Theoretical Modelling of a Dynamic Solar Thermal Desalination Unit with a Fluid Piston Engine

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Abstract: Results of theoretical simulations of the steady-state operation of the dynamic solar thermal desalination unit with a fluid piston are presented in this paper. A laboratory prototype of a dynamic thermal water distillation unit was developed and it was built around an engine with fluid pistons. In the calculation scheme, the internal circuit of the desalination unit was split into several control volumes, namely the evaporator, the condenser and the cylinder. The lumped parameter mathematical model was derived based on the differential energy and mass conservation equations written for each of the control volumes and describing heat and mass transfer processes taking place during water evaporation and condensation under the cyclic variation of the pressure and temperature inside the system when the engine operates. The solution of the set of governing equations produces information on the variation of temperatures and pressure inside the system over the thermodynamic cycle and on the water desalination capacity of the unit.

Keywords: Solar water desalination, mathematical modelling

1. Introduction

The shortage in clean drinkable water supply has become one of the most important problems due to the continued growth in the world's population. Kalogirou [1] states that the fresh water represents only about 3% of all water on the earth. Approximately 0.25% of fresh water can be directly used from lakes and rivers and the rest is in the ice form or deep ground water which is difficult to reach. As a result, novel drinkable water production technologies are being continuously developed to resolve this important problem.

Desalination techniques are among feasible solutions to produce fresh water from saline water but such technologies require significant amount of energy. Using fossil fuels for water desalination results in high plant running costs and causes a considerable negative environmental impact. As a consequence, numerous studies are being performed on utilisation of an alternative energy source, namely renewable energy, for running desalination plants. The aim of the above research studies is to make the process of water desalination with the use of renewable energy safer for the environment and sustainable.

The literature review performed in this subject demonstrates that the majority of research carried out has been focused on the static solar stills in which the saturation pressure and temperature remain constant during the desalination process. Shatat and Mahkamov presented theoretical and experimental study of a static solar thermal distillation unit in [2]. The effect of the design parameters on the performance of the unit was investigated and an optimization of unit's design parameters have been conducted. Mahkamov and Belgasim described in [3] the concept of the dynamic solar distillation system in which an evacuated tube solar collector was coupled with a fluid piston thermal engine. The laboratory prototype of the proposed system was built and tested to demonstrate its functionality and preliminary experimental results were very encouraging. Furthermore, a comparative study between static and dynamic solar distillation systems was performed in the same study which demonstrates considerably higher fresh water production capacity of the dynamic system.

2. Model Description

The dynamic solar thermal desalination unit integrated with fluid piston engine is described in *fig.1*. This unit operates under a cyclic change in the pressure and temperature during the operation of the unit due to the expansion and the compression of the volume of the fluid piston engine. Such working conditions considerably intensify the desalination processes and fresh water production.

The plant's operation can be described as follows. Saline water is heated up and evaporated in the solar collector (1) causing pressure rise in the system. The initial increase of the pressure initiates oscillations of water columns (3) and (4) of the fluid piston engine and the whole system operates as a dynamic thermal oscillation system, in which the water evaporation is intensified by volume and pressure variations in the internal circuit. In its turn, this sustains oscillations of water columns. In this particular design, the distilled water is formed in the condenser (2) surrounded by the water jacket with the saline water and the condensate is collected in the distilled water vessel (6). The heated saline water from the water jacket of the condenser is pumped to the water storage tank.

