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Experimental Analysis of Cellulose Cooling Pads Used in Evaporative Coolers

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Abstract

In this paper, performance of two types of cellulose cooling pads (5090 and 7090) which were made from corrugated papers has been investigated. They were tested in a sub sonic wind tunnel. The pads areas are $0.35\times 0.35\ m^2$ with 50, 100 and 150 mm thicknesses. Humidity variation, Pressure drop, effectiveness and evaporated water have studied for several inlet air velocities. The results show that overall pressure drop and amount of evaporated water increases by increasing the inlet air velocity and thickness in both types of pads. On the other hand, effectiveness and humidity variation decreases by increasing inlet air velocity. When compared with local materials the effectiveness of the pads in decreasing order of magnitude is Cellulose>Aspen>Khus pad. Cellulose pad effectiveness depends on thickness of pads as well as inlet velocity. Further more with proper maintenance, cellulose pads can be used for many years. This study is useful for making opportunities in residential buildings to use cellulose cooling pads instead of aspen pads in conventional desert coolers.

Keywords

Cellulose Cooling Pads, Water Evaporation Rate, Evaporative Cooler

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1. Introduction

Direct evaporative cooling process is one of the most efficient techniques used in air conditioning applications such as cooling towers, humidifiers and evaporative coolers. In this process, water and air are in contact with cross-flow arrangement, vertical channels for water flow and horizontal channels for air. First, warm air is drawn by fan into a dwelling through a porous wetted material or pads. Then, the water absorbs heat and evaporates from porous wetted medium. Finally, the air leaves the system at a lower temperature(Figure 1). During the cooling process, the wet-bulb temperature of the air remains constant and the porous pad are wetted continuously by spraying water on the surfaces of pads or by dripping water onto the upper edge of vertically mounted pads.

The efficiency of evaporative pad systems is affected by many factors including surface area and thickness of pad, the type of material used in the pad, the size of perforations, flow rate and relative humidity of air passing through the pad, and volume of water used. Evaporative pads have made from different materials such as metal, wood, plastic, and glass. Manufacturing of commercial pads made of these materials are complicated and costly. At present Aspen & Khus pads are used in evaporative coolers, which are most popular in central part of India for cooling residential buildings. Recently, manufacturers have been designed new pads made of cellulose paper to make evaporative cooling more useful and efficient in different applications including industrial and residential sectors, swine building, poultry, greenhouses, as well as storage warehouses [1–6]. These pads are energy efficient, economical, compact in size and light in weight,

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and pollution free. These advantages of the pads fabricated with corrugated papers made them so popular to be used in wide range of applications such as agriculture market, combustion turbine inlet air-cooling system, household appliances, and in horticulture. In spite of the widespread use of evaporative cooling pads made from aspen and khus in the market, there is limited information on the other alternative pad materials capable of absorbing water and allowing evaporation. Therefore, the scope of present study is to assess the thermal and hydrodynamics performance of a new type of material(cellulose papers) that could be inexpensive, easily be constructed into the required shape, visually attractive, and locally available.

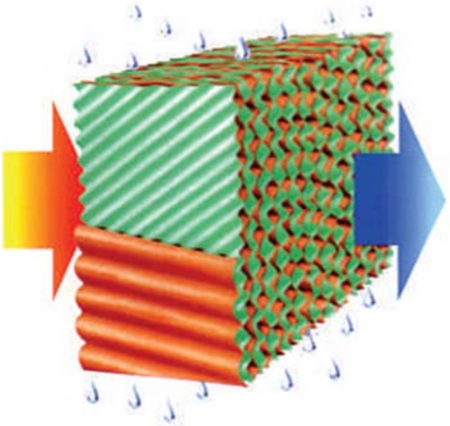

Figure 1. Diagram of evaporating process.

