ORIGINAL ARTICLE

Membrane and plastic heat exchangers performance

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Abstract

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The performance of a membrane-based heat exchanger utilizing porous paper as the heat and moisture transfer media is presented. The measured performance is compared with a plastic film heat exchanger. This novel heat exchanger is used in ventilation energy recovery systems. The results show that the sensible effectiveness is higher than the latent effectiveness. When a similar experiment was conducted using a plastic film heat exchanger surface instead of paper, where only heat is transferred, the sensible effectiveness values were lower than the effectiveness values recorded when the paper heat exchanger is used. Furthermore, energy analysis shows that utilizing a paper surface heat exchanger in a standard air conditioning system will lead to significant energy savings.

Key words : sensible effectiveness, total effectiveness, latent effectiveness, heat and moisture transfer, energy recovery

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In the last few decades, researchers have focused on the development of advanced heat exchangers due to energy conservation demands. Many countries have adopted new standards for building ventilation that specifies higher outdoor air ventilation due to concerns over indoor air quality which is affected by volatile organic compounds, smoke, dust and bacteria. As a result certain buildings may require 100% fresh air to be used in the air conditioning systems. Thus, more energy will be required to condition the outdoor air as air conditioning load constitutes 20% to 40% of the thermal load for commercial buildings (ASHRAE, 1997), and it can be even higher if 100% fresh air is used. Therefore, energy recovery ventilators are utilized to recover a fraction of that energy (Dorer and Beer, 1998). In the past, researchers have focused on the recovery of sensible heat, by utilizing devices such as sensible heat exchange wheels and plate heat exchangers (Dhital *et al*., 1995). These devices have limitations, such as condensation, suffering from corrosion if plate heat exchangers are used and requiring maintenance. In addition to these limitations, these devices could transfer sensible heat only, neglecting the recovery of latent heat that constitutes a large fraction of the total thermal load for an air-conditioned building. This led to an increased attention on developing energy recovery systems to recover both latent and sensible energy. In order to recover sensible energy, heat should be transferred and in order to recover latent energy moisture should be transferred. Heat and mass transfer are in fact analogous to each other and whenever there is a gradient in heat or mass concentration, heat and mass will be transferred from the hot and higher concentration side to the colder and lower concentration side. This phenomenon is used in ventilation energy recovery systems, where the ambient hot and humid supply air is passed over one side of a membrane heat exchanger and on the other stream the room exhaust air, which is cold and less humid is passed (Figure 1). Thereby, heat and moisture are transferred across the membrane surface due to the gradient in the heat and moisture content between the supply air and the room exhaust air, causing a decrease in temperature and humidity of the supply air stream before it enters the evaporator unit, hence both sensible and latent energy are recovered.

Zhang and Jiang (1999) conducted an experimental investigation of the performance of such systems and for simplicity they used a rectangular cross-flow heat exchanger to study the heat and moisture transferred. A numerical model was developed and validated against the experimental results. From the numerical solution, they realized that the membrane area was not effectively used to transfer heat and moisture and the highest heat and moisture transfer occurred near the inlet

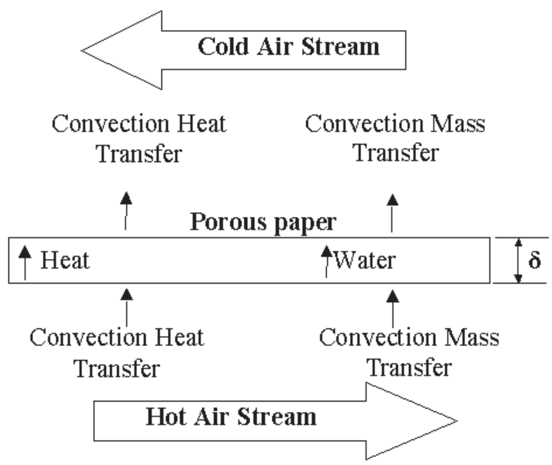

Figure 1. Schematic diagram of paper heat exchanger; heat and moisture transfer.

area. Niu and Zhang (2001) conducted a similar investigation of a square shaped heat exchanger. Their numerical results show that the temperature and humidity in a cross flow heat exchanger configuration are more evenly distributed in comparison with Zhang and Jiang results. Thus, these results show that the membrane shape plays an important role and has a significant effect on the temperature and moisture transfer. Niu, and Zhang's (2001) results show that the sensible effectiveness was typically higher than the latent effectiveness and both sensible and latent effectiveness decreased with increasing air velocities. Zhang and Jiang (1999) tried to improve the effectiveness using different types of membranes and different airflow arrangements. Their results show that the highest sensible and latent effectiveness occurred when a counter flow heat configuration is used. However in a real application it is difficult to implement a counter flow arrangement, as both inlet and outlet ducts are located on the same side of the heat exchanger.

