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Thermodynamic analysis and evaluation of a gas compression refrigeration cycle for fresh water production from atmospheric air

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ABSTRACT

In recent decades, many scientific works have been carried out to accomplish innovative solutions to achieve new resources for fresh water or improve the exploitation of current water resources. One of these new resources is the water vapor content of air. The objective of this study is to analyze the production of liquid water from atmospheric water vapor with assisted of a refrigeration cycle. The evaporator of this cycle will be as the cool surface and so the dehumidifier of the system that produces fresh water. In this study, a computer program was also developed to carry on a flexible thermodynamic model for a gas compression refrigeration cycle exclusively for fresh water production. The amount of water production and energy intensity under different climate conditions are analyzed. Despite most of previous studies, it has been tried to provide more real working conditions and some simplifying assumptions have been avoided. A case study is carried out based on ambient temperature and humidity intervals of system's best performance. The results show that a residential size of the system can produce 22–26 l/day fresh water while energy intensity is between 220 and 300 Wh/l. Since the proposed system can work without any brine discharging and environmentally friendly, a comparison of this method with other desalination technologies has been carried out, as well.

1. Introduction

Fresh water resource is categorized as conventional resources, including surface waters, ground waters and precipitations, and non-conventional resources, such as sea/saline water desalination, waste water treatment, etc. Non-conventional resources are mostly used in zones with surface or ground water absence or scarcity [1]. Although precipitations feed milliards of liters of surface and ground water resources of the planet earth, non-uniform time and place distribution makes them inadequate to fulfill the incessant demand for water. If atmospheric water vapor is condensed to liquid water in sufficient amount, it can be placed in the category of non-conventional resources of fresh water.

Dehumidification of air in air conditioning systems was widely investigated in previous studies. Liquid desiccant dehumidification is a method that used in some air conditioning systems to produce very dry air for an indirect evaporative cooler. For example, Triethylene glycol was used by Elsarrag in a structured packed column to evaluate rate of moisture removal for air dehumidification [2]. Also, a thermodynamic analysis was carried out by She et al. on an energy-efficient refrigeration system which was subcooled by evaporation and liquid desiccant dehumidification [3]. But these methods could not be used for fresh water production. Recently in 2018, Talaat et al. carried out an experimental and theoretical study of a solar-powered portable apparatus to produce water from atmospheric air [4]. The unit included a double-faced conical-finned absorber and a double-faced conical transparent surface. The measured accumulated water productivity was found to be from 0.3295 to 0.6310 $kg/m^2/day$.

Also, combination of conventional desalination with various refrigeration systems was investigated in previous studies. Some works considered the combination of absorption refrigeration cycle and a Multi Effect desalination. One of them was a two-part investigation carried out by Wang, Y et al., based on the LiBr–H2O absorption cycle [5]. Recently, Alelyani et al. has developed a technical and economic analysis on a combined ammonia-water absorption refrigeration system and desalination [6]. In addition, a combination of transcritical carbon dioxide refrigeration and MED also studied by Farsi et al. to provide cooling and fresh water simultaneously [7].

The other method to retrieve liquid water from humid air is to cool down the humid air to its dew point temperature over a cool surface. The evaporator coils of a refrigeration cycle can be used to provide this cool surface. Regarding the improvement of refrigeration systems technology and the ease of their operation and maintenance, there is a good potential to develop more investigations on their exclusive

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Nomenclature

A	Are, m^2
C	heat capacity (kj/k)
C_p	specific heat capacity at constant pressure (kj/kg·k)
D	diameter, m
G	mass flow, $kg/m^2 s$
h	convection heat transfer coefficient, $w/m^2 k$
i	enthalpy
j	j-factor
K	conduction heat transfer coefficient, w/mk
L	length, m
L_e	Lewis number
N	number of rows
Pin	pitch, m
pr	Prantel number
P_{rc}	pressure ratio
P	pressure, refrigerant (bar), air (atm)
S_t	Stanton number
T_{rc}	temperature ratio
v	Velosity
w	absolute humidity, kg/kg
x	quality of refrigerant
ncirc	number of paths in each row
ntc	number of tubes in each row
Pcr	critical pressure, bar
D	diameter, m

