Proceedings of the 7th International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT'20)
~~Niagara Falls, Canada~~ Virtual Conference – November, 2020
Paper No. 156
DOI: 10.11159/ffhmt20.156

Experimental Investigation of Humidification Efficiency of a Structured Packing-Based Counter Flow Humidification System

Sampath Suranjan Salins[1], S V Kota Reddy[2], Shivakumar[3]
[1]Manipal Academy of higher education
DIAC, Dubai, United Arab Emirates. PO: 345050
First: sampath@manipaldubai.com; Second: svk_reddy@manipaldubai.com
[2]Manipal Academy of higher education
DIAC, Dubai, United Arab Emirates PO 345050
[3]shiva.kumar@manipal.edu
Manipal Institute of technology, Manipal
Karnataka, India, PO 574104.

Abstract - Cooling & humidification process is one of the widely used AC application for cooling purposes. It is adopted where a certain amount of moisture content must be maintained, in order to achieve thermal comfort. Packing is an element which holds the fluid within its surface and interact with the intersecting fluid. Current paper focus on the construction of the humidification unit where the water is made to drip on the packing uniformly and the air is made to pass through the packing in counterflow direction. The moisture content of the air increased by 15%. The experimentation is carried out with different water temperature & the air flow rate. Optimum flow rate of air and temperature of water is determined based on trials conducted. Humidification efficiencies can be determined for varying flow rates of air & by measuring various temperatures. Results showed that there is drop-in rate of heat transfer of 25% from the peak value and the average drop in humidifying efficiency by 27% when there is an increase in the mass flow rate after a certain limit. Change in relative humidity and temperature drops by an average value of 59% and 81% respectively.

***Keywords*:** Humidification, Counterflow, Packing, sensible cooling.

1. Introduction

Humidification involves in the rise in moisture content of air. In this process the moisture or water vapor is added to air and the dry bulb temperature is maintained constant [1]. Cooling and dehumidification process is very widely used in air conditioning systems where mainly cooling is the important goal. Forced flow involves in the use of electricity for blowing the air. Evaporative cooling is most effective cooling mechanism in AC systems [2]. Humidifiers, cooling towers & evaporative coolers are some of its kind. Water and air interact in cross or counterflow direction. The warm air interacts with the water which drips on pad gets evaporated and the fluid which leaves will be at lower temperature [3]. During this phenomenon, WBT remains constant and pads get wet by dripping water on pads which is usually upper edge of vertically arranged pads. Some of the factors effecting the evaporative pads such as thickness, surface area, material, perforation size, rate of flow, wettability etc. Pads are made of different materials like wood, glass & plastic [4]. The production process involved in pads are complicated and expensive. Cellulose pads are manufactured to make evaporative cooling more effective. The evaporative cooling process is widely used in various applications like residential buildings, poultry, swine buildings, warehouses etc [5]. Cellulose pads are cheap, compact, energy efficient and light weight. Corrugated paper pads which are used are very popular has applications in air cooling, agriculture and household applications [5]. In summer season the buildings get heated up from dry wind and energy of the sun. Wall and roof stores the energy continuously in its volume or space. The heat makes the entire house warm and uncomfortable in evenings. This can be dealt with the use of evaporative cooling [6]. Evaporative cooling is a method used in providing comfort to the human beings and used everywhere. Vapor compression refrigeration cycle AC system has an disadvantage of ozone depletion, therefore use of pads in humidification are desired. It is a natural cooling effect which can be observed during warm days near river, sea or lakes [7]. This phenomenon provides cooling and comfort in buildings. Evaporative cooling can be of direct, indirect, combination or mixed type. The supply of water can be drip method, cool cells or wetted ad method or fogging method.

