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Effect of air humidity at the entrance on heat and mass transfers in a humidifier intended for a desalination system

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ABSTRACT

The aim of the present study is to investigate numerically the effect of inlet air humidity on an upward airflow in a humidifier intended for a humidification–dehumidification desalination system. A vertical parallel-plate channel constitutes the humidifier. One of the plates is wetted by a liquid water film and maintained at a constant temperature, while the other is dry and thermally insulated. The airflow enters the channel with constant temperature, humidity and velocity. The results show that the increase of air humidity at the channel entrance affects seriously the performances of the humidifier as it induces condensation of the water vapour on the walls. On the other hand, it was stated that the humidifier works well for low inlet humidity.

1. Introduction

Considering a significant increasing in population and industrialization over the past few decades, the world's fresh water resources have come under renewed pressure. Arid regions, in particular, are already facing the reality that a shortage of portable water can hinder economic development. Industrialized nations are also not immune to the problems caused by fresh water shortages. There is a growing realization in both arid and non-arid countries that the long-term solution lays in a coordinated approach involving water management and desalination.

The desalination industry, which includes desalination of brackish water and seawater, is almost equally divided between the reverse osmosis (RO) and the Multi-Stage Flashing (MSF) processes. Several other desalination technologies such as Multiple Effect Evaporation (MED), Vapour Compression (VO) have limited market shares. MSF is characterised by the large size of its plants (more than 20,000 m^3/day) and RO plants are modular by design and their capacity may vary from a few cubic meters per day to thousands of m^3/day. However, for small production capacities RO, due to its high cost and energy consumption, may not be the optimum choice [1]. When the fresh water demand is low (few m^3/day) local production using other desalination techniques, such as the humidification–dehumidification (HD) technique, may be an interesting way. The HD technique requires a low level of technical support and energy consumption when compared to the RO process. The basic elements of the HD plant are an air humidifier and a condensation unit. Evaporating the salted water humidifies hot air; the distilled water is then recovered in the condensation unit by means of humid air dehumidification.

A literature review of the HD technique is given in [2]. Low temperature humidification–dehumidification desalination process has been studied by Al-Enezi et al. [1]. The performance of a humidification–dehumidification desalination system are measured and analysed at low operating temperatures by the authors and they specified that, variations in the production rate are found to be strongly affected by the hot and cooling water temperatures. The authors show that the measured air and water temperatures, air humidity and the flow rates are used to calculate the air side mass transfer coefficient and the overall heat transfer coefficient. They affirmed that their measured data are found to be consistent with previous literature results. Goosen et al. [3] conducted a study on the thermodynamic and economic considerations in solar desalination. The authors performed a critical review of thermodynamic efficiency of single-basin and multiple effect solar water desalination systems with special emphasis on humidification–dehumidification processes. The authors claimed that the concept of using the humidification–dehumidification process in combination with the growth of crops in a greenhouse system is relatively new.

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Nomenclature

b	half-channel width, (m)
C	mass fraction, (kg vapour/kg mixture)
C_p	specific heat, (J kg^{-1} K^{-1})
D	mass diffusion coefficient, (m^2/s)
D_h	hydraulic diameter, = 4.b (m)
M_a	molecular mass of air (kg kmol^{-1})
M_v	molecular mass of water vapour (kg kmol^{-1})
Gr_M	solutal Grashof number
Gr_T	thermal Grashof number
h_{gf}	latent heat of condensation, (kJ/kg)
k	thermal conductivity, (W m^{-1} K^{-1}).
L	channel height, (m)
Le	Lewis number
P_m	modified pressure, $= p + \rho_0\, g\, x$, (Pa)
Pr	Prandtl number
Psat	saturation pressure, (Pa)
Re	Reynolds number
Sc	Schmidt number
T	temperature, (K)
u, v	axial and transverse components of velocity, (m s^{-1})
V_e	vapour transverse velocity at the liquid–gas interface, (m s^{-1}).
x	axial coordinate, (m)
y	transverse coordinate, (m)

