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Parametric Analysis of Wet-Multi-Cylinder Humidification

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ABSTRACT

Humidification is a core factor in air conditioning, agriculture, industry, and health applications. Many humidification techniques were used in the literature, and the humidification and evaporative cooling from multi-wet cylinders were investigated in this study. An experimental test rig was constructed to perform tests. The air temperature and the number of wet cylinders were varied and tested, experimental results were recorded and validated with theory, and the maximum error was recorded to be 3.3%. It has been noted that the relative humidity drops by increasing air temperature as expected from the literature. The use of multiple cylinders has the effect of humidification and evaporative cooling. The more the number of wet cylinders the more the evaporation rate. As = 0.0975 kg/s with an almost constant wet bulb temperature of 9 °C, the amount of water evaporated was calculated as 73.7, 130, and 263 g/h for single, double, and triple wet cylinders respectively.

Keywords: humidification, evaporative cooling, multi-cylinders, variable temperature, relative humidity.

INTRODUCTION

Humidification and evaporative cooling are essential in health, commercial, agricultural, and industrial applications. It may lead to an increase in productivity, improve health circumstances, increase the life of stored materials, and reduce the energy consumed in cooling devices. An experimental study on the rate of drying solids has been performed [1]; they investigated the natural convection of an indirect mode solar dryer of banana slices. As drying or water evaporation consumes energy, the energy consumption in different drying methods were evaluated [2, 3]. Theoretical approaches for evaporation from open water surfaces have been studied [4], they tested a maximum evaporation theory which has originally developed for the ocean over saturated land surfaces, it explicitly shows the interactions between radiation, T_s, and evaporation. The evaporation from droplets with internal capillary liquid flow has been studied [5]. Pure droplets and water droplets containing dissolved and suspended solids were considered in this study [6]. They reported results for pure drops in still air evaporation and then extrapolated a general correlation of their data for higher Reynolds number; also results for droplets containing soluble and insoluble materials were stated. Different models for water evaporation were proposed, and the water droplet evaporation model based on temperature was performed [7]. Turbulent flow evaporation from a sprayed flow was investigated numerically [8] for its importance in chemical industries. The performance of evaporative cooling with cellulose and polyvinyl chloride (PVC) corrugated media Figure 1 was experimentally studied [9].

As fuel spray and mixing with air is very important in combustion, spraying Urea–Water Solution (UWS) in hot exhaust gas evaporation was studied [10] for automative industry. The evaporation and spray penetration of different fuels were under investigation [11], the vapour pressure was revealed to have important effects on the dynamic shape of the evaporation process.

The wind tunnel was used to investigate the evaporation rate according to velocity and water depth [12]. Nusselt number Sherwood number and schemed number were related to vertical plate dropping water film evaporation [13]. Experimental and theoretical investigations on drying pepper slices were performed and the effect of the temperature on the diffusion model was analyzed [14]. A wetted towels and free water surfaces were compared evaporation rates under different climatic conditions were recorded and correlated with air velocity [15], water temperature, air temperature, and relative humidity. High technology has been used to study evaporation in hot ambient air and a simplified model is developed for numerical simulation.

In this study humidification of airflow from a single wet cylinder was experimentally investigated, this work aims to analyze the heat and mass transfer from single, double and triple wet cylinders. The effect of varying temperature and number of cylinders were stated. This study is a part of a detailed analysis of evaporation and humidification from various cylinders configuration under various ambient conditions.

MATERIALS AND METHODS

Experimental setup

To investigate the process of wetted cylinders humidification (WCH), an experimental testing device was built, the testing device Figure 2, consists of:

- Polycarbonate panels – the experimental device body was built of a polycarbonate sheet for its transparency, lightweight, and good insulation.
- Half-inch copper pipe – used to transmit water from the supply to the wet cylinder.
- Straw – used as strainers to achieve uniform airflow.
- Axial fan – to create airflow through the experimental test section. The fan has a 15 cm diameter, and 30 W capacity (Table 1).
- Sensors – multiple sensors were used for temperature and humidity sensing, as shown in Figure 3. A DHT11 digital temperature and humidity sensor was used to measure the humidity and temperatures of air at various positions of the experimental device. It uses dedicated digital modules capture technology to ensure that products with high reliability and excellent long-term stability. The sensor includes a resistive element and a sense of

