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EXPERIMENTAL RESEARCH OF THE INNOVATIVE ATMOSPHERIC HUMIDITY COLLECTION SYSTEM FOR USE IN CROP IRRIGATION

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Abstract

This paper presents the experimental results of an innovative atmospheric humidity collection system for irrigating crops. A humidity and temperature transducer located outside reads the temperature and relative humidity of the atmospheric air. Another transducer located on the indoor unit reads the temperature and humidity of the air leaving the humidification chamber. The controller monitors the temperatures and humidities transmitted by the transducers and when the optimal conditions are met for water to condense on the surface of the external collector, it commands the heating and humidification of the air to start. The system operates until the conditions for humidity condensation are no longer satisfied. The meteorological parameters provided by the local weather station related to the conditions under which water condenses was obtained and led to the adjustment of the automatic algorithm. During the experiments, the following parameters were determined: the flow rate of air pushed by the in-line duct fan, the temperature and humidity of the air jets at the exit from the hot air duct and the volume of water obtained.

***Key words**: atmospheric humidity, dew point, water.*

INTRODUCTION

Considering the seasonal fluctuations in water consumption and availability, recent research found that two-thirds of the global population (4.0 billion people) live under conditions of modest water scarcity for at least one month in a year (Mekonnen & Hoekstra, 2016). Even worse, a half billion people on Earth face severe water scarcity all year round. However, the atmospheric water, which is considered a huge renewable reservoir of water and enough to meet the needs of every person on the planet, is unfortunately ignored (Wahlgren, 2001**)**.
Fog and dew droplets can be confused when occurring upon natural surfaces such as beetle skin (Guadarrama-Cetina et al., 2014), the mechanisms to harvest fog and dew upon an artificial surface greatly differ at a larger scale (Jacobs et al., 2008). Moreover, the dew point depression at the study area seldom is below 0.5°C, the minimum threshold generally considered for fog deposition to occur (Hiatt et al., 2012).
Non-conventional water resources have emerged as means to meet or supplement irrigation demand for reforestation and agriculture in water scarce regions (Tomaszkiewicz et al., 2017).
In general, any viable atmospheric water-harvesting technology must satisfy five primary criteria: it should be efficient, cheap, scalable, wide-band, and stable enough to operate for a whole year or at last a monsoon season. Currently none of the existing commercial atmospheric water generators meets all these five criteria. From the point of view of thermodynamics, this is mainly due to the energy inefficiency of the process (Tu et al., 2018).
Recently, researchers from the National Institute of Research and Development for Machines and Installations Designed for Agriculture and Food Industry - INMA Bucharest have studied the possibility of obtaining an additional amount of water for crop irrigation by collecting atmospheric humidity (Manea et al., 2021; Mircea et al., 2019; Popa et al., 2021).
This paper presents the experimental results of the innovative atmospheric humidity collection system for irrigating crops, designed and manufactured at INMA Bucharest.

MATERIALS AND METHODS

The innovative atmospheric humidity collection system for use in crop irrigation is mainly composed of: the indoor unit or the air heating and humidification installation, which was located inside the solar house; the outdoor unit or the collector, which was installed outside the solar; the puffer and the automatic control system of the work process parameters (Figure 1). The outdoor unit is connected to the indoor unit by means of a PVC tube buried in the ground and thermally insulated with mineral wool covered with aluminium foil.

The air heating and humidification installation (the indoor unit) is made up of the following elements: recirculation pump model Ferro 32-60-180; warm water heating coil; air humidification chamber; air flow control flap with Belimo CM 230 servomotor; in-line duct fan RUCK ETAMASTER EM 315 EC01; peripheral pressure pump CALPEDA TPM 78; warm water spray system in the form of mist with 5 nozzles; tank with lid and volume of 40 liters, provided with electric float with counterweight model Tecno 2 on the inside; normally closed water solenoid valve, 1/2", 230 V; elastomeric foam insulation with a thickness of 19 mm; insulated flexible tube with a diameter of 315 mm, made of layers of aluminium foil and aluminized polyester.

The air humidification chamber is made of galvanized sheet, in the form of a cube with a volume of approximately one cubic meter. The upper part of the humidification chamber is sealed with a lid. Under the cover is installed the system of spraying warm water in the form of mist. At the bottom, the humidification chamber is shaped like a funnel, which allows excess water to flow into the tank.

The warm water used for heating and humidifying the air is taken from the puffer with a volume of 500 litres, which is connected to a solar panel.