2. Literature Review

Koca et al. [7] developed a procedure for testing evaporative cooling pads. They showed that face air velocity, pad angle, static pressure drop across the pads and pad thickness are important parameters affecting pad performance. Liao et al. [8] studied the effects of thickness and inlet air velocity on pressure drop and efficiency of evaporative cooling pads. They used two kinds of pad materials, a coir fiber and a nonwoven fabric perforated pads and showed that for a 15 cm pad and under operating air velocities of 2–3 m/s, cooling efficiencies varied from 81.19% to 81.89% and89.69% to 92.86% for nonwoven fabric perforated and coir fiber material pads, respectively. Al-Sulaiman [9] experimentally evaluated the performance of three natural fibers (palm fiber, jute and luffa) as wetted pads in evaporating cooling. The results indicated that for an air velocity of 2.4 m/s, the cooling efficiency is highest for jute about 62.1%, compared to 55.1% for luffa fibers, and 38.9% for date palm fiber. Liao and Chiu [10] developed a compact wind tunnel to simulate evaporative cooling pad-fan systems. They tested two different materials for pads and investigated the effects of water flow rate, pad thickness and inlet air velocity on evaporative cooling efficiency. The pads were made from coarse fabric PVC sponge mesh 2.5 mm diameter in pinhole and fine fabric PVC sponge mesh 7.5 mm diameter pinhole. Their results showed that the efficiency of fine fabric PVC sponge is lower than the one for coarse fabric PVC sponge. They also found two correlations for heat transfer coefficients. Gunhan et al. [11] experimentally evaluated the suitability of greenhouse shading net, pumice stones and volcanic tuff as pad materials for use in evaporative coolers.

They reported that volcanic tuff is a good alternative pad material at0.6 m/s air velocity. The results show that with decreasing airflow velocity and increasing pad thickness, the evaporative efficiency increases. Furthermore, they showed that with increasing water flow rate and pad thickness, pressure drop increases. Rawangkulet al. [12] experimentally analyzed the performance of coconut coir material used as a direct evaporative cooling pad. They determined evaporative cooling efficiency and pressure drop across two small coconut coir pads of different configuration in a range of velocity1.88–2.79 m/s. They confirmed that coconut coir has reasonable potential for use as a wetted media in evaporative cooling systems. Dai and Sumathy [13] solved governing equations for cross-flow direct evaporative cooler using an integration method. They used honeycomb paper as packing material and assumed constant space between channels. Their results showed that the performance improve by optimizing dimensions of honeycomb paper, mass flow rates of air and feed water. Beshkani and Hosseini [14] mathematically investigated the performance of rigid media evaporative cooler that uses corrugated papers as wetted medium. They employed finite difference method and projection algorithm tosolve the governing equations of air flow. The results shows that increasing the depth of media will cause an increase in both the pressure drop and the efficiency. On the other hand, decreasing air velocity will raise the efficiency and decreases the pressure drop. They also found that the use of corrugated papers instead of flat papers would cause higher efficiency and pressure drop about 40% and 50%, respectively. Hosseini et al. [15] numerically studied a media evaporative cooling system installed in gas turbines of the Fars (Iran). They studied the effects of geometric shape, depth and size of media and inlet air velocity on water evaporation rate, pressure of ambient, temperature drop and relative humidity. The results show that the output of gas turbine of the Fars at a given ambient temperature and relative humidity is 11MW more than that of without media evaporative cooling system. They also found that with increasing incoming air velocity, the cooler effectiveness and pressure drop increase. Wu et al. [16] conducted a numerical study to investigate the cooling efficiency of direct evaporative cooler. They studied the effect of pad thickness, frontal air velocity, and wet-bulb and inlet air dry-bulb temperatures on cooling efficiency. The results show that cooling efficiency increases with decreasing frontal velocity and increasing pad thickness. In their second paper [17], they theoretically analyzed heat and mass transfer between air and water film in the direct evaporative cooler with durable honeycomb papers as pad material. Their proposed model for cooling efficiency was based on the energy balance analysis of air. They showed that with increasing frontal velocity and decreasing pad thickness, the cooling efficiency of evaporative cooler decreases.

The above literature review shows that rarely researchers have done experimentation on performance of evaporative pads made from cellulose papers. Therefore, this paper focus on the effect of thickness, inlet air velocity, and type of pads on parameters affecting thermal and hydraulic performances of the pads. This work experimentally studied the pressure drop effectiveness, the humidity variation and the amount of evaporated water of the two types of cellulose pads (5090 and 7090) made from corrugated papers. cooling effectiveness is defined as the ratio of the difference between exit and entering dry-bulb temperatures to the difference between wet point and exit dry-bulb temperatures.