2. Literature Survey

Dipak Ashok Warke [2] Performance of cellulose cooling pad which is made of corrugated papers are investigated. The specification of the pads are 0.35 X 0.35 m^2 with varying thickness of 50, 100 and 150 mm. Results showed that evaporated water and pressure drop increases with the thickness and air velocity. Also, humidity variation and effectiveness decreases with air velocity. It is also determined that the effectiveness of the cellulose pads depends on the thickness of pads and the inlet velocity. Compared to aspen pads, cellulose pads produced best performance and used in desert coolers. Hye-Jin Cho [8] worked on a parallel and counterflow humidification and dehumidification system where the direction of air to fluid plays an vital role to evaluate the performance of dehumidification with a construction of the tower. Performance is assessed for both counter and parallel flow by performing the series of experiments. In order to predict performance of dehumidification of different flows with differing operating parameters, model uses enthalpy effectiveness and dehumidification effectiveness. These two parameters are taken as performances indices. Results indicated that counterflow humidification and dehumidification system showed better performance compared to parallel flow. the enthalpy and dehumidification efficiency of counter flow liquid dehumidification system rise from 40 to 70% and 50 to 80% . Meanwhile effectiveness of crossflow dehumidification rises from 60 to 63%. B. Kiran Naik [9] performed experimental investigation of energy exchange between ambient air and desiccant. Influence of humidity of air on performance of liquid desiccant dehumidification system is studied. An mathematical model is developed to relate process parameters at the inlet and outlet of the packing. By substituting the known parameters, unknown values are obtained. Two-dimensional thermal model is proposed to study counterflow system. Experimental and theoretical model matches, and it is found to be very accurate. The overall experimentation determines difference between the inlet and exit temperatures, humidity ratio etc. Je Lin [12] developed an dimensionless analysis for the model for the counter flow liquid humidifier or dehumidifier system. A prototype is built to assess the process parameters. A 3D CFD analysis is designed inorder to predict mass and heat transfer performance of dehumidifier. A.S.A. Mohamed [22] worked on both counter and cross flow humidification and dehumidification system where channel gauze packing is used. Inlet parameters like air velocity, humidity ratio, desiccant flow rates are considered. Results showed that there is a significant improvement in the humidification. Bari’s Kavasogullari [23] designed and tested humidification and dehumidification system which operates at peak performance value under atmospheric conditions without facing any mass transfer problems. The type of packing used here is polycarbonate panels. It is used in both desorber and absorber units. Among polymeric based packing types, polycarbonate gives very high surface tension. This improves wettability of various liquid desiccants and also mass transfer property. Various parameters such as relative humidity, velocities, temperature and concentration change in the desiccant are measured. The current work concludes that polycarbonate packing is very effective in humidification and dehumidification. Er.Satwinder Singh [26] conducted experimental analysis on counter flow humidification and dehumidification set up. The type of packing used is PVC Zig zag configuration. Three different thicknesses are used and the desiccant used is calcium chloride. Three different thicknesses 150, 300 and 450 mm are used. The operating parameters which is used to predict the performance are rate of moisture removal, air outlet temperature, humidity ratio & solution outlet temperature. Under desiccant and air parameters desiccant flow rate, air flow rate, temperature of desiccant and air and solution concentration change are measured. From the above literature it can be concluded that thickness of the pads and the air velocity is a major criterion for improving humidification performance. Counterflow offered better humidification and dehumidification performance compared to cross and parallel flows. Some of the operating parameters in dehumidification system are relative humidity, temperatures and air velocity. Among packing Celdek packing gave better performance compared to Gauze and polycarbonate packing. Literature survey reveals that most of the researchers have studied the performance of energy exchange between air and water under cross flow conditions. Studies related to the counterflow exchange of energy with varying air velocities and varying water temperature is limited. Hence in the present work, counter flow heat exchanger arrangement is considered for analysing the humidification process. The process parameters such as air velocity and the water temperatures are varied, and the system performance has been studied.

3. Methodology

The initial design is carried out using modeling platform. The materials are procured, and the construction of the entire system is done with the installation of the measuring instruments. Various measurements are carried out mainly for measuring the temperatures of water as well as air before and after heat transfer, air velocity & relative humidity. Calculations are carried out to determine humidification efficiency and the results are analyzed. The series of activities performed are shown by the flow diagram in figure 1. Area of cross section of 0.0225 m^2 and Density of air of 1.225 kg/m^3 is considered.

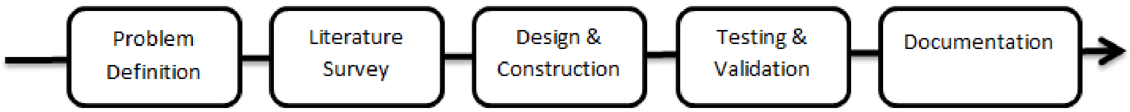

Fig. 1: Methodology of the workflow.