The collector (the outdoor unit) is made up of the following elements: collector walls; drainage and water collection system; warm air piping; roof. The collector walls are made of stainless-steel sheet profiled in V-shaped alveoli, in order to increase the area for obtaining condensation, at the contact between the cold atmospheric air and the warm and humid air generated by the heating and humidification installation. The collector walls are placed symmetrically left - right in relation to the warm air piping and inclined at an angle of 30° to the horizontal plane (Figure 2).

The warm air piping consists of a horizontal PVC tube with a diameter of 315 mm, made by the linear interconnection of some branched segments in the shape of a T, the branches being arranged in a vertical plane and having a diameter of 110 mm. At one end, the horizontal PVC tube is fitted with an air check valve, and at the other end it is closed with a plug. A double polypropylene branch is mounted on each vertical tube. Both the horizontal tube and the vertical tubes are thermally insulated with elastomeric foam insulation.

the indoor unit and the puffer *the outdoor unit (the collector)*

Figure 1. Innovative atmospheric humidity collection system for use in crop irrigation

collector wall

warm air piping

Figure 2. Component elements of the collector

The automatic control system of the work process parameters is made up of the following elements: automatic programmable Mitsubishi AL2-14MR-D; analog output extension module AL2-2DA; 24 Vcc Alpha Power Mitsubishi voltage source; air humidity and temperature transducer 0-10Vdc, located on the tubing at the exit from the humidification chamber; air humidity and temperature transducer 0-10Vdc, located on the frame of the outdoor unit and DRS-201D single-phase digital meter.

The way the system works:

The air humidity and temperature transducer 0-10Vdc, located on the frame of the outdoor unit reads the temperature and relative humidity of the atmospheric air. The other transducer 0-10Vdc located on the indoor unit piping reads the temperature and humidity of the air leaving the humidification chamber.

Through a round-trip circuit, warm water is taken from the puffer and circulated through the warm water heating coil by the Ferro 32-60-180 recirculation pump.

Through a connection located at the top of the puffer, the warm water is transferred to the 40-liter tank located at the bottom of the humidification chamber, from where it is taken over by the peripheral pressure pump CALPEDA TPM 78/A and transferred to the spray system with 5 nozzles mounted in the upper part of the humidification chamber. The water is sprayed as a mist into the warm air stream absorbed by the EM 315 EC01 in-line fan. When the accumulated water in the tank falls below a certain level, the TECNO 2 electric float commands the opening of the 1/2" solenoid valve, the warm water from the puffer replenishing the level in the tank. When the maximum level in the tank is reached, the TECNO 2 electric float commands the closing of the 1/2" solenoid valve.

The optimal conditions for water from the atmosphere to condense on the surface of the external collector are: the temperature difference between the outside air and the solar air must be greater than a predetermined value (e.g. 10°C); the combination of the temperature and the relative humidity of the outside air, to correspond to reaching the dew point.

The Mitsubishi AL2-14MR-D programmable controller continuously monitors the temperatures and humidities transmitted by the two transducers and when one of the optimal conditions mentioned above is met, commands: starting the warm water recirculation pump Ferro 32-60 180; actuation of the Belimo CM 230 L servo motor to open the air flow adjustment flap; starting the fan EM 315 EC 01; starting the peripheral pressure pump TPM 78/A.

If the temperature difference between the outside and the humidification chamber falls below the preset value, i.e. the air in the humidification chamber does not have time to heat up due to the too high flow of air pushed by the fan, the programmable automatic controls the reduction of the fan speed and the partial closing of the air flow adjustment flap, by actuating the Belimo CM 230 L servo motor.

The system continues to operate until the outside temperature and humidity reach other preset values stored in the PLC, values that no longer satisfy the conditions for condensation of moisture from the atmosphere. Then the programmable controller commands the system to shut down.

Due to the temperature difference between the flow of warm and humid air from the installation and the atmospheric air, the vapors condense on the surface of the collector walls, the water being drained and stored in the tank from where it can be used to irrigate the crops. The amount of water extracted from the atmosphere increases as the temperature difference between the ambient air and the air in the installation increases. Thus, the best performance can be obtained when the warm water in the puffer is stored during the day and used to heat the air in the installation during the night.

During the experiments, the following parameters were determined: the flow rate of air pushed by the in-line duct fan, the temperature and humidity of the air jets at the exit from the hot air duct and the volume of water obtained.

Determining the flow rate of air pushed by the in-line duct fan:

The determination of the flow rate of air pushed by the in-line duct fan was carried out under the following working conditions: warm water recirculation pump - off; the position of the air flow adjustment flap - maximum open; peripheral pressure pump - off.

