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Experimentally validated model for atmospheric water generation using a solar assisted desiccant dehumidification system

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ABSTRACT

This paper examines an alternative solution for emergency situations where freshwater and utilities are often interrupted. Generating freshwater from the atmosphere using a small-scale air-cooled desiccant wheel dehumidifier was experimented. Condensed water was collected and systematically recorded against local meteorological data. A synthetic model simulating the actual lay-out of the experiment was built in TRNSYS. The model validated the experimental results and generated approximately 52 litres in 9 days. The validated model is then run for three different climates; Sydney, Abu Dhabi and London to estimate annual water production. Abu Dhabi showed the best results compared with Sydney and London by generating 18.5 kL of water per year. The model is further developed to evaluate thermodynamic benefits of using dehumidified processed air as a feed stream for a proposed small-scale air-conditioning system. The energy required for the wheel regeneration process is met by thermal gain of modified solar PVT panels where the stagnant heat at the back is used to heat up the regeneration air stream. It was found that the dehumidification process can significantly decrease the latent load of the air-conditioner and easily bring indoor humidity level to the human comfort zone. However, dehumidified process air is also increasing the sensible load because of the higher temperature associated with dehumidification process. Rooftop solar PV panels can easily meet the power demand of appropriate lighting, a computer and mini refrigerator for extended hours if an appropriate set of batteries are fitted, but unable to exclusively meet the air-conditioner power demand to maintain indoor temperature within human comfort zone.

1. Introduction

In the last century, there has been a dramatic increase in the frequency and intensity of natural disaster rates across the globe [1]. Natural disasters are declared when the physical hazards cause a substantial damage or loss to social, economical and environmental assets that directly or indirectly threaten people's lives [2]. This dramatic increase of natural disaster rates is mainly caused by climate change phenomena which directly influence the precipitation pattern and extreme weather events [3]. When the catastrophe exceeds a society's coping threshold, an emergency is declared. In most emergency situations, local water, sanitation and power networks are disrupted and no longer can be used. Therefore, providing safe and clean drinking water along with food, shelters and medication to prevent the spread of waterborne diseases within affected communities becomes a priority. In the past, the effort was to continuously deliver large quantities of clean water via water tankers or small containers. However, delay in the delivery of this costly operation and/or the collapse of road network in some cases, pressed on crisis handling personnel to consider easier and more effective solutions. In this context, the idea of establishing onsite decentralised water generation technology might be more attractive. However, treating water up to drinking standards during an emergency situation is challenging because of inadequate infrastructure and the interruption that is often associated with the chaos of the disaster. Therefore, an emergency water generation technology must be safe, easy to establish and independent of utility networks to permit their application in disaster zones. Furthermore, the water generation device must also be a mobile or portable small-scale unit to provide a location-specific solution. Immediate and adequate medical relief is also demanding a rapid establishment of small independent field hospitals. Today, first-aid cabins similar to that shown in Fig. 1 are easy to transfer and install in disaster zones to replace old-style medical tents. These cabins are often used for initial first-aid, medical assessment and immunisation services. They contain one or two beds,

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COP	coefficient of performance
MRC	moisture removal capacity
SER	sensible energy ratio
TEC	thermoelectric cooler
Cp_{da}	dry air specific heat capacity coefficient [kJ/kg$_{da}$ K]
Cp_f	circulating fluid specific heat capacity coefficient [kJ/kg K]
h_{da}	dry air enthalpy of the air [kJ/kg$_{da}$]
h_{ma}	moist air enthalpy of the air [kJ/kg$_{ma}$]
h_{wv}	water vapour enthalpy of the air [kJ/kg$_{wv}$]
ω	humidity ratio [kg$_{wv}$/kg$_{da}$]
υ	the specific volume of the air [m$^3_{ma}$/kg$_{da}$]
d_v	the absolute humidity of the air [kg$_{wv}$/m$^3_{ma}$]
ρ_{da}	dry air density [kg$_{da}$/m$^3_{ma}$]
ρ_{ma}	moist air density [kg$_{ma}$/m^3]
$\dot{F}_{vma}$	moist air volumetric flow rate [m$^3_{ma}$/h]
$\dot{F}_{ma}$	moist air mass flow rate [kg$_{ma}$/h]
$\dot{F}_{da}$	dry air mass flow rate [kg$_{da}$/h]
$\dot{m}_w$	water condensate mass flow rate [kg$_w$/h]
$\dot{m}_f$	circulating fluid mass flow rate [kg/h]
γ	specific humidity of the air [kg$_{wv}$/kg$_{ma}$]
η_d	dehumidifier efficiency
γ_e	emperical PV curve-fitting parameter
ς	solar thermal collector efficiency
I_L	PV module photocurrent
$I_{L,ref}$	PV module photocurrent at reference conditions
I_{mp}	current at maximum power point along IV curve
I_o	Diode reverse saturation current [Amp]
$I_{o,ref}$	diode reverse saturation current at reference conditions [Amp]
R_s	PV module series resistance
N_s	number of individual cells in the module
T_c	solar module temperature [°C]
k	Boltzmann constant [J/K]
q	electron charge constant [C]
G_T	total solar radiation incidence [W/m^2]
Q_u	total thermal gain by the collector [kJ/h]

