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Air-conditioning condensate recovery and applications—Current developments and challenges ahead

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ABSTRACT

The quest for water sustainability, energy conservation and environment-friendly technologies has necessitated development of alternate water and energy resources that are clean, energy-efficient and cost-effective. The condensate from heating, ventilation and air-conditioning (HVAC) systems has been identified as potential source of clean water, which is typically removed and disposed of in a sanitary drain. The condensate can be beneficially used for water sustainability and building energy recovery. The focus of this article is a state of the art review of HVAC condensate recovery, the progress in research and development of condensate recovery systems (CRSs), quality concerns and potential applications. Specific attention is given to review all the existing CRSs around the globe, theoretical and experimental studies on condensate recovery, mathematical models proposed and evaluation of quality characteristics. The issues and challenges involved and suggestions for future work are highlighted. The review reveals that, given the importance of water conservation and clean and sustainable energy resources, the domain of HVAC condensate recovery and utilization has significant scope for research and development in order to realize practical CRSs that can contribute for water sustainability and energy management in buildings.

1. Introduction

The most treasured resource in the world is fresh water, and its demand is particularly great in regions with hot and dry climates. The major part of the earth is covered by water with a total volume of about 1.4 billion km^3 out of which the fresh water resources represent merely 2.5% (Anonymous, 2017a). According to the World Health Organization (WHO), more than one out of six people lack access to safe drinking water. Shortage of fresh water is prevalent in many developing and developed countries, especially in arid countries across the globe (Ahmad and Schmid, 2002; De Gois, Rios, & Costanzi, 2015; Fiorenza, Sharma, & Braccio, 2003; Molden, 2007; NafeyAS, Abdelkader, & Abdelmotalip, 2001;). In view of the current physical and economic water-scarcity issues, innovative technologies that can produce fresh water at a minimal cost are becoming increasingly important, and the development of such technologies should be encouraged.

Numerous technologies to supplement potable water are in use and are termed as alternative technologies for fresh water. A comprehensive study on innovative ideas to obtain potable water was published by experts of the United Nations in 1985 (United Nations-Natural Resources/Water Series, 1985), and this work was later elaborated upon (Habeebullah, 2009; Milani, Qadir, Vassallo, Chiesa, & Abbas, 2014). Guaranteeing future water security needs extensive community support to make changes in policy, practice and technology, such as those involved in supplying alternative water resources (Dean, Fielding, Lindsay, Newton, & Ross, 2016). Many technologies have been developed to produce fresh water, such as desalination, solar distillation, cloud seeding and atmospheric water vapor harvesting.

The principal desalination methods, namely, evaporation, reverse osmosis and electro dialysis have been in use for more than 50 years (Fiorenza et al., 2003; Kahraman and Cengel, 2005; Ibrahim and Dincer, 2015; Mokheimer, Sahin, Al-Sharafi, & Ali, 2013). These techniques consume appreciable amount of energy compared to other water treatment technologies developed so far. In fact, the energy efficiency of water treatment technologies depends on chemical and biological characteristics of water source and type of technology in use. Natural filtration techniques namely riverbank filtration and slow sand filtration hardly consume any energy. However, membrane filtration technology for bacterial and protozoan removal based on pressurized systems consumes more energy than other membrane systems (e.g. gravity fed systems) due to electrical or mechanical systems required to maintain the pressure in the system. The abovementioned desalination

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Nomenclature

Abbreviations

AD	Air density (lb/ft^3)
AED	Arab Emirates dirham
AF	Air flow (ft^3/min)
AHU	Air handling unit
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
AWVH	Atmospheric water vapor harvesting
CAP	Condensate-assisted pre-cooling
Avg. DP	Annual average dew point (F)
CDD	Cooling degree days
CFP	Carbon footprint
CRSs	Condensate recovery systems
DPT	Dew point temperature
DBT	Dry bulb temperature
DOAHU	Dedicated outdoor air handling unit
DX	Direct expansion
EC	Electrical conductivity
EES	Engineering Equation Solver
EPA	Environmental Protection Agency
FAHU	Fresh air handling unit
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air conditioning
KSA	Kingdom of Saudi Arabia
LEED	Leadership in Energy and Environmental Design
NTU	Nephelometric turbidity unit
RH	Relative humidity
SHR	Sensible heat ratio
TDS	Total dissolved solids
TR	Ton of refrigeration

