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Development of a desalination system driven by solar energy and low grade waste heat

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ABSTRACT

Various thermal power systems emit flue gases containing significant amount of waste energy. The aim of this research is to recover a valuable amount of this energy to develop an efficient desalination system coupled with solar energy. Experiments were performed in the month of June 2014 at Al-Qassim, Saudi Arabia (26°4′53″N, 43°58′32″E) for different hot air (waste gas) flow rates and evaporator inlet water temperature to study the effect on daily potable water productivity. The proposed setup comprised an evaporator, condenser, air blower, electric heaters, storage tank and evacuated tube solar collectors. It was found that increasing the hot air flow rate increases the water productivity up to the critical flow rate after which the productivity decreases. Analytical model was developed for this desalination setup and the results were compared to that obtained from experiments. The overall daily (9 AM–5 PM) potable water productivity of the proposed system is about 50 L for corresponding useful waste heat varying from 130 to 180 MJ/day and a global solar radiation on a horizontal surface ranging from 15 to 29 MJ/m^2/day. Water is produced at the cost of 0.014 USD/L and the fuel saving equal to 1844 kg/h is achieved for the proposed desalination system.

1. Introduction

Lack of potable water is becoming an increasingly important issue in arid regions where fresh drinking water is scarce and expensive. In arid areas, especially the Middle East and North Africa (MENA), potable water is scarce and survival of human population in these areas strongly depends on the availability of fresh drinking water. Desalination of sea or brackish water is the most feasible solution to overcome this challenge in these areas. Different water desalination technologies are presently used such as multi-effect desalination, flash desalination, humidification–de humidification distillation and reverse osmosis, but these methods fulfill energy needs from conventional fossil fuel. It has been estimated that the production of 1000 m^3 of potable water per day requires 10,000 tons of oil per year [1].

In the last few decades, due to large energy consumption in commercial desalination processes and its impact on environment, an urge for the development of efficient energy saving desalination systems have been proposed by researchers. In this regard, the idea of driving the desalination process by hybrid thermal energy using waste heat and solar heat has been devised in an attempt to develop an energy saving desalination system. Waste heat recovery is important not only for its economic benefits, but also for its environmental outcomes and resource saving [2]. As a consequence of rising cost of electricity and global warming, alternative and renewable energy sources are receiving much attention [3]. Among the solar assisted seawater desalination techniques, the most commonly used are solar stills, solar assisted humidification–dehumidification, multi-effect desalination, reverse osmosis and heat pump desalination [4]. It has been shown by Cohen et al. [5] that the low temperature flash desalination technology is a viable solution from both technical and economical point of view, and can be installed effectively in a steam power station located in Mediterranean shore operating at base load with a minimum seawater temperature increase of 8 °C. A mathematical model has been developed and analyzed to study the feasibility of using waste heat from an internal combustion power plant for seawater desalination [6]. Kumar et al. [7] designed a vacuum desalination system to evaporate saline water at reduced pressure using power plant waste heat. Wang et al. [8] reviewed different configurations of rankine cycle with different working fluids for exhaust heat recovery. The heat needed for evaporation was supplied by the heat released from dew fall condensation on opposite sides of heat transfer wall. Adsorption desalination systems using low-temperature waste heat were also studied to produce

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Nomenclature

AMC	annual maintenance cost
ASV	Annual Salvage Value
ARC	Annual Running Cost
AC	Annual Cost
AY	annual yield, L
a	Instrument accuracy
CRF	Capital Recovery Factor
C_p	specific heat capacity, kJ kg^{-1} K^{-1}
E	energy consumption, kW h
FAC	First Annual Cost
h_{fg}	latent heat of vaporization, kJ kg^{-1}
i	annual interest rate
HHV	high heating value of fuel, kJ kg^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}
m	mass, kg
n	lifetime of considered desalination system, years
P	initial investment on proposed desalination system
Q	air flow rate, m^3 s^{-1}
$\dot{Q}$	heat duty, W
SFF	Sinking Fund Factor
S	salvage value
T	temperature, K
t	time, s
u	standard uncertainty
$\dot{W}$	power, W
Z	electricity cost per kW h

Subscripts

av	average
e	evaporative
f	fuel
g	gas
i	inlet
l	loss
o	outlet
sto	storage
sat	saturation
t	total
w	water
y	annual

high-grade potable water with dissolved solids less than 10 ppm. Such systems also introduced a heat recovery loop between the condenser and evaporator [9–11]. Gude and Nirmalakhandan [12] analyzed a new low-temperature desalination process utilizing low-grade thermal energy from a waste heat source. Based on simulation results, the proposed desalination process was capable of producing potable water at 4.5 kg/h.

