Numerical Investigation On Water Extraction From The Atmosphere By Underground Condensation Water Production System

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Research

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Numerical investigation on water extraction from the atmosphere by underground condensation water production system

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Abstract

Underground condensation water production system is a low capacity water harvesting method that is suitable for hot and humid climate regions. In this method, the hot and humid airflow is directed to the buried pipes in the ground and, the air is gradually cooled down and the vapor contained therein appears as droplets of water on the pipe surface. The assessment of the amount of water extraction in the condensation system of hot and humid air is the main objective of this investigation. A computational code using MATLAB software is developed to evaluate the amount of water production from humid air in the buried pipes into the ground at a depth of 0.5 m with various lengths and obtain the optimal length of the pipe. Numerical results indicate that water production by considering the initial conditions in this study is about 1 kg per day. The influence of important and effective parameters in underground condensation water production system such as pipes material, air temperature, air humidity, soil temperature, input speed have been investigated. Also, the influence of effective parameters on the performance of the condensation system, including temperature and humidity of inlet air, soil temperature and inlet air velocity, have been evaluated.

Keywords: Underground condensation water production system, Numerical study, Heat transfer, Humid and hot air

1. Introduction

Half of the world's population will live in water-stressed areas by 2025 [1]. As global warming causes drought to intensify dry areas the population facing water scarcity is projected to reach 5 billion by 2050[2]. Technologies such as desalination provide water in many areas of the globe[3,4]. Due to climate change and reduced rainfall, conservation and protection of environmental resources, especially water resources, are of great importance. Enabling access to

fresh potable water in desert and arid regions is a critical challenge and tightly coupled to social and economic development. Recent research found that almost 4.0 billion people on earth live under conditions of modest water scarcity for at least one month in a year. Also, half billion people around the world are facing severe water scarcity throughout the year [5]. Rainwater harvesting is one of the methods of obtaining drinking water that has been used for a long time. During past years several literature reviews around rainwater harvesting for different countries and comprehensively have been published [6-13]. But this method may be suitable for areas with high rainfall. The atmospheric air can be considered as a huge renewable reservoir of water which can be used as a water source everywhere on the earth [14]. Atmospheric water usually exists in three basic types: 3 clouds floating in the sky, fog close to the land, and water vapor in the air [15].

Fog is a potential source of water that could be exploited using the innovative technology of fog collection [16]. Abdul Wahab has conducted a review study on the extraction of water from fog [17]. Also, some researchers have recently addressed this issue [18,19]. Atmospheric water harvesting is the capture and collection of water that is present in the air either as vapor or small water droplets [20]. In recent years, water harvesting from humidity has been dealt with in a number of ways. El-Ghonem published a review study of water production from air [21]. Kim et al. studied a device using MOF to produce water. They predict that this device delivered over 0.25 L of water per kg of MOF for a single daily cycle [22]. Elashmawy and Alshammari proposed a system of air-water harvesting using tubular solar still [23]. Sharan and et al. presented a dew plant for bottling water. They described the construction and functioning of a water production plant in northwest India (Kothara) by collecting dew [24]. Islami et al. have studied water harvesting with thermoelectric in the process of extracting water. It was found that the use of this method requires expenditure of a lot of energy. However, in conditions of high relative humidity found that their design, is the most energy efficient system among similar devices [25]. Tu and Hwang proposed a new system for atmospheric water harvesting using multistage desiccant wheels and vapor compression cycles [26]. This system would increase the evaporator temperature and the water-harvesting rate as well. The proposed system was able to produce 32.5 kg/h. Talaat et al. developed a double-faced conical-finned (18 fins) absorber of cloth layers saturated with calcium chloride and covered by the same shape of transparent material. 0.631 L/m² per day yield was obtained [27]. Also various theoretical studies were performed for desiccant water extraction technique with solar stills [28]. The humidification dehumidification process could be used with a closed desiccant loop for water extraction [29]. Maggelli et al. have studied systems for the recovery of water from humidity airborne HVAC systems [30]. Bagheri has studied on industrial devices that produce water from air humidity named atmospheric water harvesting (AWH) systems [31]. Qasem et al. studied the impact of thermodynamic balancing on the performance of the humidification dehumidification with a desiccant system for atmospheric water harvesting [32]. Kumar and Yadav performed an experimental study in India for desiccant water extraction with a single basin solar still [33]. One of the most common methods of producing drinking water is seawater desalination which is suitable for coastal countries. The availability of saline water in most coastal regions allows the possibility of sweetening water in these areas. Water sweetening methods, commonly used for high capacity are multi-stage distillation and reverse osmosis. Recently, researches have focused on the development of steam condensation technology among these options [34-36]. Some innovations have been made to provide energy for heating and cooling using the potential of the earth such as geothermal heat pumps, electricity generation in geothermal

power plants, water heating of pools, aquaculture, melting of snow and ice in passages[37,38]. But the use of land potential as a source for cooling and condensation of humidity in the air has been less widely considered[39,40].

