DIRECT-CONTACT DEHUMIDIFICATION AS A SUSTAINABLE FRESH WATER PRODUCTION TECHNIQUE: A REVIEW

Abubaker Sayed Omer
Department of Mechanical and Industrial Engineering, College of Engineering, Sultan Qaboos University

Abdulrahim M. Al-Ismaili
Department of Soils, Water and Agricultural Engineering, College of Agricultural and Marine Sciences, Sultan Qaboos University

Nasser A. Al-Azri
Department of Mechanical and Industrial Engineering, College of Engineering, Sultan Qaboos University

Keywords: Direct-Contact Dehumidification; Heat Transfer; Mass Transfer; Condensation; Freshwater Production; Seawater Desalination**.**

Contents

Summary

This chapter provides a literature review of the direct-contact dehumidification (DCD) concept, process and devices. Its starts with an introductory that highlights the main results collected from literature. Then, it briefly explains the humidification and dehumidification (HDH) phenomenon and introduces the DCD concept with illustration and psychrometric calculations. Next, it provides information on the historical development of the DCD devices starting with the first recorded use of the DCD concept. After that, it highlights the main findings of past publications and scientific works relating to the parameters involved in the DCD process; in HDH systems and sustainable energy systems. Additionally, it provides brief definitions of the parameters that evaluate the technical effectiveness of the DCD devices and some past scientific works that evaluated the DCD's economic effectiveness.

Introduction

Direct Contact Dehumidifiers (DCDs) are devices used to extract moisture from humid air stream through a direct contact between two phases: relatively cold freshwater and warm humid air. In comparison to indirect contact dehumidifiers, DCDs proved superiority in terms of being corrosion- and fouling-free, no water leakage and more heat transfer. This chapter presents a review of the various aspects of DCD systems such as the working principle, historical development, applications in different Humidification-De-Humidification (HDH) systems, energy sustainability and technical and economic effectiveness. The literature on he subject reports three main types of DCDs: (i) spray type, (ii) packing type and (iii) bubble column (pool condensation) type. Freshwater production is directly proportional to air temperature, air humidity, water-to-air ratio, and apparatus height, and inversely proportional to water temperature. Water-to-air ratio, DCD height and air flowrate have optimal values of 2, 60 cm and 0.16 kg/s, respectively, that correspond to highest production rates and beyond these values production decreases. Several methods to calculate numerical values for DCD technical effectiveness are reviewed along with experimental results. For large-scale use, a direct contact HDH system operated with renewable energy was found to be the most efficient and profiting desalination technique reported. Therefore, direct contact HDH systems are very promising desalination methods due to their enhanced economic effectiveness.

1.1. Background

Dehumidification is the process of removing moisture from a gas-vapor stream through contact with a cold surface of liquid or solid form. The dehumidification process involves a phase change of matter from gas to liquid, which is known as condensation. When a relatively-warm air-water mixture makes contact with a cold surface, the mixture reaches its dew point and consequently water-vapor molecules condense on the cold surface (Collins Dictionary,2017; Brundrett 1987). This process is a naturally-occurring phenomenon, and can also be artificially implemented in several areas in science and industry. For instance, commercial dehumidifiers are used to enhance air quality in residential, industrial and medical premises (Allergyandair, 2017; Thepurefactory, 2013; AMFA, 2017; Aprilaire, 2018). The commercial dehumidifiers are essential in areas of increased humidity because moisture in the air can cause a number of drawbacks like; health problems and discomfort, accumulation of mold in households and acceleration of metal corrosion over time (Brundrett, 1987 ; Arundel et al, 1986 ; Davis et al, 2016 ; Shaman et al, 2010 ; Yang et al, 2015; Li et al, 2010 ; Hayes et al, 2013). Along with the removal of moisture, dehumidifiers take out micro-size pollutants like pollens from the atmospheric air (Iihf, IIHF Arena Man, 2002; Airconditioning-systems Dehumidifier, ;2017; Mohammad et al, 2015; Chung et al, 1995). Another industrial purpose for dehumidification is desalinating saline water through Humidification-Dehumidification (HDH) systems (Huang et al, 2017 ; Niroomand et al, 2015; Al-Ismaili et al, 2016; Klausner et al, 2004; Narayan et al, 2010; Eslamimanesh et al, 2010).

The HDH systems are used to desalinate water through imitation of the natural hydrologic cycle. These systems have attracted the attention of scientists who wish to alleviate the drawbacks of fresh water scarcity in many parts of the world. The HDH systems are basically composed of three major components; a humidifier, a dehumidifier and a heat-providing system (solar stills, waste heat, electric heaters, etc…) (Parekh et al, 2004; Al-Hallaj et al, 2006; Farid et al, 2003; Ettouney, 2005; Hou, 2008; Xiong et al, 2006; Al-Enezi et al, 2006; Zheng, 2017; Sharshir et al, 2016; Yildirim and Solmuş, 2014). Usually in the HDH systems, the dehumidifier component is mainly a surface heat exchanger, which was found to be costly due to the corrosion and blockage damages caused by the saline water (Huang et al, 2017; Alsadaie and Mujtaba, 2017; Somerscales, 1997). One method to eradicate the technical and economic disadvantages of the surface heat exchangers is to replace them with direct contact dehumidifiers (DCD). These devices offer a long mean lifetime and are cost-effective due to the ease of construction and the absence of contact between saline water and transporting elements which eliminate typical problems like; fouling, corrosion and water leakage (Niroomand et al, 2015; Al-Ismaili et al, 2016; Zamen et al, 2013).

1.2. DCD Concept

Direct-contact dehumidifiers (DCD) condense water vapor that is residing in a humid air stream with high temperature and a near saturation humidity by means of direct contact of the humid air stream with a relatively cold fresh water stream. The idea is that heat and mass transfer will take place as a result of the temperature differential between the two fluids as the contact is occurring. Compared to indirect contact dehumidifiers, the DCDs achieve more heat transfer due to the absence of barriers between the two fluids and the increased surface area of contact (Zamen et al, 2013; Li et al, 2006). The DCDs can be categorized according to the flow pattern of both fluids. There are three flow patterns of the DCDs which are: (i) counter-flow contact pattern in which the air and water streams flow in opposite directions to each other, (ii) concurrent flow contact pattern in which the two streams flow in the same direction and (iii) cross-flow contact pattern in which the direction of flow of one stream is perpendicular to the other (Niroomand et al, 2015; Li et al, 2006; McNaught, 2011).