Fig. 1. Solar cabin where PV panels are flat mounted on the rooftop.

a table and a computer, a small refrigerator, small air-conditioner and adequate lighting. These cabins are designed to accommodate up to four medical personnel and patients at a time. The major portion of energy requirement for these cabins is met by five mono-crystalline silicon photovoltaic panels flat mounted on the rooftop (Fig. 1). A simple vapour-compression air-conditioning unit is used to bring the temperature and humidity level inside the cabin to meet human comfort level. In hot humid regions such as tropical and coastal areas, the thermal load often exceeds the capacity of the designated air-conditioning unit. This is mainly because of high atmospheric humidity ratio which possesses a high latent load resulting from atmospheric water vapour condensation. Therefore the idea of using a pre-treatment dehumidification unit to mitigate the humidity content of the feed air and harvest the condensate could be attractive.

This paper examines the possibility of using a dehumidification system run by solar thermal energy for two specific purposes; (i) to pre-treat feed air stream for the air-conditioning unit and reduce latent heat and consequently electrical power consumption. (ii) to condense atmospheric moisture and use it as an additional renewable source of water and further enhance the sustainability and independence of first-aid cabins. The objective is to experimentally quantify collected water and energy consumption to compare with a synthetic mathematical model built in a TRNSYS 17 platform using the real-time weather data recorded at the same time and location where the experiment took place. Agreement between experimental and mathematical model can validate the modelling process to predict the techno-economics of the atmospheric water generation anywhere and at anytime.

2. Atmospheric water dehumidification

The atmosphere surrounding the earth is estimated to contain a total of over 12.9×10^{12} m^3 of renewable water. This amount is even greater than the total available freshwater in marshes, wetlands and rivers around the world [4]. Water generation from atmospheric air is considered as a renewable water source and has sporadically appeared in the literature [5–14]. Most of these works have praised the viability of the process, especially near tropical, temperate and coastal areas where temperature and humidity levels are typically high. However, their arguments were about the energy intensive operation of water generation. High energy requirement was declared as the biggest obstacle of the process and became a driving force for a variety of innovations. Dehumidification is a widely used technology in many industrial processes where a stream of dry air is needed. It is also an essential part for heating and air-conditioning process where humidity level of the air is controlled to meet human comfort requirements. The heating, ventilation and air conditioning (HVAC) system consumes the prime share of the energy consumption and can account in some cases for 70% of the total energy consumption of buildings [15]. Traditionally, condensed water is drained away of air-conditioning systems and the energy consumed for condensation is wasted. Fig. 2 presents a detailed classification of various dehumidification techniques with at least one example of each technique being given. The first category of methods is represented by cooling surfaces that cool the moist air feed to below dew point temperature and condense the moisture content over specially designed cooling surfaces. This category was comprehensively addressed in a previous study [16] where a generic no-refrigerant TEC dehumidification technique was modelled and evaluated. In the second category, sorption is a mechanism in which water vapour molecules are captivated by a distinctive solvents or solid mediums that are specially affiliated toward water vapour molecules. In a later stage, after specific diffusion time, captured water vapour molecules will be desorbed by subjecting the carrier medium to heat. A sorption system has an exceptional capability of transforming thermal energy directly into cooling. Sorption cycle works by way of interaction of two or more substances, one of them at least is changing phase during the operation from liquid to vapour and vice versa. Among the pair of substances, the substance with the lower boiling temperature