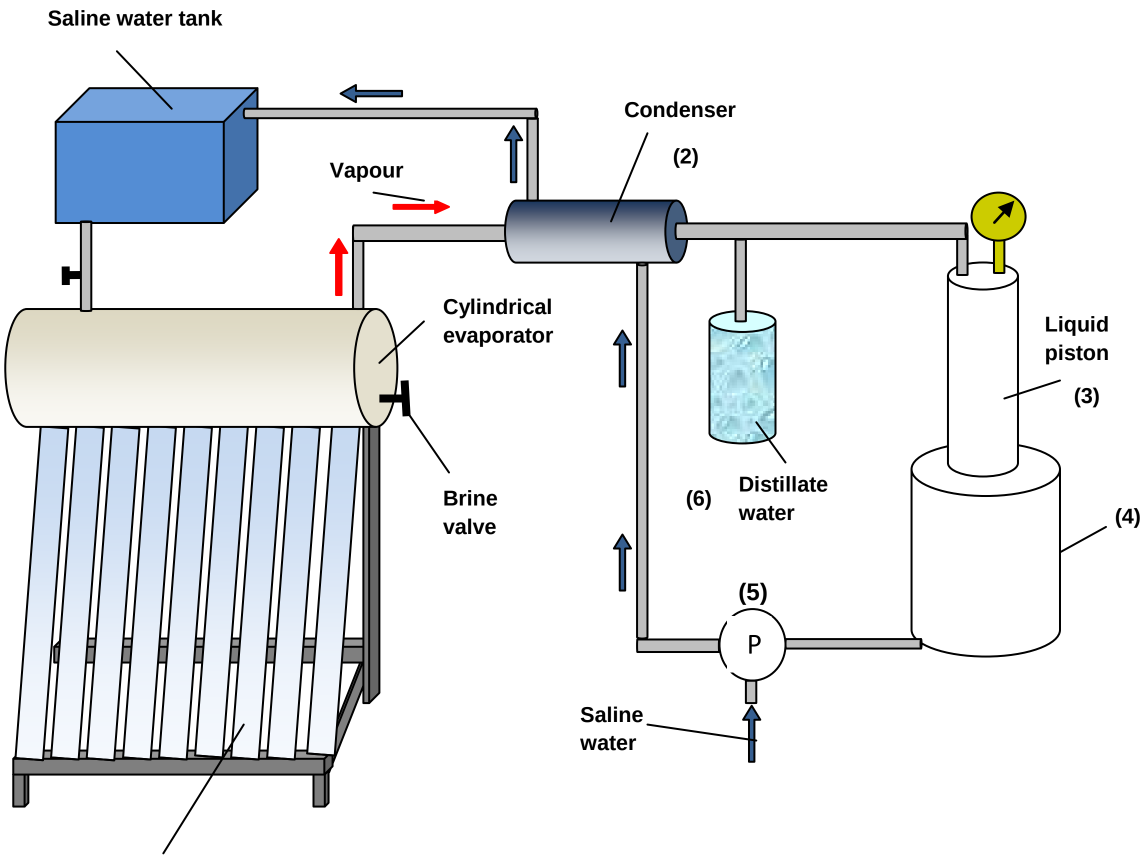

Fig. 1 . (1) Evacuated tube solar collector

The above system was tested under a number of constant heat flux conditions created with application of a sun simulator: an array of 110 halogen floodlights placed above evacuated tubes. The heat flux magnitude is set using a three-phase transformer which controls the voltage of the electrical current supplied to the floodlights. Preliminary results obtained clearly show that such dynamic system has a considerable advantage in fresh water production capacity over conventional static systems. Currently the unit is being equipped with sensors to record oscillations of the liquid piston, temperature and pressure variations in components of the installation.

3. Theoretical Modelling

In order to perform the theoretical analysis, the unit was divided into three separate control volumes, namely the evaporator, the condenser and the fluid piston cylinder. The lumped mathematical model was derived based on energy and mass conservation differential equations written for each control volume taking into accounts the cyclic variation of the pressure and temperature inside the system during its operation.

3.1. Evaporator

The mathematical model of the system consists of the mass and energy balance equations written for each component. The mass conservation equation could be written as

$$\frac{d}{dt}(\rho V) = (\rho \dot{v})_{sw} - (\rho \dot{v})_v - (\rho \dot{v})_b \tag{1}$$

where t is time, V is volume, ρ is density and $\dot{v}$ is volume flow rat.