3. Experimetal Set up

The experiments have been conducted in steady state conditions on two types of cellulose pads made from corrugated papers in an open loop, low speed, compact humidity and temperature controlled wind tunnel. Two types of pads (recorded as pad 5090 and 7090) with 50, 100, 150 mm thicknesses and 0.35×0.35 m^2area have been used in the experiments (Figure 2a, 2b). In this commercial identification [18, 19], the first two digits indicate the average distance between the two adjacent layers in millimeter and the last two digits refer to the angle between two sequential corrugated layers. Test pad modules are fabricated from several wavy thin layers of corrugated papers bonded together to make a structurally supporting module of thicknesses 50, 100, 150 mm.

Figure 2a. Cellulose Pad 7090.

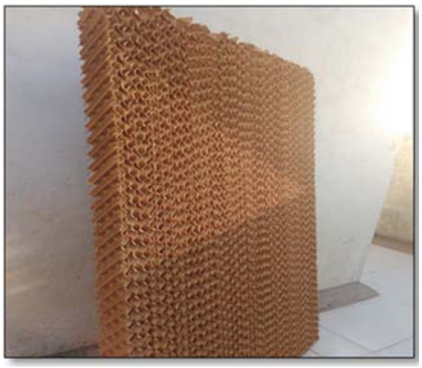

Figure 2b. Cellulose Pad 5090.

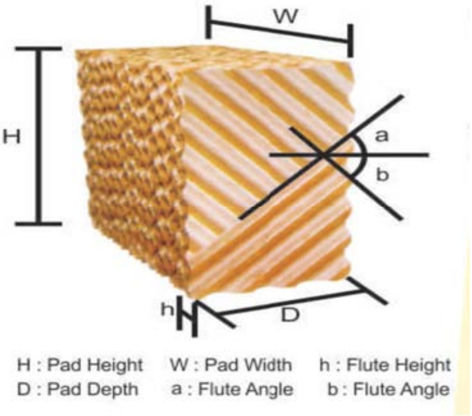

Figure 3. The angle between two adjacent corrugated papers.

Figure 3 shows the air flow channels formed by the alternate wavy thin layers of cellulose papers and the angle between two adjacent corrugated papers. The variable parameters in the experiment that studied are variation of humidity, pressure drop, amount of evaporated water and effectiveness. Used wind tunnel with square cross section and with dimensions of 0.35×0.35m^2 and total length of 3m. To minimize heat loss to the surrounding; the test section was insulated with fiber glass. The dimensions of pads are 0.35×0.35m^2 which exactly fitted to test section and positioned 80 cm after tunnel entrance. To ensure a constant air intake and minimize the effect of flow distribution in the experiment, an anti-turbulence screen (honeycomb baffle)were provided at the entrance of tunnel. Air heater was used to heat the inlet air. To spray water uniformly with different flow rates and perpendicularly to the test pad media, three header tubes are used on the top of the pads. In order to control water flow, each header tube has a particular valve. Pumps were used for circulating water from reservoir and header tubes. The excess water flows through a gutter at the bottom of test section. Water flow rate was measured by collecting the water at this point. The ambient airflow is driven to the test section by a centrifugal fan of 0.46m diameter controlled by a regulator. The flow rates were controlled by a 12 A motor varying from 0 to 3000 rpm to provide inlet air speeds of 1.6, 2.3, 2.6, 3,3.2, 3.6 and 4 m/s.

4. Instrumentation and Procedure

To do experimentation on evaporative pads, an environmentally controlled room is prepared by providing air conditioner to keep the dry-bulb temperature of room at 19 ± 5°C in the test room. For measurement of mean inlet velocities of the airflow entering to the test section a differential pressure flow meter has been used. A digital pressure gauge is used for measuring pressure. T-type thermocouples with accuracy ±0.1°C were utilized for obtaining wet-bulb and dry temperatures. In order to validate the thermocouple reading, during each test, wet and dry-bulb temperature were manually recorded at all measuring positions. The mean difference in wet bulb and dry-bulb temperatures were ±0.9°C and ±0.21°C with standard deviations 0.15°C and 0.37°C, respectively. All thermocouples have been installed 30 cm far from the both sides of pads. Before the commencement of the experiments, all pressure and humidity sensors and thermocouples were carefully fixed at the specific location. A 0.5m^3 water tank was isolated completely. Evaporated water measured by reading from reservoir. The uncertainty of experimental results may be originated from measuring errors of parameters such as flow rate and temperature. Using a method described by Taylor and Kuyatt [20] the maximum uncertainties of effectiveness, inlet air velocity, pressure drop, temperatures and humidity variation are estimated to be ±4.8%, ±3%, ±2.1%, ±1.1% and ±2.3%. The experimental uncertainty in thermocouple's location was estimated to be ±7%. In order to ensure that the pads are wetted completely, evaporative pads were wetted for 24 hour before experiments. At the start of each test and before changing air velocity a waiting period of at least 20 min ensured equilibrium between room air conditions and the evaporative pad. After this, the fan was turned on for 20 min and when steady state conditions reached; the temperature, humidity, water consumption and pressure at the inlet and outlet of the pads were recorded. Figure 4 shows a schematic of experimental set up.

