Humidification– Dehumidification (HDH) Spray Column Direct Contact Condenser
Part I: Countercurrent Flow
A. Karameldin, L. Shouman and D. Fadel
Reactors Department, Nuclear Research Center, Atomic Energy Authority, Cairo, Egypt
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ABSTRACT
Humidification-Dehumidification (HDH) is a low grade energy desalination technology. Hot humid air and cooling spray water in counter current flow with direct contact is theoretically analyzed in the present work. Direct contact spray condenser is studied to obtain the effect of various parameters on its performance. A computer program describing the theoretical model is designed to solve one-dimensional differential equations by using Runge-Kutta method. The results show that the column length has a great effect on the performance of the spray condenser. At a column height of 2, 5, 10, and 20 m the humidity of the outlet air decreases by 72, 89, 97, and 99% respectively. The humid air temperature has a great influence on the productivity; meanwhile the temperature difference between the humid air and sprayed water has less effect. A case study of a contiguous co-generation electricity and water in Nuclear Power Plants (NPP) shows that the optimal productivity by HDH is feasible and can reach more than 15 m³/day.m², enabling a total productivity that varied from 120,000 to 300,000 m³/day. The design curves describing the process are obtained together in addition to a formula for the optimal productivity in terms of humid air and sprayed water fluxes at different humid air temperatures is derived.

INTRODUCTION
The need for new fresh water resources to balance the growing consumption rate represents one of the major worldwide challenges in the near future. Seawater distillation processes that have attracted interest over the past century provide serious solutions for increasing the water supply. Humidification - Dehumidification (HDH) is a promising technology as it operates at low temperature and can be driven by low grade waste heat, enabling the production of unlimited freshwater supply. HDH process operates on the principle of mass diffusion from sea or brackish water by passing and heating of low humid air(ambient air) through it (Humidification), followed by condensing the diffused mass from the humid air via a direct contact (open) condenser (Dehumidification).

The whole HDH process was analyzed in the literature by many researchers. Parametric studies, thermodynamic analysis, modeling, and performance evaluation were performed by Al-Hallaj et al (1), Saadawy et al (2), Chafik, (3, 4, and 5), Orfi et al (6), Fath et al (7), Nafey et al (8, 9), Hashemifard and Azin (10), Al-Enezi et al (11), Xiong et al (12 and 13), Ettoney (14), and Narayan et al (15). The operating conditions of all these investigations have indicated that the maximum allowable temperature range is from 46 to 90°C, the water stream range is 0.0167 up to 4.25 kg/m².s, and the air stream range is 0.01 to 2.5 kg/m².s.

The modeling of the evaporative tower (Humidification), was performed by Klausner et al (16, 17), Dalili (18), and the Authors (19).

Corresponding authors E-mail:AlyKarameldin@hotmail, loulashouman@yahoo.com, dalia_shaaban@windowslive.com.
The modeling and enhancement of the dehumidifier researches were very limited. This includes the work of in Klausner et al. (16 and 17), Tow and Lienhard (20), Knight (21), and LI (22). Meanwhile, the same essence of mathematical model is found in the evaporative cooling by Raouf and Jasim (23) and Fisenko et al. (24).

The main limitations of the HDH desalination process is the low thermal effectiveness of dehumidification section. It exists as a direct contact condenser which can take the form of backed bed, bubbling column, spray column (co-current and/or countercurrent). The packed bed direct contact condenser type has the highest effectiveness compared to the other types. Unfortunately, it is subjected to fouling problems resulting in the deterioration of its effectiveness.

Recently, a comprehensive work in the area of HDH condenser, including spray column and bubbling column direct contact condenser is being done. The present work is performed through the construction of an experimental setup to investigate the effect of the operating parameters on the performance of the direct contact condensation process. This comes in this context, where the HDH countercurrent flow Spray Column Direct Contact Condenser is evaluated theoretically. This evaluation can be done through studying the effects of the spray column parameters such as: the column height, the humid air and spray water mass fluxes, the humid air and spray water inlet temperatures and their temperature differences, and the column height versus the productivity costs, of the condenser.

THEORETICAL MODEL

A one-dimensional, quasi-steady mathematical model for a falling droplet in the direct contact condenser (without packing) is presented based on the conservation principles (16, 17 and 24). The following physical assumptions are made to simplify the model:

1. Droplets are of spherical shape and a uniform droplet distribution.
2. No droplet interactions with one another in the axial or transverse direction.
3. An average droplet temperature is considered for the quasi-steady state calculations on the droplet side.
4. Empirical correlations are used for the heat and mass transfer coefficient calculations.