Another proposed plans for extracting water from humidity is condensation of humid air in hot and humid areas using potential of underground low temperature. In this method, for the production of water from air humidity, the sun's energy is used to humidify air and low temperature underground is used to dehumidifier it. These systems are known as condensation water systems, examples of which have been operating in North African countries, including Tunisia and Algeria near the Mediterranean Sea[41]. The initial idea of the use of condensation water production systems for drinking and farming purposes was introduced at the Lula University of Technology in the 1980's[42], and to date, a research effort has been initiated at this university to expand the idea to include examples of agricultural practices and the extraction of water needed in greenhouses and greenhouses from available saline water sources[43]. In condensing water production systems, hot and humid air is directed to a grid of buried pipes in the ground (with a depth of about half a meter). The temperature in the warm season is colder than the air temperature of the inlet to the pipes, so the wet air, by passing through the buried pipes, gradually cooled down to the dew point temperature. As the air temperature reaches the dew point, the moisture content appears as droplets of water at the pipe surface. These systems can be considered in hot and humid areas for water production for drinking and irrigation purposes[44 and 45]. With the cooling of the soil during the night and the approximate return of its temperature to the initial condition, it is possible to resume the cycle of recovery at the beginning of the following day.

To increase the efficiency of condensation water production systems, a solar distiller that illustrated in Fig.1 can be used. In this method, by evaporation of saline water by solar energy, the air is first warmed up inside the device, and then the saturation air is driven into the buried pipes using a fan. Solar distillation devices increase the condensation of water. This means that the higher temperature and humidity of the inlet, the higher amount of water produced. The comprehensive study on the effect of important parameters on the efficiency of condensation drinking water production system such as pipes material, air temperature, soil temperature and input speed is the main novelty of this investigation.

Fig. 1 A schematic of condensation drinking water production system

2. Describing the model studied

In this research, a condensation water production system has been studied numerically for the production of drinking water. In this system, hot and humid air is transferred to the buried pipe in the soil with the specifications given in Table (1) and is cooled along the pipe through heat transfer with the surrounding soil, and the vapor contained therein after reaching the dew point temperature is condensed and collected at the end of the tube (Fig.2).

Table 1-Specifications input air, soil and geometry of the tube studied in this study

Features	Values
Inlet air temperature	70 °c
Relative humidity of the inlet air	70 %
Average air temperature inside the pipe	3.5 m/s
Inlet air pressure	1 atm
Diameter pipe	20 cm
Tube thickness	5 mm
The depth of the buried pipe in the soil	50 cm

Figure 2- Schematic of the condensation system of the studied water production

3. Governing equations

In this study, finite volume method for governing equations and their initial boundary conditions is considered. The equations of heat transfer between the soil and wet air, as well as water condensation in underground condensation water production systems for drinking, are extracted and presented separately.

3.1 Heat transfer in the soil

During the day, heat is transferred from air to soil, causing an increase in soil temperature (Fig. 3).

Figure 3- Three-dimensional schematic of tube placement in soil

The three-dimensional form of transient heat transfer in the soil is as follows Ref.[44]:

$$\alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = \frac{\partial T}{\partial t} \quad (1)$$

In (1), α is the heat transfer coefficient of soil and is equal to $\alpha = k_s / \rho_s C_s$. The temperature field in the soil can be obtained by solving the numerical equation of the aforementioned energy by applying the boundary and initial conditions at the pipe surface, as well as the four extremities of the studied region.

3.2 Heat transfer in the buried pipe

Heat transfer from air to soil is carried out by two methods of displacement (total length of pipe) and condensation (from the part where the air temperature reaches the temperature of the dew point), and the related equations are presented below.