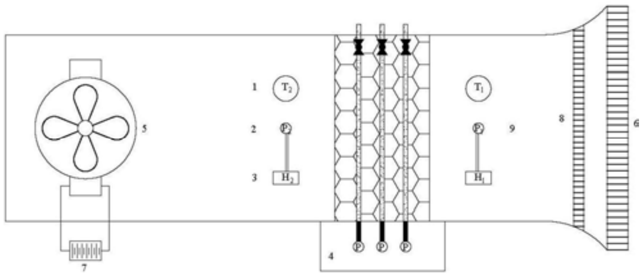

Figure details

1	Thermometer	4	Sump	7	Supply
2	Pressure diff.	5	Fan	8	Baffle
3	Humidity meter	6	Heater	9	Air duct

Figure 4. Experimental set up.

5. Result and Discussion

The results of experimental analysis consist of three parts in a range of inlet wind velocity 1.6–4 m/s. First, the effect of thickness and type of pads on the overall pressure drop along the evaporative pads is studied. Then, the effect of these parameters on the humidity variation along the evaporative pad is investigated. Finally, the effects of thickness and type of pads on the amount of evaporated water and effectiveness are studied. For performance assessment of investigated pads, the effectiveness of evaporative pads is calculated using the following equation:

Thermal effectiveness

$$\varepsilon = \frac{T_{out} - T_{in}}{T_{out} - T_{wb}}$$

where T_{in} and T_{out} denotes the inlet and outlet dry bulb temperatures of the air at the test section, respectively and T_{wb} is the temperature of wet bulb. Indices in, out, wb refer to inlet, outlet and wet bulb temp, respectively.

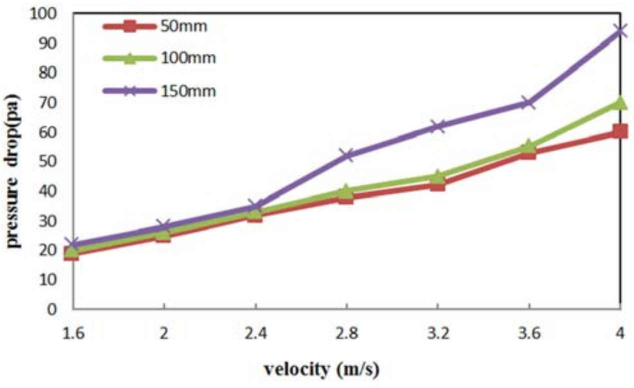

Figure 5a. Pressure drop for pad 5090.

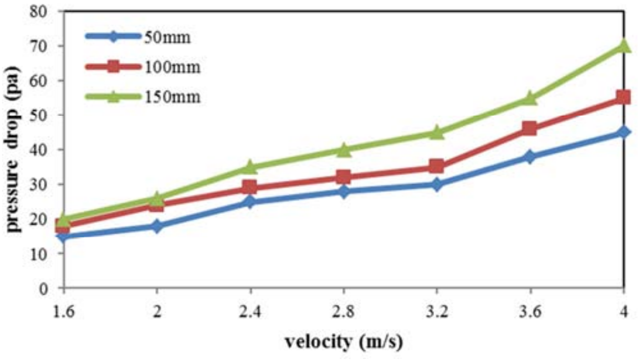

Figure 5b. Pressure drop for pad 7090.

