Efficient Type of Steam Condenser for Water Desalination of Solar Thermal Energy in Remote Arid Areas and Islands

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***Abstract*-** **Comparison of material usage and cost of two types of cross-flow steam condensers is reported in this study which can be used for water desalination in conjunction with a parabolic trough solar energy concentrator plant. Traditional shell and tube condensers (where steam flows inside the tubes) and surface condensers (where steam flows in the shell and cooling water flows in the tubes) are considered in this study. It has been found that the energy production from the PTC of dimensions 4.5 m × 4.8 m with an aperture area of 21.6 m^2 was 19.4 kW. It has been calculated that the distilled water production capacity of the solar energy harnessing system per day is 55.6 l, assuming solar irradiance to be 0.9 kW m^{-2} and the efficiency of solar energy harnessing system as 50% if the sun is available for four hours. The cooling water input temperature was assumed to be 30 ℃. The minimum length required for a SS 304 tube of Ø 9.5 mm was 7.16 m for the traditional condenser and 1.30 m for the surface condenser. The efficiency of the traditional condenser reduced due to the formation of a condensed water layer on the surface of the tube, as it acts as a thermal barrier. However, in the surface condenser, efficiency was enhanced due to easy condensation while increasing the system pressure. Further, efficiency is enhanced due to density separation of wet vapour by changing the flow direction near the wet sump. Fabrication cost and maintenance cost are also found to be less in the surface condenser. As such, it can be concluded that use of surface condenser is the most cost effective method, which uses a smaller amount of material making the condenser smaller and lighter.**

Keywords- Heat exchanger; Parabolic trough concentrator; Steam condenser; Steam condensing methods; Surface condensation; Water desalination

MNEMONICS

- $\dot{Q}$ – Heat transfer rate, kW
- $\dot{m}$ Production rate, kg/s^{-1}
- C_p – Specific heat capacity of water, kJ/kg K
- T – Temperature, K
- L – Latent heat water vaporization, kJ/kg
- h_α – Surface heat transfer coefficient, W/m^2 K
- l – Length of pipe, m
- d – Diameter of pipe, m
- Re_τ – Shearing Reynolds number
- V – Velocity, m/s
- ρ – Density, kg/m^3
- μ – Viscosity, Pa s
- g – Acceleration of gravity, m/s^2
- λ – Thermal conductivity, W/ m K
- x – Wall thickness, m
- A_m – Mean area, m^2

SUPERSCRIPTS

- 1 – Condensation component
- 2 – Evaporation component
- s – Steam component
- w – Liquid component
- l – Characteristic length is diameter
- i – Inlet condition
- e – Exit condition

SUBSCRIPT

- + – Dimensionless symbol

I. INTRODUCTION

With an increase of the population and development of economies, freshwater shortage has become a serious problem in the world. The UN water recourses committee is alarmed that the freshwater shortage is going to be a profound social crisis after the oil crisis in the world [1]. Seawater desalination is one of the possible approaches to solve the problem of lack of fresh water. Desalination might be a more practical way for seawater utilization, because it not only reduces the consumption of freshwater, but also generates more freshwater for dry regions. The main seawater desalination methods used are reverse

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osmosis and multi-effect distillation [1]. At present, the distillation and membrane methods are the two main seawater desalination processes. The distillation methods are multi-stage flash, multi-effect distillation, vapour compression and the membrane methods, reverse osmosis and electro dialysis. Among these methods, multi-stage flash, multi-effect distillation, vapour compression and the reverse osmosis are the more commonly used [2]. In addition, seawater desalination technologies include freezing, solar energy, and others [3]. The type of driving energy used determines the type of desalination process that can be used. For example, if there is residual thermal energy available, the distillation process can be installed. The reverse osmosis method is more suitable with lower electricity price [4].

Aside from hydroelectric energy, the other principal resources (solar, wind, geothermal) cover together little more than 1% of the energy production worldwide [5]. Owing to the diffuse nature of solar energy, the main problems with the use of solar thermal energy in large-scale desalination plants are its relatively low productivity rate, low thermal efficiency and considerable land area required. However, since solar desalination plants are characterized by free energy and insignificant operation cost, this technology is suitable for small-scale production, especially in remote arid areas and islands, where the supply of conventional energy is scarce [6].