Symbols

A	Area (m^2)
Q	Heat capacity (kW)
T	Temperature (K)
U	Heat transfer coefficient (kW/m^{2}K)
m	Volume flow rate (L/s)
$\dot{m}$	Mass flow rate (kg/s)
cfm	Cubic feet per minute
cmm	Cubic meter per minute
gal	Gallon
ρ	Density of dry air (lb/ft^3)
ω	Humidity ratio, absolute humidity
$\Delta\omega$	Change in humidity ratio across the cooling coil
$\forall_C$	Condensate production potential (gal/ft^3)
M	Quantity of condensate (kg)
G	Fresh air circulated in m3/hour
d_c	Specific humidity at the condensing side, g/Kg
d_L	Specific humidity at the entering point, g/Kg

Subscripts

a	Air
e	Cooling coil exit
i	Cooling coil inlet
f	Fin
o	Overall
off	Off-coil
a, e	Air at the exit of the cooling coil
a, i	Air at the inlet of the cooling coil
a. ev	Air through the evaporator
amb	Ambient

methods are based on membrane technology. The energy required for these techniques is mainly produced from fossil fuels, which generate detrimental carbon emissions. As is well known, fossil fuels should be used judiciously in the future (Ray and Jain, 2011). A review on prospects for solar water desalination is presented in (Shatat, Worall, & Riffat, 2013). In addition, seawater has a high tendency for scale formation and fouling problems are common in desalination applications because of the dissolved salts and finely suspended solids (Buros, 2000). Another major issue related to desalination technologies is the huge quantity of brine and its adverse effect because of its high salinity (Younos, 2005). Several viable brine disposal and treatment methods are described in (Afrasiabi and Shahbazali, 2011; Morillo et al., 2014). Therefore, it would be worthwhile to develop low cost and green technologies from other innovative water sources.

The solar distillation technology was developed many years ago and has been the focus of several studies (Al-HinaiH and Al-Nassri, 2002; El-Sebaii, 2004; Kalita, Dewan, & Borah, 2016; Kabeel, Omara, & Essa, 2014; Minasian and Al-Karaghouli, 1995; Samuel, Nagarajan, Sathyamurthy, El-Agouz, & Kannan, 2016; Zheng, Zhang, Zhang, & Wu, 2002). However, its low productivity that varies from 2.5–5 L/m^2/day (Goosen, Sablani, Shayya, Paton, & AL-Hinai, 2000) offsets its advantages such as simplicity and free energy costs. In cloud seeding, clouds are intercepted and seeded, which triggers the condensation of the water vapor in the clouds, subsequently showering down this condensate as rain (Bruintjes, 1999). Even though this technology represents a pioneering approach, it would not be promising in areas of low cloud cover. Moreover, the method itself is expensive and has low potential.

Atmospheric water vapor harvesting (AWVH) is an old technique, which had been in use for many years with air wells in the Middle Eastern deserts and in Europe. In 1400, dewponds were used to collect water, and later on, fog fences were used to exploit the technique called fog harvesting or fog collection or even cloud stripping, to gather water from the humidity in the fog. In all these methods, water vapor in the atmosphere is condensed and collected (Nelson, 2003; Wahlgren, 2001). According to the literature, there are three significant approaches for AWVH (Beysens, Milimouk, Nikolayev, Muselli, & Marcillat, 2003; Cook, Sharma, & Gurung, 2014; Kabeel, 2006; Zhang, Zhu, Deng, & Hua, 2012):

a) Condensate collection on cold surfaces in heating, ventilation and air conditioning (HVAC) units
b) Absorption of the water vapor by means of desiccants followed by its release in a regeneration process
c) The generation of convection currents in a tall tower structure to push humid air to a high altitude (cold zone) where condensation takes place. The condensed fresh water, which is directly obtained from the atmosphere, is anticipated to be soft and neutral with very low contents of minerals and metals.

Among the aforementioned techniques to produce potable water via AWVH, the one that extracts air-conditioning condensate through condensate recovery systems (CRSs) has great potential and could be exploited in rather more efficient ways. The heating, ventilation and air-conditioning (HVAC) systems in buildings produce a considerable amount of condensate, especially in hot-humid climates. On the other hand, buildings use about 40% of global energy, 25% of global water, 40% of global resources, and they emit approximately 1/3 of GHG (greenhouse gas) emissions (Anonymous, 2017b). Hence, any cost-effective development that makes buildings more energy efficient would