Many industrial processes produce large amounts of waste gases. It is estimated that industrial energy losses occur in the range between 20% and 50% as waste heat [13]. Goldstick [14] categorized waste heat energy sources as low (232 °C and lower), medium (232–650 °C) and high quality (650 °C and higher). A number of feasibility studies have been implemented to combine power generation plants with desalination systems [15–17]. Ophir and Lokiec [18] discussed the feasibility of waste heat utilization for multi-effect sea water desalination. Absorption heat pumps and heat transformer systems using solar energy, geothermal energy and waste heat energy as potential energy sources have also been studied to drive desalination systems [19,20]. Gude et al. [21] presented a feasibility study of a two-stage low temperature desalination process using a cheap waste heat source at 0.5 $/GJ. This desalination system has the energy consumption of 1500 kJ/kg of freshwater with cost around 3 USD/m^3. Maraver et al. [22] proposed the assessment of organic rankine cycle for energy generation, multi-effect desalination and cold generation. Aly [23] used the steam produced in the generator of the absorption cycle as a heat source for multi-effect desalination system.

The present study highlights and explains the great importance of using waste gas emitted by thermal plants to drive water desalination system coupled with solar collectors. This study also shows the feasibility of using waste gas of a combined cycle gas turbine power plant for proposed desalination system. This study can further be used to optimize the waste gas flow rate and its temperature at evaporator inlet to maximize daily distillate productivity.

2. Experimental setup

An experimental study was conducted to investigate the feasibility of using waste heat and solar energy for water desalination. The schematic diagram of the experimental test rig is shown in Fig. 1.

The proposed desalination system mainly consists of an internally insulated horizontal fire tube evaporator with a circular cross section of diameter 0.50 m and length 1.4 m. The evaporator consists of 14 horizontal fire tubes mounted inside the two pass evaporator to exchange waste heat with saline water and the outside surface of the evaporator is covered with 5 cm thick glass wool to reduce the heat loss. The tubes are fabricated from steel with inside diameter D_i = 49.76 mm and outside diameter D_o = 53.98 mm. During the tests, the tubes are assured to be completely submerged in water. Water used in the proposed desalination system comes from the treatment plant where sea water is pre-treated against different types of fouling (such as biological fouling, particle fouling and colloidal fouling) using chlorination, coagulation and filtration techniques. Saline water is pumped firstly into the condenser to condense the vapor coming from the evaporator and then passed into the water storage tank. Evacuated tube solar collector is used to maintain a constant water temperature inside the storage tank. The solar collector consists of 15 units of 1.20 m long co-axial glass tubes with outer diameter 47 mm and inner diameter 33 mm separated by vacuum. When the desired water temperature (50, 60, 70 °C) inside the storage tank is achieved, the pump circulating the water in a loop containing the collector and the storage tank is automatically switched off. When the water temperature inside the storage tank falls below the desired level, the pump is switched on once again and the water in storage tank takes the heat from solar collector until it reaches the desired temperature again. Since evacuated tube collectors are more efficient than flat plate collectors, evacuated tube collectors are used to heat water inside the storage tank to reach the desired temperature in short time. Therefore, the system reaches a steady state in short time duration which results in high productivity. Moreover, evacuated tube collectors perform better under low solar insolation conditions (morning, evening, cloudy weather, etc.) compared to flat plate collectors. Pre-heated saline water from storage tank goes directly into the evaporator where it is heated by the induced ambient air. Ambient air is forced inside the evaporator using an air blower of 0.5 kW and heated by four