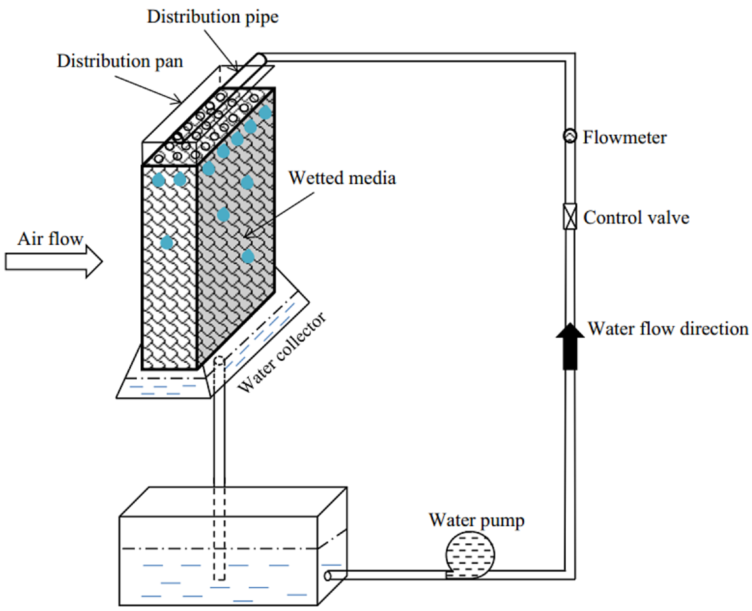

Figure 1. Water flow system [9]

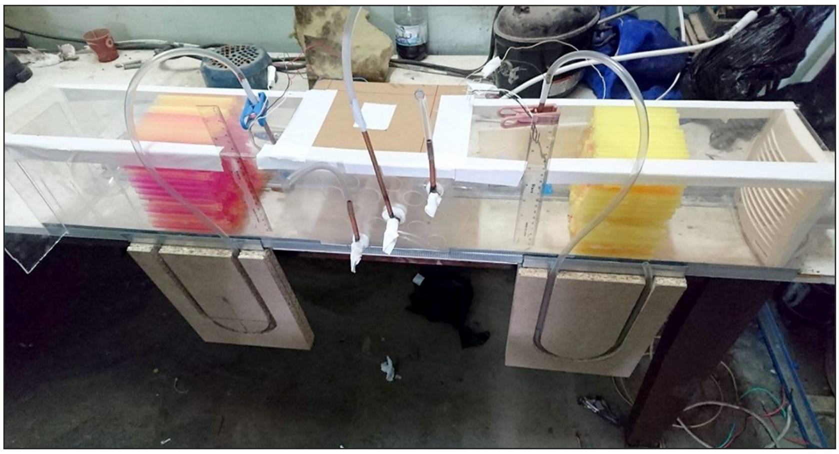

Figure 2. An experimental testing device built in the laboratory

Table 1. Fan technical dimensions and specifications

Color	White
Body material	Polypropylene
No. of blades	5
Sweep	150 mm
Speed	1350 rpm
Air delivery	250 m^3/h = 70 L/s
Power	30 W
Voltage	230 V
Length	27 cm
Width	14.5 cm
Height	27 cm

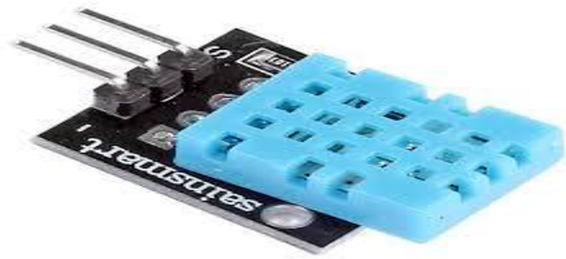

Figure 3. Sensors for temperature and humidity sensing

wet NTC temperature measurement devices with a high-performance 8-bit microcontroller connected.
- Different capacity tungsten lamb – used to heat air with different wattages to control the supplied air temperatures.
- Breadboard – 840 tie points round hole designed for easy plug and pull expandable by combining several boards to meet the different requirements. Wear proof material made of ABS & phosphor bronze with good flexibility and electric conductivity.
- Cotton and gauze – were used to cover a copper pipe that continuously supplied the cylinder with water (Figure 4).
- Arduino Uno R3 – uses an ATmega16U2 instead of the 8U2, allowing faster transfer rates and more memory (Figure 5). No drivers are needed for Linux or Mac. The Uno R3 works with all existing shields but can adapt to new shields that use these additional pins.