The work presented here involves a new Z type flow heat exchanger, which utilizes either thin porous paper film or plastic film as the heat transfer surface (Figure 2). With this new flow configuration, the heat and moisture transfer is improved relative to the counter flow arrangement, as this flow configuration combines both counter and cross flow configurations and as a result, the effectiveness is significantly improved. Moreover the cost of the heat exchanger is low because it is based on cheap material such as thin paper and plastic sheet.

Experimental Set up

The performance of a Z flow heat exchanger shown in Figure 2, was investigated under laboratory conditions. The experimental rig shown schematically in Figure 3, has an overall dimension of 4m x 0.71m x 1.03m and consists of two separate air ducts arranged in parallel. The ducts walls are made of 25 mm thick polystyrene sandwich panels with thin steel sheet. As shown in Figure 3, the experimental rig is divided into three sections, namely entry section, test section and outlet section.

In the entry section, two centrifugal fans are mounted to supply variable airflow. In the hot air stream, steam is injected and air is heated using three heaters. While the cold stream uses ambient air. Both hot and cold stream mass flow rates are equal. Plastic and paper air-to-air heat exchanger surfaces are used and experiments were conducted on each one to evaluate its effectiveness. For the

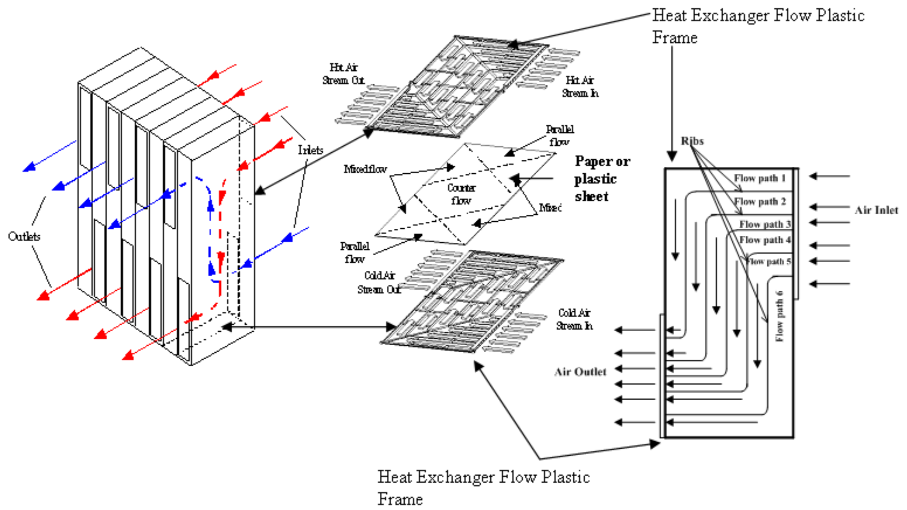

Figure 2. Z type flow heat exchanger.

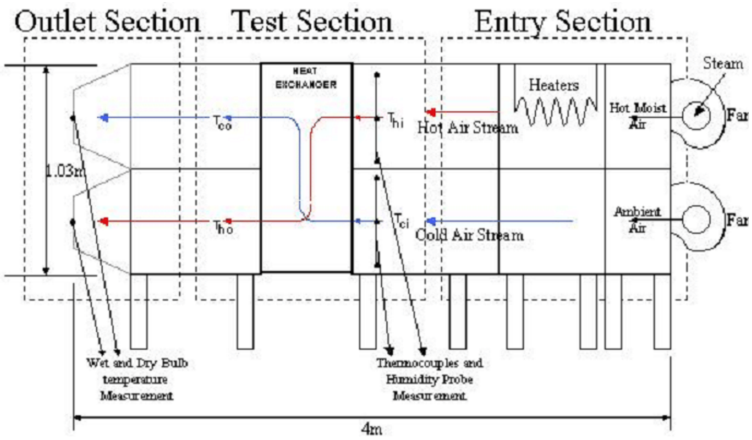

Figure 3. Experimental rig for testing Z flow heat exchanger.