The conservation equations for mass, momentum, and energy of a moving droplet are:

1-Variation of Droplet Size-Mass Transfer

The cold fresh-spray water droplets at temperature \( T_d \) will increase in size due to the condensation of the vapor, which is contained in the gas stream at a higher temperature \( T_a \). Considering a single droplet in the control volume, the rate of change in the droplet radius, \( R_d \), as it flows down the condenser chamber can be calculated as:

\[
\frac{dR_d}{dz} = \gamma_d \left( \frac{\rho_v(T_a) - \rho_{sat}(T_d)}{\rho_w \nu_d} \right)
\]

Where: \( z \) is the vertical coordinate, measuring from where droplets are introduced; 
\( \rho_w \) is the spray water droplet density (kg/m\(^3\)); 
\( \rho_v \) is the vapor density at temperature \( T_a \); 
\( \rho_{sat} \) is the vapor density corresponding to temperature \( T_{sat} \); 
\( R_d \) and \( \nu_d \) are the radius and velocity of the droplet; and 
\( \gamma_d \) is the mass transfer coefficient (m/s).

The mass transfer coefficient \( \gamma_d \) is empirically calculated from:

\[
\gamma_d = \frac{D(2 + 0.5 \ Re^{1/2})}{2R_d}
\]
Where; $D$ is the diffusion coefficient of water vapor and Reynolds number is based on the relative velocity between the droplet, $v_d$, and gas/vapor velocity, $u_a$:

$$\text{Re} = \frac{2 \rho_a R_d |v_d - u_a|}{\mu_a} \quad (3)$$

Where, $\mu_a$ is the dynamic viscosity of humid air.

2- Droplet Velocity - Momentum Transfer

To predict the droplet velocity $v_d$, Newton's second law is applied. The rate of change of momentum of the continuously accelerating droplet considers the aerodynamic drag force and the gravitational force:

$$\frac{dv_d}{dz} = \frac{g}{v_d} - C_{\text{drag}} \frac{\rho_a (v_d - u_a)^2}{2m_d v_d} \pi R_d^2 - \frac{3}{R_d} v_d \frac{dR_d}{dz} \quad (4)$$

Where, $C_{\text{drag}}$ is the aerodynamic drag coefficient on the droplet based on a standard empirical correlation, $u_a$ is the velocity of air/vapor mixture; $m_d$ is the droplet mass; and $g$ is the gravitational acceleration.

The drag coefficient $C_{\text{drag}}$, is estimated using the empirical relation,

$$C_{\text{drag}} = \frac{24}{Re} \left(1 + \frac{1}{6} Re^{2/3}\right) \quad (5)$$

The mass of an individual droplet is given as

$$m_{\text{drop}} = \frac{4}{3} \pi R_d^3 \rho_l \quad (6)$$

The mass flow rate of humid air assumed to be constant at an average air density $\rho_a$ of 1.16 kg/m$^3$. Hence, the air/vapor velocity $u_a$ is calculated as:

$$u_a = \frac{G}{\rho_a + \rho_v} \quad (7)$$

3- Droplet Temperature - Energy Transfer

The droplet temperature is affected by the convective heat transfer of air/vapor flow around the droplet and the phase change. The rate of change of droplet volume-average (bulk) temperature due to condensation of water vapor on the droplet surface is given by:

$$\frac{dT_d}{dz} = \frac{3 \left[U(T_a - T_d) + \gamma_d (\rho_v(T_a) - \rho_{\text{sat}}(T_d)) \left(h_{fg} - C_{pw} T_d\right)\right]}{\rho_w C_{pw} \rho_v v_d R_d} \quad (8)$$

Where: $U$ is the heat transfer coefficient; $h_{fg}$ is the latent heat of vaporization at $T_a$; and $C_{pw}$ is the specific heat of the spray water droplet.

The heat transfer coefficient, $U$ is estimated from:

$$Nu = 2R_d U / \kappa_a$$

rearranging $U = Nu k_a / 2R_d \quad (9)$

Nusselt number is given by the following empirical correlation:

$$Nu = 2 + 0.5 \text{Re}^2 \quad (10)$$
Where, $D$, $\mu_a$, and $k_a$ are the droplet physical properties, which they are temperature dependent.