The initial condition for the above equation is the amount $(\rho V)_0$ of the seawater at the beginning of the operation. Two assumptions are made: the amount of saline water inside the evaporator is constant; all the vapour produced in the evaporator will be then condensed in the condenser.

The salt concentration conservation equation is

$$\frac{d}{dt}(\rho V c) = (\rho \dot{v} c)_{sw} - (\rho \dot{v} c)_b \tag{2}$$

where c is salt concentration.

The initial amount of salt is $(\rho V c)_0$

Finally, the energy conservation equation can be derived by applying the energy balance principle for the same control volume.

$$\frac{d}{dt}(\rho V c_p T) = Q_{in} + (\rho \dot{v} c_p T)_{sw} - (\rho \dot{v} h_{fg})_v - (\rho \dot{v} c_p T)_b - Q_{loss} \tag{3}$$

where Q is the heat flow, T is temperature h is enthalpy and c_p is heat capacity at constant pressure.

The energy $(\rho V c_p T)_0$ is at the starting time. In this equation the heat capacity of the system material has been neglected so no heat storage is considered in the evaporator substance.

3.2. Condenser

It was assumed in the simulation process that all the produced vapour is converted into fresh water. The condenser design represents the counter flow tube-in-tube heat exchanger in which the condensation process takes place on the internal surface of the inner tube while the cooling water passes through the outer tube. In order to enhance the productivity and the thermal efficiency of the system, the seawater fed to the evaporator is first used as cooling water in the condenser's water jacket to gain the latent heat of condensation.

The mathematical description of the condensation process depends on a number of factors including the condenser shape, the flow pattern and the condensation rate. The inner heat transfer coefficient in the case when the condensation rate is low and the vapour has a low velocity in a short condenser, can be calculated as [4]

$$h_i = 0.555\left[\frac{g\rho_l(\rho_l-\rho_v)k_l^3 h'_{fg}}{\mu_l(T_{sat}-T_s)D}\right]^{1/4}$$

where the modified condensation heat is $h'_{fg} = h_{fg} + \frac{3}{8}c_{p,l}(T_{sat} - T_s)$

The outer heat transfer coefficient is mainly effected by Nusselt Nu number which is a function of the flow pattern and depends on the Reynolds number Re. If $Re < 2300$ the flow is laminar and if $Re > 2300$ then the flow is turbulent. The outer heat transfer coefficient can be calculated as $h_o = \frac{k_l}{D_h}Nu_i$ [5]. Therefore, the overall heat transfer coefficient is $U = \frac{h_o h_i}{h_o + h_i}$

The condenser is considered as a control volume and using the mean temperature difference technique, the governing energy equation for the condenser can be written as:

$$Q = UA_s\frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)} = \dot{m}c_{p,sw}\left(T_{c,in} - T_{c,out}\right) \quad (4)$$

where U is the overall heat transfer coefficient, A surface area, $\dot{m}$ is mass flow rate, $\Delta T_1 = T_{sat} - T_{c,out}$ and $\Delta T_2 = T_{sat} - T_{c,in}$

In the above equation, the produced fresh water is assumed to be condensed at the saturation temperature.

3.3. *Fluid piston engine*

The fluid piston engine consists of two concentric cylinders attached to the collector at the top of the inner cylinder. The two cylinders are filled with water to work as a piston in both cylinders. After the solar collector starts to heat up the saline water, its temperature gradually increases leading to the rise in the pressure in the system. The pressure continue to rise until the inner cylinder piston, which is at the top position in the beginning of heating process, is pushed down. This results in expanding the volume of the system. The expansion process continues until the air pressure at the top of the outer cylinder balances the system pressure and then the system returns to the original position under the effect of the water weight and air pressure leading the cycle to be repeated again.

The expansion and compression processes are repeated continually allowing the unit to work under variable volume and pressure conditions. The change in the volume is important to estimate the change in pressure and in this study, the volume has been assumed to vary harmonically:

$$V_{tot} = V_{dead} + \pi A\frac{D^2}{8}[1 - cos(\omega t)] \quad (5)$$

where V_{dead} is the dead volume of the system, A is the amplitude of the fluid piston oscillations; D is the diameter of the piston and f is the frequency of oscillations.