Four fan speeds were set from the automatic programmable (25%, 50%, 75% and 100% of maximum speed). For each set speed, the speed of the air stream at the exit from the terminal tubes was measured with the Anemometer CIH20DL (Figure 3).

The total air flow pushed by the fan, at the exit from the warm air pipe, Q_t, was calculated with formula (1):

$$Q_t = \sum_{i=1}^{5} Q_i \text{ (m}^3\text{/h)} \quad (1)$$

where:

- Q_i is the air flow rate pushed through a vertical tube and was calculated with formula (2):

$$Q_i = 3600 \cdot S \cdot (v_{i,l} + v_{i,r}) \text{ (m}^3\text{/h)} \quad (2)$$

where:

- $v_{i,l}$ and $v_{i,r}$ are the speeds of the air current pushed through the left / right branch of a vertical tube, in m/s;
- S is the air outlet section through the terminal tube of the branch, in m^2.

The measurement of the temperature and humidity of the air jets at the exit from the warm air duct was carried out with the Digital Thermohygrometer P330 for the following working conditions: fan speed - 25%, 50%, 75% of the maximum speed; warm water recirculation pump - on; the position of the air flow adjustment flap - maximum open; peripheral pressure pump - on; the temperature of the hot water in the puffer - 22°C; air temperature inside the solarium - 21°C; the relative humidity of the air inside the solar house - 56% (Figure 4).

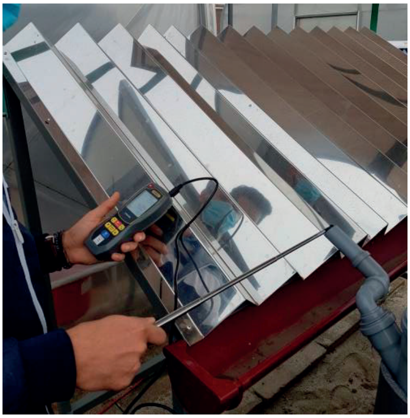

Figure 3. Measurement of the speed of the air current at the exit of the terminal tubes, with the Anemometer CIH20DL

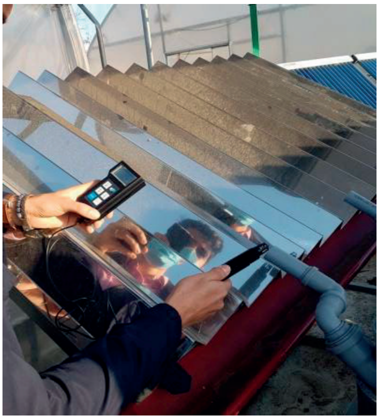

Figure 4. The measurement of the temperature and humidity of the air jets at the exit from the warm air duct with the Digital Thermohygrometer P330

The values of temperature and relative humidity of the air circulated through the heating and humidification installation were measured by the 0-10Vdc transducer located on the piping and displayed on the display of the automatic programmable.
The monitoring and recording of meteorological parameters provided by the local weather station iMetos 3.3 was carried out over three periods (September, October, November 2023) of three consecutive days. The following meteorological parameters were monitored and recorded: air temperature, dew point, relative air humidity, wind speed and precipitation amount.
The collection and measurement of the volume of water obtained during the experiments was carried out in the three periods of three consecutive days, and the averages were calculated. The water was collected in the systems tank, and the measurement of the collected water volume was made with a graduated cylinder, once a day at the same hour. For each monitored period, a different exit angle of the warm and humid air jets from the terminal tubes was adjusted, in relation to the surface of the collector walls.
The innovative atmospheric humidity collection system was supplied with electricity from an off-grid system with photovoltaic panels.

RESULTS AND DISCUSSIONS

The vertical tubes were numbered from 1 to 5, number 1 being the tube closest to the warm air duct entry. For all four set speeds of the fan (25%, 50%, 75% and 100% of the maximum speed), a relatively uniform distribution of the flow of air pushed through the vertical tubes (Qi) was observed, so along the warm air duct and implicitly along the length of the collector walls (Table 1).

