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Hydropower Generation by Solar Thermosyphon

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Abstract

Solar thermosyphon (TS) consists of thermal collector, condenser (recuperater), reservoir, and heat exchanger. The TS collects solar heat at the roof and carries it to the downstairs 4 m below the collector without using pumps. The working medium of the TS is water. Temperature of the collected heat ranges 70 to 80 ^{o}C at the highest (low temperature heat). Hydropower generation using the TS was attempted for the first time. At present, the observed power output was 10^{-6} W in the order of magnitude for the solar irradiation of 500 to 1400 W and the thermal coefficient was in 10^{-9} level, very low. Since Carnot's coefficient is 0.13 for the present heat sources, there is a great margin for the future improvement. The main reasons of such low efficiency were considered to be due to 1) lack of stability of the TS circulating flow, 2) losses of heat and fluid flow, and 3) improper design of impellors. A mathematical model of the TS performance was given. In the model main driving force of the TS is assumed to be the buoyancy force by the steam bubbles. Verification of the model is under study.

Key words: Solar Thermosyphon, Water, Low Temperature Heat, Hydropower Generation

1. Introduction

If we simply place a water tank under the sunshine, we may see often that the temperature of the water in the tank indicates 50 - 70 ^{o}C in a couple of hours. It is true in the Kanto area, Japan. We know that heat at those temperatures (low temperature heat) is abundant and easy to collect. Utilization of the solar energy is the worldwide issue these days. There are numerous attempts on the power generation using solar heat. In most cases, however, the solar irradiation is collected by using the optical equipment such as mirrors and lenses in order to focus the solar beam and to get higher temperature working medium. In such cases, the temperatures are above 300^{o}C (see, for example, Ma, Glatzmaier, and Kutscher, 2012) .The heated medium is used to run the gas- or the steam-turbines. On the other hand, the solar devices utilizing low temperature heat below 100^{o}C are relatively limited. In most cases, the solar heat is used as the heat, such as the bath, shower, floor-heating and so on. The solar thermosyphon (hereafter, TS) is one of the useful devices for collecting solar heat. The authors developed a self-circulating solar thermosyphon (Ito, Tateishi, and Miura 2007, Hagino and Yoshida 2011, Imada, Hagino, and Yoshida 2013). The TS is a closed loop of a pipe and has a simple structure. It collects solar heat at the roof and transports it to the ground floor, which is 4m below the collector, without using pumps.

As far as we use the TS as a heat supplying device, its major purpose seems to be almost attained. We know that the amount of the heat (below 100 ^{o}C) collected by the TS is enormous and the ways of the usage of the low temperature heat has been rather limited. Thus the authors come to think of the hydropower generation using the TS. Such idea may be profitable for the effective utilization of the low temperature heat which has been dumped so far. In this paper we describe the first attempt of the hydropower generation by TS.

2. Experimental setup

Figure 1 shows the schematic diagram of the TS (Yoshida, Imada, and Hagino, 2014). In this figure, T1-T8 and P1-P2 are the sensor locations for the temperature and pressure. The temperature was measured by thermocouple of K-type, whose precision was ∓0.1 ^{o}C. The TS is a closed loop of cupper pipe with 20.2 mm

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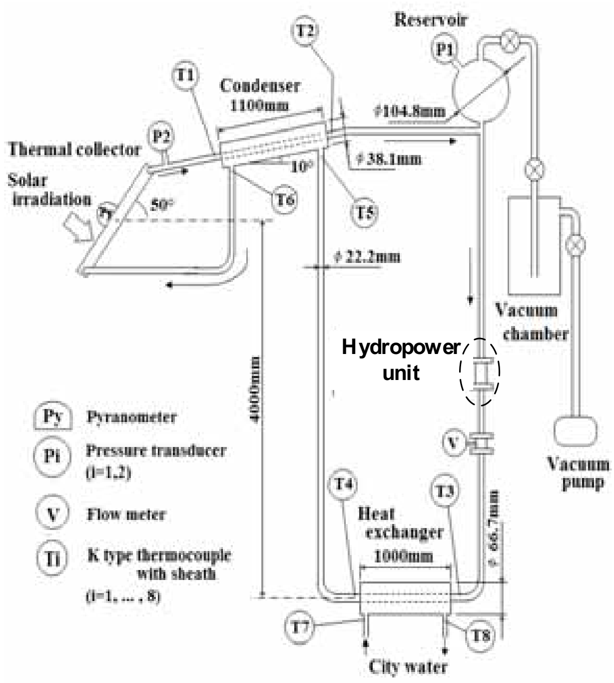