Equation 1 which is shown used to determine the flow rate of air. It is calculated with the consideration of density of air, area of crossection and the velocity of the air. Equation 2 gives the flow rate of water can be directly calculated by multiplying water discharge with the density of water.

$$\dot{m}_{air} = \rho AC \tag{1}$$

$$\dot{m}_{Water} = Q_d \, \rho \tag{2}$$

Air passing through a spray chamber with recirculated water gets cooled by the evaporation of water. Such cooling of air accompanies humidification. Specific humidity vs. the dry bulb temperature shows the drop in the temperature and the rise in specific humidity. Desert coolers use this principle for cooling buildings in hot and dry climate to make them comfortable [11,13]. Since the cooling cannot be achieved below wet bulb temperature of the outside or incoming air, at which temperature the leaving air will be saturated, this technique of cooling has only limited use. Hence the system becomes ineffective in monsoon season [14,15]. Perfect humidification is not possible in actual practice due to its inefficiency of spray chamber [16,17,18]. Therefore, the final condition of air at outlet is represented in between 1 and 2. The effectiveness or the humidifying efficiency of the spray chamber is given by the ratio of actual drop in DBT to ideal drop in DBT is given by equation (3). Also, it is defined as ratio of actual increase in humidity to the ideal increase in humidity.

$$\eta = \frac{t_1 - t_3}{t_1 - t_2} = \frac{w_3 - w_1}{w_2 - w_1} \tag{3}$$

By using the dry bulb temperature & relative humidity other thermal parameters like enthalpy, specific humidity, specific volume, vapor pressure & Wet bulb temperature are obtained. By varying the inlet parameters, output can be obtained, and an optimum value is obtained. Equation (4) represents the total heat dissipation rate when there is an interaction between the two fluids [19,20].

$$\dot{Q} = \dot{m} \, C_P \, \Delta T \tag{4}$$

Methodology gave a brief idea about the process and the governing principles & equation involved. Next section shows the method of construction of the model, its parts, working and measuring instruments.

4. Design, Construction and Working

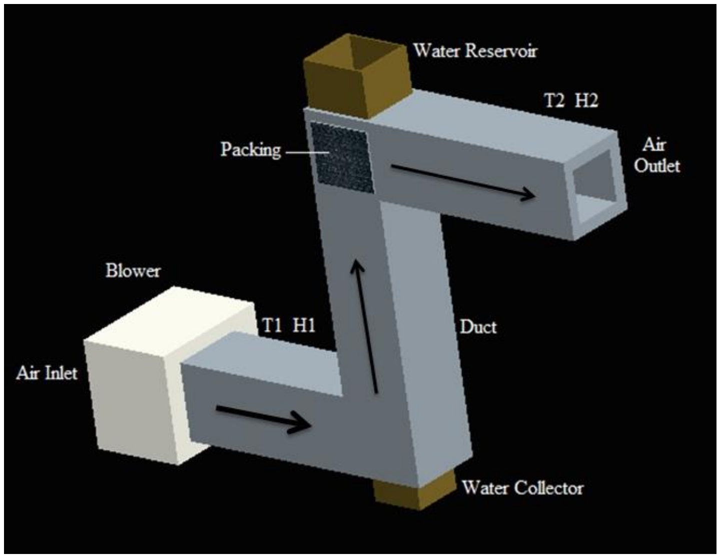

Fig. 2: CAD Model of the counter flow Humidification system.

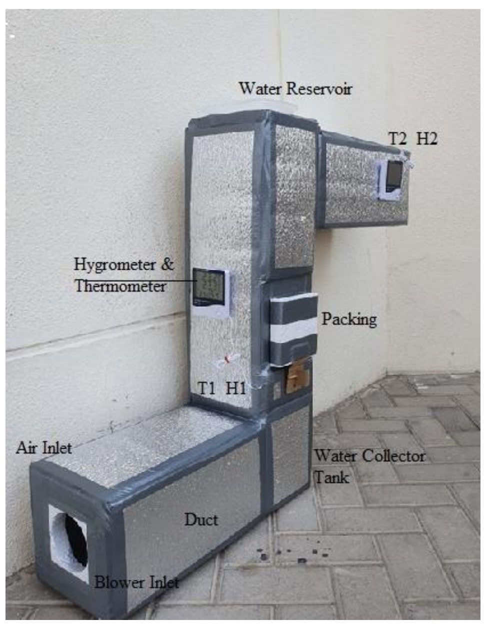

Fig. 3: Experimental Set up the counter flow Humidification system.

