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Automatic Thermal Water Pump with Water Vapor

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Abstract

The aim of this research was to study the electrical power input of an automatic thermal water pump (ATWP) with water vapor. The ATWP comprised three main parts: heater tank, liquid piston tank and storage tank. The working principle consisted of heating stage, pumping and vapor flow stage, cooling stage and water suction stage. The pump used liquid piston to pump water. The power input varied at 1500 W, 2000 W, 2500 W and 3000 W for 2 hours per test. The suction height was set at 2 m. The discharge height was set at 1 m. The total pumping water head was set at 3 m with temperature in heater tank of 103^{o}C and cooling water of 0.3 l. From the experiments, in the heating stage, it was found that initial cycle takes a longer time because heat was input until the specified temperature was reached. Consequently, the next cycle would gain a shorter operating time, because of the heat re-input to a working fluid (water) at high temperature. At 3000 W, we got 227 l stored hot water, 14.12 MJ stored energy, 81.71% thermal efficiency and 0.03866% pump efficiency superior to the results at other electrical power. In conclusion, adding more electrical power to the system will get more hot water but it requires more energy too.

Keywords: Electrical Power/Pump Pfficiency/Thermal Water Pump

1. Introduction

Thirty-four years ago, Pytlinski [1] gave reviews of the historical developments of the use of solar energy installations for pumping irrigation water. Wong and Sumathy [2] had concluded that ethyl ether was the best choice in terms of efficiency and economics. Jenness, Jr. [3] showed some considerations relative to a solar power water pump using Savery's technique. Roonprasang et al. [4] developed the solar water heater (SWH) integrated with a new solar water pump. Their system consisted of 1.58 m^2 flat plate solar collector (SC). The pump was workable when solar energy input was equal to or greater than 580, 600 and 630

W/m^2 for discharge heads of 1, 1.5 and 2 m. The mean water temperature in the SC was about 75-78 ^{o}C. The mean pump efficiency was about 0.0014-0.0019%. Sumathy [5] did an experiment on a solar thermal water pump, which comprised a one m^2 solar collector (SC), had overall efficiency of 0.12-0.14% for 6-10 m discharge heads and performed 12-23 cycles a day. The water mass of 15 kg was lifted for each cycle.

Liengjindathaworn et al. [8] presented the experimental and theoretical studies of a pulsating-steam water pump. The pumping system used an electric heater as an energy source to produce a working water vapor at low temperature (90-120^{o}C). The experimental pump efficiency was around 0.005-0.03% for the pumped water of 1-8 l/cycle and suction heads of 1-2.5 m. However, the system was manually operated. Cooling time was still long.

Picken et al. developed [9] a water piston solar powered steam pump, which had efficiency in the order of 0.05% for the pumped water of 10-20 l/h. The failure was attributed to the late start of condensation at the end of the pumping stroke. An automatic blow-down valve could work out this problem. The remaining difficulty was inefficient condensation due to lack of cool water to mix with a hot vapor.

A new design of automatic thermal water pump (ATWP) with water vapor was shown in Fig. 1. It has a liquid piston tank (LT) higher than a heating tank (HT). Heat input to a heater had varied. In this research, the parameters affecting the system performance had been investigated. Cooling time was adjusted to decrease. The mathematical model at each stage was also developed.

2. The Experimental setup

An ATWP consists of various parts as shown in Fig. 1.

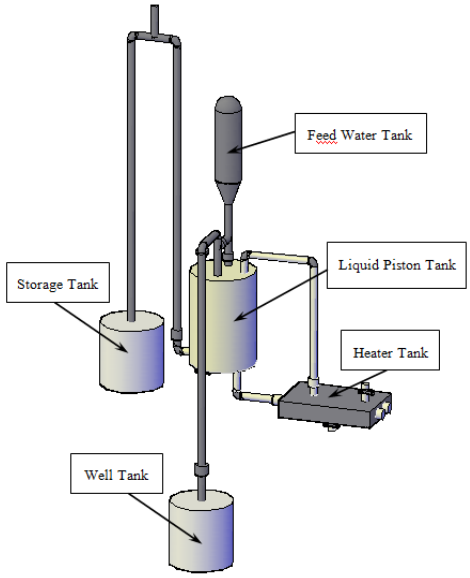


Fig.1. A schematic diagram of ATWP.