Figure 5a and 5b show the effects of thickness and inlet air velocity on the overall pressure drop along the length of evaporative cooler. As expected, the pressure drop increases by increasing the inlet air velocity in both types of pads. The reason is that increasing inlet air velocity will lead to higher distribution of flow field at inlet of pads as well as higher air resistance between corrugated papers. It can also be seen that with increasing the thickness, the pressure drop across pads increases. This is due to higher resistance of the air flowing across the pad. Another important result that can be obtained from the figures is that at a same thickness and inlet velocity, the pressure drop in pad 5090 is higher than that of for pad 7090. This is due to the smaller pinholesize in a unit area for pad 5090 with respect to pad 7090 which leads to higher contact area and consequently higher friction in pad 5090 with respect to pad 7090.

Figure 6a and 6b demonstrate variation of humidity versus inlet air velocity for different thicknesses. It can be seen that the variation of humidity decreases with increasing the velocity. As can be noticed from these figures, in both types of pads (5090 and 7090) with increasing the thickness the variation of humidity increases. Increasing humidity variation with increasing thicknesses is due to increasing the contact between wetted areas and the flowing air.

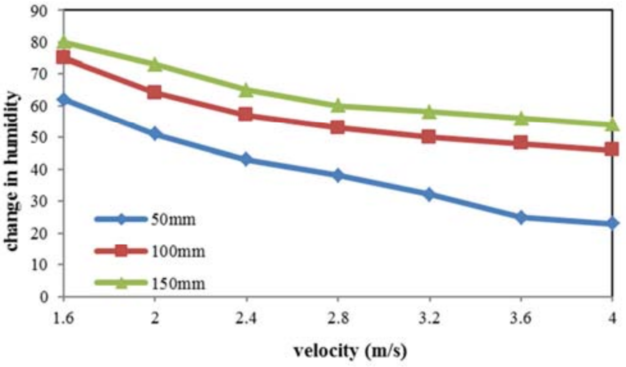

Figure 6a. Humidity drop for pad 5090.

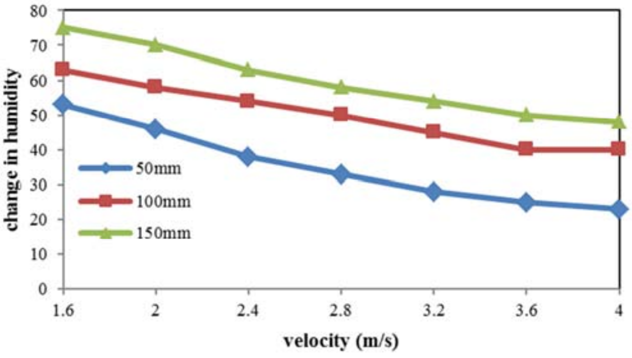

Figure 6b. Humidity drop for pad 7090.

In Figure 7a and 7b the amount of evaporated water for different air speeds and thicknesses can be seen. From the figures, it is evident that with decreasing the thickness of pads the amount of evaporated water decreases. It is due to the fact that decreasing the thickness of pads leads to decreasing the contact surfaces between corrugated papers and the flowing air. Moreover, with increasing the inlet air velocity the amount of evaporated water increases. With increasing the inlet air velocity, the mass transfer coefficient on the surfaces of pads increases which leads to higher amount of evaporated water.

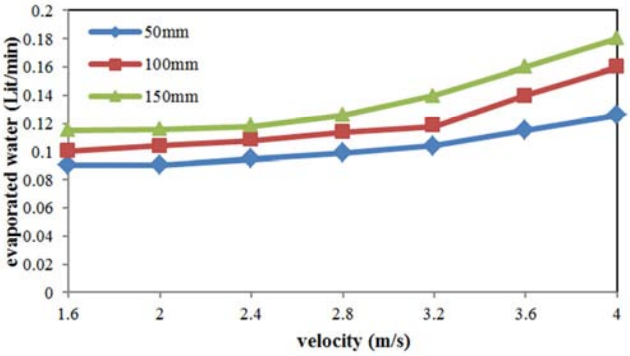

Figure7a. Amount of evaporated water for pad 5090.

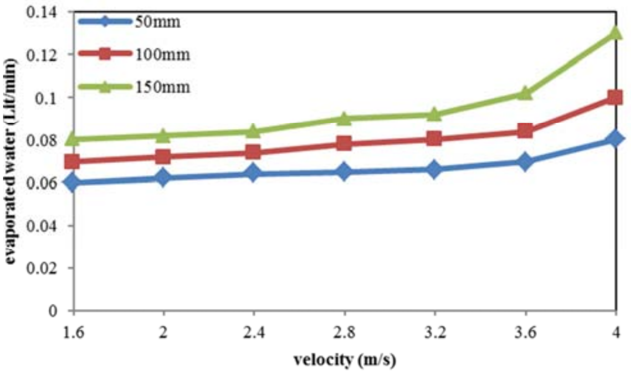

Figure 7b. Amount of evaporated water for pad 7090.

