Experimental Study on Desalination System Using the Waste Heat of Nuclear Power Plants and Solar Energy Systems

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1. Introduction

Due to the shortage of fresh water resources; desalination is used to convert the abundant seawater or brackish water into fresh water. Many current desalination plants are powered by fossil fuels, which pose economic problems and environmental concerns.

In this study a new desalination system using the waste heat of nuclear power plant or solar energy system is under consideration. An experiment study will performed to evaluate the performance of the system. In this paper, the experimental design of the system and steady-state and transient analysis, using MATLAB and MARS code respectively, will be presented.

2. System Description

In this section the desalination system design and the experiment loop design are described.

2.1 Desalination System Description

The outline of the desalination system is schematically shown in Fig.1. Two main phenomena take place in the system; namely, the evaporation and the condensation of the heated water to produce fresh water and the natural circulation based on temperature and salinity difference between two successive units. Currently only the first phenomenon is considered, that is, the condensation in a single unit which allows to evaluate the production rate for a single unit.

The working principle of the proposed system depends on heating the seawater using the waste heat of nuclear power plant or heat from solar energy, the exact procedure will be studied and evaluated later. In one pool we have a cylinder which allows the water level increase. The water column level will increase until it balances the atmospheric pressure and it will imposes a pressure equal to the saturation pressure corresponding to the temperature of seawater in the pool, this allows seawater evaporation and as a result saturated vapor on the top of the cylinder will exist. And since the atmospheric temperature is assumed to be lower than the steam temperature; the steam will condenses and fresh water will produced in the inner side of the cylinder.

Due to water evaporation and steam condensation, seawater temperature will decrease and its salinity will increase, causing density difference between two successive pools which allows seawater circulation between the two pools.

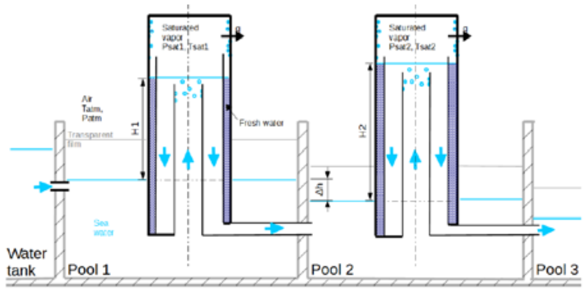

Fig.1: Desalination system schematic

2.2 Experimental Apparatus Description

As mentioned earlier, only the condensation phenomenon is considered in this paper, and an experimental loop was designed in order to verify the system's performance.

If the seawater temperature in the system is 80ºC, for example, the saturation pressure is 47.4kPa, the water height in the cylinder will be 5m in order to achieve the required operating condition. However, this cylinder height is practically difficult to be achieved in our experimental space, we are limited to 3m total height maximum. That is, apparatus is not open to atmosphere, as in the proposed system, and the required pressure will be achieved by a specific technique discussed later on.

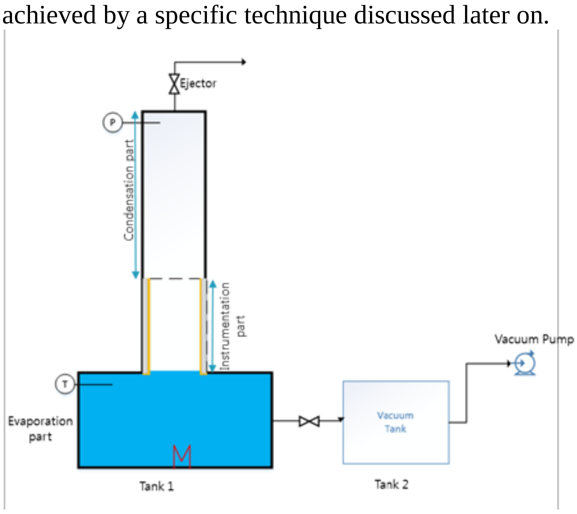

Fig.2: Experimental apparatus schematic

The experiment apparatus schematic is shown in Fig.2. The facility consists of the following parts:

1- Evaporation part: where the evaporation of the seawater takes place.
2- Instrumentation part: where the condensed water accumulated and the system's production rate measured.
3- Condensation part: where the steam condenses and fresh water produced.
4- Water discharge system: consists of vacuum tank and vacuum pump, used to reduce the pressure to the operating pressure in the condensation part.

3. Model Calculations

Steady-state and transient analysis have been conducted to verify the proposed model.

3.1 Steady-State Calculations

Steady-state calculations were performed to verify the system's performance, that is, calculating the steady-state condensation flow rate (the production rate of the system). The heat transfer rate between the steam and the ambient air is defined by:

$$q = \frac{T_{sat} - T_{atm}}{\frac{1}{h_{cond}A} + \frac{\ln(R_2/R_1)}{2\pi K_{cylinder}L} + \frac{1}{h_{air}A}} \quad (1)$$

The condensation heat transfer coefficient was defined using Nusselt's film theory [1], as follows:

$$h_{cond} = 0.943\left[\frac{g h_{fg}\rho_w(\rho_w - \rho_g)H^3}{\mu_w K_w(T_{sat} - T_{wall})}\right]^{1/4} \times K_w \quad (2)$$

The air heat transfer coefficient, an external free convective flow on a vertical plate was assumed and the Churchill and Chu correlation [2] was applied as follow:

$$Nu_{air} = 0.68 + \frac{0.670 \times Ra_{air}^{1/4}}{\left[1 + (0.492/Pr_{air})^{9/16}\right]^{4/9}} \quad (3)$$

$$h_{air} = \frac{Nu_{air} \times K_{air}}{L} \quad (4)$$

After defining the above parameters, the condensed water mass flow rate can be calculated as:

$$\dot{m} = \frac{q}{h_{fg}} \quad (5)$$

And by mass conservation, the mass flow rate of the condensed water is assumed to equal the evaporation rate in the evaporation part and the condensation rate in the condensation part.