3.3 Convection heat transfer

The heat transferred from the air to the tube surface is as follows[46]:

$$q_{conv} = h(T_a - T_p) \quad (2)$$

where " T_a " is the temperature of the air, " T_p " is the temperature of the pipe wall, and " h " is the heat transfer coefficient of the air displacement.

$$Nu = \frac{hD}{K_a} = \frac{((f/8)(Re - 1000)Pr)}{1 + 12.7(f/8)^{0.5}(Pr^{2/3} - 1)} \quad (3)$$

In the above relation Nu , Re , Pr is the Nusselt number, Reynolds number and Prantel respectively. K_a is the transmission coefficient of air conductivity and D is the diameter of the pipe. The friction coefficient of the pipe (f) is obtained from the following equation[46]:

$$f = (0.79 \ln Re - 1.64)^{-2} \quad (4)$$

3.4 Condensation heat transfer

The transition heat transfer from air to the tube surface is calculated as condensation from the following equation [44]:

$$q_{cond} = L_f h_m (\rho_{(T_a)} - \rho_{(T_p)}) \quad (5)$$

where L_f is latent heat of steam $\rho_{(T_p)}$ and $\rho_{(T_a)}$ respectively saturated water vapor density and temperature of the tube wall temperature is ongoing. h_m is the mass transfer coefficient which depends on the heat transfer and conduction heat transfer coefficient and is calculated according to the following equation[44]:

$$h_m = \frac{h \alpha^{1/3} D_{a-w}^{2/3}}{k_a} \quad (6)$$

α is the heat transfer coefficient of soil, h is the heat transfer coefficient of air displacement and D_{a-w} is the air-water diffusion coefficient and k_a is the air conduction coefficient. The amount of produced water can also be calculated from the following equation:

$$m_w = \frac{Q_{cond}}{L_f} \quad (7)$$

where m_w is the amount of water generated and Q_{cond} is a condensation heat transfer.

4. Modeling and Simulation

In this section, the discretization of equations and the application of boundary and primary conditions for soil and air are described and the hypotheses are presented for modeling purposes.

4.1 Discretization of governing equations on the soil side

To solve equation (1), a three dimensional finite volume method is used which, by integrating the control volume of Fig.4 and time, obtains the following algebra [47] :

Figure 4- Schematic of soil cell for discretization of the equation of energy

$$T_P^{n+1} - T_P^n = \alpha dt \left\{ \left(\frac{1}{dx} \left[\left(\frac{\partial T}{\partial x} \right)_e - \left(\frac{\partial T}{\partial x} \right)_w \right] \right) + \left(\frac{1}{dy} \left[\left(\frac{\partial T}{\partial y} \right)_s - \left(\frac{\partial T}{\partial y} \right)_n \right] \right) + \left(\frac{1}{dz} \left[\left(\frac{\partial T}{\partial z} \right)_b - \left(\frac{\partial T}{\partial z} \right)_u \right] \right) \right\} \quad (8)$$

where in:

$$\begin{aligned} \left(\frac{\partial T}{\partial x} \right)_e &= \frac{T_E^n - T_P^n}{EP} & \left(\frac{\partial T}{\partial x} \right)_w &= \frac{T_P^n - T_W^n}{PW} \\ \left(\frac{\partial T}{\partial y} \right)_s &= \frac{T_S^n - T_P^n}{SP} & \left(\frac{\partial T}{\partial y} \right)_n &= \frac{T_P^n - T_N^n}{PN} \\ \left(\frac{\partial T}{\partial z} \right)_b &= \frac{T_B^n - T_P^n}{BP} & \left(\frac{\partial T}{\partial z} \right)_u &= \frac{T_P^n - T_U^n}{PU} \end{aligned} \quad (9)$$

Accordingly, the central node distance is from the eastern, western, southern, northern, back, and faces of EP, PW, SP, PN, BP, and PU. Since the survey method is used at the time, the dependent variable values at time "n" are known from the solution of the previous step or the initial conditions, and thus its values can be obtained at the time "n + 1".