Figure 1. Schematic diagram of solar thermosyphon with hydropower unit.

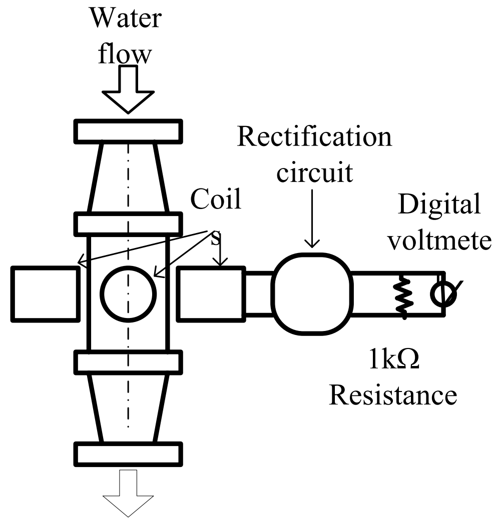

Figure 2. Hydropower unit in TS.

inner diameter. The working fluid is water. The TS loop is kept under 10 kPa to allow boiling of water at low temperatures, i.e. 60 – 70 ^{o}C. It consists of the solar thermal collector, the condenser (recuperater), the reservoir, and the heat exchanger. The thermal collector is 1.98 m tall and 0.98 m wide, i.e. 1.94 m^2. Center of the thermal collector is 4 m above the ground. When the thermal collector receives the solar irradiation, the water contained in the collector is heated and partly boils to generate steam bubbles. The buoyancy force of the steam bubbles is considered to be the driving force of the TS circulating flow. The circulating flow conveys thermal energy collected by the thermal collector to the downstairs. The condenser is set to remove the latent heat of the steam bubbles and to condense them. The condenser consists of inner and outer pipes. The hot fluid flows in the inner pipe and the cold fluid flows in outer pipe. The condenser also acts as a recuperater, which preheats the inlet flow to the thermal collector. Actually, however, the condensation process in the condenser is not always complete. There are cases in which some of the bubbles seem to flow in to the reservoir. Although the steam bubbles finally disappear in the reservoir, the excess bubbles flowing to the reservoir often disturb the base pressure in the TS. This pressure change causes boiling temperature change in the thermal collector. As a result, intermittent boiling (burst boiling) occurs and such boiling incidence results in the violent oscillation of the TS circulating flow.

In the first step, we consider a hydropower generation instead of Rankin cycle. The largest difference between the TS hydropower generation and Rankin cycle is that the former needs no compressor. The present TS power generation system is the simplest one. The hydropower generation unit is set between the reservoir and the heat exchanger. The generation unit is shown in Figure 2 (Yoshida, Imada, and Hagino, 2014). Precision of the electric volt measurement has not exactly evaluated yet due to the threshold voltage of the diodes in the rectification circuit. The true wattage must be somewhat higher than the measured values.

3. Mathematical model of TS flow

3.1. Driving Force

Since the contribution of the density change of water to the buoyancy force is negligibly small, the driving force of the TS circulation, F_b, is assumed as the buoyancy force by the steam bubbles. The driving mechanism of the TS may resemble that of the air-lift pump (JSME Handbook, 1986). The buoyancy force is given as:

$$F_{b} = gM_{h}\chi\left(\frac{\rho'}{\rho''}-1\right) \tag{1}$$

, where g, M_h, χ, ρ', and ρ'' are the acceleration of gravity, the mass contained in the thermal collector section, dryness of the fluid, density of liquid water in the thermal collector, and density of gaseous steam, respectively. The dryness is defined as the mass ratio of the steam to the density of the gas-liquid mixture. In some experiments, the χ is common but the background pressure is different. In those cases, ρ''should be modified according to the pressure to represent the buoyancy force correctly.