### 4-Air Temperature Variation- Energy Transfer

Similarly, conservation of energy and mass on the air-vapor mixture yields expression for the change in the humid air temperature.

$$\frac{dT_a}{dz} = -4\pi R_d^2 N_d \left\{ U(T_a - T_d) - h_l \gamma_d (\rho_v(T_a) - \rho_{sat}(T_d)) \right\} \rho_{mix} C_{p_{mix}} U_a$$

Here, the saturated vapor density and relative humidity are related to

$$\rho_{sat}(T_a) \phi = \rho_{sat}(T_d)$$

Where: $h_l$ is the specific liquid enthalpy at $T_a$, $N_d$ is the specific number of droplets (number of droplets per unit volume) at any axial location. $N_d$ is related to the mass flux of spray water, $L$, droplet radius, and droplet velocity as:

$$N_d = \frac{L}{(4/3)\pi R_d^3 \rho_v \nu d}$$

The density and specific heat of the air/vapor mixture are computed as:

$$\rho_{mix} = \rho_a + \rho_v$$
$$C_{p_{mix}} = \frac{\rho_a}{\rho_a + \rho_v} C_{p_a} + \frac{\rho_v}{\rho_a + \rho_v} C_{p_v}$$

In the analysis, $N_d^* \nu_d$ is the specific number of droplets flux through the cross section, and it assumed is constant.

### 5-Mass Flux of Condensed Vapor

The rate of condensed liquid into the spray water droplets is given by:

$$m_{cond, vap} = 4/3\pi \left( R_{df}^3 - R_{d0}^3 \right) \rho_w N_{d0} \nu_{d0}$$

To verify the mass balance, the rate of vapor condensed out of the air/vapor mixture,

$$m_{cond, vap} = (\rho_{v0} - \rho_{vf}) u_a$$

Where: $R_d$ and $\rho_d$ are the final droplet radius and water vapor density of air/vapor mixture leaving the condenser, respectively. Also, verifying the rate of condensed vapor out of air/vapor mixture which can be calculated from the absolute specific humidity $\omega$, as:

$$m_{cond, vap} = (\omega_0 - \omega_f) G/(1 + \omega_0)$$

For an air/vapor mixture, $P_{sat}(T_a)$ is the saturation pressure at $T_a$ and the relative humidity $\phi$.

### 6-Boundary Conditions

The initial droplet radius, temperature, and injection velocity at the top of the condenser ($Z=0$) are $R_{d0}, T_{d0}$, and $\nu_{d0}$. At the same time, the air/vapor inlet at $Z=H$, the air temperature is $T_{a0}$ and vapor density is $\rho_{v0}$, which is taken as the saturated vapor density corresponding to air temperature $T_a$.  

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7-Solution Methodology

Equations (1), (4), (8), and (11) comprise a set of coupled ordinary differential equations (ODE), that are used to solve for the variation of droplet size, droplet velocity, droplet temperature and air/vapor mixture temperature distributions, and humidity ratio along the height of the condenser. The coupled first order nonlinear ODEs are solved by fourth order Runge-Kutta method. These coupled differential equations are simultaneously solved numerically by means of a developed computer program which predicts the behavior of the droplet and state variables with column height.

To examine the validity of the mathematical model, a comparison between the present program and Klausner\[17\] results, at the same input data, is carried out. Which shows a good agreement as demonstrated in Table (1).

Table (1): Validation of the computer program.

<table>
<thead>
<tr>
<th>Operating parameters</th>
<th>Input data</th>
<th>Klausner[17]</th>
<th>Program</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet humid air temperature,(°C)</td>
<td>34.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water droplet temperature,(°C)</td>
<td>26.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humid air mass flux,(kg/m².s)</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spray water mass flux,(kg/m².s)</td>
<td>0.066</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Droplet radius,(m)</td>
<td>5*E-4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Droplet velocity,(m/s)</td>
<td>0.65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column height,( m)</td>
<td>0.762</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculated parameters:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outlet air temperature, (°C)</td>
<td>30.78</td>
<td>30.25</td>
<td>1.73</td>
<td></td>
</tr>
<tr>
<td>Outlet droplet temperature,(°C)</td>
<td>29.1</td>
<td>28.74</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>Droplet radius,(m)</td>
<td>5.0067E-4</td>
<td>5.008E-4</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Droplet velocity,(m/s)</td>
<td>2.75</td>
<td>2.87</td>
<td>4.37</td>
<td></td>
</tr>
</tbody>
</table>

It should be mentioned that the data listed in Table (1) are primitive owing to the low ranges of air–water fluxes and the column height. From previous studies \[9-25\], the input temperatures of humid air varied from 34.2 to 80°C and the inlet spray water droplets temperature varied from 25 to 45°C. Meanwhile, the humid air and spray water mass fluxes varied from (0.25 to 3.5 kg/m².s) and (1.25 to 100 kg/m².s) respectively.