4.2 Discretization of governing equations on wet air side

According to Fig. 5, the energy conservation equation for intracellular air cells can be expressed as follows:

$$-Q_{tot} + m_a h_{a,k} + w_k m_a h_{v,k} = m_a h_{a,k+1} + w_{k+1} m_a h_{v,k+1} + (w_k - w_{k+1}) m_a h_w \quad (10)$$

168

Figure 5- Schematic of wet air cell for discretization of the equation of energy

where the total heat transferred from soil to air is equal to:

$$Q_{tot} = q_{tot} dz \quad (11)$$

P is the circumference of pipe and dz is the length of element along z and q_{tot} of total flux, which is equal to:

$$q_{tot} = q_{conv} + q_{cond}$$

173

(12)

The air can be considered in the temperature range of 10 to 50° C (less than 2% error) of ideal gas with $C_{p,a} = 1.005 \frac{\text{kJ}}{\text{kg.K}}$. Therefore, the air mass rate of the cell under study can be obtained from the following equation:

$$\dot{m}_a = \frac{P_a V}{R_a T_a} \quad (13)$$

The volume of air in the cell can be calculated as follows:

$$\dot{V} = C_{in} A \quad (14)$$

C_{in} is the speed of air inlet and A cross-section of the pipe.

If we take zero centigrade as the reference, the air enthalpy can be obtained from the following equation[48]:

$$h_a = C_{p,a} T \quad (15)$$

The water enthalpy at 0 ° C is $h_0 = 2501.3 \frac{\text{kJ}}{\text{kg.K}}$ and its mean specific heat is $C_{p,v} = 1.82 \frac{\text{kJ}}{\text{kg.K}}$, resulting in the water enthalpy according to the relation The following is calculated[48]:

$$h_v = C_{p,v} T + h_0 \quad (16)$$

Given that " w_k " is the absolute humidity of the air entering each element, it is the condition of the input into each cell, and w_{k+1} the relative humidity of the air at the exit of each element can be Obtained from the following equation:

$$w_{k+1} = w_k - \frac{m_w}{m_a} \quad (17)$$

Therefore, the air temperature of the air outlet can be calculated as follows:

$$T_{a,k+1} = \frac{-Q + m_a C_{p,a} T_{a,k} + m_a w_k h_{v,k} - m_a w_{k+1} h_0 - m_a (w_k - w_{k+1}) h_l}{m_a C_{p,a} + m_a w_{k+1} C_{p,v}} \quad (18)$$

The exhaust air temperature is used to find the amount of heat released through displacement and condensation. It should be noted that the energy equation of air and soil are solved simultaneously.

5. Boundary conditions

5.1 Soil:

The temperature of the earth's surface is influenced by the air temperature adjacent to the earth's surface and the sun's radiation. The change in ground temperature can be calculated from the following sinusoidal function[49]:

$$T(t) = T_G + A_{Gs} \sin(2\pi \times t / 24 \times 3600) \quad (19)$$

The above equation is derived from solving the transient energy equation in a one-dimensional semi-infinite object (soil). In this study, $T_G = 20$ and " $A_{Gs} = 8$ "[44].

199 In depth, $y = L_y$, the soil temperature is constant and equal to the average surface temperature. So we have:

$$200 \quad y=L_y : \quad T=\bar{T}_G=20 \text{ }^{\circ}\text{C} \quad (20)$$

201 The first and the end of the tube can be assumed to be insulator

$$202 \quad z = 0 \quad L_z : \quad \left(\frac{\partial T}{\partial z} \right) = 0 \quad (21)$$

203 Due to the low coefficient of conductivity of heat conductivity of the soil, it can be assumed that the soil is insulated
204 along the $x = 0, L_x$ axis.

$$205 \quad x = 0 \quad L_x : \quad \left(\frac{\partial T}{\partial x} \right) = 0 \quad (22)$$

206 5.2 Wet air in the pipe

207 The boundary conditions for the cells around the tube are as follows, depending on which cell line it is in contact with:

$$208 \quad \left(\frac{\partial T}{\partial x} \right)_w = \frac{-q_{tot}}{k_s} \quad \left(\frac{\partial T}{\partial x} \right)_e = \frac{q_{tot}}{k_s}$$

$$209 \quad \left(\frac{\partial T}{\partial y} \right)_n = \frac{-q_{tot}}{k_s} \quad \left(\frac{\partial T}{\partial y} \right)_s = \frac{q_{tot}}{k_s} \quad (23)$$