plastic heat exchanger surface, only sensible heat will be transferred. At the inlet and outlet on both hot and cold streams nine thermocouples were installed and the temperatures were averaged at each inlet and outlet section. In the paper heat exchanger surface, nine thermocouples were installed at each inlet stream, and the relative humidity was measured using a humidity probe in order to obtain the inlet air moisture content. At the outlet section of the paper heat exchanger, a sampling tree (Figure 4) was used which is connected to a suction fan that sucks the air through a main monitoring tube. Two thermocouples were installed inside this tube to measure the average wet and dry bulb temperature, thereby the moisture content of the outlet air was obtained. The two thermocouples were calibrated in a thermocouples calibration bath in order to obtain the correct measurement. The sampling tree was needed to ensure that the correct average temperature and moisture fraction were determined from the non-uniform outlet stream. In order to obtain accurate results for every measurement recorded, energy and mass balance between the two streams was

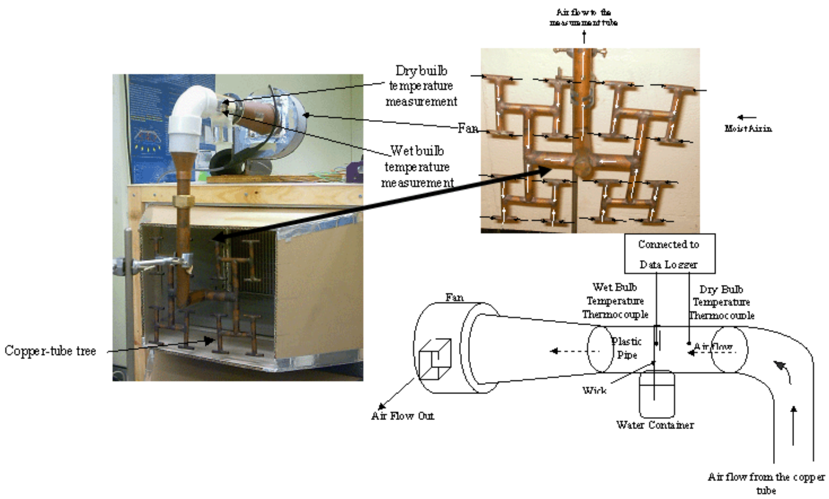

Figure 4. Sampling tree.

achieved as in the following for sensible energy balance

$$m_{hot-air} Cp(T_{hi} - T_{ho}) = m_{cold-air} Cp(T_{Co} - T_{Ci}) \quad (1)$$

for latent energy (moisture) balance

$$m_{hot-air} H_{fg}(\omega_{hi} - \omega_{ho}) = m_{cold-air} H_{fg}(\omega_{Co} - \omega_{Ci}) \quad (2)$$

for total energy balance

$$m_{hot-air}(H_{hi} - H_{ho}) = m_{cold-air}(H_{Co} - H_{Ci}) \quad (3)$$

The heat exchanger had an overall dimension of 0.6m x 0.72m x 0.3m and was made of 98 plastic frames with 49-inlet air passages in each of the air streams.

As can be seen in Figue 2, each flow passage was made of plastic frame flow passage and designed with a 'Z' shape flow configuration. The plastic frames were assembled together in an alternating pattern. The passage (plastic frame flow path) of the cold air stream was laterally inverted from the passage direction of the hot air stream.

In the paper heat exchanger the heat transfer surface was made of 78 µm thick porous 45gsm Kraft paper, whereas, in plastic heat exchanger, the heat transfer surface was made of 23 µm thick Mylar plastic film. The overall heat transfer coefficient (Us) is given by equation (4)

$$U_s = \left[\frac{1}{h_{h,conv}} + \frac{\delta}{k} + \frac{1}{h_{c,conv}} \right]^{-1} \quad (4)$$

The first term represents the convection heat transfer resistance on the hot side of the heat exchanger. The second term represents the conduction resistance and the third term represents the convection heat transfer resistance on the cold side of the heat exchanger.