RESULTS AND DISCUSSION

Evaluation of the HDH countercurrent flow Spray Column Direct Contact Condenser is performed through the parametric study of the effects of the spray column operating parameters such as: the spray column height, the temperatures and the mass fluxes of the humid air and the sprayed water droplet, on the productivity of the spray column.

1- The effect of Column Height

The effect of the column height H on the output absolute humidity and condensate flow rate of the humid air is studied (at the same operating conditions). As shown in Fig. (1), the increase of the column height reduces the output absolute humidity of the humid air and subsequently increases the condensate flow rate. The absolute humidity of the output air at H = 0.76 m is about 50% of the inlet humid air (0.035). Meanwhile, it is found at column heights of 2, 5, 10 and 20 m, that the absolute humidity of the outlet air decreases by 72, 89, 97, and 99% respectively. The figure clearly indicates that the column height from 5 to 10 m gives the maximum attainable productivity in the aforementioned operating conditions, while for a column height over 10 m, the productivity is not noticeable.
In an attempt to find the column productivity, the effect of different operating parameters are studied. Fig. (2-1) depicts the effect of the humid air mass fluxes variations (at different column heights and a fixed spray water mass flux of 0.066 kg/m².s) on the column productivity. It is noticed that the maximum productivity is attained at the humid air mass flux G from 0.1 to 0.25 kg/m².s, depending on the column height. Also the productivity does not noticeably increase that the maximum productivity is attained at the humid air mass flux G from 0.1 to 0.

Fig. (2-2) depicts the effects of the spray water mass flux variations (at different humid air mass fluxes and column heights) on the column productivity. It is noticed that the maximum productivity is attained at a liquid mass flux (L) from 0.1 to 0.35 (kg/m².s), depending on the humid air mass flux and the column height. The higher the humid air mass flux and the higher the spray water mass flux, the higher the productivity.

**Fig. (1):** Effect of the column height on the absolute humidity and the condensate flow rate.

**Fig. (2-1):** Effect of different column heights at various values of absolute humidity and condensate flow rate with humid air mass flux.

**Fig. (2-2):** Effect of spray water mass flux on the condensate flow rate at different column height.
2-The Effect of Humid Air Temperature

As shown in the previous figures, the spray column height has a significant effect on condensate and output air humidity. Therefore, the influence of inlet humid air temperature $T_a$ has been studied and presented in Fig. (3). Fig. (3)(1a, 1b, 2a, 2b, 3a and 3b) illustrate variation of the inlet humid air temperature on the output air humidity and water production at different ranges of column height and the temperature difference between humid air and the spraying water ($15^\circ C$ and $25^\circ C$). As shown in the figure, the inlet humid air temperature has a great effect on the water productivity. At column height 10m and $\Delta T$ 15 $^\circ C$ (Fig. (3-1a), the productivity increases approximately 10 times when the temperature increase from 40 to 80 $^\circ C$. As the inlet humid air temperature increases the productivity increases, and the required column height quietly decreases. Meanwhile as the temperature difference between the humid air and the spraying water increases, the productivity increases, and the required column height quietly increases but with lower rate less than the former.

Fig. (4)(1a, 1b, 2a and 2b), illustrates the variations of productivity, by the humid air temperatures at different values the mass fluxes, different column heights of 5 and 10 m, and the different spraying water fluxes. It is clear that the productivity increases with the humid air temperature increases, the productivity increases, which are emphasized in Figs. (1b and 2b). The figure illustrates that the higher the temperature of the humid air or the higher the column height or the higher the mass fluxes of the humid air and the spray water, the greater the productivity.

![Graph](image)

**Fig. (3):** Effects of the column height and the humid air temperature on the absolute humidity, the humidity percentage and the condensate flow rate at different temperature difference.
The value of the humid air mass flux for each spray water droplets is presented in Fig. (4). The variation of the condensate flow rate with the humid air and the spray water mass fluxes at different humid air and droplet temperature and different column height.