Table 1. The results obtained when determining the air flow rate pushed by the in-line duct fan

Fan speed (% of max. speed)	No. vertical tube	Measured values		Calculated values	
		inner diameter of terminal tubes: d = 0.028 m		air outlet section: S = 0.0006 m^2	
		Left branch	Right branch	Air flow per vertical tube, Q_i (m^3/h)	Total air flow, Q_t (m^3/h)
		Air current speed (m/s)			
		$v_{i,l}$	$v_{i,r}$		
25	1	4.39	4.57	19.35	94.78
	2	4.13	4.45	18.53	
	3	4.33	4.94	20.02	
	4	4.30	4.10	18.14	
	5	4.73	3.94	18.73	
50	1	9.65	9.15	40.61	201.64
	2	8.45	9.20	38.12	
	3	8.95	9.60	42.34	
	4	9.21	9.01	39.36	
	5	10.15	8.93	41.21	
75	1	14.62	14.38	62.64	311.58
	2	13.35	14.65	60.48	
	3	13.65	15.93	63.89	
	4	14.02	14.15	60.85	
	5	15.65	13.85	63.72	
100	1	17.21	17.13	74.17	369.04
	2	15.20	17.87	71.43	
	3	16.25	19.04	76.23	
	4	16.79	16.73	72.40	
	5	18.40	16.23	74.80	

Table 2. The results obtained from the measurements of the temperature and humidity of the air jets at the exit of the warm air duct fan

Fan speed (% of max. speed)	Read values (at inlet)		No. vertical tube	Measured values (at outlet)					
				T [°C]			RH [%]		
	T (°C)	RH [%]		Left branch	Right branch	Average per tube	Left branch	Right branch	Average per tube
25	21.8	95.4	1	13.0	13.3	13.15	89.7	90.6	90.15
			2	13.1	13.1	13.1	90.1	90.9	90.5
			3	12.9	12.9	12.9	90.9	90.5	90.7
			4	12.7	12.8	12.75	91.7	88.8	90.25
			5	12.0	12.3	12.15	91.1	83.9	87.5
			Average			12.81			89.82
50	21.4	92.6	1	15.1	14.7	14.9	91.0	91.4	91.2
			2	15.0	14.5	14.75	91.0	91.3	91.15
			3	14.8	14.5	14.65	91.0	91.3	91.15
			4	14.7	14.7	14.7	91.4	90.9	91.15
			5	14.3	14.3	14.3	91.3	91.3	91.3
			Average			14.66			91.19
75	21.0	90.2	1	16.3	16.6	16.45	89.2	88.9	89.05
			2	16.2	16.6	16.4	89.6	88.9	89.25
			3	16.2	16.5	16.35	89.6	89.3	89.45
			4	16.5	16.4	16.45	89.7	89.3	89.5
			5	15.9	15.9	15.9	90.4	90.0	90.2
			Average			16.31			89.49

Analysing the data in Table 2, the following observations emerge:

- in the condition where the temperature of the warm water in the puffer was 22°C, the air temperature in the heating and humidification installation was maintained in the range of 21°C÷21.8°C; from this it follows that the heat losses of the installation are small, and the thermal insulation is done properly;
- in the condition where the relative humidity of the air inside the solar house was 56%, and the humidity of the air inside the heating and humidification installation was between 90.2% and 95.4%, we can say that the mist water spray system makes a significant contribution to increasing the humidity of the air absorbed through the installation;
- the differences between the temperature of the air entering the pipe (21.8°C, 21.4°C and 21.0°C) and the average temperature of the air leaving the pipe (12.81°C, 14.66°C and 16.31°C), for 3 set fan speeds (25%, 50%, 75% of max. speed) are: 8.99°C, 6.74°C and 4.69°C;
- the differences between the humidity of the air entering the pipe (95.4%, 92.6% and 90.2%) and the average humidity of the air leaving the pipe (89.82%, 91.19% and 89.49%), for 3 set speeds of the fan (25%, 50%, 75% of the max. speed) are: 5.58%, 1.41% and 0.71%.
- It was observed that these differences decrease with increasing fan speed, both in the case of temperature and in the case of air humidity.

If we compare the air temperature and humidity values measured by the 0-10Vdc transducer located on the pipe with the air temperature and humidity values measured at the exit of the air pipe, the following observations emerge:

- the decrease of the air temperature at the pipe entrance, with the increase in fan speed, while the air temperature at the pipe outlet registers an increase;
- the decrease of air humidity at the pipe entrance, along with the increase in fan speed, while the air humidity at the pipe outlet registers an increase up to 50% of the maximum speed of the fan and then a decrease when the fan speed increases to more than 50% of the maximum speed.

Results obtained from the monitoring and recording of meteorological parameters provided by the local weather station iMetos 3.3:

By monitoring and recording the meteorological parameters provided by the local weather station iMetos 3.3, important information was obtained related to the conditions under which water in the atmosphere condenses, information that led to the adjustment of the data used by the automatic adjustment algorithm of the innovative atmospheric humidity collection system.