210

211 During the tube to obtain heat from the condensation, the pipe can be divided into two parts (Fig.6):

212

213

214 Figure 6- Schematic reduction of temperature along pipe

215 A) The length at which the air temperature is greater than the dew point and the heat transfer to the soil is carried
216 out only through the displacement mechanism. In this case, the absolute humidity of the air and its relative
217 humidity are obtained according to the following formula[50]:

$$218 \quad \varphi = \frac{w P_a}{0.622 P_g} \quad (24)$$

219 where P_g is calculated from the following equation[46]:

$$P_g = \frac{e^{(77.345 + 0.0057(T_a + 273.15) - \frac{7235}{T_a + 273.15})}}{(T_a + 273.15)^{8.2}}$$

221

222 B) The length in which the air temperature is lower than the dew point is the exchange of heat in both forms of
 223 condensation and displacement. In this way, relative humidity is 100% and absolute humidity is obtained in
 224 accordance with equation (17).

225 6. Efficiency of condensation water production system

226 From the relationships described in the preceding sections, it can be concluded that the efficiency of condensation
 227 water production systems depends on the following factors:

- 228 • Climatic conditions and soil area
- 229 • Length and shape of the pipe
- 230 • Speed, relative humidity and inlet air temperature

231 The maximum condensation heat transfer ($Q_{\max, \text{cond}}$) can be calculated according to (25):

$$Q_{\max, \text{cond}} = q_{\max, \text{cond}} \times \Delta t \times A = L_f \times h_m \times (p_{(T_{\max, a})} - p_{(T_{\min, p})}) \times \Delta t \times \pi \times D \times L_z \quad (26)$$

233 Where $q_{\max, \text{cond}}$ is the maximum thermal flux, Δt the system operating time, A and L_z are respectively the length and
 234 area of the pipe. On the other hand, we know:

$$Q_{\max, \text{cond}} = m_{\max, w} L_f \quad (27)$$

236 where $m_{\max, w}$, is the maximum amount of water produced and L_f is the water vapor.

237 Therefore, the maximum recoverable water can be obtained according to equations (25) and (26).

$$m_{\max, w} = h_m \times (p_{(T_{\max, a})} - p_{(T_{\min, p})}) \times \Delta t \times \pi \times D \times L \quad (28)$$

239 By the definition of the system efficiency as the amount of produced water to the maximum water that can be generated
 240 by the maximum heat transfer, the efficiency of the condensation water production systems is calculated according to
 241 the equation.

$$\eta = \frac{m_w}{m_{w, \max}} \quad (29)$$

243

244

7. Assumptions

In modeling, the following logical assumptions are applied for ease of solution:

- The mixture of air and steam (wet air) is considered an ideal gas[45].
- Soil, air and water properties are calculated except for the fixed equations in the mean temperature[43].

8. Validation

In order to validate the developed numerical model, the independence of the solution from the grid and also the comparison of the results of the modeling of the present research with the available data of previous research is examined.

9. Mesh Independence

Generally, grid generation algorithms can be classified into two groups of bodies matching the body and non-conforming mesh. In this investigation, a mesh with a non-conforming three-dimensional body (Fig.7) has been used[51]:

Figure 7- Mesh around pipe

As shown in Table (2), in the number of nodes of $100 \times 100 \times 300$, the error in predicting the water produced compared to the $200 \times 200 \times 600$ state is about 1.6%, which can be ignored. Therefore, this number of nodes is the basis of the calculation.

Table 2- Mesh independence study for 15-meter-long tubes

Number of nodes)dx×dy×dz)	The amount of produced water (kg)
50*50*150	1.201
100*100*300	1.125
200*200*600	1.107

10. Comparing the results of modeling with previous researches

Despite the simplicity of using condensation water production systems, numerous laboratory and numerical results are not available for a wide range of applications. Because of the differences between the soil and tube material and the geometric characteristics of the pipe and its depth in the present study and previous studies available at Ref. [44] and Ref. [45], comparison of the results in terms of the efficiency of the condensation water production system was considered.

As Table 3 shows, the efficiency of the condensation water production system in the present numerical research is consistent with the available experimental data. A closer examination of the results of this study and earlier studies suggests that the input air conditions are over saturated in Ref.[44], which is why the calculated efficiency for this system (in accordance with equation 29)

Table 3-comparison of the parameters of the production of water and the efficiency of the system in a tube of 25 meters in length and 8 hours operating for saturated input air at 70 ° C.