The data on solar radiation and its components at a given location are essential for studies of solar energy. In other words, reasonably accurate knowledge of the availability of solar resources at a given place is required. The average values for the hourly, daily and monthly global irradiation are needed for many applications of solar energy designs [7, 8]. Solar energy, along with other renewable energy resources, does not deplete in source, but is reliable and environment-friendly. Grid-connected solar PV continues to be the fastest growing power generation technology, with a 70- percent increase in existing world capacity to 13 GW in 2008. Including off-grid applications, total PV existing worldwide in 2008 increased to more than 16 GW [9].

Solar thermal energy is rarely used in large scale water desalination plants since it requires a considerably large land area. However, free availability and insignificant operation cost make solar thermal power based desalination plants more suitable for small-scale industries especially in remote arid areas and islands where there is no conventional energy supply [10]. Since it is suspected that one reason for spreading chronic kidney disease in the north-central province of Sri Lanka is heavy metal content in drinking water, solar energy based desalination plants are an ideal alternative for purifying the water taken from lakes.

Among solar thermal technologies, solar ponds and parabolic troughs are the most frequently used for desalination [11]. Considering the following two main solar thermal energy harnessing technologies, solar ponds and parabolic troughs, parabolic troughs are more effective for water desalination [12]. Linear parabolic trough concentrators focus direct solar radiation on a receiver tube. When those plants are used for steam generation, the receiver tube itself can be used as the boiler for generating steam. When steam pressure increases in the boiler, steam can be transferred to the condenser automatically. The efficiency of this type of plant depends mainly on the performance of the solar energy harnessing system, energy transmission system and condenser [13]. This paper compares the efficiency of two types of cross-flow condensers (by interchanging the carriers of heat transferring fluids: steam and cooling water) by considering material availability (standard sizes), material cost and construction & maintenance easiness. The process block diagram for generation of steam and condensing is given in Figure 1.

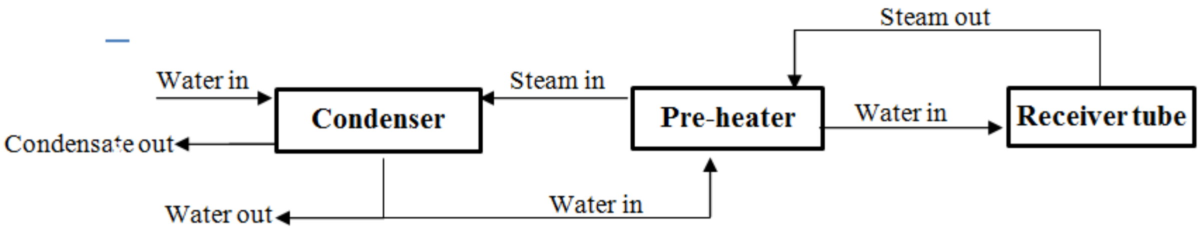

Fig. 1 Process block diagram for generation of steam and condensing

In this research, the use of cross-flow steam condensers for water desalination in conjunction with a parabolic trough concentrator was studied. Further, five different tube diameters were tested.

II. METHODOLOGY

The thermal energy harnessing capability of the parabolic trough concentrator was calculated using standard models at 9.12 kW for a parabolic trough solar concentrator of aperture area 21.6 m^2 having 50% thermal energy harnessing capability. Assuming that the inlet water temperature is 40 ℃ (pre-heated), the steam production rate $\dot{m}_s$ can be calculated as 3.63 g s^{-1}. Hence, distilled water production from the plant per day is 55.6 l, assuming the solar harnessing system can be operated only for 4 hours per day. Assuming that cooling water input and output temperatures are 30 ℃ and 32 ℃ respectively, it is required to maintain a flow rate ($\dot{m}_w$) of 927 g s^{-1}.