The DCDs can also be categorized according to the working protocol of the apparatus where the DCD unit is involved. Several types of apparatus were reported in the literature that include packing type (Huang et al, 2017; Eslamimanesh et al, 2010; Li et al, 2013; Jacobs, 1988; Trofimov, 2011), spray (fogging or jet) type (Niroomand et al, 2015; Klausner et al, 2004; Jacobs, 1988; Trofimov, 2011; Hijikata, 1984; Lekic, 1980; Ford and Lekic, 1973; Lin Jie Huang and Ayyaswamy,1987; Celata et al, 1989; Ayyaswamy, 1995) and bubble-column or pool-condensation type (McNaught, 2011; Narayan, 2014; Mahood et al, 2014; Shah and Sekulić, 2003; Tow and Lienhard, 2013; Chehayeb et al, 2014; Schmack et al, 2016; Youn, 2003; Kim et al, 2004; Gulawani et al, 2006). In the packing type DCD, contact between the humid air and the cold fresh water takes place through the distribution of both fluids evenly along the packed bed. For even mass transfer of water along the packing bed which is essential for dehumidification, liquid distributors (such as nozzles) are used (Seader and Henley, 2006). In addition, liquid desiccant solutions are used as packing bed DCD coolants because of their great water absorbance and capability of dehumidifying humid air that comes in contact with them (Sahlot and Riffat, 2016; Yutong and Hongxing, 2007; Yin et al, 2014; Jain and Bansal, 2007; Campen et al, 2003; Mei and Dai, 2008;

Pahlavanzadeh and Nooriasl, 2012; Xiong et al, 2010; Elsarrag, 2006; Babakhani and Soleymani, 2009). Although the use of liquid desiccants in packed bed DCDs is very common, the concept is beyond the scope of this review because liquid desiccants DCDs do not offer direct freshwater production. In the spray type DCD, the contact between air and water occurs with spraying water droplets through nozzles or water jets directly on the air stream (Niroomand et al, 2015; Jacobs, 1988; Trofimov, 2011). In the pool-condensation type, vapor in the form of bubbles is injected through a perforated pipe to come in contact with a relatively cold pool of liquid as exemplified with the Sparge Pipe (McNaught, 2011).

Figure 1 illustrates the DCD working principle; the air stream enters the DCD with relatively high temperature and a humidity level close to saturation where it meets with the coolant fluid (a low-temperature water stream) that acts as the heat sink during contact (Kandlikar et al, 1999). Heat and mass transfer takes place in a direction governed by the temperature gradient during contact as implied by the second law of thermodynamics. In the DCD system, the latent heat load in the humid air is normally released onto the surface of the low-temperature water which causes the vapor to condense on the water surface. Hence, the mass of vapor in the air stream will transition to the surface of the water. Due to this mass transfer, the vapor molecules coalesces on the surface of the water droplet causing its mass to increase (Kandlikar et al, 1999; Oueslati and Megriche, 2017). Finally, the water droplet with its added mass is collected at the bottom of the DCD and the air exits the DCD seemingly drier.

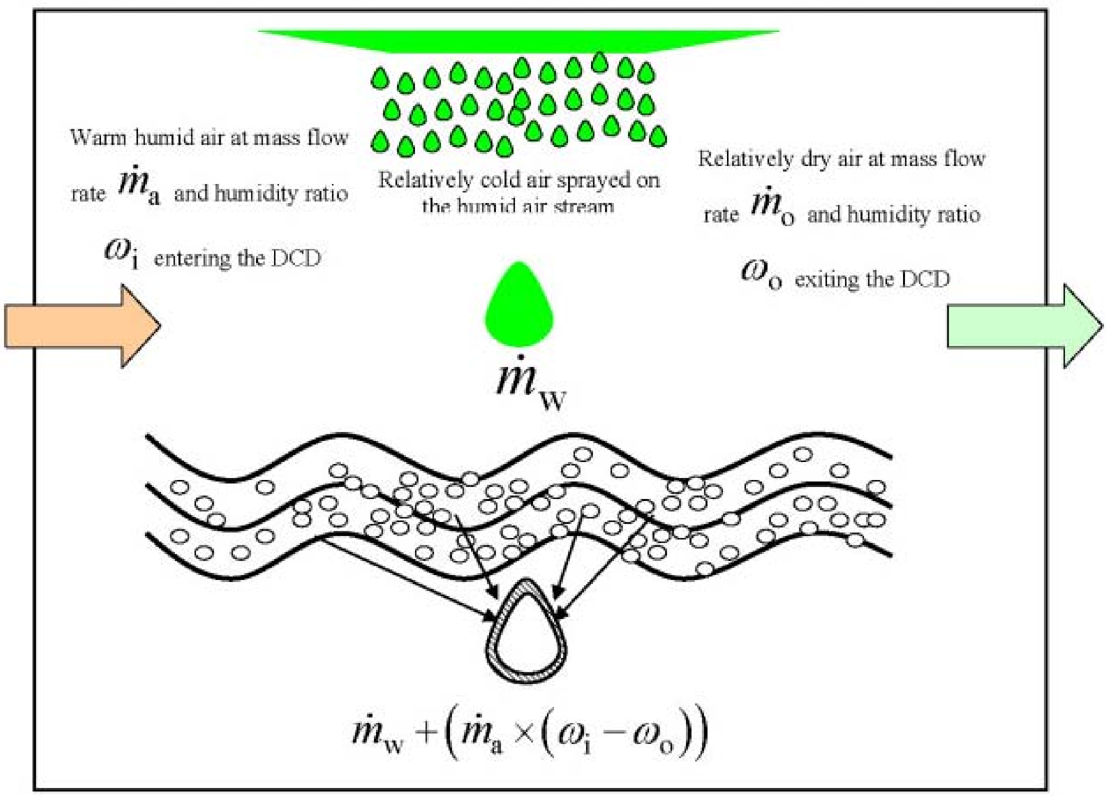

Figure 1. Schematic of the DCD working principle.

1.3. Psychrometric Calculations

Modeling of HDH systems is mainly based on psychrometric calculations of moist air. At a given atmospheric pressure, the thermodynamic state of air-water mixture can be identified by knowing any two of its intensive properties such as dry bulb temperature (°C), wet bulb temperature (°C), specific humidity (kg water/kg dry air), relative humidity (%), specific volume (m^3/kg dry air) and specific enthalpy (kJ/kg dry air). Specific humidity and enthalpy are the most relevant properties to HDH systems. With the knowledge of dry bulb temperature and relative humidity, these two values can be calculated using the following equations (ASHRAE, 2009):

$$\omega = \frac{0.62198P^{\mathrm{v}}}{P - \varphi P^{\mathrm{v}}} \ , \qquad (1)$$

where ω is the specific humidity (kg moist/kg dry air), φ is the relative humidity and P^{v} is the water vapor pressure (Pa) that can be calculated using:

$$P^{\mathrm{v}} = 610.78\exp\left(17.\frac{269T}{237.78+T}\right), \qquad (2)$$

where T is the dry bulb temperature (°C).