The relationship between the change in volume and in the pressure is calculated as

$$\Delta P = P_{sat}\left[\left(\frac{V_{tot(1)}}{V_{tot(2)}}\right)^{k} - 1\right] \tag{6}$$

where ΔP is the pressure change due to the variation in the total volume of the system.

It was assumed that the expansion and the compression processes are isentropic processes.

4. Results and Discussion

The governing equations of the theoretical model are the set of ordinary differential equations with the time being the independent variable. The input parameters of the system include the initial conditions, the properties of water, the value of constant solar radiation and dimensions of the unit. In order to simulate the operation of the system, a MATLAB program has been written which uses Euler technique to solve the differential equations with a time step $\Delta t = 0.01\ sec$.

The theoretical simulations have been carried as set of a number cases with constant heat flux values, which are typical for different hours of the mid-summer day in the Middle East region.

The theoretical results on pressure and temperature variations inside the system for the heat flux corresponding to 12 noon are illustrated in *fig. 2* and *fig. 3*, respectively. During the expansion in the cylinder, the pressure drops to approximately 0.7 *bar* (minimum pressure) and rises to 1.15 *bar* (maximum pressure) during the compression stroke. These values are also close to experimental values of the minimum amd maximum pressures in the cycle, measured using a manometer. The temperature during the cycle varies between 92 and 105 degrees C.

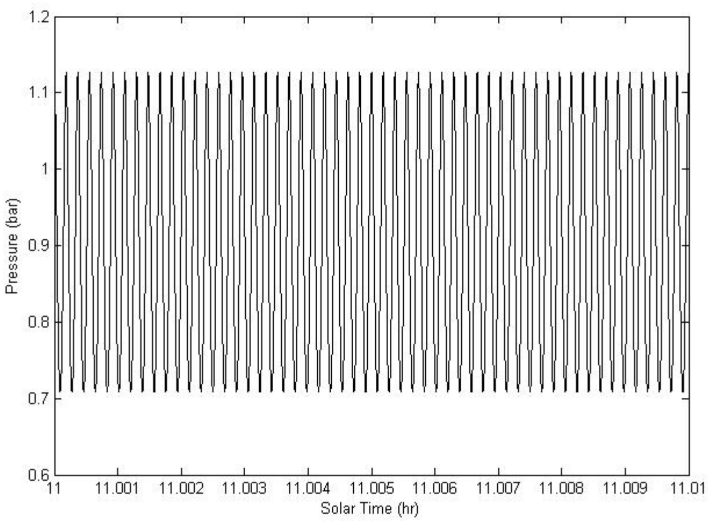

Fig. 2 The saturation pressure oscillation.

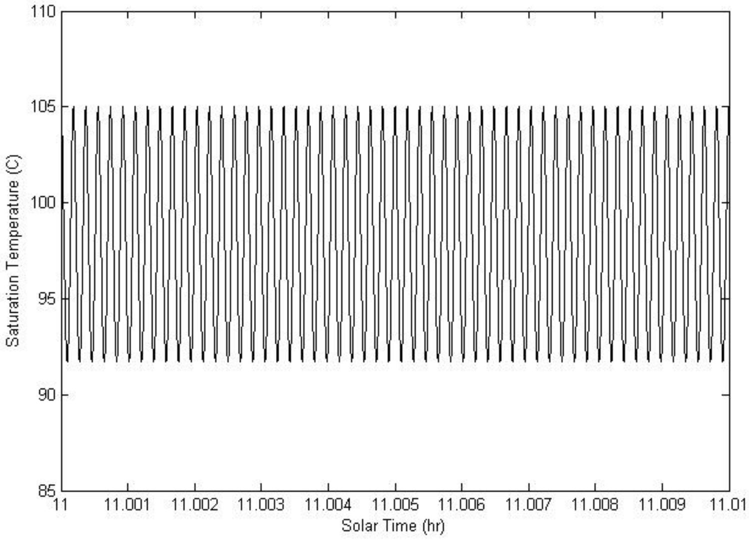

Fig. 3 The saturation temperature oscillation.