3-The Effect of Air-Water Temperature Difference

The effect of the temperature difference between the humid air and the sprayed water droplets on the productivity is elaborated in Fig. (5) at different humid air temperatures, and the column heights (5 and 10m). It is clear from the figure that the humid air inlet temperature has the dominant effect on the productivity, meanwhile, the temperature difference (\( \Delta T \)) and the column height (\( H \)), have considerable effect on the productivity. The productivity increases when the temperature difference increased from 7.5 to 15 °C by about 90, 82, and 79 % at humid air temperature of 40, 50, and 60 °C respectively (at a column height of 10m). Meanwhile the productivity increases by about 56, 51, and 42% at the humid air temperature of 40, 50, and 60 °C, respectively, as the column height increased from 5 to 10 m.

As previously shown in Fig. (3), the variations of the absolute humidity, the humidity percentage, and the productivity at the temperature difference 15 and 25 °C, are noticeable. The temperature difference effect is more obvious at lower inlet humid air temperature (40 °C) and/or at higher inlet humid air temperature (80 °C), where the productivity increases by about 55 and 35% at humid air temperature of 40, and 80 °C respectively when the temperature difference increased from 15 to 25 °C.

4-The Effect of The Humid Air And the Spray Water Mass Fluxes

A comparison between the effect of humid air temperature (at the same temperature difference between the humid air and the sprayed droplets), at different humid air-spray water mass fluxes on productivity, is depicted in Fig. (6). Fig. (6)(1a, 1b, 2a and 2b), illustrates the variations of the productivity flux, by the spray water droplets flux and the humid air mass flux respectively, at different humid air temperature. As shown in the figure, the increase of the humid air and the spray water mass fluxes increases the productivity to a certain limit, where there are no radical increase of productivity as the increase of the humid air and the liquid mass fluxes above 1.5 and 5 kg/m .s respectively. Therefore, there is an optimum value of the humid air mass flux for each spray water...
mass flux. The broken vertical line in the figure characterizes the mass flux of 1.75 Kg/m$^2$.s, which is apparently used in the literature.

**Fig. (5):** Effect of temperature difference on condensate flow rate at different column height.

**Fig. (6):** Variation of the condensate flow rate with the humid air and the spray water mass fluxes at different humid air and droplet temperature.
A CASE STUDY

As the HDH process makes use of and operates at low grade and/or waste heat, therefore, the unlimited and massive quantities of rejected heat at the condenser section of a power plant can be harvested to drive the HDH unit. The cooling spray water temperature can vary between 25 to 40 °C (day and night, or winter and summer), meanwhile the cooling spray water can be heated by about 10 to 15 °C through the condenser section. At these given data and in the light of the discussion of Figs. (2 through 6), the operating conditions of the HDH unit are induced to be 10 m, 30 to 40 °C, and 10 °C for the column height H, the humid air temperature T_a, and the temperature difference ΔT, respectively.

In this case, as the cooling spray water mass flux increases, the productivity increases to a certain value (for each humid air mass flux), meanwhile, the spray water pumping costs increase. Therefore, the financial returns of the productivity and pumping condenser cost are studied at different spray water and humid air mass fluxes as shown in Fig.(7). It is clear from the figure that the spray water pumping costs rise with the spray water mass flux increase, meanwhile, the productivity increases with the increase of humid air mass flux and the increase of spray water mass flux to a certain value at each humid air mass flux. The figure indicates that the productivity increases about five times with increasing the humid air mass fluxes from 1 to 7 Kg/m².s. The net profit of the productivity returns and the spray water pumping costs are included in the difference between them. This profit increased to a maximum value and then declined again, for each humid air mass flux. Therefore, Fig.(8), depicts the net profit and productivities variations with the spray water and the humid air mass fluxes. It is clear from the figure that the productivity can reach 8.5 m³/day.m² at humid air and the spray water fluxes of 7 and 22.5 Kg/m².s, respectively, and the maximum net profit increases with the mutual increase of the spray water and the humid air.