The enthalpy (referenced to kJ/kg dry air at $T = 0$ °C) can be calculated from (Cengel and Boles, 2015):

The enthalpy (referenced to $h = 0$ kJ/kg dry air at $T = 0$ °C) can be calculated from (Cengel and Boles ,2015):

$$h = 1.005T + \omega\left(2500.9 + 1.82T\right). \qquad (3)$$

Al-Azri et al, (2013) extensively described psychrometric calculations of any moist-air property with the knowledge of another two properties. In the dehumidification process (Figure 2), air-water mixture is cooled down to its wet bulb temperature value (1-1' line) which corresponds to 100% relative humidity. Any further cooling will result in the formation of water condensate and a decrease in the specific humidity of air (1'-2 line). The mass flow of the collected water can be calculated from:

$$\dot{m}_{\mathrm{w}} = \dot{m}_{\mathrm{a}}\left(\omega_2 - \omega_{1'}\right), \qquad (4)$$

where $\dot{m}_{\mathrm{a}}$ is the mass flow rate of dry air which can be calculated using the ideal gas equation :

$$\dot{m}_{\mathrm{a}} = \frac{P_{\mathrm{a}}\dot{V}}{R_{\mathrm{a}}T} \ , \qquad (5)$$

where $\dot{V}$ is the mixture volumetric flow rate (m^3/s) and P_a is the dry air partial pressure which can be calculated from:

$$P_a = P - P^v . \tag{6}$$

The change in the enthalpy of air can be calculated from:

$$\Delta H = \dot{m}_a \left(h_2 - h_1 \right) . \tag{7}$$

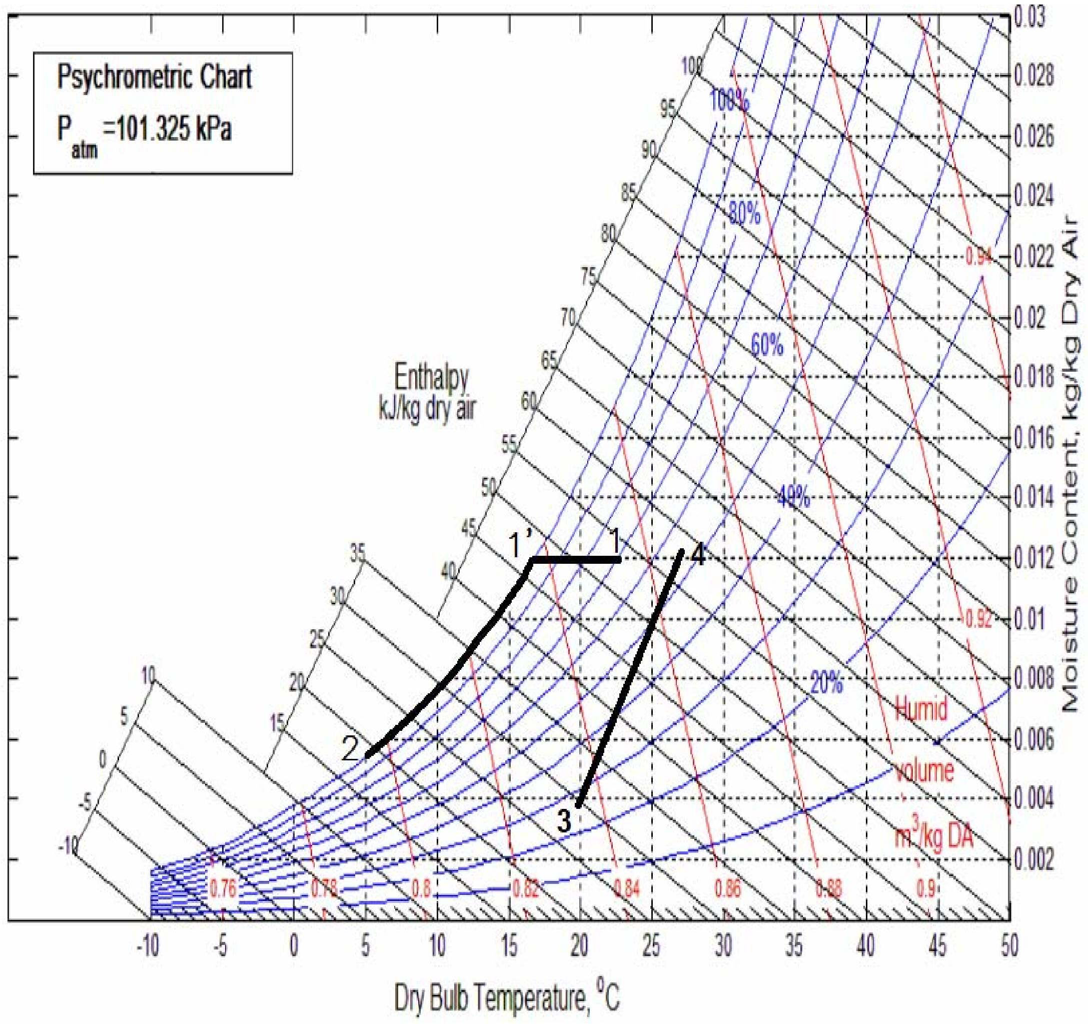

Figure 2. Dehumidification process.

Figure 2 also shows a humidification process of air-water mixture stream (3-4 line). The air stream is heated with direct contact with warmer water, which results in water mass transfer to the air stream and hence increasing its specific and relative humidity.

The amount of water vapor absorbed by air is:

$$\dot{m}_w = \dot{m}_a \left(\omega_4 - \omega_3 \right) . \tag{8}$$

The amount of heat transferred in the process is:

$$\Delta H = \dot{m}_{\text{a}} \left(h_4 - h_3 \right). \tag{9}$$

1.4. Historical development

In 1765 James Watt revolutionized the Newcomen steam engine with the idea of using a separate direct-contact condenser to make use of the latent heat of steam (Figure 3). The Newcomen steam engine relied on condensation of steam to create partial vacuum pressure needed for pumping, and the condensation occurred in the cylinder through indirect contact between cold water and the high pressure steam. James Watt invented a detached condensation chamber where the steam was condensed through direct contact with the cold water; consequently a great amount of heat loss was avoided (Kandlikar et al, 1999; Kingsford, 2017; The Hunterian Museum and Art Gallery, 2017).