The model shown in the figure consists of a duct where the air flows through it. Blower supplies the air into it at varying inlet velocities. A packing which is placed is soaked in water due to the flow of water by gravity. Water is constantly dripped on the packing. When the air pass through it the moisture content of the air increases. Thermal parameters are noted down. The water gets collected in the collector tank. Same water is reused again. The air flow and the water flow take place in opposite directions this leads to maximum interaction of air and water. Thermometer and Hygrometer measures the temperature & relative humidity of air [21]. Figure.3 shows experimental set up of counter flow dehumidification system. Where the duct is constructed out of hard thermocol. Duct tape and thermal blanket acts like an insulating material to the system.

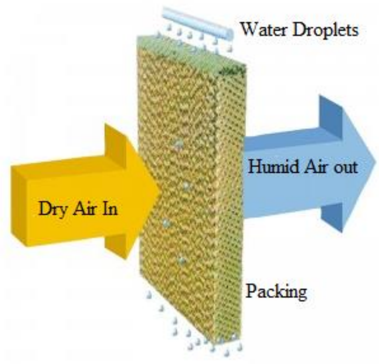

Fig. 4: Celdek Packing.

Celdek Packing shown in figure.4 with known wettability provides surface area to hold the water. Air velocities are varied to obtain the various humidification values is measured by using anemometer. By using various thermal parameters, humidification factors are evaluated, and the optimum flow rate of air & water is determined.

Table 1: Specification of Measuring Instruments and their accuracy levels.

Sl. No	Instrument	Used to measure	Specification	Accuracy
1.	Thermometer (digital)	Temperature	Temperature range: -20 to 100˚C Probe Diameter= 6 mm Probe Material: Stainless steel Resolution: 0.1˚C	± 0.1˚C
2.	Hygrometer	Relative Humidity	RH Range: 0%-99% Power supply: 1.5 V Display resolution: 0.1 %	±2.0%
3.	Anemometer	Air Velocity	Speed range: 0 to 50 m/s Threshold sensitivity: 1 m/s Resolution:0.05 m/s	± 0.3 m/s

After construction, experimentation is carried out various parameters are measured using instruments. The least count of thermometer is 0.1 degrees that are 5 subdivision for every division. Least count of anemometer is 0.3 m/s and the minimum value of the wind velocity measured is 1 m/s. Similarly, least count of hygrometer is 2% which measures relative humidity. The accuracy of the instrument is given in the Table.1. The instruments which are used gave consistently same results. The output which is plotted in the graph is purely experimental results when the counter flow humidification is performed. Water dripping on the packing interacts with the air and the humidity raises along with cooling effect. Lower water temperature gave more humidification efficiency. According to theories of heat transfer increase in the air velocity after a limit the heat transfer rate drops since there is minimum interaction time period. the nature of the graph for humidification efficiency and heat transfer rate for various air velocities and water temperature remained constant. Similarly, the relative humidity drops, and the temperature drop for various air velocities and water temperature remains same. This shows that results consistently follow similar pattern and the results are accurate. Next section gives the details of the experimental results obtained.

5. Results and discussions

Experiments have been conducted for various air velocities and the different water temperature. Throughout the study equation (1) shows the mass flow rate of the air flowing into the duct. Equation (2) shows the mass flow rate of the water which is a product of water discharge and density. Equation (3) represents the humidification efficiency which is a ratio of actual temperature drop to ideal temperature drop. Equation (4) shows the heat transfer rate when there is an interaction of water and the air.