Comparative Parameters	Experimental data of Ref.[45]	Numerical results of Ref.[44]	Numerical results of this study
Amount of water produced (kg)	4	89	1.5
Pipe material	UPVC	Unknown	Steel
Tube thickness	Unknown	Unknown	5mm
Diameter pipe	63 mm	200 mm	200 mm
The depth of the buried pipe in the soil	40 cm	50 cm	50 cm
Efficiency in accordance with equation (29)	40 %	More than 100% (over saturated air)	31 %

(Length of pipe: 25 m, system operating time per day: 8 hours, inlet air temperature: 70 ° C, relative humidity: 100%)

11. Simulation and discussion results

In this section, the results of modeling for different pipe lengths are presented and the sensitivity of the water production in the condensation system has been studied in relation to different parameters.

11.1 Wet air temperature throughout the pipe

Fig.8 shows the temperature of the air entering the system throughout the pipe. As it is seen in this figure, at the length of less than 3 meters, the air temperature is higher than the dew point (62 ° C in the present study), but with increasing length, the temperature decreases until it reaches the dew point and the humid air is saturated.

Figure 8 – Temperature of the wet air during the first hour of operation

11.2 Prediction the amount of produced water in short length pipes

Fig.9 shows that at the first 3 meters of the pipe, the water does not produce because the temperature has not reached the dew point. But by increasing the length of the pipe, due to the reduction of the air temperature, its capacity to keep the steam vapor decreases, until air is saturated and reaches dew point. Therefore, from this point, in proportion to the lowering of the air temperature, some of the water vapor in the air is distilled and water is accumulated at the end of the tube.

Figure 9- The amount of produced water for short length pipe during 12 hours of system operation

As it is seen in Fig.9, the heat transfer rate is reduced due to the lower temperature difference between the air and the soil, so the amount of water decreases. This can be seen in Fig.10.

Figure 10- Heat transfer rate in short length pipe

As seen in Fig.11, the air temperature of the outlet decreases with the advance of wet air throughout the pipe. But this temperature drop is desirable until the temperature difference between the soil and the wet air is tangible (At a point

where the length of the pipe is 15 meters, the temperature changes are from about 20 ° C to 45 ° C, and within 25 m between 20 ° C and 35 ° C, and eventually, at a distance of 100 meters, this temperature difference does not exceed C ° 3). Therefore, there is always an optimal length, because the increase in pipe length is not more cost effective due to the small increase in the amount of water produced.

Figure 11- Cantor of soil and air temperature at the last hour of operation for different lengths A: 15 meters B: 25 meters C: 50 meters D: 100 meters

Fig.12 shows the amount of extraction water in condensation systems for different pipe lengths. As seen in this figure, the use of five pipes of 20 meters in length, produces more water than a pipe of 100 meters in length.

Figure 12- The amount of water extraction for various lengths of pipe in 12-hour system

11.3 The optimal length

The efficiency of condensation systems depends on the relationships mentioned in various factors, such as initial temperature, relative humidity of the wet air, diameter, pipe length, soil, etc. In Fig.13, the efficiency is plotted in terms of pipe length. In Fig.13, the efficiency is plotted in terms of pipe length. Obviously, in the initial lengths (less than 3 meters), the wet air is not saturated, so the system returns to zero, and with increasing length and production of water, the yield increases to the maximum.

Figure 13- The efficiency of condensed water production system for pipes of different lengths

In this study, the optimum length, which has the maximum yield based on length, was obtained at 15 meters, taking into account the initial conditions. As expected, the efficiency decreases for longer than optimal lengths due to a decrease in the difference between wet air temperature and soil (reducing heat transfer rate, which reduces the amount of water produced).

11.4 Effect of input speed

With increasing the air velocity, the Reynolds number and subsequently the Nusselt number increase, so the amount of heat transfer and the amount of produced water will be increased (Fig. 14).

Figure 14-The effect of wet entry air velocity on the amount of produced water in pipe with length of 15 meters

11.5 Effect of soil temperature

In Fig.15, the effect of soil temperature on the amount of produced water is plotted. As it is seen, with increasing soil temperature, the amount of produced water decreases due to the reduction of temperature difference between air and soil.

Figure 15-The effect of soil temperature on the amount of produced water in pipe with length of 15 meters

11.6 Effect of temperature and relative humidity of inlet air

As shown in fig.16 by increasing the temperature of the air, the amount of produced water can be increased, so if the temperature of the air is increased in some way, such as wet air preheating with the solar distiller, we can raise the amount of water significantly. By increasing the temperature of the inlet fluid, the temperature difference between the pipe wall and the air increases and the heat transfer subsequently increases, and as a result, the amount of produced water is increased.