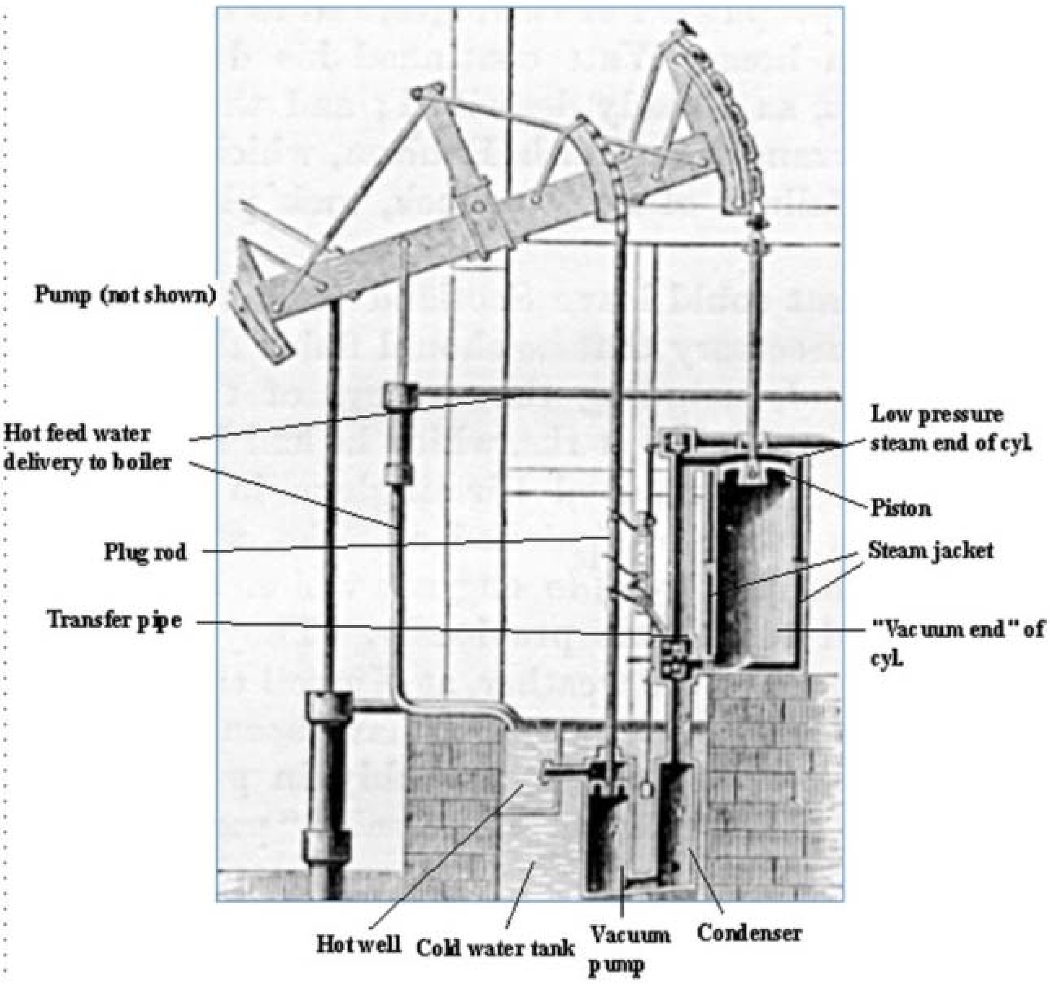

Figure 3. Modified James Watt's Newcomen steam engine (www.Sussexvt.k12.de.us).

Hausbrand in 1900 explained another type of direct-contact heat exchangers called the barometric condenser (Jacobs, 2011). This type of condenser is mainly composed of a shell body and a bundle of jet nozzles, and the discharge of the condensate and coolant is achieved through the use of a vertical tailpipe, if the apparatus is elevated to a certain height otherwise a discharge pump is used (Graham Corp, 2009). In 1923, Schutte and Koerting manufacturing company produced several types of barometric condensers including the first multi-jet barometric condenser. This condenser was working without air pumps and consisted of water jets only. Also, in 1936 they introduced a new multi-jet condenser with dual water inlets; top inlets with water jets of different flows to do most of the condensation and center inlets with fixed pressure jets to condense the uncondensed particles. In 1940, they introduced a modified version of their 1936 invention with a countercurrent flow pattern, Figure 4 (Schuttle and Koerting, 2014).

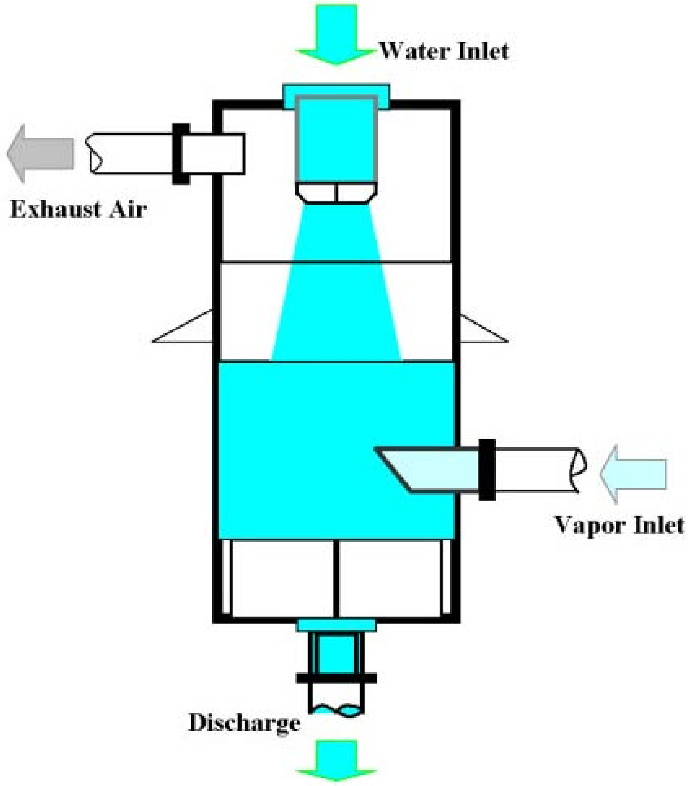

Figure 4. Counter-current barometric condenser **(**Schuttle and Koerting, 2014).

In 1961, a mathematical simulation for a direct-contact condenser showed that liquid film condensation resistance is negligible in packing type DCDs (Olander, 1961). In 1965, it was proposed to employ direct-contact condensation of refrigerants in all hydrate and freezing processes that use water-immiscible refrigerants (Saline Water Convers. Act). In 1974, Barrett and Dunn (Barrett and Dunn, 1974) simulated a DCD that is composed of a stack of trays inside a sealed tower where coolant water flows from top to trays underneath through a perforation at the bottom. Contact between coolant and vapor as vapor is injected in bubble form through the perforation at the bottom of the trays. They validated their work through comparison with experimental results collected from a hydrogen sulfide water dehumidifier. They proved the effectiveness and applicability of their simulation on several systems operating on condensation of superheated and supersaturated vapor. In 1988, direct contact heat transfer devices were classified according to their applications in different systems

(Kreith and Boehm, 1988). One of these systems was a dry cooling tower that was combining direct and indirect heat transfer processes (Figure 5). In this system, water is indirectly cooled via cooling coils and subsequently, this water is used to directly condense water vapor leaving the exhaust of a steam turbine. Further elaboration on the application of DCDs is given below.