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A. Condenser Type 1 (Traditional Method)

In this type, steam flows though the tube and cooling water flows through the shell. Then, the surface convection dimensionless heat transfer coefficient inside the tube $h^{+}_{(\alpha)_1}$ can be calculated using the following equation proposed by reference [14].

$$h^{+}_{(\alpha)_1} = \beta_1 \left(\frac{l}{d}\right)^{n_3} . (Re_\tau)^{n_4} \tag{1}$$

where shearing Reynolds number (Re_τ)can be calculated by using equation 2 and the experimental values of β_1, n_3, n_4 are 0.3582, -0.1929, 0.0643 respectively [14].

$$Re_\tau = \frac{d. V_s.\ \rho_{1w}}{\mu_{1L}} \tag{2}$$

where V_s is tail velocity.

The surface convection heat transfer coefficient inside the tube $h_{\alpha i}$ can be calculated using equation 3 [14].

$$h^{+}_{(\alpha)_1} = \frac{h_{\alpha i}}{\left\{\frac{g(\rho_{1w}-\rho_{1s}).\lambda^3\left[L+\frac{3}{8}C_{p1L}\,(t_1-t_w)\right]}{\mu_{1L}.d.(t_1-t_w)}\right\}^{1/4}} \tag{3}$$

Convection heat transfer coefficient outside the tube $h_{\alpha 0}$, can be calculated using equation 4 [15].

$$\overline{Nu_D} = \frac{h_{\alpha 0} d}{\lambda} \tag{4}$$

The local Nusselt number $\overline{Nu_D}$ can be calculated using equation 5 [14].

$$\overline{Nu_D} = C Re_l^m Pr^{1/3} \tag{5}$$

where the Reynolds number Re_l can be calculated using equation 6 and constants C and m can be selected from the engineering design tables in reference [15] by considering the tube shape and Reynolds number. The Prandtl number (Pr), can be selected according to the fluid properties [16].

$$Re_l = \frac{(d. V_w. \rho_w\ )}{\mu_w} \tag{6}$$

Then the overall heat transfer coefficient U can be calculated as follows [17],

$$\frac{1}{U} = \frac{1}{h_{\alpha 0}} + \frac{x}{\lambda} + \frac{1}{h_{\alpha i}} \tag{7}$$

The required minimum length of a tube l to complete the desalination process can be calculated using equation 8 [17, 18].

$$\dot{Q} = U \pi d l (t_s - t_w) \tag{8}$$

B. Condenser Type 2 (Surface Condenser Method)

In this type, cooling water flows though the tube and steam flows through the shell. Then, the surface convection heat transfer coefficient inside the tube $h_{\alpha i}$ can be calculated using following equation proposed by reference [19].

$$\dot{Q} = h_{\alpha i} A_m \Delta T_{ln} \tag{9}$$

where ΔT_{ln} is logarithmic mean temperature difference which can be calculated by equation 10 given bellow [19].

$$\Delta T_{ln} = \frac{\Delta T_e - \Delta T_i}{ln(\Delta T_e | \Delta T_i)} \tag{10}$$

The temperature differences between fluid and the surface at the inlet and exit can be found as follows [19].

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$$\Delta T_i = T_a - T_i \quad (11)$$

$$\Delta T_e = T_a - T_e \quad (12)$$

where, T_a is surface temperature and assumed to be 60 ℃.

The exit temperature of cooling water (T_e) can be determined using equation 13.

$$\dot{Q} = \dot{m}_w C_p (T_e - T_i) \quad (13)$$

The tube outside convection heat transfer coefficient $(h_{\alpha 0})$ can be calculated at horizontal position by using equation 14.

$$h_{\alpha 0} = 0.729 \left[\frac{g\rho_w(\rho_w - \rho_s)h_{fg}^* \lambda_w^3}{\mu_w(T_s - T_a)d}\right]^{1/4} \quad (14)$$

The modified latent heat of vaporization h_{fg}^*, can be calculated using equation 15.

$$h_{fg}^* = h_{fg} + 0.68\, C_{pw}(T_s - T_a) \quad (15)$$

Then as in the previous method calculations (Condenser Type 1), the overall heat transfer coefficient U can be calculated as follows, [17]

$$\frac{1}{U} = \frac{1}{h_{\alpha 0}} + \frac{x}{\lambda} + \frac{1}{h_{\alpha i}} \quad (16)$$

The required minimum length of a tube l to complete the desalination process can be calculated using equation 17 [17].

$$\dot{Q} = U\pi dl(t_s - t_w) \quad (17)$$

III. Results and Discussion

The models (equation 8 and 17) were evaluated using MATLAB, a mathematical software application, for five different tube diameters, and the results are given in Table 1.

