is constant since the fluid is water and the effect of temperature on Pr is neglected.

Using values of Nu and Re in Table 2, constants a and b have been determined through linear regression analysis. The result is

$$Nu = 0.0015\, Re^{0.75}\, Pr^{1/3}. \tag{20}$$

The correlation parameter in the regression was 0.95. In obtaining heat transfer coefficient and subsequent Nusselt number to develop the above correlation, simplified experimental techniques have been used and the data are correlated through simplified analysis. As an example, in the calculation of A_i through Eq. (16) it is assumed that solar radiation does affect all surface areas of all tubes. This is not the case and for this reason calculated h_i may not be a true heat transfer coefficient for such systems. But as stated before, the purpose of this experimental work was not to measure true heat transfer coefficient but to measure rate of heat transfer to water in such solar heater systems under similar conditions. Through use of these equations one can predict the outlet water temperature (T_o) through Eqs. (2), (14) and (15). This is demonstrated in the following example.

Example. A polypropylene tube collector is installed with a slope of 36° at the latitude of 36° north of the equator. The collector is made of 20 parallel tubes of length 1 m, inside diameter of 15 mm and thickness of 1 mm. The water flow rate is measured at the rate of 30 cm^3/s. The air temperature is 30 °C and average surface temperature of tubes is measured as 50 °C. If the water inlet temperature is at 20 °C calculate the increase in water temperature after leaving the collector.

Solution. Based on the information available we have $n=20$, $d=1.5$ cm and $\ell=100$ cm and from Eq. (16): $A_i=9420$ cm^2. The physical properties of water at 30 °C are given by Rowley et al. (2002) as: $\rho_w=944$ kg/m^3, $\mu_w=0.82\times10^{-3}$ kg/m s, $C_P^L=4.18\times10^3$ J/kg K, $k_w=0.613$ W/m K. $Pr=(4.18\times10^3\times0.82\times10^{-3})/0.613=5.59$. From Eq. (17) we have: $Re=(4\times944\times30\times10^{-6})/(3.14\times1.5\times10^{-2}\times0.82\times10^{-3})=2933$. From Eq. (20): $Nu=0.0015\times(2933)^{0.75}\times(5.59)^{0.333}=1.06$. From Eq. (18): $h_i=(1.06\times0.613)/1.5\times10^{-2})=43.3$ W/m^2 K. $\Delta T=T_{si}-T_{water}$ where $T_{si}=50-3=47$ °C. Assuming 10 °C increase in water temperature, from Eq. (15): $T_{water}=(30+20)/2=25$ °C. $\Delta T=47-25=22$ °C. Eq. (14) should be used to calculate the rate of heat transfer to water: $Q_w=43.3\times9420\times10^{-4}\times22=897.3$ W. From Eq. (4) $\dot{m}=944\times30\times10^{-6}=0.02832$ kg/s. From Eq. (2) the rise in temperature of water can be calculated as: $\Delta T_w=897.3/(0.02832\times4.18\times10^3)=7.6$ °C. In the next round of calculations we assume the temperature rise is 8 °C which gives $T_{water}=24$ °C and $Q_w=978.9$ W. New calculated water temperature rise is $\Delta T_w=8.3$ °C. There is no need for another round of calculations and the answer is 8.3 °C.

4. Conclusion

In this study heat transfer rate in polypropylene tubes used in solar water heaters with thermo-siphonic flow has been determined from experimental measurements for the Reynolds number range of 800–5600. A correlation in terms of Nusselt number versus Reynolds and Prandtl numbers has been derived which may be used to calculate heat transfer coefficient and subsequent heat transfer rate in polypropylene tubes under similar conditions.

Table 2
Calculation of heat transfer rate and Nusselt number

Experiment	Q_r (W)	Q_w (W)	h_i (W/m^2 °C)	Re	Nu
1	2350	2239	41.2	5600	1.05
2	2551	2457	53.0	5400	1.28
3	2700	1668	14.0	2500	0.39
4	2693	2264	21.2	3230	0.51
5	2928	1765	14.6	1900	0.41
6	3028	1613	13.1	1400	0.38
7	3088	1217	8.1	800	0.23

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