Theoretical results on the fresh water production capacity obtained by using the above mathematical model for a number of constant heat fluxes typical for different periods of the mid-summer day were used to produce the variation of the fresh water production capacity over the day, as shown in *fig 4*.

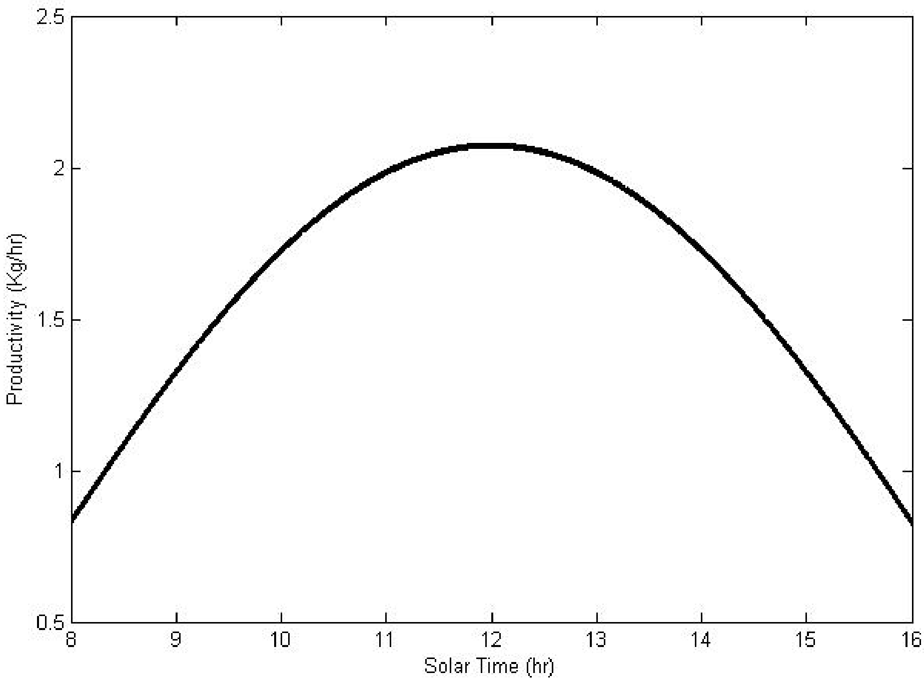

Fig.4 The productivity variation during the mid-simmer day

The theoretical value for the daily fresh water production capacity is obtained by integration water production capacity curve in *fig. 4* and it is about 9 litres, which is greater than 6 litres for the conventional static solar stills. During preliminary experiments at the same heat flux value the fresh water production capacity was about 8.2 litres.

5. Conclusions

The paper presents results of theoretical modelling of the steady-state operation of the proposed dynamic water desalination system with a number of constant heat flux values upon the evacuated tubes of the solar collector. The heat flux values used are typical for a different periods of the mid-summer in the Middle East region. The fresh water production, obtained from this study, was found to be about 9 litres/day which is greater than the most of conventional static solar distillation designs. The theoretical data obtained on the fresh water production capacity is in a good agreement with data obtained on the test rig which was run simulating variation of insolation over the summer day.

Currently the unit is being equipped with sensors to record oscillations of the liquid piston, temperature and pressure variations in components of the installation. Such experimental information can be used for calibration of the mathematical model.

It is planned to conduct modelling of unsteady operation with at variable heat flux conditions in the future. The unsteady model also will describe processes taking place in the evaporator and condenser in more details making it possible to take into account the effect of the insolation variation on the levels of the saturated pressure and temperature.

The further development of the mathematical model will also include an optimization procedure for design parameters of the unit.

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