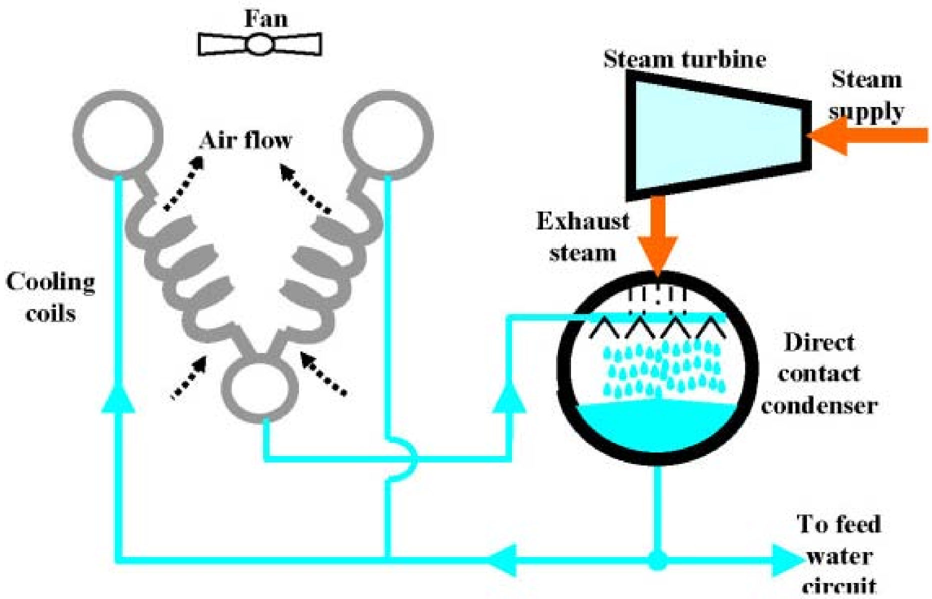

Figure 5. Dry cooling tower with a direct-contact condenser (Kreith and Boehm, 1988).

-

-

Bibliography

Airconditioning-systems, Dehumidifier, (2017). http://www.airconditioning-systems.com/dehumidifier.html (accessed October 23, 2017).

Al-Azri N.A., Y.H. Zurigat, N.Z. Al-Rawahi (2013), Development of bioclimatic chart for passive building design, *Int. J. Sustain. Energy*. 32, 713–723. doi:10.1080/14786451.2013.813026.

Al-Enezi G., H. Ettouney, N. Fawzy (2006), Low temperature humidification dehumidification desalination process, *Energy Convers. Manag*. 47, 470–484. doi:10.1016/j.enconman.2005.04.010.

Al-Hallaj S., S. Parekh, M.M. Farid, J.R. Selman, Solar desalination with humidification-dehumidification cycle: Review of economics, *Desalination*. 195 (2006) 169–186. doi:10.1016/j.desal.2005.09.033.

Al-Ismaili A.M. (2012), Water Production of Seawater Greenhouse in Oman, in: Abstr. Fog Collect. Symp., Salalah, Oman.

Al-Ismaili A.M. (2014), Seawater greenhouses in Oman: Experimental results, in: Int. Agric. Congr. Putrajaya, Malaysia.

Al-Ismaili A.M., E.K. Weatherhead, H. Jayasuriya (2012), Mathematical Simulation of the dehumidifier of Seawater Greenhouse, in: Int. Conf. Agric. Eng., Valencia, Spain,.

Al-Ismaili A.M., H. Jayasuriya (2016), Seawater greenhouse in Oman: A sustainable technique for freshwater conservation and production, Renew. *Sustain. Energy Rev*. 54, 653–664. doi:10.1016/j.rser.2015.10.016. [A review of the seawater greenhouse technology with emphasis on water production techniques to provide irrigation demand].

Allergyandair, Dehumidifiers, (2017). https://learn.allergyandair.com/indoor-air-quality-3/dehumidifiers/ (accessed October 22, 2017).

Alnaimat F., J.F. Klausner, R. Mei (2011), Transient analysis of direct contact evaporation and condensation within packed beds, *Int. J. Heat Mass Transf*. 54, 3381–3393. doi:10.1016/j.ijheatmasstransfer.2011.03.048. [A transient one-dimensional model used to simulate the heat and mass transfer occurring inside DCDs’].

Alsadaie S.M., I.M. Mujtaba (2017), Dynamic modelling of Heat Exchanger fouling in multistage flash (MSF) desalination, *Desalination*. 409, 47–65. doi:10.1016/j.desal.2017.01.020.

AMFAH dehumidifier, Dehumidifiers for Health Care, (2017). http://www.amfahdehumidifier.com/health-care.html (accessed October 22, 2017).

Arilaire.com, Aprilaire, (2018). https://www.aprilaire.com/whole-house-products/dehumidifier (accessed February 18, 2018).

Arundel A. V., E.M. Sterling, J.H. Biggin, T.D. Sterling, (1986) Indirect health effects of relative humidity in indoor environments, *Env. Heal. Perspect*. 65, 351–361. doi:10.1289/ehp.8665351.

ASHRAE (2009), *ASHRAE Handbook Fundamentals*, Atlanta, GA.

Ayyaswamy P.S. (1995), Direct-Contact Transfer Processes with Moving Liquid Droplets, *Adv. Heat Transf.* 26, 1–104. doi:10.1016/S0065-2717(08)70295-8.

Babakhani D., Soleymani M. (2009), An analytical solution for air dehumidification by liquid desiccant in a packed column, *Int. Commun. Heat Mass Transf.* 36, 969–977. doi:10.1016/j.icheatmasstransfer.2009.06.002.

Baharathan D., Parent Y, Hassani A.V. (1999), Method and apparatus for high-efficiency direct contact condensation, US5925291 A, 1999.[A novel multi-type and multi-flow-patter DCD invention].

Barrett E.C., Dunn S.G. (1974), Design of Direct Contact Humidifiers and Dehumidifiers Using Tray Columns, *Ind. Eng. Chem. Process Des. Dev*. 13, 353–358. doi:10.1021/i260052a009.

Bejan A. (1996), Entropy generation minimization: The new thermodynamics of finite-size devices and finite-time processes, *J. Appl. Phys.* 79, 1191–1218. doi:10.1063/1.362674.

Bejan A., Lorente S. (2013)., Constructal law of design and evolution: Physics, Biology, Technology, and Society, *J. Appl. Phys*. 113, doi:10.1063/1.4798429.

Boehlert C.R. (1971), Saline water conversion program, in: Legis. Hist. Saline Water Convers. Act, Vol. 6, Issue 1, n.d.: pp. 158–159.

Brundrett G.W., (1987) Handbook of Dehumidification Technology, in: Hand book. Dehumidification Technol., British Library Cataloguing in Publication Data, pp. 13–24. doi:10.1016/B978-0-408-02520-1.50005-9.

C. Yildirim, I. Solmuş (2014), A parametric study on a humidification-dehumidification (HDH) desalination unit powered by solar air and water heaters, *Energy Convers. Manag*. 86, 568–575. doi:10.1016/j.enconman.2014.06.016. [A case study that uses Fourth-order Runge–Kutta method to simulate the DCD operation].

Campen J.B., G.P.A. Bot, H.F. De Zwart (2003), Dehumidification of Greenhouses at Northern Latitudes, *Biosyst. Eng.* 86, 487–493. doi:10.1016/j.biosystemseng.2003.08.008. [Results of using GX software to simulate the heat and mass transfer occurring in a greenhouse to evaluate the evapotranspiration condensation occurring inside].

Celata G.P., M. Cumo, G.E. Farello, G. Focardi (1989), A comprehensive analysis of direct contact condensation of saturated steam on sub-cooled liquid jets, *Int. J. Heat Mass Transf.* 32, 639–654. doi:10.1016/0017-9310(89)90212-3.