The dryness χ is correlated with the heat input (the solar irradiation) Q:

$$Q = m(C'\Delta T + C_l \chi) \tag{2}$$

, where m, C', C_l, and ΔT are the mass flow rate, specific heat of water, the latent heat of evaporation, and the temperature difference between the outlet and the inlet temperatures of the medium, respectively. Thus the driving force F_b is given as a function of the Q:

$$F_b = \left(\frac{gM_h}{C_l}\right)\left(\frac{\rho'}{\rho''} - 1\right)\left(\frac{Q}{m} - C'\Delta T\right) \tag{3}$$

3.2. Equation of Motion

According to the results in the laboratory experiment, the entire flow behavior of the TS is empirically supposed to be governed by the following equation:

$$M\frac{du}{dt} = F_b - Ru \tag{4}$$

, where M, u, t, and R are the total mass of water contained in the TS, the velocity, the time, and a factor of resistance, respectively. The u and R in eq.(4) are considered as the averaged values for the whole TS. In the laminar pipe flow, the flow resistance is proportional to the u (Bird, Stewart, and Lightfoot, 1960), i.e.

$$Ru \approx A\Delta p = A\left(\frac{64}{Re}\right)\left(\frac{L}{D}\right)\left(\frac{1}{2}\rho u^2\right) = 8\pi\nu L\rho u \tag{5}$$

, where A is the averaged cross section, Δp is the total pressure loss, Re is Reynolds number defined by Du/ν, L is the total pipe length, D is the averaged diameter of the pipe, ν is the kinematic viscosity, and ρ is the density of the medium. Eq.(4) can be solved analytically under the initial condition of u=0 at t=0:

$$u = u_f\left[1 - \exp\left(-\frac{R}{M}t\right)\right],\; u_f = \frac{F_b}{R} \tag{6}$$

, where u_f is the final velocity. The mass flow rate m is given as:

$$m = A\rho u \approx A\rho u_f \approx F_b \tag{7}$$

, where A and ρ are the averaged cross sectional area of the pipe and the density of the medium.

3.3 Power

Referring to eqs.(3) and (6), the power P_w of the TS is roughly estimated as

$$P_w \approx u_f F_b \propto Q \tag{8}$$

Equation (8) is not necessarily exact, but it suggests a possible trend of P_w as a function of Q i.e. P_w tends to increase as Q increases. Equations (7) and (8) and suggests

$$m \propto Q \tag{9}$$

The mathematical model was considered based on our experience in the series of laboratory experiments (Hagino and Yoshida, 2011, 2012). Verification of the model is under study.

4. Experimental results

4.1. Solar irradiation and induced flow

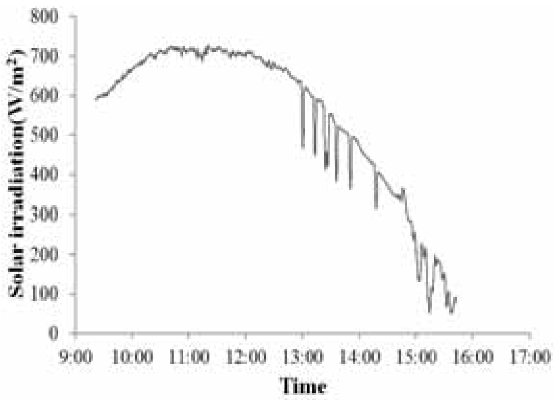

Figure 3 Solar irradiation at Nov 5, 2013.