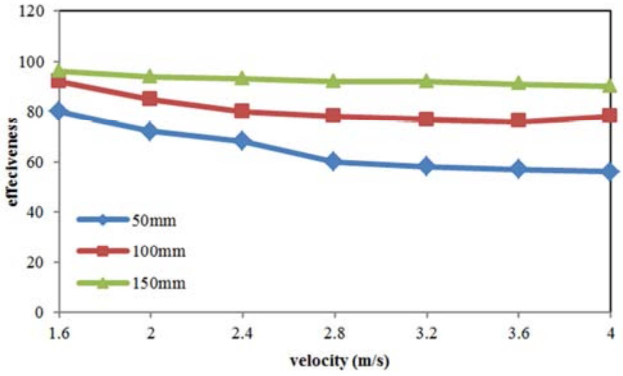

Figure 8a. Effectiveness for pad 5090.

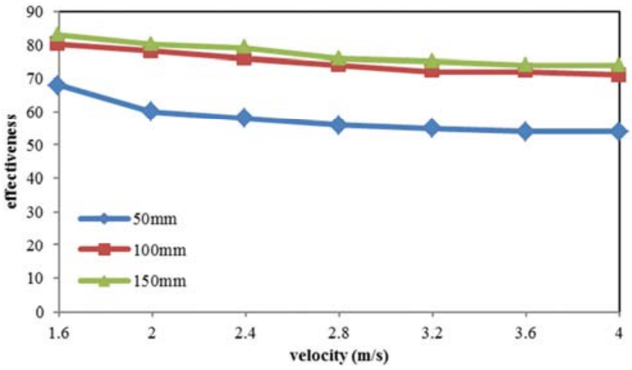

Figure 8b. Effectiveness for pad 7090.

Figure 8a and 8b indicate the effect of thickness on effectiveness of pads. It can be seen that for each thickness in both types of pads the effectiveness decreases with increasing the inlet air velocity from 1.6 to 4 m/s. The reason is that with an increase in velocity the time for heat and moisture transfer between water and air is shortened and meanwhile a higher pressure drop occurs. It should be noted that low velocity may require a large frontal area of pad to achieve the needed air flow. Therefore, a reasonable inlet air velocity should be chosen with consideration of pad thickness. Moreover, as seen with increasing the thickness, the effectiveness increases and it may approach 100% when the pad thickness reaches a certain value. This means there exist an optimum pad thickness according to the needed effectiveness.

Significance of the thickness of pad material:

Pad material thickness plays an important role in the performance of the evaporative cooler. Various thickness are used for Cellulose, Aspen, Khus evaporative cooling pads. A comparative study is also carried out for maximum thickness of aspen and khus pads. Table 1 gives the thickness data used for all three types of cooling pads.

Table 1. Thickness of cooling pad materials.

Pad Material	Pad Thickness(*l*) (mm)
Cellulose Pad	50
Cellulose Pad	150
Aspen Pad	18
Aspen Pad	16
Khus Pad	20
Khus Pad	40

Cellulose Pad:

In case of cellulose pad, the 150mm cellulose pad shows the maximum efficiency (90.37%) as compared to the 50mm cellulose pad with (61.19%), speed of cooling fan being same in both the cases i.e. 1300 rpm.

Figure 9a shows the comparison between the 50mm and 150mm thick cellulose pad for speed and saturation efficiency.

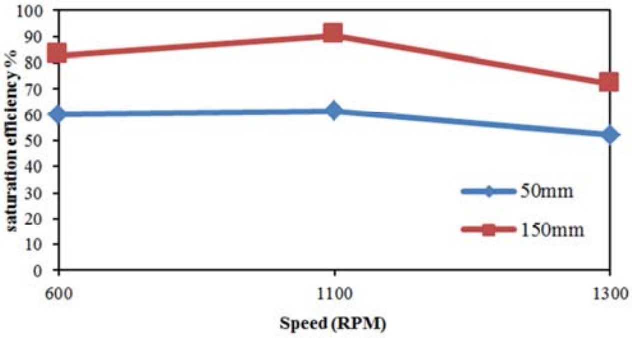

Figure 9a. Speed Vs Saturation efficiency for Cellulose pad.