Cengel Y.A. (2005), *Heat Transfer*: *A Practical Approach*, in: 2nd ed., McGraw-Hill: pp. 667–697.

Cengel Y.A., Boles M.A. (2015), *Thermodynamics: an Engineering Approach* 7th Edition, McGraw-Hill.

Chehayeb K.M., F.K. Cheaib, J.H. V Lienhard (2014), A numerical solution algorithm for heat and mass transfer model of a desalination system based on Packed-Bed Humidification and Bubble Column Dehumidification, Proc. 15th Int. Heat Transf. Conf. 1–15.

Chung T.W., A.L. Hines, D. Novosel (1995), Dehumidification of moist air with simultaneous removal of selected indoor pollutants by triethylene glycol solutions in a packed-bed absorber, *Sep. Sci. Technol*. 30, 1807–1832. doi:10.1080/01496399508010378.

Collins dictionary, Definition of “dehumidification,” (2017). https://www.collinsdictionary.com/dictionary/english/dehumidification (accessed October 3, 2017).

Condensation, *Natl. Geogr. Mag*. (2017). https://www.nationalgeographic.org/encyclopedia/condensation/ (accessed October 4, 2017).

Davis R.E., G.R. McGregor, K.B. Enfield (2016), Humidity: A review and primer on atmospheric moisture and human health, *Environ. Res*. 144, 106–116. doi:10.1016/j.envres.2015.10.014.

Elsarrag E. (2006), Dehumidification of air by chemical liquid desiccant in a packed column and its heat and mass transfer effectiveness, *HVAC R Res.* 12, 3–16. doi:10.1080/10789669.2006.10391164.

Eslamimanesh A., Hatamipour M.S. (2009), Mathematical Modeling of a Direct Contact Humidification – Dehumidification Desalination Process, Desalination. 237, 296–304. doi:10.1016/j.desal.2008.01.023. [A study that shows the criticality of the water-to-air-ratio on the DCD process].

Eslamimanesh A., Hatamipour M.S. (2010), Economical study of a small-scale direct contact humidification-dehumidification desalination plant, *Desalination*. 250, 203–207. doi:10.1016/j.desal.2008.11.015. [This study compares the economical aspects of using DCDs and compares it to the use of indirect-contact dehumidifiers].

Ettouney H. (2005), Design and analysis of humidification dehumidification desalination process, *Desalination*. 183 341–352. doi:10.1016/j.desal.2005.03.039.

Farid M.M., S. Parekh, J.R. Selman, S. Al-Hallaj (2003), Solar desalination with a humidification-dehumidification cycle: Mathematical modeling of the unit, *Desalination*. 151, 153–164. doi:10.1016/S0011-9164(02)00994-3.

Ford J.D., Lekic A. (1973), Rate of growth of drops during condensation, *Int. J. Heat Mass Transf.* 16, 61–62. doi:10.1016/0017-9310(73)90251-2.

Graham Corp., *Barometric Condenser*, *Prod. Man*. (2009) 2. http://www.graham-mfg.com/usr/Product Manuals/OMI_BARO_1097.pdf (accessed November 10, 2017).

Gulawani S.S., J.B. Joshi, M.S. Shah, C.S. Rama Prasad, D.S. Shukla (2006), CFD analysis of flow pattern and heat transfer in direct contact steam condensation, *Chem. Eng. Sci.* 61, 5204–5220. doi:10.1016/j.ces.2006.03.032.

Hashemifard S.A., Azin R. (2004) (2004), New experimental aspects of the carrier gas process (CGP), *Desalination*. 164, 125–133. doi:10.1016/S0011-9164(04)00171-7.

Hassaboua A., M. Spinnlerb, W. Polifkeb (2014), The Role of Conductive Packing in Direct Contact Humidification-Dehumidification Regenerators - Part I: Theoretical Analysis, *Int. J. Mech. Eng. Technol*. 5, 126–138.

Hayes D., M.A. Jhaveri, D.M. Mannino, H. Strawbridge, J. Temprano (2013), The effect of mold sensitization and humidity upon allergic asthma, *Clin. Respir. J.* 7, 135–144. doi:10.1111/j.1752-699X.2012.00294.x.

He W.F., L. Huang, J.R. Xia, W.P. Zhu, D. Han, Y.K. Wu (2017), Parametric analysis of a humidification dehumidification desalination system using a direct-contact dehumidifier, *Int. J. Therm. Sci*. 120, 31–40. doi:10.1016/j.ijthermalsci.2017.05.027. [A case study to use DCD to disalinate brakish water by utilizing waste heat].

Hijikata K., Y. Mori, S. Kawaguchi (1984), Direct contact condensation of vapor to falling cooled droplets, *Int. J. Heat Mass Transf.* 27, 1631–1640. doi:10.1016/0017-9310(84)90275-8. [Experimentally utilizing the subcooled state of the condensed droplets for condensation enhancement].

Hou S. (2008), Two-stage solar multi-effect humidification dehumidification desalination process plotted from pinch analysis, *Desalination*. 222, 572–578. doi:10.1016/j.desal.2007.01.127.

Iihf, Technical guidelines of an ice rink, in: *IIHF Arena Man*., 2002: pp. 15–37.

Incropera F.P., DeWitt D.P. (1990), *Fundamentals of Heat and Mass Transfer*, 3rd ed., John Wiley & Sons.

Jaber H., Webb R.L. (1989), Design of Cooling Towers by the Effectiveness-NTU Method, *J. Heat Transfer*. 111, 837. doi:10.1115/1.3250794.

Jacobs H.R. (1988), Direct-Contact Condensation, in: Kreith F., Boehm R.F. *Direct-Contact Heat Transf.*, Springer, Berlin, Heidelberg, doi:https://doi.org/10.1007/978-3-662-30182-1_12.

Jacobs H.R. (2011), Direct Contact Heat Exchangers, *THERMOPEDIATM*. doi:10.1615/AtoZ.d.direct_contact_heat_exchangers.

Jain S., Bansal P.K. (2007), Performance analysis of liquid desiccant dehumidification systems, *Int. J. Refrig.* 30, 861–872. doi:10.1016/j.ijrefrig.2006.11.013.

Kandlikar S.G., V.K. Dhir, M. Shoji (1999), *Handbook of Phase Change: Boiling and Condensation*, doi:10.1017/CBO9781107415324.004.

Kim Y.-S., J.-W. Park, C.-H. Song (2004), Investigation of the stem-water direct contact condensation heat transfer coefficients using interfacial transport models, *Int. Commun. Heat Mass Transf.* 31, doi:10.1016/j.icheatmasstransfer.2004.02.010.

Kingsford P.W., James Watt, *Encycl. Br.* (2017). https://www.britannica.com/biography/James-Watt (accessed November 5, 2017).

Klausner J.F., L. Yi, M. Darwish, R.W. Mei (2004), Innovative diffusion driven desalination process, *J. Energy Resour. Technol*. ASME. 126, 219–225. doi:10.1115/1.1786927.