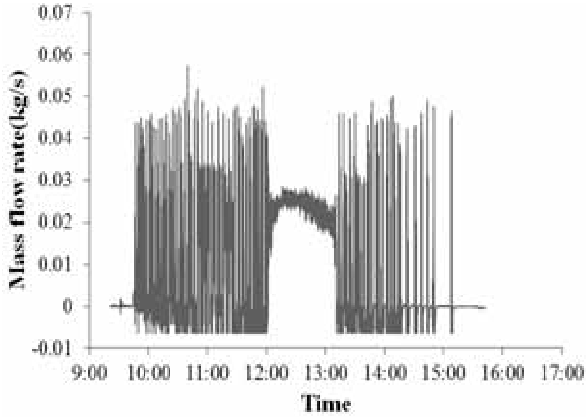

Figure 4 Mass flow rate on the same day.

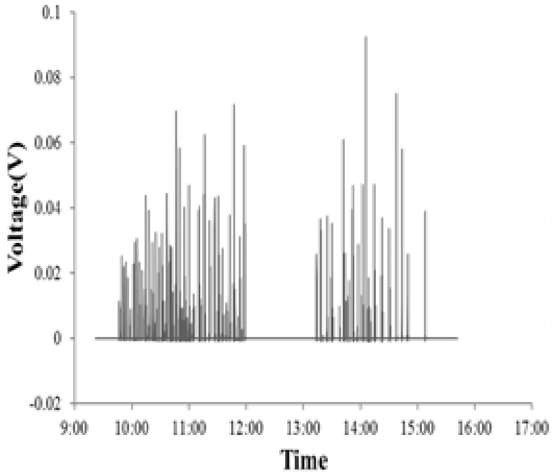

Figure 5 Output voltage on the same day.

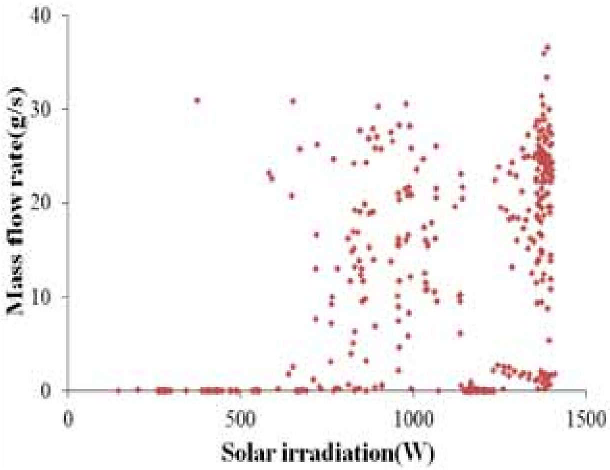

Figure 6 Mass flow rate vs solar irradiation.

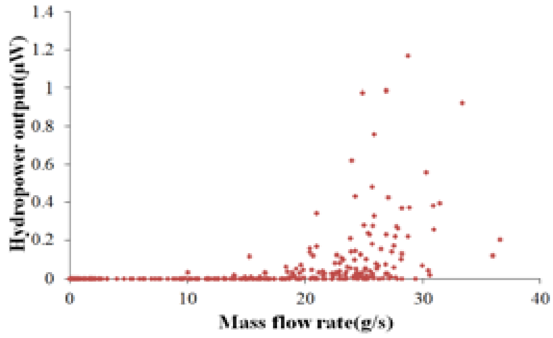

Figure 7 Hydropower output vs mass flow rate.

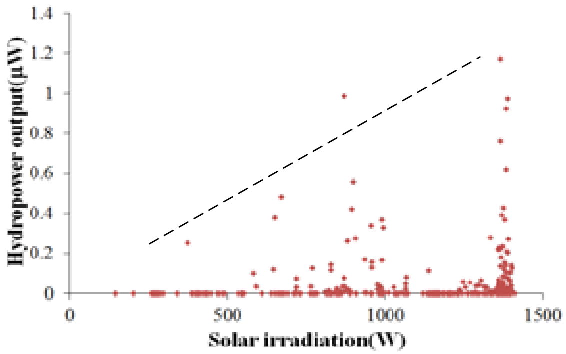

Figure 8 Hydropower output vs solar irradiation. Dotted line shows a trend of maximum power output drawn empirically.