Figure16-The effect of humid air temperature on the amount of produced water in pipe with length of 15 meters

In Fig.17, the effect of relative humidity on extracted water is plotted. Due to the fact that condensation heat transfer (the amount of produced water) depends directly on relative humidity, so the efficiency of condensation systems can be increased by the proper humidification and the transfer of wet air to saturation.

Figure 17-The effect of relative humidity of the incoming air on the amount of produced water in pipe with length of 15 meters

11.7 Effect of pipe material

One of the effective parameters in the amount of produced water in the studied system is the type of pipes and their materials. The Comparison between four types of pipe material including Copper, Steel, PVC, Polyethylene with a thickness of 5 mm, shows that the highest amount of water harvesting is obtained in pipes made of copper and steel, respectively. The results of this comparison are shown in Table 4. The operation was considered during 12 hours for 15 meters of pipe.

Table 4-The effect of pipe material on the amount of water produced

Pipe material	Thermal conductivity coefficient W/m. K	Thermal resistance $m^2 \cdot K/W$	Total heat transfer coefficient $W/m^2 \cdot K$	The amount of water produced Kg
Copper	420	$1.21 \cdot 10^{-5}$	12.30	1.12
Steel	18	$2.84 \cdot 10^{-4}$	12.26	1.12
PVC	0.33	0.015	10.33	0.98
Polyethylene	0.16	0.032	8.82	0.85

11.8 Effect of soil type

The amount of produced water depends on the type of soil. The values of the conduction coefficient and heat dissipation that are effective in heat transfer are presented in Table 5 for different soils. As predicted, the soil with the highest heat transfer coefficient and heat conductivity will have the highest amount of water produced.

Table 5-The effect of soil type on the amount of produced water

Soil type	Soil diffusion coefficient (m/s^2)	Thermal conductivity coefficient ($W/m \cdot ^\circ C$)	The amount of produced water (kg)
(Clay)	$2.72 \cdot 10^{-7}$	0.9	0.78
(Sand)	$1.35 \cdot 10^{-6}$	1.9	1.44
(Wet Soil)	$4 \cdot 10^{-4}$	2	1.33
(Sandstone)	$8.39 \cdot 10^{-7}$	3	1.45

12. Sensitivity analysis

In Fig.18, the effect of important parameters on the amount of produced water in drinking water condensation systems has been investigated. The analysis showed that by changing the ± 20 percent of these parameters, the parameters of inlet air temperature, relative humidity, diameters, velocity, and soil temperature, have the most effect on the amount of produced water in the condensation system.

Figure 18- Sensitivity analysis of various parameters on the amount of produced water in pipe with length of 15 meters

13. Conclusion

In this research, the amount of water extraction from air humidity in drinking water condensation systems has been studied and evaluated numerically. The results of the study show that the average fresh water extracted from air humidity in these systems for buried pipes at a depth of 0.5 m, with a diameter of 0.2 m and a length of 15 meters for inlet air with a temperature of 70 ° C and a relative humidity of 70%, is equal to 1.2 kg.

The numerical results show that with the advancement of wet air, the temperature decreases throughout the pipe to reach the dew point, consequently, water is not produced at the initial part of the tube. Also, for longer pipe lengths, in the end sections, the air and soil temperatures are approximately the same and little water is produced. Therefore, there is always the optimal length in which the average water produced per unit length of the pipe is maximal. According to the results of the sensitivity analysis, it can be stated that the relative humidity and temperature of the incoming air are important factors in the amount of water produced, respectively. Therefore, for increasing the amount of water extraction, the system can be equipped with a solar humidifier that is a cheap and suitable way to saturate the air.

However, the amount of produced water by condensation method is not competitive with the conventional methods of industrial freshwater production, but in remote and remote areas, or, in the coastal strip that faces shortages of

416 drinking and irrigation water, these systems can be economically attractive and can be part of a solution to reduce
417 water demand.