Kreith F., Boehm R.F. (1988), Direct-Contact Devices and Application, in: *Direct-Contact Heat Transf.*, Springer-Verlag Berlin Heidelberg: pp. 3–9. doi:10.1007/9783662301821.

Kumar, R., & Asati, A. K. (2014). Simplified Mathematical Modelling of Dehumidifier and Regenerator of Liquid Desiccant System. International Journal of Current Engineering and Technology, 4(2), 557–563.

Lekic A., Ford J.D. (1980), Direct contact condensation of vapour on a spray of sub-cooled liquid droplets, *Int. J. Heat Mass Transf.* 23, 1531–1537. doi:10.1016/0017-9310(80)90156-8.

Li C., Y. Ma, Y. Li, F. Wang (2010), EIS monitoring study of atmospheric corrosion under variable relative humidity, Corros. Sci. 52, 3677–3686. doi:10.1016/j.corsci.2010.07.018.

Li X., S. Liu, X. Cui, H. Li (2013), Experimental study of direct contact steam condensation in structured packing, *Asia-Pacific J. Chem. Eng*. 8, 657–664. doi:10.1002/apj.1706. [This study presents a primary parametric analysis of variables affecting direct contact condensation].

Li Y., J.F. Klausner, R. Mei, J. Knight (2006), Direct Contact Condensation in Packed Beds, *Int. J. Heat Mass Transf.* 49, 4751–4761. doi:10.1016/j.ijheatmasstransfer.2006.06.013.[Experimental work to investigate the use of DCD to condense vapor in a diffusion driven desalination process].

Lin Jie Huang, Ayyaswamy P.S. (1987), Heat and mass transfer associated with a spray drop experiencing condensation: a fully transient analysis, *Int. J. Heat Mass Transf*. 30, 881–891. doi:10.1016/0017-9310(87)90007-X. [A study that presents A unit cylinder cell model with a body-fitted coordinate system to examine the interaction between neighbouring droplets in a spray-type DCD]

Maalouf S., E. Boulawz Ksayer, D. Clodic (2016), Investigation of Direct Contact Condensation for Wet Flue-Gas Waste Heat Recovery Using Organic Rankine Cycle, *Energy Convers. Manag*. 107, 96–102. doi:10.1016/j.enconman.2015.09.047.

Mahood H.B., A.O. Sharif, S. Al-Aibi, D. Hawkins, R. Thorpe (2014), Analytical Solution and Experimental Measurements for Temperature Distribution Prediction of Three-Phase Direct-Contact Condenser, *Energy*. 67, 538–547. doi:10.1016/j.energy.2013.12.026.

McNaught J.M. (2011), Condensers, THERMOPEDIATM. doi:10.1615/AtoZ.c.condensers.

Mehrgoo M., Amidpour M. (2012), Constructal Design and Optimization of a Direct Contact Humidification-Dehumidification Desalination Unit, *Desalination*. 293, 69–77. doi:10.1016/j.desal.2012.02.025.

Mei L., Dai Y.J. (2008), A technical review on use of liquid-desiccant dehumidification for air-conditioning application, *Renew. Sustain. Energy Rev*. 12, 662–689. doi:10.1016/j.rser.2006.10.006.

Mohamed E.S., G. Papadakis, E. Mathioulakis, V. Belessiotis (2006), An experimental comparative study of the technical and economic performance of a small reverse osmosis desalination system equipped with an hydraulic energy recovery unit, *Desalination*. 194, 239–250. doi:10.1016/j.desal.2005.10.031.

Mohammad A.T., S.B. Mat, A.A. Al-abidi (2015), Liquid desiccant dehumidification in air-conditioning systems.

Narayan P. G., J.H. Lienhard, S.M. Zubair (2010), Entropy generation minimization of combined heat and mass transfer devices, *Int. J. Therm. Sci*. 49, 2057–2066. doi:10.1016/j.ijthermalsci.2010.04.024. [A study that introduces a modified heat capacity ratio rate as a mean of evaluating the technical effectiveness of heat exchangers]

Narayan P. G., K.H. Mistry, M.H. Sharqawy, S.M. Zubair, J.H. Lienhard (2010), Energy effectiveness of simultaneous heat and mass exchange devices, Front. *Heat Mass Transf*. 1, doi:10.5098/hmt.v1.2.3001. [A study of literature on technically evaluating the effectiveness of heat exchanging devices].

Narayan P.G., G.P. Thiel, R.K. McGovern, J.H. Lienhard, M.H. Elsharqawy (2014), Humidification-Dehumidification System Including a Bubble-Column Vapor Mixture Condenser, US8778065 B2,. https://www.google.com/patents/US8778065. [A novel multi-type DCD invention]

Nellis G., Klein S. (2009), Heat Transfer, Cambridge University Press.

Niroomand N., M. Zamen, M. Amidpour (2015), Theoretical Investigation of Using a Direct Contact Dehumidifier In Humidification- Dehumidification, *Desalin. Water Treat*. 54, 305–315. doi:10.1080/19443994.2014.880157. [This paper studied the use of DCD in a HDH system to show the most critical parameters that affect water production].

Olander, D.R. (1961). Design of direct cooler-condensers. Industrial and Engineering Chemistry, Vol. 53, No. 2, (February 1961), pp. 121-126, ISSN 0019-7866

Oueslati A., Megriche A. (2017), Performance analysis of a new humid air dehumidifier, *Energy Procedia*. 119, 453–465. doi:10.1016/j.egypro.2017.07.049.

Pahlavanzadeh H., Nooriasl P.(2012), Entropy generation in liquid desiccant dehumidification system, in: *Energy Procedia*,: pp. 1855–1860. doi:10.1016/j.egypro.2011.12.887.

Parekh S., M.M. Farid, J.R. Selman, S. Al-Hallaj (2004), Solar desalination with a humidification-dehumidification technique - A comprehensive technical review, *Desalination*. 160, 167–186. doi:10.1016/S0011-9164(04)90007-0.

Perret J.S., A.M. Al-Ismaili, S.S. Sablani (2005), Development of a humidification-dehumidification system in a Quonset greenhouse for sustainable crop production in arid regions, *Biosyst. Eng*. 91, 349–359. doi:10.1016/j.biosystemseng.2005.04.009. [A paper on constructing a seawater greenhuse in the sultanate of Oman].

Perret J.S., A.M. Al-Ismaili, S.S. Sablani (2005), Humidification-dehumidification system in a greenhouse for Sustainable Crop Production, in: Ninth Int. Water Technol. Conf., Sharm El Sheikh, Egypt: pp. 849–862.

Rahimi A., D. Babakhani (2013), Mathematical modeling of a packed-bed air dehumidifier: The impact of empirical correlations, *J. Pet. Sci. Eng*. 108, 222–229. doi:10.1016/j.petrol.2013.03.031. [A study that presents empirical correlations for both; structured and random packing-bed heat exchangers]

Sahlot M., Riffat S.B. (2016), Desiccant cooling systems: A review, *Int. J. Low-Carbon Technol.* 11, 489–505. doi:10.1093/ijlct/ctv032.