- Evolution of meteorological parameters in period 1 (September 2023). The dew point had values in the range of 0.1°C÷5.6°C. The minimum dew point (0.1°C) was obtained on 27.09.2023 at 08.00 am, when the average air temperature was 0.14°C and the relative air humidity was 99.98%.
- Evolution of meteorological parameters in period 2 (October 2023). The dew point had values in the range 6.9°C÷10.8°C. The minimum dew point (6.9°C) was obtained on 02.10.2023 at 00:00 am, when the average air temperature was 7.04°C and the relative air humidity was 99.98%.
- Evolution of meteorological parameters in period 3 (November 2023). The dew point had values in the range of 7.5°C÷13.7°C. The minimum dew point (7.5°C) was obtained on 04.11.2023 at 08.00 am, when the average air temperature was 7.57°C and the relative air humidity was 99.98%.

In all three monitored periods, both the amount of precipitation and the wind speed recorded insignificant values, close to zero.

Table 3. Validation of experimental data

Period/ month	Day no.	Air temperature (°C)			Air relative humidity (%)		
		transducer 0-10Vcc outdoor	weather station iMetos 3.3	Difference	transducer 0-10Vcc outdoor	weather station iMetos 3.3	Difference
1 / September	Day 1	0.16	0.14	0.02	98.90	99.98	-1.08
	Day 2	0.85	0.79	0.06	98.80	99.99	-1.09
	Day 3	0.98	0.90	0.08	98.90	99.98	-1.08
2 / October	Day 1	9.30	8.97	0.33	98.90	99.98	-1.08
	Day 2	9.15	8.93	0.22	98.90	99.98	-1.08
	Day 3	8.72	8.56	0.16	98.80	99.97	-1.07
3 / November	Day 1	7.95	7.57	0.38	98.90	99.98	-1.08
	Day 2	8.45	8.03	0.42	98.90	99.98	-1.08
	Day 3	8.86	8.40	0.46	98.80	99.97	-1.07

Table 4. The results obtained from the collection and measurement of the volume of water obtained

Period / month	Day no.	Warm and humid air jet exit angle (°)	Measured water volume (l)	Total water volume (l)
1 / September	Day 1	5	1.87	4.09
	Day 2		1.40	
	Day 3		0.82	
		Average	1.36	-
2 / October	Day 1	10	1.15	3.34
	Day 2		1.35	
	Day 3		0.84	
		Average	1.11	-
3 / November	Day 1	15	1.10	2.44
	Day 2		0.76	
	Day 3		0.58	
		Average	0.81	-

In order to validate the experimental research carried out in the three periods, the values of temperature and relative humidity of the air read by the 0-10Vdc transducer located on the outdoor unit were compared with the values of temperature and relative humidity provided by the local weather station iMetos 3.3. The readings were taken every day at 08:00 am, and the values are presented in Table 3. The differences obtained are of a maximum of

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0.46°C for the air temperature and of a maximum of 1.09% for the relative humidity, which results in a good accuracy of the transducer 0- 10 Vdc (Table 3).

Analysing the results from Table 4, it was found that the largest volume of water collected (4.09 l) was in period 1 (September 2023), for the exit angle of the air jets of 5°.

Comparing periods 2 (October 2023) and 3 (November 2023), which were similar from the point of view of meteorological parameters, it was found that with the increase of the exit angle of the air jets from the piping, the volume of water collected decreases.

If we refer to the average volumes of water collected in each period, related to the total surface of the collecting walls of 5.5 m^2, we obtain 0.25 $l/m^2 \cdot day$ for period 1, 0.20 $l/m^2 \cdot day$ for period 2 and 0.15 $l/m^2 \cdot day$ for period 3.

CONCLUSIONS

Atmospheric humidity collection is a technology that has greatly evolved in the past decades, but challenges remain to be optimized for efficiency and to ensure the delivery of water with a quality and amount appropriate to its end use. The experimental results presented in this paper demonstrated that atmospheric humidity can be successfully extracted using the innovative atmospheric humidity collection system. By developing and experimenting the innovative atmospheric humidity collection system, an important step was taken to understand the condensation technique.

The research results allow useful recommendations for farmers who are interested in obtaining an additional amount of water needed to irrigate crops in the open field or in protected environments (greenhouses, solariums), by capitalizing on air humidity at a minimum installed energy.

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