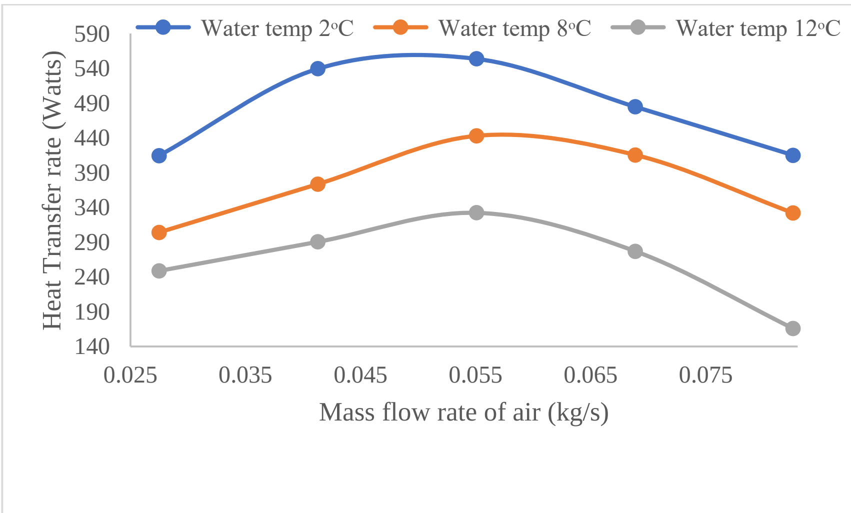

Fig. 5: Variation of heat transfer rate with the mass flow rate.

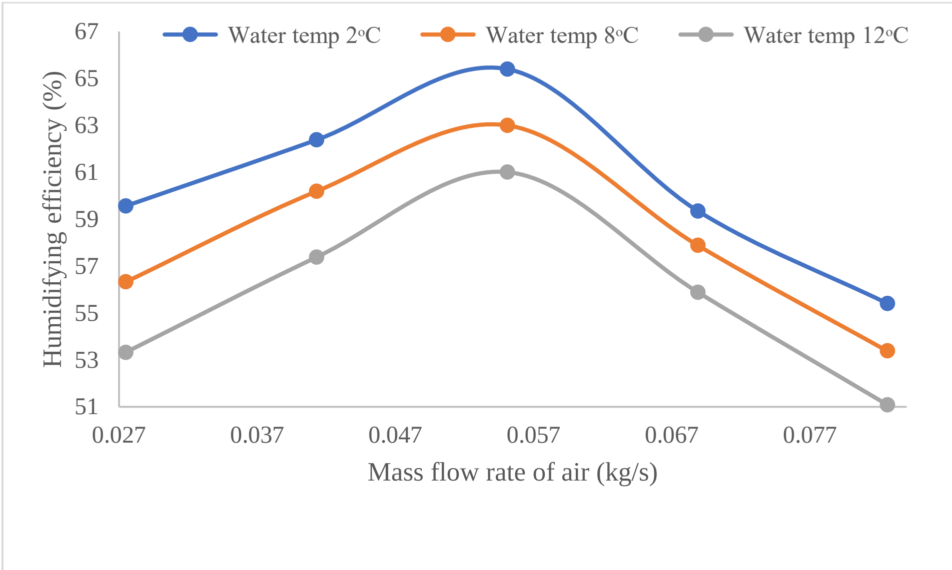

Fig. 6: Variation of humidifying efficiency with the mass flow rate.

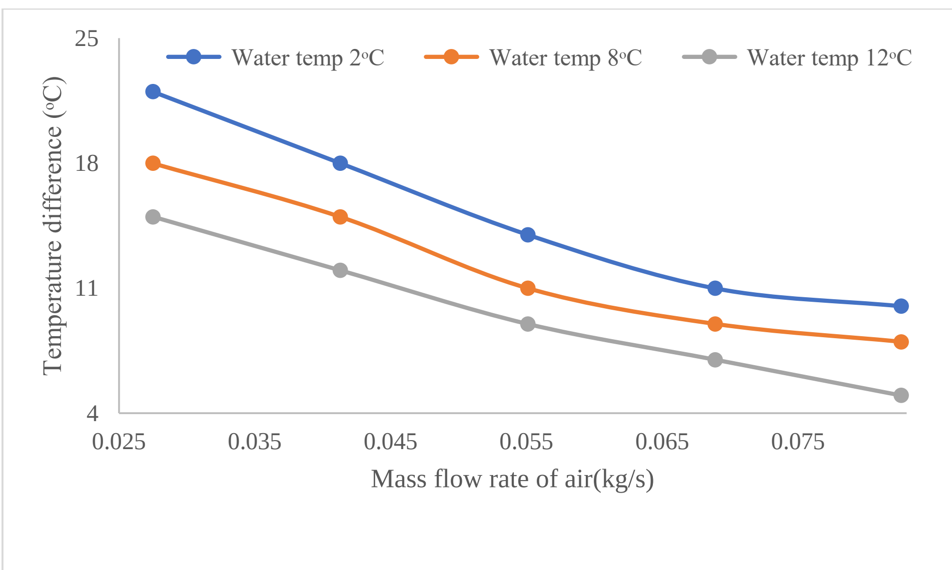

Fig. 7: Variation of temperature difference with mass flow rate.