Since the temperature variation of the power plant rejected cooling spray water temperature from the condenser section which fluctuated between 30 to 50 °C during day and night, and summer and winter, the net profit of the productivity changed accordingly. Fig.(9) depicts HDH optimal productivity variations with the humid air and the corresponding sprayed water fluxes, at humid air temperature of 30, 40, and 50 °C. At these temperatures the corresponding optimal productivities are about 6.754, 8.611 and 15.785 m³/m².day respectively. The figure shows that the higher the temperature and the flux (of the humid air), or the higher the mass fluxes (of humid air and the spray water), the greater the productivity. The figure shows also that, the productivity at the maximum profit is increased to be about 4.5, 5.2 and 5.6 times with increasing the humid air mass fluxes from 1 to 7 Kg/m² and the spray water mass flux from 2.5 to 22.5 Kg/m².s at the humid air temperature 30, 40 and 50 °C respectively. The curves of the figure are of great importance, these are the design curves of the HDH contiguous co-generation of electricity and water production in the power plants.

An approximate formula of the curves shown in Fig.(9) is presented in Equation (20) to obtain the optimal productivity at different operating conditions. The humid air temperature is 303 K, up to 323 K, the humid air mass flux is 1 up to 7 Kg/m².s, and the spray water mass flux is 2.5 up to 22.5 Kg/m².s. The formula of all data has a maximum error ranged from -5% up to +7% all over the studied range.

\[
\text{Prod} = -33.61 - 2.234G + 1.006L + 0.112T_a
\]

(20)

It is worth mentioning that, the nuclear power plant (NPP) site’s evacuate zone is 5Km². Therefore an area of 1Km² is a reasonable area that can be utilized for constructing HDH units. As the condenser area is represent one third of the HDH unit area. Accordingly, the HDH productivity can vary from 120,000 to 300,000 m³/day. Emphasizing that, HDH can be feasible to be constructed contiguously with NPP in large scaleproduction.
**Fig. (7):** Effect of spray water mass fluxes on Product returns and pumping costs at different humid air mass fluxes

**Fig. (8):** Variation of the max profit and productivity with the humid air and the spray water mass fluxes
**Fig. (9):** The variation of optimal productivity with humid air and spray water mass fluxes at different inlet humid air temperature.

**CONCLUSION**

1. The evaluation of falling droplets in the direct contact condenser (without packing) is performed through studying the effect of spray column parameters (column height, air and water mass fluxes, air and water inlet temperatures and their temperature difference), versus productivity of the condenser by a one-dimensional, quasi-steady mathematical model.

2. The results show that the productivity increases as the humid air water vapor content increases (as a function of air temperature ($T_a$) and mass flux ($G$)), meanwhile the condensation process increases as expanding condensation catalysts by the increase in the sprayed water droplets, mass flux ($L$), travel ($H$), and temperature difference with humid air ($\Delta T$).

3. A case study of a contiguous cogeneration electricity and water in power plants, shows that the optimal water production by HDH is feasible, where the water productivity can reach more than 15 m$^3$/day.m$^2$. Large scale of HDH can be feasible to be constructed contiguously with NPP.

4. The design curves describing the process are obtained together with a formula for the optimal productivity in terms of humid air and sprayed water fluxes at different humid air temperatures are also obtained.

**Nomenclature**

- $A$: Cross section area, m$^2$.
- $C_{drag}$: Drag coefficient.
- $C_p$: Specific heat at constant pressure, kJ/kg.K.
- $D$: Diffusion coefficient of water vapor, m$^2$/s.
- $G$: Air mass flux, kg/m$^2$.s.
- $g$: Acceleration due to gravity, m$^2$/s.
- $H$: Spray column height, m.
- $h$: Enthalpy, kJ/kg.
- $h_{fg}$: Latent heat of vaporization, kJ/kg.
k Thermal conductivity, W/m K.
L Spray water mass flux, kg/m².s.
m Mass flow rate, kg/s
m\text{drop} Mass of an individual droplet ,kg.
N\text{d} Specific droplet number
p Pressure, Pa.
R\text{d} Radius of droplet, m.
T Temperature, K.
v\text{d} Droplet velocity, m/s.
u Velocity, m/s.
U Heat transfer coefficient, W/m² K.
ω Absolute humidity.
Z Column axial Coordinate, m.
ϕ Relative humidity.
μ Dynamic viscosity, kg/m s.
ρ Density, kg/m³.
γ\text{d} Mass transfer coefficient for droplet condensation, m/s.

\textbf{Subscript}

a Air.
d droplet.
f Final condition.
l water in liquid phase.
mix Mixture of air and vapor.
o initial condition
sat. Saturation
v Vapour
w Water

\textbf{Dimensionless numbers}

Re Reynold number
Nu Nusslet number

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