Figure 4. Cotton and gauze

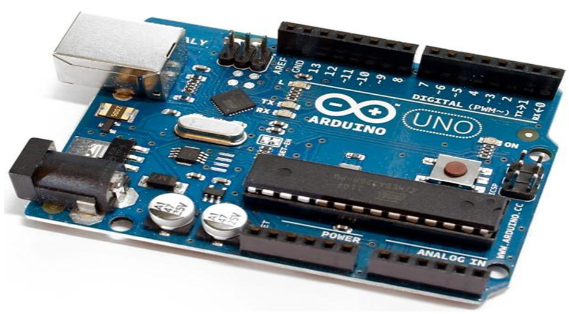

Figure 5. Arduino Uno R3

METHODOLOGY

To study the humidification resulting from flow over the wet cylinder, an experimental test rig was constructed as shown in Figure 1. The fan, heater, strainers, test section and sensors were assembled and connected to the PC to collect data for different flow conditions. One, two, and three cylinders were inserted in the test section to evaluate the effect of multi-cylinder configurations (Figure 6).

The air inlet temperature was varied to study the effect of temperature on humidification capacity. Temperatures before, and after the test section and ambient conditions were recorded with time.

Theory and validation

To analyze the humidification from different wetted cylinders, experiments were performed and compared to previous studies. Theoretically, the evaporative rate from a water body to the ambient air can be found in [15]:

$$\dot{m}_e = h_m * (P_w - \emptyset * P_a)^n \qquad (1)$$

where: $\dot{m}_e$ is the evaporation mass flow rate, h_m is the mass transfer coefficient due to wind speed, P_w is the saturation pressure of the water body, $\emptyset$ is relative humidity, P_a *is* saturated vapor pressure at ambient air temperature.

The mass transfer coefficient may be calculated from:

$$h_m = 0.2792 + 0.2685 * v \qquad (2)$$

where: v is the wind speed over the water's surface, n = 0.82 for free water surface, and 0.7 for wet cloth surface.

The dew point temperature can be found as [16]:

$$T_{dp} = 6.983 + 14.38\, ln(e) + 1.079(ln(e))^2 \qquad (3)$$

Where e is found from:

$$e = 0.61078 * exp(\frac{17.269382*T}{237.30 + T}) \qquad (4)$$

To validate the results of the constructed device the results of the evaporative cooling were compared to the theoretical results from [17], which states that evaporative cooling is a constant enthalpy process:

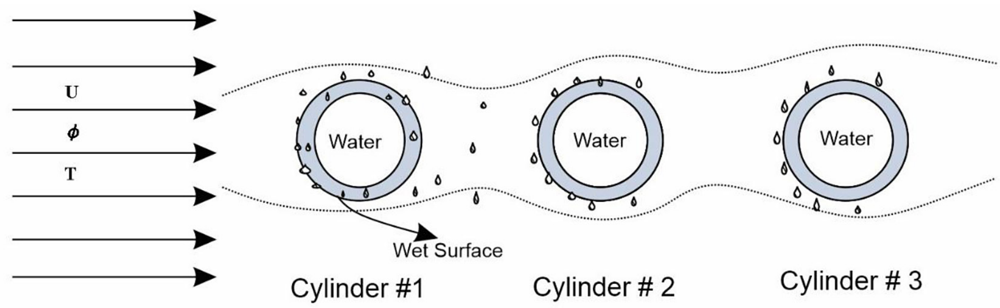

Figure 6. Flow over multiple wet cylinders

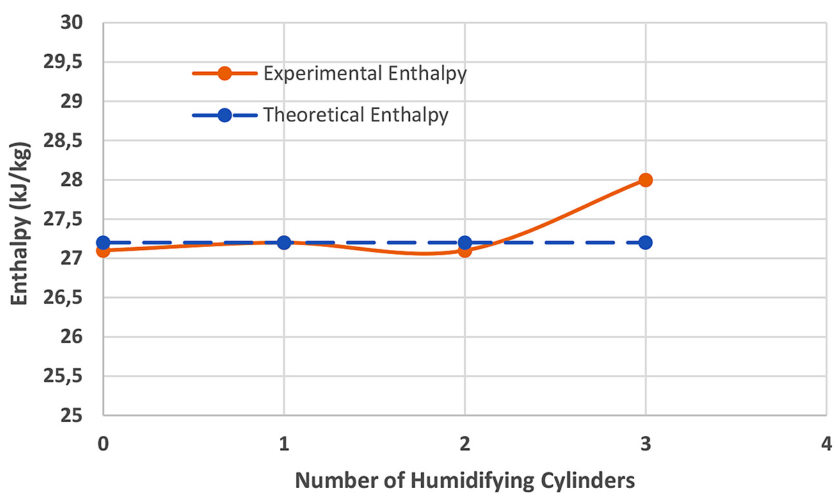

Figure 7. Theoretical and experimental enthalpy (results validation)

$$h_i = h_e = c \quad (5)$$

The values of the experimental enthalpy results almost fit with the theoretical results. The maximum variation is 3.3% only.

RESULTS

The humidification performance of the investigated device was tested for various air temperatures and for single, double, and triple wet cylinders (Figure 8).

The experimental device was tested for the change in air temperature and its effect on the relative humidity of the air. Figure 9 shows how the temperature and relative humidity of the sensors (2 and 3) change with using the heating element.

As the heating element is on the temperature of sensors 2 and 3 increases as indicated by Figure 9a, whereas the relative humidity of

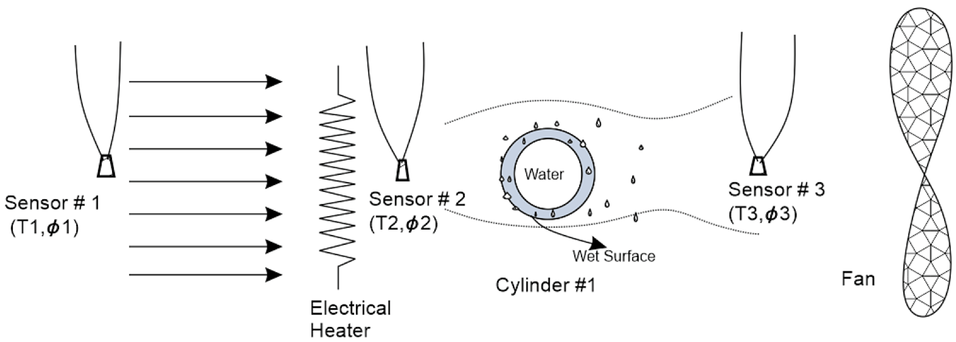

Figure 8. Schematic diagram of the constructed device showing the sensors and heating element