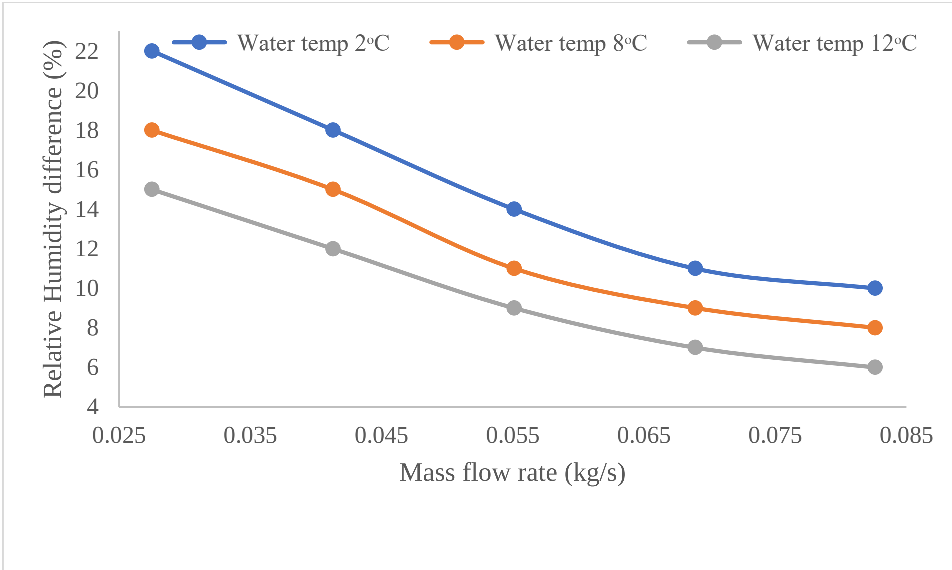

Fig. 8: Variation of relative humidity difference with the mass flow rate.

Humidification efficiency is defined as ratio of actual increase in humidity to ideal increase in humidity. Operating parameters like air velocity, air inlet temperature values in addition to humidity values decides the humidification efficiency. Figure 6 shows variation of the humidification efficiency with mass flow rate. Results show that there is an increase in heat humidification efficiency till the flow rate of 0.055 kg/s and then there is a drop in the curve. This is because of increased air velocity, where there is not enough time to take away the moisture along with it. The humidification efficiency is high for the low temperature of the water. When the water temperature is 2˚C there is a drop in the humidification efficiency by 11%, when water temperature is 8˚C, humidifying efficiency drops by 27% and when water temperature is 12˚C there is a drop of humidifying efficiency by 44%. Humidifying efficiency drop increases almost twice its original value for increase in the water temperatures. For a mass flow rate of 0.55 kg/s the percentage drop in the peak point from 2˚C to 8˚C is 3.6% and from 8˚C to 12˚C is 3.1%.Relative humidity is the ratio of partial pressures of the water vapor to the partial pressure of the saturated mixture. Relative humidity mainly depends on the pressure and temperature of system. For the same quantity of water vapor, the relative humidity of cool air is higher than warm air. Hygrometer measures the relative humidity. Using psychrometric chart both relative and specific humidity can be determined. Air velocity is varied, and the relative humidity difference values are noted and plotted. Figure 8 shows variation of humidity difference with mass flow rate. It exhibits drop in the value. For the water at 2˚C there is a drop in the relative humidity difference of 54%, for water temperature of 8˚C the drop observed is 55% and for 12˚C the drop observed is 66%. There is an increase in the drop in the relative humidity percentage. For the mass flow rate of 0.55 kg/s, the relative humidity difference value drops by 21% for the water temperature increase from 2˚C to 8˚C and there is a drop in the relative humidity difference by 18.1 %.