TABLE 1 PIPE LENGTH AND COST REQUIREMENT FOR TYPE 1 (TRADITIONAL CONDENSING METHOD) AND TYPE 2 (SURFACE CONDENSING METHOD)

Tube Diameter (mm)	Tube Thickness (mm)	Required Length (m)		Cost (LKR) 1 US$ = 136 LKR	
		Type 1	Type 2	Type 1	Type 2
9.5 (3/8 inch)	1.0	7.16	1.30	8234.00	1495.00
12.5 (1/2 inch)	1.2	6.21	1.10	9936.00	1760.00
15.9 (5/8 inch)	1.2	5.45	0.90	11445.00	1890.00
19.0 (3/4 inch)	1.2	5.02	0.75	12299.00	1837.50
25.4 (1 inch)	1.2	4.47	0.58	14304.00	1856.00

The pipe length and cost comparison are shown on Figure 2 and 3 with respect to the condensing method.

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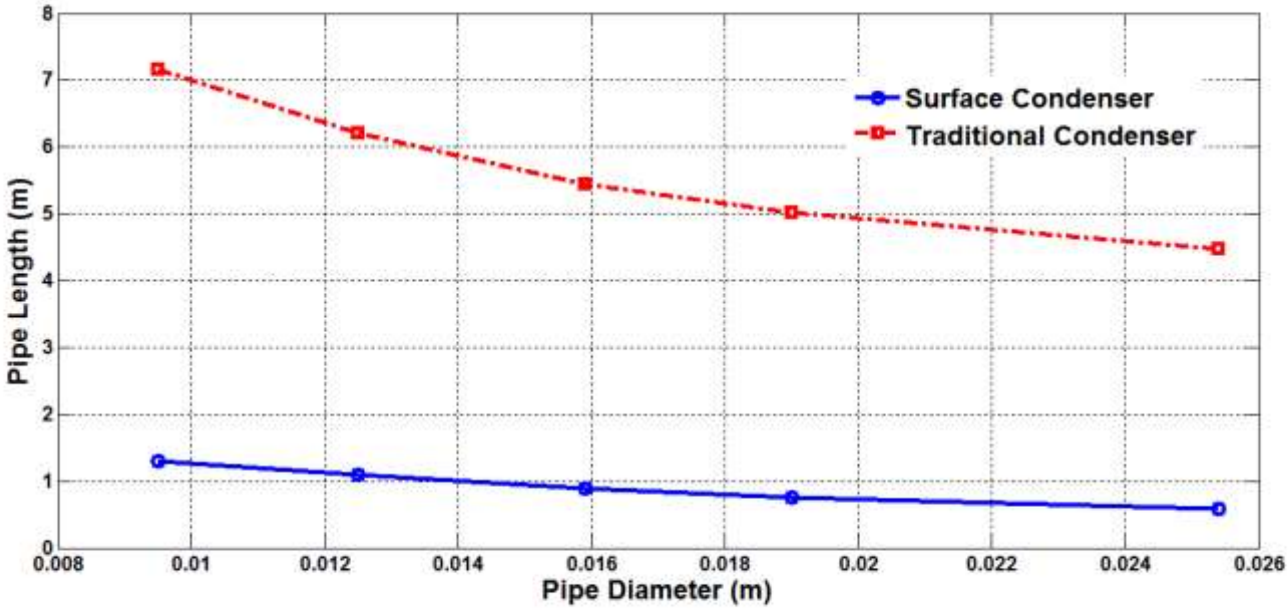