Figure 3 shows a trace of the solar irradiation intensity on November 5, 2013. In Atsugi area Japan, the maximum irradiation intensity is not beyond 1000 W/m^2 though a year. The spikes in the afternoon are due to shades of clouds and the artificial obstacles. The corresponding mass flow rate is shown in Fig.4. Except the period of 12noon to 13:30pm, sever oscillatory flow occurs in the TS. This phenomenon of instability is considered to be due to the burst boiling at the thermal collector (Imada, Hagino, and Yoshida, 2013). The burst boiling is brought by the remarkable fluctuation of the background pressure, which is caused by the lack of condensation ability of the condenser. That is, the solar irradiation causes boiling in the collector. The steam bubbles by the boiling need to be properly condensed. Otherwise, excess bubbles increase the background pressure in the TS and the boiling temperature changes. It is understood now the proper design of the condenser and the reservoir can overcome such instability.

Figure 5 shows the voltage of the hydropower generation. The voltage output can be perceived in the period except noon and 13:30pm. In the period of noon to 13:30pm, the mass flow rate seems to be under a threshold level for the power generation. Figure 6 shows the mass flow rate as a function of the solar irradiation. The TS starts to circulate when the irradiation is over 500 W. Figure 7 shows the hydropower generation as a function of the mass flow rate. The threshold value of the power generation is above 20 – 30 g/s. Although the power output is very small at this stage of the research, this is the first attempt of the power generation using the solar thermosyphon. It should be emphasized that the temperatures of heat source and sink are 70 and 25 ^{o}C, respectively. Figure 8 shows the hydropower generation as a function of the solar irradiation. The power can be detective for the mass flow rate above 0.03kg/s.

4.2 Thermal coefficient

Carnot's coefficient of the TS is calculated as 0.13 for the temperatures of 70 ^{o}C (heat source) and 25 ^{o}C (heat sink). On the other hand, the actual coefficient is calculated as the order of 10^{-9}, extremely low. The main reasons of this are considered to be due to 1) lack of stability of the TS circulating flow, 2) losses of heat and fluid flow, and 3) improper design of impellors.

5. Conclusions

Hydropower generation using the self-circulating solar thermosyphon was first attempted for the temperature range of 25 – 70 ^{o}C, i.e. low temperature heat. At present, the thermal coefficient for the power generation is extremely low. Comparing to the Carnot's coefficient (theoretical maximum), however, there is a great margin for the further improvement of the hydropower generation by the solar thermosyphon. Reminding that the yearly averaged coefficient of the photovoltaic cell is 7 % (Chen and Riffat, 2011), we may say that the present generation system with 0.1 % coefficient, i.e. roughly 1/10 of the yearly averaged coefficient of the PV cell, still seems to be meaningful. The present research was supported by the special fund of KAIT.

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Appendix: NOMENCLATURE

Symbols	Notes	Units
A	cross section of pipe	m^2
C'	specific heat of water	$Jkg^{-1} K^{-1}$
C_l	latent heat of evaporation	Jkg^{-1}
D	inner diameter of thermosyphon pipe	m
F_b	buoyancy force by boiling bubbles	N
g	gravitational acceleration	ms^{-2}
L	total length of pipe, eq.(5)	m
m	mass flow rate	kgs^{-1}

M	total mass of water contained in thermosyphon	kg
M_h	mass of water contained in heating section	kg
Q	heat input at heating section	Js^{-1}
P_w	power generated by thermosyphon	Js^{-1}
R	coefficient of flow resistance, eqs.(4), (5), (6)	Nms^{-1}
Re	Reynolds number, $uD\nu^{-1}$	non-dimensional
ΔT	difference between outlet and inlet temperatures of heating section	K
t	time, eqs.(4), (6)	s
u	flow velocity	ms^{-1}
u_f	final velocity defined by eq.(6)	ms^{-1}
χ	dryness in heating section	non-dimensional
ρ, ρ', ρ''	density, $'$ and $''$ indicate densities of water and steam, respectively	kgm^{-3}