Greek letters

ρ	density, kg/m^2
μ	viscocity pas
η	efficiency
δ	fin thiknesscm

Subscripts

diag	related to diagonal distance between tubes
long	related to vertical distance between tubes
trans	related to horizontal distance between tubes l
po	including tubes
to	including tube and fin
fr	frontal of heat exchanger
TP	two-phase
av	moist air
a	air
r	refrigerant
c	dry surface/condenser
W	wet surface water film
o	tube external
i	tube internall
p	tube
f	fin
l	liquid
v	gas
in	inlet
e	outlet/evaporator
m	mean
s	saturate
sh	superheat section
sat	saturated section
sc	subcooled section

utilization as water producers. Compared with desalination technology, these systems have the possibility of water production in remote zones. Because, as an advantage, despite desalination, not only is there no exigency to set up the system close to sea/saline water resource but also the cost, work and infrastructures in order to provide feedwater are removable.

Atmospheric water vapor processing (AWVP) technology in recent decades was reviewed by Wahlgren [8]. Three classifications of machines have been introduced in his study and some patented devices with different scales were also reviewed. Along with water cost estimation, workability and appropriateness of their application were also argued. According to daily minimum water-quantity requirements in houses and other buildings, an individual in a house needs 15–25 l/day [8]. It was noticeable that a number of the highlighted prototypes could sufficiently provide basic water requirements for drinking, bathing, sanitation and cooking of an average family, but the report lacks the technical information about the details of the systems' component.

Potential of water production from atmospheric water vapor in air-conditioner refrigeration machines, while fresh hot humid air is cooled over their evaporator coils, were evaluated by Habeebullah [9]. As a result, a working chart was developed with the aim of quick prediction of the amount of water production in any combination of ambient temperature and relative humidity in the range of 25–40 °C and 30–100%. The diagrams of daily water yield followed the similar pattern to that of relative humidity. The maximum production was predicted to be 17.6 kg per heat exchanger surface area per day for a humid air speed of 2.25 ms^{-1}. In his study, produced potable water was a by-product of the air conditioning process, therefore, it was considered at a free cost, and the refrigeration cycle was not analyzed as an exclusive atmospheric water producer. Nada et al. [10] present a theoretical investigation of integrative air-conditioning and humidification–dehumidification desalination systems proposed for hot and dry climatic regions. Fresh air firstly humidified in an evaporative cooler and then water produced in cooling coil of the vapor compression refrigeration system (as dehumidifier).

In current study, fresh water production from atmospheric air technology has been also investigated from the energy point of view. So, investigations in this field of study were also reviewed. A wind turbine, with combined production of electricity and water, has been designed by a French company (EOLE) [11]. The aim of this large-size system was to produce potable water in remote areas, wherever feasible. It has been claimed that the turbine is able to produce up to 1000 l of water per day in coastal areas. The machine was an innovative combination of wind turbine technology and gas compression refrigeration cycle technology. The prototypes could produce 62 l of fresh water per hour in air temperature of 24 °C and relative humidity of 45%.

In 2014, in order to maximize the quantity of condensed water in any combination of ambient humidity ratio and temperature, a gas compression refrigeration cycle with specified refrigeration- power was analyzed by Bortolini et al. [12]. In their study, volumetric flow of humid air was optimized and energy consumption per liter of produced water was also evaluated. A case study was carried out in Dubai, as well. Exit air from the system was assumed to be saturated; therefore, all calculations and equations were simplified based on this assumption. In their work, the whole cycle has been considered as a block and the cycle's parameters have been limited to air volumetric flow and a given refrigeration-power.

Since refrigeration cycle components' modeling, namely finned-tube heat exchangers, is an important part of current study, a number of scientific works in this field have been studied. Finned-tube heat exchangers are widely used in a variety of applications. Ma et al. [13] used a wavy finned-tube heat exchangers to evaluated the effects of hydrophilic coating on air side heat transfer and friction characteristics