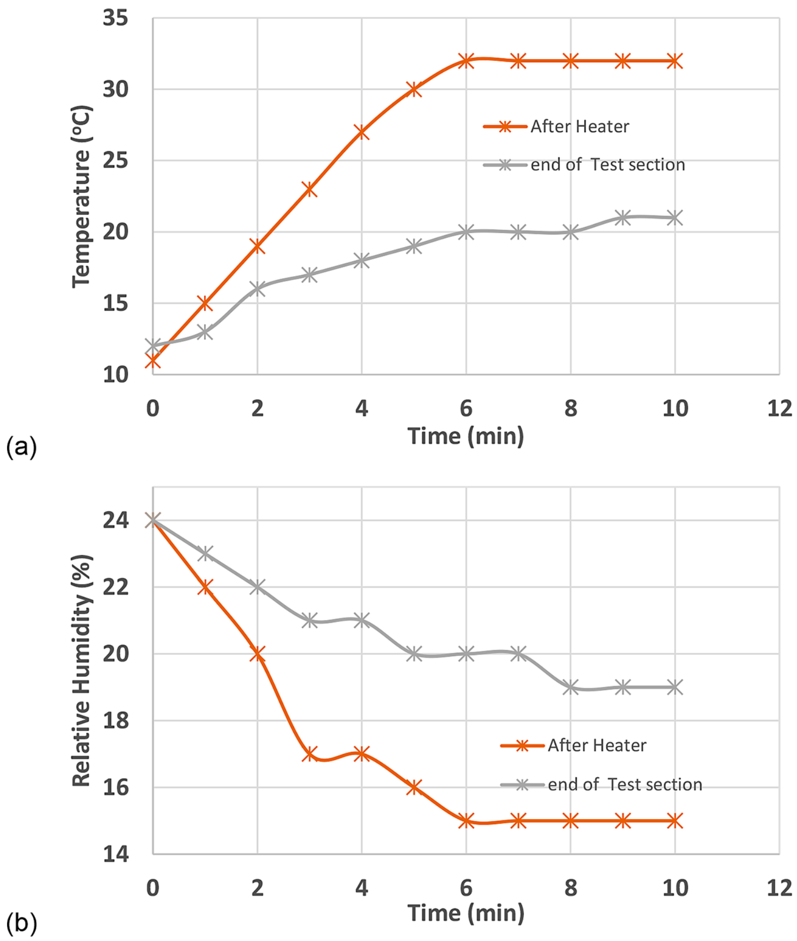

Figure 9. Heating without using wet cylinders

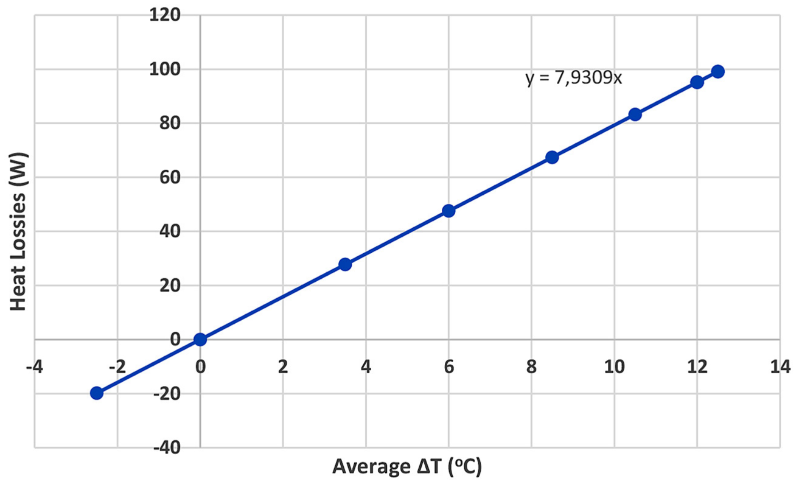

Figure 10. Test section heat losses versus test section average temperature difference

air decreases since heating is sensible without a change in humidity ratio (Figure 9b).

Figure 10 shows the behavior of humidity and temperature through the test section. As the test section is subject to the ambient conditions the heat transfer from the test section should be analyzed:

$$\dot{Q} = \dot{m} * c_p * (T_e - T_i) \quad (6)$$

The flow rate of the fan is taken from Table 1. and the specific volume from the psychrometric chart is according to the inlet conditions $\dot{m}$ = 0.0079 kg/s. Thus, the thermal resistance of the test section:

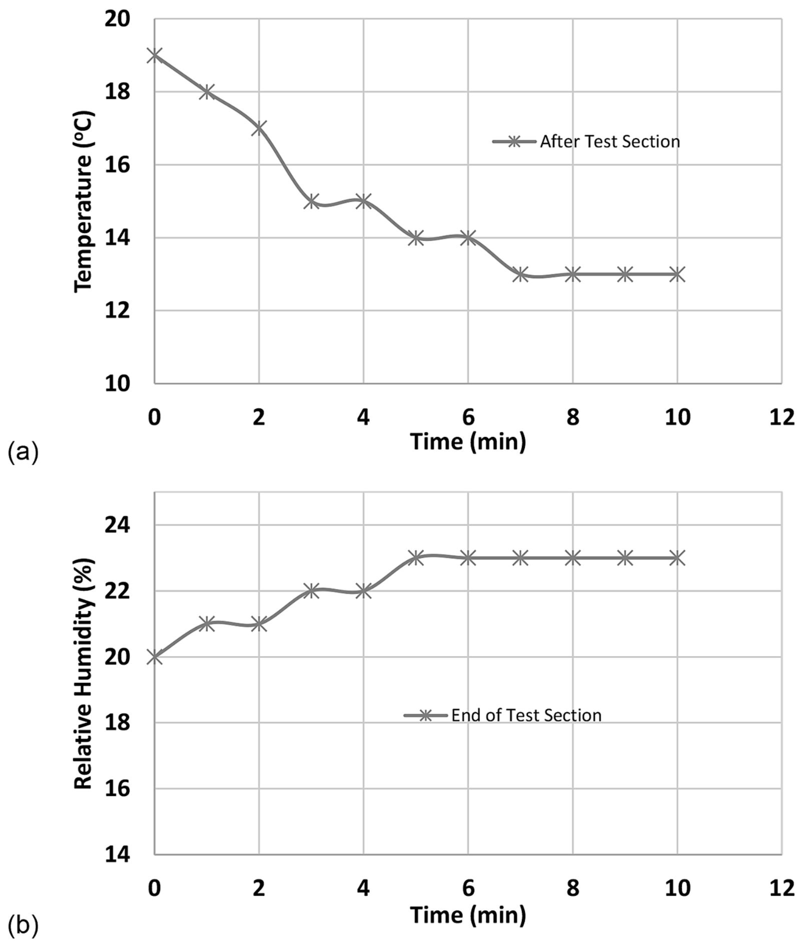

Figure 11. The implemented one wet cylinder

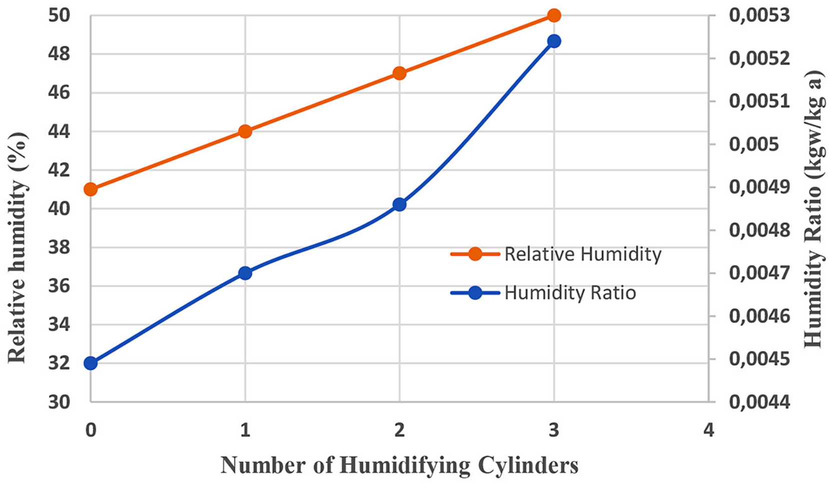

Figure 12. Effect of using multiple wet cylinders on evaporation

$$\dot{Q} = \frac{\Delta T}{R} \tag{7}$$

where: R is the thermal resistance calculated to be 0.126 K/W, and ΔT is the difference between the average flow temperature and ambient temperature (Figure 10).

As the flow in the test section is 0.3 m/s for a 25 L/s flow rate, the velocity cooling effect can be calculated from [18]:

$$CE = 8.10 * va - 0.89 \tag{8}$$

where: CE is the cooling effect of air velocity va, for 3 m/s a temperature drop of about 1.5 °C is calculated.

The cooling effect shows a higher relative humidity than ambient. After varying the inlet air temperature, the effect of using wet cylinders on evaporation has been investigated. Figure 11 shows the results of temperature and relative humidity of one wet cylinder for sensor 3 (after the wet cylinder). The temperature has dropped as a result of evaporation and relative humidity increased.

To analyze the multiple wet cylinders single, double, and triple successive wet cylinders were tested, and results were recorded and plotted on Figure 12. It shows the variation of relative humidity and humidity ratio when single, double, and triple wet cylinders are used, as expected the relative humidity has been increased with continuous increments in the amount of water in the air. The higher number of wet cylinders resulted in a higher amount of water evaporating.

CONCLUSIONS

In this study, the influence of using multiple wet cylinders on evaporation rate has been investigated. A test rig was constructed to collect the experimental results, and the number of wet cylinders used and the change in air temperature were tested. The results were validated with the theoretical results and the error was a maximum of 3.3%. Results showed a reduction in relative humidity as the temperature rose as expected. The amount of water in the air was increased by using double and triple wet cylinders. As $\dot{m}_a = 0.0975$ kg/s with an almost constant wet bulb temperature of 9 °C, the amount of water evaporated were calculated as 73.7, 130 and 263 g/h for single, double and triple wet cylinders respectively.

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