3.2 Transient Analysis

MARS code was used to verify the system's transient performance. The water discharge from the system and the condensation rate have been analyzed.

3.2.1 Water discharge process

Since we are limited on the height of the cylinder, we should achieve the operating pressure within the allowed height. The desalination system has been designed with a water discharge system. Firstly the desalination system will fully filled with water, and the water will discharged until the water level in the system reached the pre-determined level (the top of the evaporation part). In this case the pressure in the cylinder will be the saturation pressure. This process was firstly simulated using the MARS code. The system's MARS nodalization is shown in Fig.3.

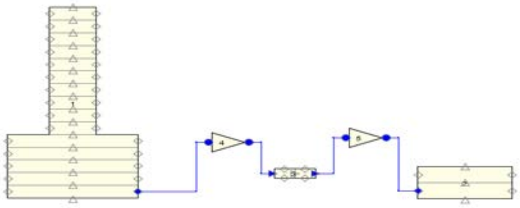

Fig.3: MARS nodalization

3.2.2 Condensation mass flow rate

The condensation flow rate in the condensation part was analyzed using MARS code. The system was divided to three parts, where the evaporation part was modeled as a time dependent volume, the instrumentation part as a single volume and the condensation part as a pipe portioned into 10 sub-volumes and 9 junctions points. The three parts are connected by junctions. A heat structure was added to the condensation part and was connected to a hydraulic volume which simulates cooling by the atmosphere. The MARS nodalization of the system is shown in Fig.4. This calculations allow us to define when the system will reach steady-state.

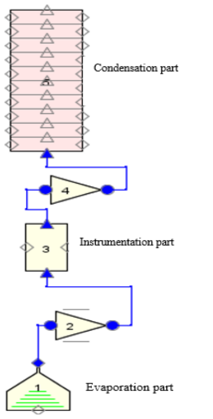

Fig.4: MARS nodalization

4. Results

4.1 steady-state calculations

For various temperatures the steady state fresh water production rate was calculated, this is to establish the test matrix for the future experiment. The results are:

Temperature (°C)	Mass flow rate (Kg/s)
40	6.30E-06
50	1.57E-05
65	3.31E-05
70	3.95E-05
80	5.34E-05
90	6.82E-05

Table1: Steady-state results.

4.2 Transient Analysis

For the water discharge process, the pressure on the condensation part was measured, the calculations were performed for different water temperatures; however, only for 40 °C will is shown here.

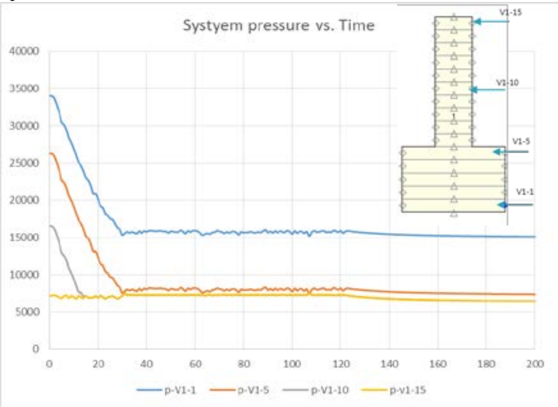

Fig.5: System pressure during water discharge

For the condensation mass flow rate simulations part, only a sample of the results will be shown here. For the water temperature of 60 °C. The condensation flow rate was calculated at different parts of the system, the net condensation rate from all parts is equivalent to the junction mass flow rate shown on Fig.6 and Fig.7.

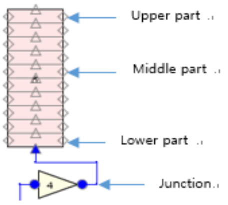

Fig.6: Condensation part nodalization

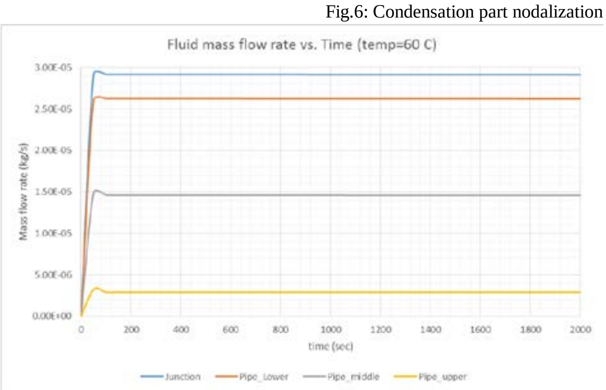

Fig.7: Condensation mass flow rate simulation results.

5. Conclusion

A new desalination system using the waste heat from nuclear power plants or solar energy was proposed and the design of an experimental facility to evaluate the system's performance was presented. The analytical steady-state analysis using MATLAB and transient MARS calculations have been performed. An Experiment will be performed to verify the model. Moreover a feasibility study for the proposed design and a comparison with the conventional desalination system will be performed.

REFERENCES

[1] Mostafa Ghaiaasiaan, Two-phase flow boiling and condensation, Cambridge University Press, 595 pages.
[2] Incropera, Dewitt, Bergam and Lavine, Fundamentals of heat and mass transfer, sixth edition, page 645.