Fig. 2 Pipe length comparison for surface and traditional condensing methods

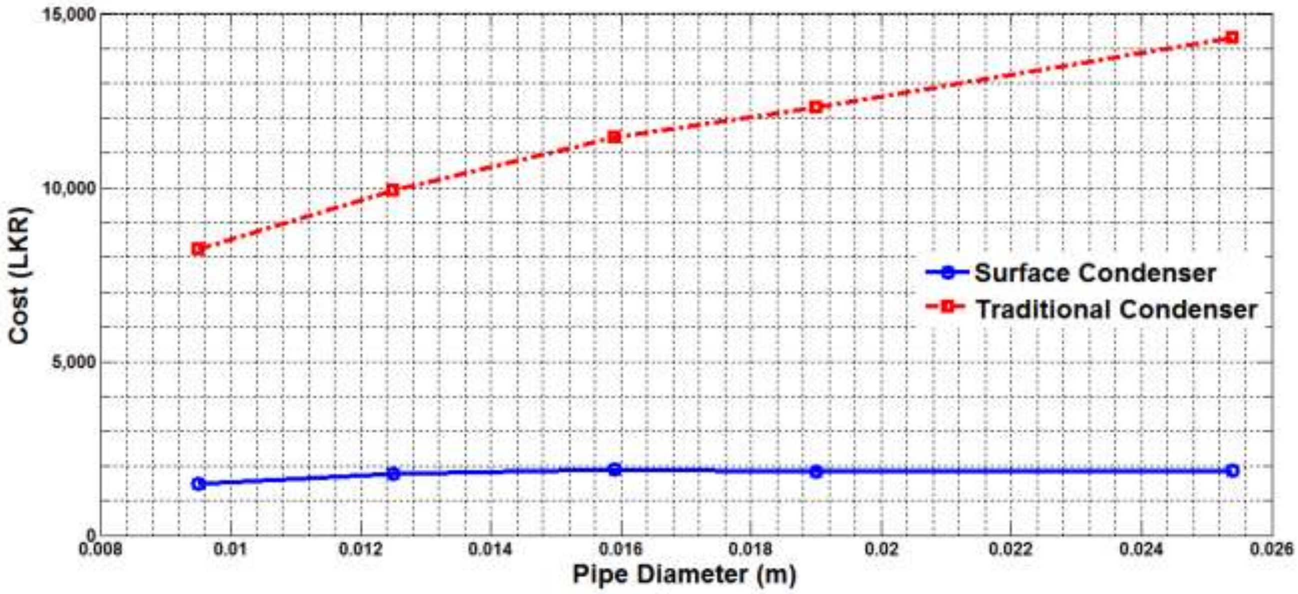

Fig. 3 Pipe cost comparison for surface and traditional condensing methods

According to the Figure 2, the required pipe length is always shorter in the surface condenser compared to the traditional one. Hence, the cost is always higher in Figure 3 for the traditional one. It can be clearly seen that in Figure 3, in the surface condensing condenser, when the tube diameter is 15.9 mm (5/8 inch) there is a maximum cost, and then it decreases. Use of tubes of diameter 9.5 mm (3/8 inch) is the cheapest, and for the water desalination application use of tubes of smaller diameter does not affect the maintenance or construction. As such, it can be concluded that use of tubes of 9.5 mm in surface condensation mode is the most cost effective method, which uses a smaller amount of material, making the condenser smaller and lighter.

IV. CONCLUSIONS

Traditional shell and tube condensers as well as surface condensers are considered in this study, and it appears to be appropriate to use them in small-scale solar thermal powered desalination plants, especially in remote arid areas and islands. The comparison of material usage and cost of two types of cross-flow steam condensers that can be used for water desalination in conjunction with a parabolic trough solar energy concentrator type plant (PTC) were studied. The efficiency of the traditional condenser is reduced due to the formation of a condensed water layer on the surface of the tube, as it acts as a thermal barrier, but in the surface condenser, efficiency is enhanced due to easy condensation while increasing the system pressure and density separation of wet vapour by changing the flow direction near the wet sump. Fabrication cost and

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maintenance cost are also found to be less in the surface condenser. As such, it can be concluded that use of surface condensers is the most cost effective method, which uses a smaller amount of material, making the condenser smaller and lighter.

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