1. A feed water tank (FT) was a cylinder tank of 40 cm height and 30 cm diameter with air vent above and no insulation. It had a control valve (CV) to supply 300 cc water at 30 ^{o}C to liquid piston tank (LT).

2. The Liquid piston tank (LT) was a cylinder tank of 30 cm height and 20 cm dia. made from 2 mm stainless, with insulation. It could pump water to the storage tank (ST) by vapor from the water heating tank (HT).

3. An heater tank (HT) of 20×30×5 cm made from 2 mm stainless, aero flex insulation (0.040 W/mK thermal conductivity). It was closed and contained 3 l water. It had 3000 W heater installed inside to produce vapor at 103 ^{o}C to supply the LT. It was lower than the LT to ensure that it is always full of water for safety.

4.The storage tank (ST) was a cylinder tank of 110 cm height and 50 cm dia, without insulation. It was open to the air outside and used to store water from the LT.

5. Well tank (WT) was a well that stored water to be pumped.

6. A one-way valve (CV) was used to control direction of fluid flow.

The pumped water flowed by vapor pressure from the LT to the ST where the water was stored. The experiment was tested for electrical power input of ATWP at 1500 W, 2000 W, 2500 W and 3000 W for 2 hours per test with the suction height of 2 m, the discharge height of 1 m and the total pumping water head of 3 m, at School of Energy Environment and Materials, King Mongkut's University of Technology Thonburi.

A pressure transducer (Cole Parmer) measured the vapor gage pressure with accuracy of ± 0.25 %. Nine sets of K-type thermocouples connected with a hybrid recorder (Yokogawa) were used to measure temperatures of surrounding air, water, and vapor at the FT, HT, LT and ST with accuracy of ± 0.5 ^{o}C. Kilowatt-hour meter with accuracy ± 2.5 %. measured energy input.

3. System operation

An operation of the ATWP involves mainly five stages as shown in Fig.2 and as follows.

Heating stage: Fig.2a, During this stage, water in the HT is heated by a heater. The produced vapor flows to the LT. The heating stage continues until the pressure in the LT is high enough to move water from the LT to the ST.

Pumping stage: Fig.2b, when the vapor pressure head in the LT is slightly more than the discharge head of the system, the LT water then is lifted upward through the connecting pipe to the air vent outlet (AV) by a pressure and to the ST by a gravitational force.

Vapor flow stage: After that (Fig.2c), the LT vapor can flow to surrounding air at the AV due to buoyancy force. Vapor from the LT continues flowing to the AV until the LT pressure balances with the surrounding.

Cooling stage: Fig.2d, then the water head at the FT is greater than the head loss across the CV so that it is open automatically, the 300-cc water at 30^{o}C from the FT moves down to the LT by a gravitational force.

Suction stage: The CV then closes temporarily due the blockage by a floating ball within the FT (Fig.2e). The cool water mixing with hot LT vapor provides suction. The WT water is then suctioned to the LT until the latter is full. One cycle of the operation of self-pumping is completed and the system is now ready for the next cycle.

4. System analysis

Mean pump efficiency is defined as a ratio of total hydraulic work done by ATWP to total electric energy input to the pump during a 2-h period [6]:

$$\eta_p = \frac{NW_h}{E_{tot}} \times 100, \qquad (1)$$

E_{tot} is the total electrical energy input to the ATWP, N the total number of the pumping cycles and h the discharge head of the pump. W_h is the required pump hydraulic work per cycle as expressed by

$$W_h = V_c \rho_w g h \qquad (2)$$

Where V_c is the pumped water volume per cycle, ρ_w the water density, g the acceleration of gravity, h the total head of the system

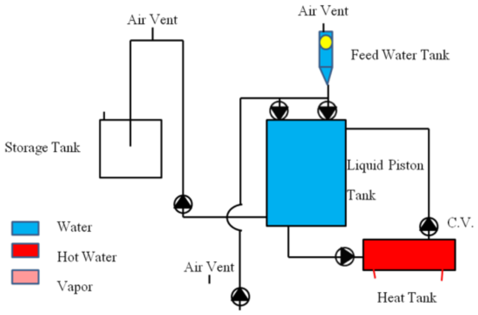
The overall thermal efficiency of the ATWP, η_t is a ratio of total stored thermal energy in the ST to total electric energy input to the HT during a 2-h period:

$$\eta_t = \frac{Q_{storage}}{E_{tot}} \times 100, \qquad (3)$$

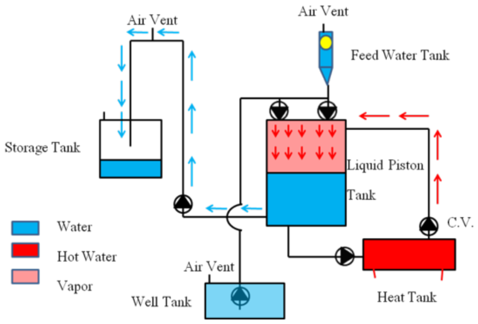
Total stored thermal energy in the ST was expressed as follows :

$$Q_{Storage} = \int Q_S dt = m_{w,s} \cdot c_{p,w} \cdot \Delta T_S, \quad (4)$$

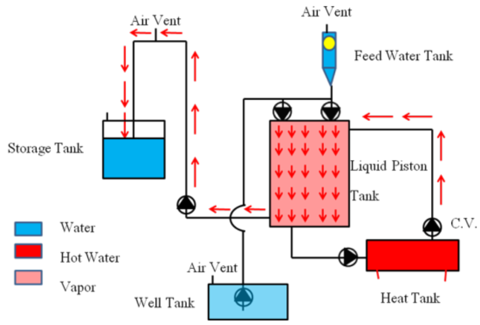
where Q_s is the heat stored by water in the ST, dt the time period, $m_{w,s}$ the mass of water in the ST, $C_{p,w}$ the water specific heat and ΔT_s is the rise in water temperature in the ST.



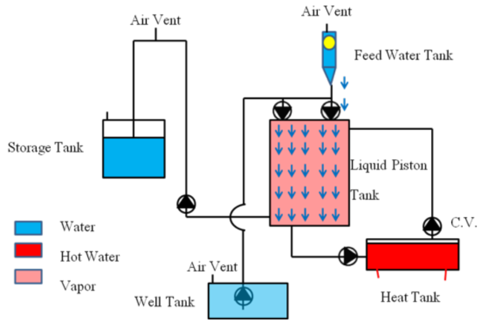
(a) Heating stage



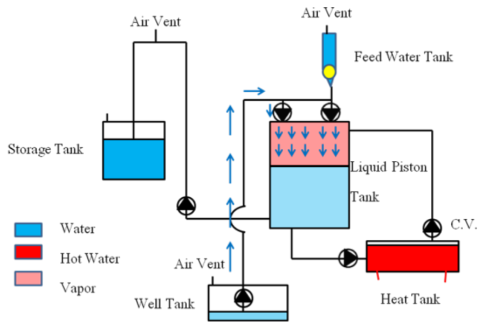
(b) Pumping stage



(c) Vapor flow stage



(d) Cooling stage



(e) Suction stage

Fig.2. The operation of the ATWP.

HEATING STAGE

For heating of HT water, lumped model is used [6-7]:

$$Q = m_w c_{pw} \frac{dT_h}{dt} + \text{loss} \qquad (5)$$

Where Q is energy rate from the heater, m_w the HT water and vapor masses, c_{pw} the specific heat, and T_h the HT temperature. The corresponding pressure in the HT is calculated from a perfect gas law:

$$PV = mRT \qquad (6)$$

P is pressure, V the room occupied by gas, m the gas mass, R the gas constant, and T the temperature. Vapor pressure is dependent on only temperature.

The temperature that provides sufficient pressure to pump the water is around 103°C.

FLUID FLOW STAGE

The fluid flows to the discharge tube according to the Bernoulli's equation [6-7]:

$$\frac{P_h}{\gamma} = h + (1+k_d)\frac{v_d^2}{2g} \qquad (7)$$

where P_h is the LT gage pressure, γ the specific weight, v_d the discharge fluid velocity, and k_d the loss coefficient for discharge (0.5). It is assumed that fluid velocity within the LT is zero and is the same along the discharge tube. The vapor mainly flows out at the AV due to buoyancy force.

The critical pressure that water is about to flow is as follows:

$$P_h = \gamma h, \quad h = 1 \text{ m} \qquad (8)$$

Where h is a discharge head. In all cases, discharge head varies between 1m and less.