When the air is blown over the packing containing cold water, there is a change in temperature because there is a heat dissipation taking place. During the process air temperature also will be reduced. The important operating parameters are air velocity, flow rate, air temperature at the inlet & outlet. Figure 5 shows variation of the heat transfer rate with mass flow rate. Results show that there is an increase in heat transfer rate till the flow rate of 0.055 kg/s and then there is a drop in the curve. This is because of increased air velocity, where there is not enough time to take away the moisture along with it. The heat transfer is high for the low temperature of the water. For the water temperature of 2˚C there is a drop in the heat transfer rate by 25%, 26% for 8˚C and drop of 50% for 12˚C. For mass flow rate of 0.55 kg/s the heat transfer rate value reduces by 20% when the water temperature increases from 2˚C to 8˚C and 25% when temperature increases from 8˚C to 12 ˚C. Digital thermometers are placed at inlet and outlet. The difference between higher to lower temperature comprises the change in temperature. For lower water temperature magnitude of the temperature difference is high. As the cold-water temperature rises there is drop in the magnitude of temperature difference. Air velocity is varied, and the temperature difference values are noted down. Figure 7 shows variation of temperature difference with mass flow rate. Graphical representation exhibits the drop in the value. For the water temperatures 2˚C,8˚C and 12˚C there is a drop in temperature difference by 66%, 68.30% and 77.77%. There is a rise in the overall percentage values. For the mass flowrate of 0.55 kg/s there is drop in the difference in the temperature by 20% when there is an increase in the water temperature by 2˚C to 8˚C and there is an drop in the difference in the temperature by 25% when there is an increase in water temperature from 8˚C to 12˚C.

6. Conclusions

The current developed system is used in the humidification and cooling of the air in the dry regions. Graphical representation signifies that there is an increase in heat transfer rate and humidification efficiency till air velocity of 2 m/s is attained & after that there is a drop in these values. The humidification efficiency is high for the low temperature of the water. When the water temperature is 2˚C, 8˚C and 12˚C there is a drop in the humidification efficiency by 11%, 27% and 44%. Humidifying efficiency drop increases almost twice its original value for increase in the water temperatures. For the water at 2˚C there is a drop in the relative humidity difference of 54%, for water temperature of 8˚C the drop observed is 55% and for 12˚C the drop observed is 66%. There is an increase in the drop in the relative humidity percentage. For fixed flow rate of 0.55 kg/s, the relative humidity difference value drops by 21% for the water temperature increase from 2˚C to 8˚C and there is a drop in the relative humidity difference by 18.1 %. With increase in flow rate there is a drop in the temperature & relative humidity difference. The heat transfer is high for the low temperature of the water. For the water temperature of 2˚C there is a drop in the heat transfer rate by 25%, 26% for 8˚C and drop of 50% for 12˚C. For mass flow rate of 0.55 kg/s the heat transfer rate value reduces by 20% when the water temperature increases from 2˚C to 8˚C and 25% when temperature increases from 8˚C to 12 ˚C. For the water temperatures 2˚C,8˚C and 12˚C there is a drop in temperature difference by 66%, 68.30% and 77.77%. For the mass flowrate of 0.55 kg/s there is drop in the difference in the temperature by 20% when there is an increase in the water temperature by 2˚C to 8˚C and there is an drop in te difference in the temperature by 25% when there is an increase in water temperature from 8˚C to 12˚C. Change in configuration which indirectly changes the wettability will makes a significant difference to obtain for improved humidification condition.

Nomenclature

A= Area of crossection, m^2
ρ= Density, kg/m^3
C= Velocity of air, m/s
$\dot{m}$ = mass flow rate, kg/s
Q_d= Discharge, m^3/s
η= Humidifying efficiency, %
t_1= Inlet temperature, ˚C
t_2= ideal Outlet temperature, ˚C
w_1= Specific humidity at the inlet, g/kg
w_2= ideal specific humidity at the outlet, g/kg
$\dot{Q}$ = Heat transfer rate, watts
C_p= Specific heat at constant pressure, J/kg˚C
t_3= Actual Outlet temperature, ˚C
w_3= Actual specific humidity at the outlet, g/kg

Acknowledgements

Authors are thankful to the lab support provided by the School of Engineering & IT, Manipal Academy of Higher education, Dubai, UAE.

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