Greek letters

β_T	coefficient of thermal expansion, $= 1/T_0$, (K^{-1}).
β_M	coefficient of mass fraction expansion, $= (M_a/M_v)-1$.
μ	dynamic viscosity, (Pa s)
γ	aspect ratio, = 2 b/L
ρ	density, (kg m^{-3}).
ϕ	relative humidity, (%)
ψ	streamline function

Subscripts

g	gas
0	at the inlet
m	mean value
w	at the wall

Regarding fundamental studies on HD technique, Orfi et al. [4] have studied the evaporation of a thin liquid film flowing down on the internal face of one plate of a vertical channel. The wetted plate is subjected to a uniform heat flux while the second plate is taken isothermal and impermeable. The results obtained by the authors for an air-water system show that the interfacial heat and mass transfers depend largely on the liquid film temperature and mass flow rate as well as on the external heat flux. The effect of thermal and solutal buoyancy forces on both upward and downward airflow in a vertical parallel-plate channel was investigated numerically by Azizi et al. [5]. The plates are wetted by a thin liquid water film and maintained at a constant temperature lower than that of the air entering the channel. Results show that buoyancy forces have an important effect on heat and mass transfer. It has been established that the heat transfer associated with these phase change may be more or less important compared to sensible heat transfer. The authors show that, flow reversal may occur for an upward flow with a relatively high temperature difference between the incoming air and the walls. Chouikh et al. [6] conducted a numerical study on heat and mass transfer in inclined glazing cavity for application to a solar distillation cell. Their results show that the desirable flow for enhancing the performance of the solar distiller is characterized by a single cell, which rotates in a sense that allows enough time for the vapour to cool down.

Convective heat and mass transfer with evaporation of falling film in a cavity was studied by Ben Jabrallah et al. [7]. The system is formed by a rectangular cavity. One of the cavity walls is wetted by a falling water film and heated with a constant heat flux. This film evaporates into the trapped air and the vapour is condensed on the opposite wall maintained at a constant and uniform temperature. The authors showed that the film presents two zones: a heating one located near the inlet of the cavity and an evaporation zone, which covers the rest of the wetted surface.

Boukrani et al. [8] have investigated theoretically the effect of water film evaporation on parallel-plate channel natural convection heat and mass transfer. One of the plates is wetted by a thin liquid water film and maintained at a constant temperature while the other is isothermal and dry with a temperature higher than that of the wetted one. The effect of the relative humidity of the ambient moist air on heat and mass transfers were examined. Their results show that better latent heat transport is noticed for the flow with a lower ambient humidity.

An experimental study of heat and mass transfer in natural and forced convection in a vertical parallel-plate channel humidifier intended for a desalination system has been conducted by Cherif et al. [9]. The plates are symmetrically wetted by falling liquid water films and heated by means of a constant heat flux. The experimentation consists in determining the evaporation rate of the water films in both natural and forced convection conditions. The authors studied the operating parameters effects on the temperature profiles in both water and air flows. Their results show that the increase of the airflow velocity results in an increase of the thermal efficiency of the evaporation. On the other hand, the authors show that for given water flow rate, the Sherwood number increases with respect to the heat flux in an exponential way.

In this paper, a numerical study of heat and mass transfers in a humidifier dedicated to HD desalination system is performed. The specific objective of the present study is to investigate the effect of air humidity at the inlet of the humidifier on flow and heat-mass transfer characteristics. As suggested by the above listed literature, the inlet air humidity is expected to influence the performances of the HD desalination system.

2. Analysis

2.1. Conservation equations

The studied humidifier is a vertical parallel-plate channel (Fig. 1). One of the plates is wetted by a thin liquid water film and maintained at a constant temperature while the other is dry and thermally insulated. A hot upward airflow enters the channel with uniform velocity, temperature and humidity. We consider that the liquid film is extremely thin, so that it can be treated as a boundary condition [10]. Steady state conditions are considered and the flow is supposed to be laminar.

Viscous dissipation, radiation heat transfer, Dufour and Soret effects are negligible. Thermodynamic equilibrium is assumed at the film-air interface. The physical properties are taken to be constant except for density in the body forces, which is considered to be a linear function of temperature and mass fraction,