WATER SUCTION STAGE

This stage occurs when LT vapor of 9.5 l at 103 °C mixes with FT water of 300cc at 30°C. This similar stage was previously found in [4, 6-7]. All vapor condenses and becomes 0.003 l water. The LT pressure drops to around 80-90 kPa vacuum. Water from well then is suctioned to fill the LT space until it nears one atmosphere. Some remaining water temperature decreases. Some water at mixing temperature vaporizes. Energy balance in the LT is then as follows:

Energy decrease in 103°C vapor that condenses + energy decrease in LT hot water = Energy increase in 30°C water + latent heat of water that vaporizes at mixing temperature(T_x)

$$m_v (hg_{103} - hf_{Tx}) + (m_w c_{pw} + m_a c_{pa})(103 - Tx) = m_f (hf_{Tx} - hf_{30}) + m_e\, hfg_{Tx} \qquad (9)$$

when m_v is vapor mass at 103 °C, m_w the remaining LT water mass at 103 °C, m_f the 300cc water mass at 30 °C, hg the vapor enthalpy, h_f the water enthalpy, hfg the latent heat of vaporization, m_e the water mass that vaporize at Tx, and Tx the mixing temperature. The suction head is constant at 2m.

5. Results and discussion

It was found that the pump could circulate max 9.5 l water for each cycle. The cycle period was about 4-12 min. The 300 cc FT water flowed to the LT before the suction started.

Considering Fig.3-6, HT temperature increased according to eq.(5). Mean LT temperature increased while LT water decreased at constant heat input. Both temperatures decreased during the suction time.

Consequently, the HT and LT pressures changed according to eq.(6). In Fig.3-6, for the power inputs 1500, 2000, 2500 and 3000 W, total pumped waters were 80, 120, 197 and 227 l. Vapor energy loss to the atmosphere were 0.00336, 0.0072, 0.0092 and 0.0138 kg respectively, net pumped waters were 10, 7.5, 7.9 and 8.1 l per cycle, respectively.

In Fig.6, the cooling time of the condenser in this study was very rapidly. It had no heat exchanger in the condenser. The cool working fluid could mix with the hot working one by a direct contact. At 3000 W, we got 0.03866% pump efficiency superior to the results at other electrical power. In Fig.7, mean pump efficiency increases with power input.

5.1 The effect of the electrical power input on the number of the pumping cycles

It can be seen that as the electrical power input increases, the number of the pumping cycles increases (Fig.3-6). Numbers of pumping cycles were 8, 16, 25 and 28 for the power inputs 1500, 2000, 2500 and 3000 W respectively.

