Applied Thermal Engineering 128 (2018) 1446–1455

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

The mass transfer coefficient assessment and productivity enhancement of a vertical tubular solar brackish water still

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HIGHLIGHTS

- A novel vertical tubular solar brackish water still is described.
- Mass transfer coefficients are calculated from the experimental results.
- The maximum discrepancy is relatively small compared with previous study.
- The maximum yield can reach 653.89 g/h at operation pressure of 75 kPa.

ARTICLE INFO

Article history:
Received 8 March 2017
Revised 31 July 2017
Accepted 25 September 2017
Available online 27 September 2017

Keywords:
Vertical tubular solar still
Brackish water
Mass transfer coefficient
Vacuum pressure
Mass transfer enhancement

ABSTRACT

This paper presents an experimental investigation of a single-effect vertical tubular solar brackish water desalination device, with an aim to determine the mass transfer coefficient and its enhancement. The device consists of two closely spaced concentric pipes. The outside of the inner pipe is covered with a wicking material and wetted with hot brackish water. The water vapor evaporated from the wicking material condenses on the inside of the outer pipe. The measured productivity and temperatures at various points are given for different wicking materials thickness, water flow rates and chamber pressure under the condition of given heating power. Mass transfer coefficients are calculated from the experimental results and then applied in the prediction of water productivity. The maximum discrepancy between the calculation yield and measurement yield is relatively small compared with previous study. In addition, it was found that the yield of the solar still is 23.9% higher when the chamber pressure is lower by 25 kPa due to the enhanced mass transfer. Similar, doubling the ambient air velocity can increase the water yield by about 17.0%.

1. Introduction

Fresh and safe water is not only a necessity for healthy human habitation but also for industrial and agricultural production. While water covers approximately 70% of the world, more than 97% of the water is saline and brackish [1], while freshwater is distributed at percentage of 2.53% [2], and only ~0.36% of the fresh water is directly available for human [3]. The demand for fresh water production is growing day by day with the expansion of the population, the development of urbanization and the progress of industrialization. Mostly, arid and semi-arid regions are severely affected by facing scarcity of drinking water, water is available, but it is brackish in nature and therefore harmful to human health. Brackish water desalination is believed to be an effective way to solve the shortage of fresh water. However, in current situation nearly 1 kWh of energy is required for desalination process to produce 1.0 m^3 of fresh water [4]. Solar brackish water desalination has become one of more preferred methods for obtaining clear water without CO_2 emission during its life time especially in arid and semi-arid with abundance sunshine. Among solar desalination technologies, Solar Multi Stage Flash (SMSF) and Solar Multi Effect Distillation (SMED) are commercially utilized in cities and always can be made even more economical based on large capacities [5].

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https://doi.org/10.1016/j.applthermaleng.2017.09.129
1359-4311/

Nomenclature

C	constant number
C_p	specific heat, J/(kg K)
D_v	mass diffusion coefficient, m^2/s
Gr	Grashof number
g	gravitational constant, 9.8 m/s^2
h_m	mass transfer coefficient, m/s
h_c	Convective heat-transfer coefficient, W/m^2 K
Le	Lewis number
M	molar mass, kg/mol
n	constant number
p_a	dry air pressure, Pa
p_w	vapor pressure, Pa
p_T	total pressure, Pa
Ra	Rayleigh number
R_o	universal gas constant, 8.3145 J/(mol K)
R_g	gas constant, J/(kg K)
Sc	Schmidt number
Sh	Sherwood number
T_{av}	average temperature, K
t_w	condensation temperature, °C
x_l	feature size, m
v	kinematic viscosity, m^2/s
ρ	density, kg/m^3
μ	dynamic viscosity, N s/m^2
Σ_v	molecular diffusion volume

Subscripts

a	air
e	evaporating surface
c	condensing surface
m	mixed gas
w	water vapor

However, these technologies are not suitable for remote regions, e.g. the arid northwest of China.

Among solar brackish water desalination technologies, solar stills have been considered potentially applicable device to produce clean drinking water to rural, arid and remote communities, which assembles simple, costs effective and operates simple. However, they have the major drawbacks of lower productivity compared with conventional solar desalination methods. The solar still has an efficiency of 30–45% and a less than 5 L/m^2/d freshwater yield [6]. By now, many researchers have been involved in their work by structural optimization and redesigning to enhance the productivity and to improve the applicability [7–10].

Kaushal et al. [11] proposed an improved basin type vertical solar still consisting of two closely vertical parallel plates. The evaporation efficiency of the unit was increased compared with previous reported results by other researchers due to better soaking, high rate of temperature equalization within the copper plate. The experimental results show that the cumulative efficiency of the improved still with 10 mm partition gap was 10–15% higher than the conventional basin type still. Reddy and Sharon [12] have carried out performance optimization evaluation studies for an active multi-effect vertical solar still using the developed mathematical model. It has been observed that optimum numbers of effects, mass flow rate and gap were found to be five, 7.20 kg/h and 0.05 m based on the distillate yield and practical conditions.

A novel family scale inflatable plastic solar still was described by Bhardwaj et al. [13]. The passive condenser was placed to the basin solar still for providing additional condensation surface. Results indicated that the fresh water yield of the still increased more than 0.95 L/h due to the effect of evaporation cooling or an external fan which suggest that the inflatable plastic still have the potential to provide sufficient drinking water for one family. Estahbanati et al. [14] experimentally investigated the effect of the number of stages on the productivity of multi-effect active solar still for the first time. In their work, performances comparison of the continuous and non-continuous model was carried out. Experimental results showed that by increasing the still's number of stages, the positive effect of performances in continuous mode increased outstandingly, which can be predicted by a quadratic function. El-Agouz et al. [15] theoretical evaluated the performance for a continuous water flow inclined solar still unit. Three models were studied for the system with and without water close loop. Mostly, the effects of the water mass, water film thickness, water film velocity and air wind velocity on the performance of three models were compared. The results showed that the productivity of the inclined solar still with a makeup water was 57.2% higher than that of a conventional basin-type solar still.

Among the solar stills, the vertical solar stills have been extensively studied using theoretical models and experimental methods, which can be found from the literatures above. However, few investigations on vertical tubular solar brackish water still have been reported. Furthermore, of all the vertical tubular solar stills, it can be clearly seen that the area of the condensing surface of vertical tubular solar still is larger than that of the evaporating surface leading to more yield. However, there is no reported mass transfer correlation for vertical tubular stills. Hence, an attempt has been made by this study to determine the mass transfer coefficient of vertical tubular solar still under the conditions of various heating temperature and water flow rates. In addition, this paper presents an experimental investigation of a single-effect vertical tubular solar brackish water still with a concentric structure, in which the outside of the inner pipe is covered with a wicking layer to provide a uniform of water film. The experimental results will be used to calculate the mass transfer coefficient, based on which the water yield of a vertical tubular solar still can be predicted.

2. Development of single vertical tubular solar brackish water still

2.1. Structure parameters and characteristics

Since the vertical tubular solar brackish water still is believed to be a relatively new way to meet the fresh water demands for remote villages and pastoral areas, e.g. the northwest of China. However, the optimized operational conditions and mass transfer process were also not fully known. Hence it is necessary to develop a single small scale operational mode and study its performance, before making a full scale device of the present vertical tubular solar brackish water still. The structure diagram of the proposed small scale vertical tubular solar brackish water still mode as shown in Figs. 1 and 2 illustrates a schematic and photograph of the experimental set-up.

The vertical tubular solar brackish water still is compounded of two water collection tanks, a vacuum pump, a heating element, the measurement instruments and two concentric circular stainless