Above graph shows that the as the thickness of cooling material increases the efficiency increases as the air get maximum area for the evaporation of water.

Aspen Pad:

In case of Aspen pad, the 36mm aspen pad shows the maximum efficiency (78.31%) as compared to the 18mm thick aspen pad with (54.51%).

Figure 9b shows the comparison between the 18mm and 36mm khus pad for speed and saturation efficiency.

The maximum efficiency is observed for the moderate speed, as the fan speed increases the efficiency decreases, reason being that at higher speed the contact time between the air and the wet surface decreases, results in reduction in effectiveness, although there is increase in the convective heat transfer co-efficient.

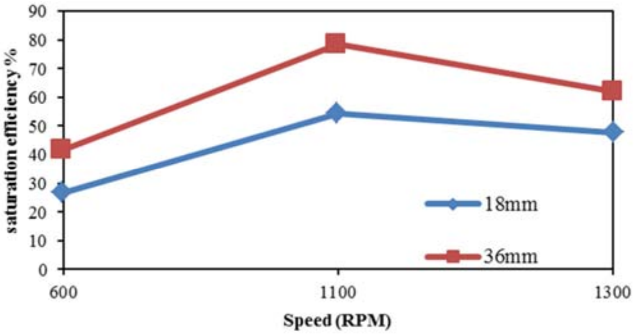

Figure 9b. Speed Vs Saturation efficiency for Aspen pad.

Khus Pad:

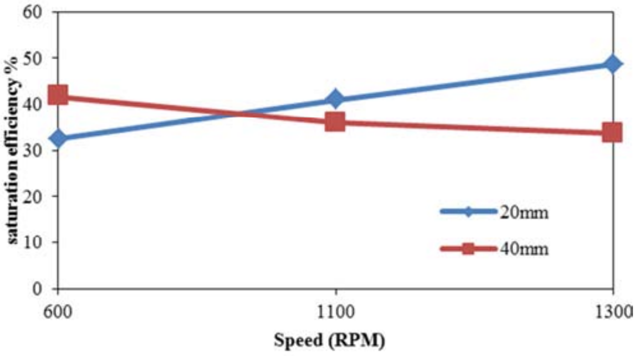

Figure 9c. Speed Vs Saturation efficiency for Khus pad.

Figure 9c shows the comparison between the 20mm and 40mm khus pad for speed and saturation efficiency.

In case of khus pad, the 20mm khus pad shows the maximum efficiency (48.62%) as compared to the 40mm khus pad with (33.72%), speed of cooling fan being same in both the cases i.e. 1300 rpm, reason being that due to its dense nature, air does not get sufficient gap for the evaporation. So it is better to use the minimum thickens in case of khus pad.

6. Conclusion

Cellulose cooling pad is an alternative evaporative cooling pad material with a maximum effectiveness occurs at velocity 1.6 m/s for thickness 150 mm in pad 5090. However, the minimum pressure drop occurs at thickness 50 mm for pad 7090 and velocity 1.6 m/s. Also, the minimum evaporated water is about 0.06 Lit/min for thickness 50 mm at 1.6 m/s air speed in pad 7090. Hence effectiveness depends upon thickness of the pad because higher thickness of pad increases the contact surface area and also depends on the velocity of air passing through the pad.

The cellulose pad with thickness 150mm is found to be the most efficient than the other cooling materials with the maximum saturation efficiency of 90.37%, also aspen pad with thickness 36mm gives maximum saturation efficiency of 78.31%

The efficiency increases as the thickness of the pad increases in case of cellulose and aspen pad But in case of khus pad with increase in thickness, the efficiency decreases because it restricts the flow of air due to its high density.

Hence the effectiveness of the pads in decreasing order of magnitude is Cellulose>Aspen>Khus pad.

It is concluded that for cellulose pad by increasing inlet air speed, pressure drop and amount of evaporated water increases but effectiveness and humidity variation decreases. but when the air speed decreases and pad thickness increases, the optimum point may occur. Hence further investigations are required to find the optimum speed and optimum thickness to use cellulose pad in residential building effectively.

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