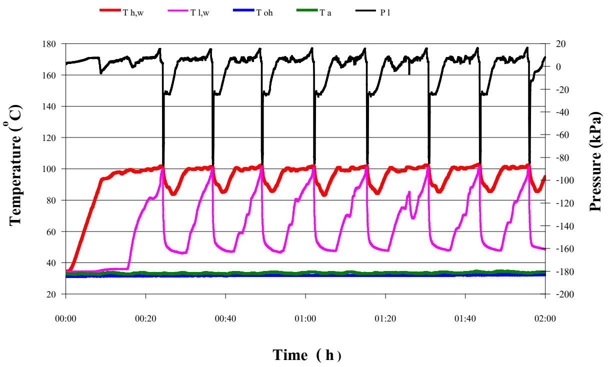


Fig.3. Temperature and pressure at 1500 W

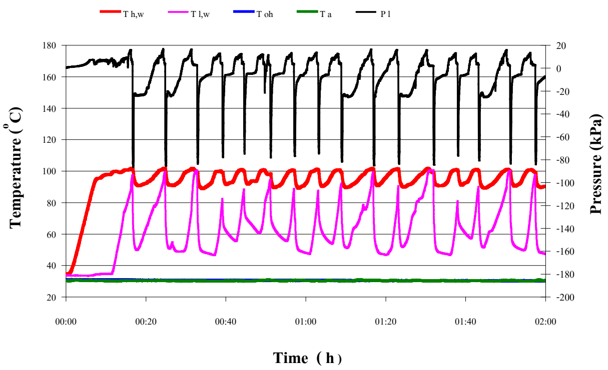


Fig.4. Temperature and pressure at 2000 W

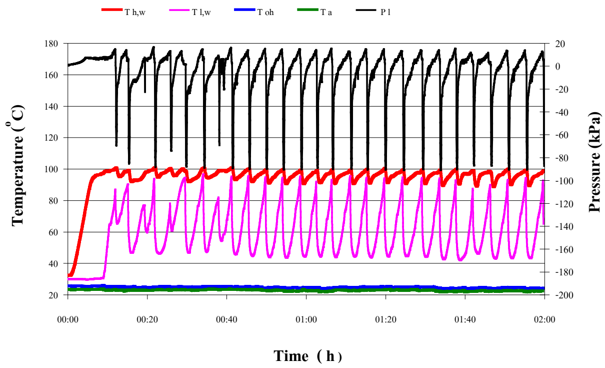


Fig.5. Temperature and pressure at 2500 W

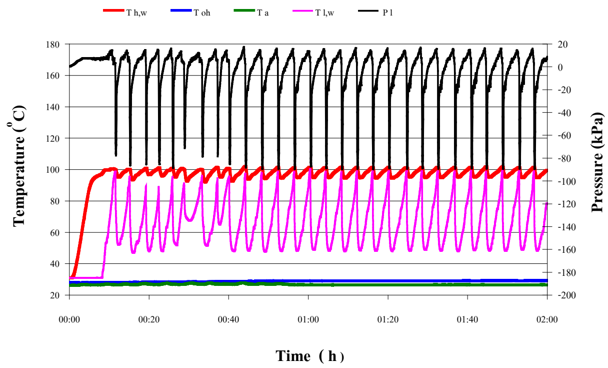


Fig.6. Temperature and pressure at 3000 W

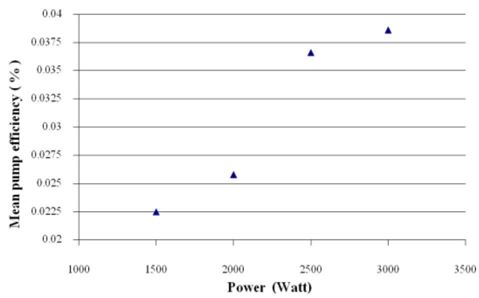


Fig.7. Mean Pump efficiency as a function of power

6. Conclusions

A new simple design of ATWP has been developed. The LT volume was increased. And appropriate heat inputs are investigated. The cooling stage was improved due to a direct mixing of cool water and a steam in the LT. The pumped water increased when the electrical power input increased. At 3000 W, we got 227 l stored hot water, 14.12 MJ stored energy, 81.71% thermal efficiency and 0.03866% pump efficiency superior to the results at other electrical power. Only 2 h operating time is selected in order to keep the control valve long life.

Recommendation

Usually, efficiency of the pump (heat engine) increases with temperature as found in a steam power plant according to the Carnot efficiency. Reduction of all losses will further increase efficiency. We also plan to construct a larger thermal water pump that can have 500l capacity or more. Other usage of the pump in solar application now is being studied by our colleagues.

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Nomenclature

C_{pw}	water specific heat (kJ/kg.^{o}C)
g	acceleration of gravity (9.806 m/s^2)
h	overall head (m)
hf	water enthalpy (kJ/kg)
E_{tot}	heat input (kJ)
k_d	loss coefficient for discharge (dimensionless)
m_e	mass of water in the LT at the mixing temperature (kg)
m_f	mass of water in the FT (kg)
m_v	vapor mass (kg)
m_w	mass of water in the HT (kg)
$m_{w,s}$	mass of water in the ST (kg)
N	total number of pumping cycle
Q_s	heat stored in the ST (kJ)
Pl	fluid gage pressure in the LT (kPa)
t	time (s)
T_a	ambient temperature (^{o}C)
T_h	mean water temperature in the HT (^{o}C)
$T_{h,w}$	water temperature in the HT (^{o}C)
$T_{l,w}$	water temperature in the FT (^{o}C)
T_{oh}	water temperature in the FT (^{o}C)
T_s	water temperature in the ST (^{o}C)
Tx	mixing temperature (^{o}C)
V_C	volume of pumped water per cycle (m^3)
v_d	discharge fluid velocity (m/s)
W_h	required hydraulic work per cycle (kJ)
γ	specific weight (N/ m^3)
ρ_w	water density (kg /m^3)
η_p	pump efficiency (%)
η_t	thermal efficiency (%)

Acronyms

CV	one-way valve
HT	heat tank
LT	liquid piston tank
FT	feed tank
ST	storage tank
ATWP	automatic thermal water pump
WT	well tank

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