418

419 **Symbols**

420 A: Cross section of pipe (m^2)

421 AGS: Annual range of ground temperature ($^{\circ}C$)

422 BP: Distance of the rear node from the center node (m)

423 C_{in} : Input speed (m / s)

424 C_p : Specific heat capacity at constant pressure (J / kg. $^{\circ}C$)

425 C_s : Soil heat capacity (J / kg. $^{\circ}C$)

426 C_v : Specific heat capacity in constant volume (J / kg. $^{\circ}C$)

427 Da_w : air distribution coefficient - water (m^2 / s)

428 dt : time interval (s)

429 dx : cell length in the z-axis direction (m)

430 dy : cell length in y (m) direction

431 dz : Cell length in x-axis direction (m)

432 EP: Distance from the center node (m)

433 f : Pressure drop coefficient

434 h : heat transfer coefficient of displacement ($W / m^2. ^{\circ}C$)

435 hm : mass transfer coefficient (m / s)

436 k : mean thermal conductivity coefficient ($W / m. ^{\circ}C$)

437 L_f : Water vapor heat (J / kg)

438 L_x : The length of the soil model along x (m)

439 L_y : The length of the soil model along y (m)

440 L_z : pipe length along z (m)

441 m : mass (kg)

442 Nu: Nusselt number

443 P: Pressure (Pa)

444 p: environment (m)

445 PN: Central node distance from the north node (m)

446 Pr: Prandtl number

447 PU: Distance of the central node from the front node (m)

448 PW: Distance of the central node of the eastern node (m)

449 q: thermal flux (W / m²)

450 Q: Transferred heat (J)

451 R: Global gas constant (j / kg.K)

452 Re: Reynolds number

453 SP: Distance of the southern node from the center node (m)

454 t: time (s)

455 TG: mean ground temperature (° C)

456 To: Time Delay (s)

457 V: volume (m³)

458 w: Specific humidity

459 **Greek signs**

460 α : Soil heat transfer coefficient (m² / s)

461 ρ : density (kg / m³)

462 φ : Relative humidity

463 **Superscript**

464 n: time period

465 **subtitle**

466 s: soil

467 a: air

468 B: back node
469 b: back wall
470 cond: condensation
471 conv: convection
472 E: Eastern knot
473 w: western wall
474 g: saturation mode
475 N: Northern node
476 n: north wall
477 o: original mode
478 P: central node
479 S: Southern node
480 s: south wall
481 tot: total heat transfer
482 U: upward node
483 u: facing the wall
484 v: Steam
485 w: water
486 W: Western knot
487 e: Eastern knot
488 x: Horizontal direction
489 y: axis along the depth of the earth
490 z: Axis along the tube
491
492
493

494 **Declarations**

495 **Availability of data and materials**

496 The datasets used and analyzed during the current study are authentic and reliable.

497 **Competing interests**

498 The authors declare that they have no competing interests.

499 **Authors' contributions**

500 Zarabadi wrote the manuscript, researched the methods, and conducted the studies. Mafi presented scientific
501 supervision and responsible for code debugging and critical evaluation of hypotheses and results. Soltani and Jatin
502 presented scientific supervision of the study, which led to this article, ideas for evaluating and representing data and
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Figures

Figure 1

A schematic of condensation drinking water production system

Figure 2

Schematic of the condensation system of the studied water production

Figure 3

Three-dimensional schematic of tube placement in soil

Figure 4

Schematic of soil cell for discretization of the equation of energy

Figure 5

Schematic of wet air cell for discretization of the equation of energy

Figure 6

Schematic reduction of temperature along pipe

Figure 7

Mesh around pipe

Figure 8

Temperature of the wet air during the first hour of operation

Figure 9

The amount of produced water for short length pipe during 12 hours of system operation

Figure 10

Heat transfer rate in short length pipe

Figure 11

Cantor of soil and air temperature at the last hour of operation for different lengths A: 15 meters B: 25 meters C: 50 meters D: 100 meters

Figure 12

The amount of water extraction for various lengths of pipe in 12-hour system

Figure 13

The efficiency of condensed water production system for pipes of different lengths

Figure 14

The effect of wet entry air velocity on the amount of produced water in pipe with length of 15 meters

Figure 15

The effect of soil temperature on the amount of produced water in pipe with length of 15 meters

Figure 16

The effect of humid air temperature on the amount of produced water in pipe with length of 15 meters

Figure 17

The effect of relative humidity of the incoming air on the amount of produced water in pipe with length of 15 meters

Figure 18

Sensitivity analysis of various parameters on the amount of produced water in pipe with length of 15 meters