Schmack M., G. Ho, M. Anda (2016), Technical evaluation of simple condenser devices for a bubble column desalinator, Desalin. Water Treat. 57, 18573–18587. doi:10.1080/19443994.2015.1096835.

Schutte and Koerting. (2014), Barometric Condensers, 1–12. https://www.s-k.com/pdf/5AA_barometric_condensers_brochure.pdf (accessed November 5, 2017).

Seader J.D., Henley E.J. (2006), Separation process principles, in: *Choice Rev. Online*, 2nd ed., http://choicereviews.org/review/10.5860/CHOICE.36-5112.

Shah R.K., Sekulić D.P. (2003), Classification of Heat Exchangers, in: Fundamentals of Heat Exchanger Design,: pp. 4–6. doi:10.1007/BF00740254.

Shaman J., V.E. Pitzer, C. Viboud, B.T. Grenfell, M. Lipsitch (2010)., Absolute humidity and the seasonal onset of influenza in the continental United States, PLoS Biol. 8, doi:10.1371/journal.pbio.1000316.

Sharshir S.W., G. Peng, N. Yang, M.A. Eltawil, M.K.A. Ali, A.E. Kabeel (2016), A hybrid desalination system using humidification-dehumidification and solar stills integrated with evacuated solar water heater, *Energy Convers. Manag*. 124, 287–296. doi:10.1016/j.enconman.2016.07.028. [A novel design of a hybrid solar desalination system that reuses warm water drained from a DCD].

Somerscales E.F.C. (1997), Fundamentals of corrosion fouling, *Exp. Therm. Fluid Sci*. 14, 335–355. doi:10.1016/S0894-1777(96)00136-7.

Survey U.S. Department of the Interior | U.S. Geological, Condensation - The Water Cycle, (2016). https://water.usgs.gov/edu/watercyclecondensation.html (accessed February 18, 2018).

The Hunterian Museum and Art Gallery, Model Newcomen Engine, Repaired by James Watt, (2017). http://www.huntsearch.gla.ac.uk/cgi-bin/foxweb/huntsearch/DetailedResults.fwx?collection=all&SearchTerm=C.29&mdaCode=GLAHM (accessed November 5, 2017).

Thepurefactory, Dehumidifier, (2013). http://thepurefactory.com/en/catalog/pure-factory/climate-control/humity/dehumidifier (accessed October 22, 2017).

Tow E.W., J.H. Lienhard (2014), Experiments and Modeling of Bubble Column Dehumidifier Performance, *Int. J. Therm. Sci*. 80, 65–75. doi:10.1016/j.ijthermalsci.2014.01.018.

Tow E.W., Lienhard J.H., Analytical modeling of a bubble column dehumidifier, in: ASME 2013 Heat Transf. Summer Conf. Collocated with ASME 2013 7th Int. Conf. Energy Sustain. ASME 2013 11th Int. Conf. Fuel Cell Sci. Eng. Technol. HT 2013, 2013. doi:10.1115/HT2013-17763. [Introducing algebraic equations to model bubble column condensation].

Trofimov L.I. (2011), Intensification of heat transfer in a jet condenser by additional jet splitting using a grid, *Theor. Found. Chem. Eng*. 45, 75–80. doi:10.1134/S004057951101012X.

Wang K., T. Hu, A.H. Hassabou, M. Spinnler, W. Polifke (2013), Analyzing and modeling the dynamic thermal behaviors of direct contact condensers packed with PCM spheres, *Contin. Mech. Thermodyn.* 25, 23–41. doi:10.1007/s00161-012-0246-9. [Experimental work that shows the insignificance of the effect of using phase changing materials on water production in case of co-curent stream of fluids].

Xiong R., S. Wang, Z. Wang 2006), A mathematical model for a thermally coupled humidification-dehumidification desalination process, *Desalination*. 196, (177–187. doi:10.1016/j.desal.2006.01.012.

Xiong Z.Q., Y.J. Dai, R.Z. Wang (2010), Development of a novel two-stage liquid desiccant dehumidification system assisted by $CaCl_2$ solution using exergy analysis method, *Appl. Energy*. 87, 1495–1504. doi:10.1016/j.apenergy.2009.08.048.

Yang H., J. Wu, J. Cheng, X. Wang, L. Wen, K. Li, H. Su, (2015), Is high relative humidity associated with childhood hand, foot, and mouth disease in rural and urban areas?, *Public Health*. 1–7. doi:10.1016/j.puhe.2015.03.018.

Yin Y., J. Qian, X. Zhang (2014), Recent advancements in liquid desiccant dehumidification technology, *Renew. Sustain. Energy Rev.* 31, 38–52. doi:10.1016/j.rser.2013.11.021.

Youn D.H., K.B. Ko, Y.Y. Lee, M.H. Kim, Y.Y. Bae, J.K. Park (2003), The Direct Contact Condensation of Steam in a Pool at Low Mass Flux, *J. Nucl. Sci. Technol*. 40, 881–885. doi:10.1080/18811248.2003.9715431.

Yutong L., Hongxing Y. (2008), Investigation on solar desiccant dehumidification process for energy conservation of central air-conditioning systems, *Appl. Therm. Eng.* 28, 1118–1126. doi:10.1016/j.applthermaleng.2007.08.006.

Zamen M., M. Amidpour, M.R. Firoozjaei (2013), A novel integrated system for fresh water production in greenhouse: Dynamic simulation, *Desalination*. 322, 52–59. doi:10.1016/j.desal.2013.04.024.[A case study that investigates the ude of DCD in greenhouses through dynamic simulation].

Zheng H. (2017), Humidification–Dehumidification Solar Desalination Systems, in: *Sol. Energy Desalin. Technol*.: pp. 447–535. doi:10.1016/B978-0-12-805411-6.00006-3.

Biographical Sketches

Abubaker S. Omer received his Bachelor of Science degree in mechanical engineering from University of Khartoum, Sudan in 2015. After that he received his Master of Science degree early in 2020 from Sultan Qaboos University, Oman. His interest is directed towards agriculture and renewable energy.

Abdulrahim M. Al-Ismaili received his Bachelor of Science in agricultural engineering in 1999 and in 2003. He received his Master of Science in agricultural and bio-resource engineering, both from Sultan Qaboos University. In 2009, he received his PhD from Cranfield University, UK. His key-expertise is in the areas of greenhouses, heat and mass transfer, irrigation water provision and supply.

Nasser A. Al-Azri received his Bachelor of engineering degree in chemical engineering at Sulatn Qaboos University in 1999. He received his MS from the University of Texas A&M, USA in 2002. In 2007, he received a business graduate degree from Texas A&M. In 2007, he received his Master of Engineering in industrial engineering. In 2008, he received his PhD in chemical engineering. In 2018, he became an associate professor at the mechanical engineering department in Sulatn Qaboos University.