For the paper heat transfer surface, the thermal conductivity (k) was approximately 0.12 W/mK (Bejan 1993), and the thickness is 78 µm and the conduction resistance was $6.5*10^{-4} m^2 K/W$. For the plastic film, the thermal conductivity was approximately 0.35 W/mK (Bejan, 1993) and the thickness was 23 µm and the conduction resistance term was $6.5*10^{-5} m^2 K/W$. In both cases the heat transfer surface conductance resistance was very small compared to the convection resistance terms.

Effectiveness Calculation

Heat exchanger effectiveness was calculated using (Figure 5) and equations 5 to 7:

Sensible Effectiveness

$$\varepsilon_s = \frac{(\dot{m}c_{pa})_s (T_{hi} - T_{ho})}{(\dot{m}c_{pa})_{\min} (T_{si} - T_{Ci})} \quad (5)$$

Latent Effectiveness

$$\varepsilon_L = \frac{\dot{m}_s H_{fg}(\omega_{hi} - \omega_{ho})}{\dot{m}_{\min} H_{fg}(\omega_{hi} - \omega_{Ci})} \quad (6)$$

Effectiveness

$$\varepsilon_{tot} = \frac{\dot{m}_s (H_{hi} - H_{ho})}{\dot{m}_{\min} (H_{hi} - H_{Ci})} \quad (7)$$

Results and Discussion

Figure 6 shows the measured performance of the paper membrane heat exchanger. The sensible effectiveness was higher than the latent and total effectiveness, and the effectiveness decreased as the air flow rate increased, which is due to the

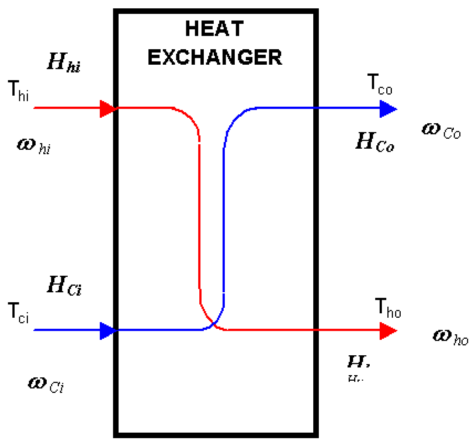

Figure 5. Heat exchanger flow paths.

variation of air residence time in the heat exchanger. When the velocity was high the residence time was short and the amount of heat transfer and moisture transferred per kilogram of airflow would be less than when the air velocity is low. This is accounted for in terms of heat and moisture number of transfer units (NTU_s and NTU_L).

The sensible heat transfer effectiveness of the plastic and paper heat exchange surface is shown in Figure 7. It could be seen that the paper sensible effectiveness was higher than the plastic heat exchanger by approximately 5 to 7% (Figure 7). This could be attributed to the moisture and air transferred through the paper. A slight increase of mass flow rate by 0.01 kg/s was detected on the cold stream indicating that air was leaking through the paper. This leakage will carry additional sensible heat together with the moisture transferred (diffuses through the paper) and that could be the reason that the sensible effectiveness of the paper heat exchanger was higher.

The amount of sensible energy needed to cool or heat the ventilation air is

$$q_s = \dot{m}\, Cp_a (T_{hi} - T_{ci}) \qquad (10)$$

The amount of energy needed for moisture control (latent energy) to dehumidify the ventila-tion air is calculated as

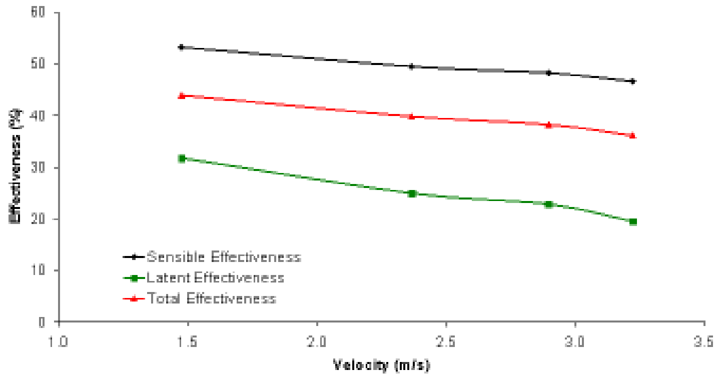

Figure 6. Paper heat exchanger sensible, latent and total effectiveness.

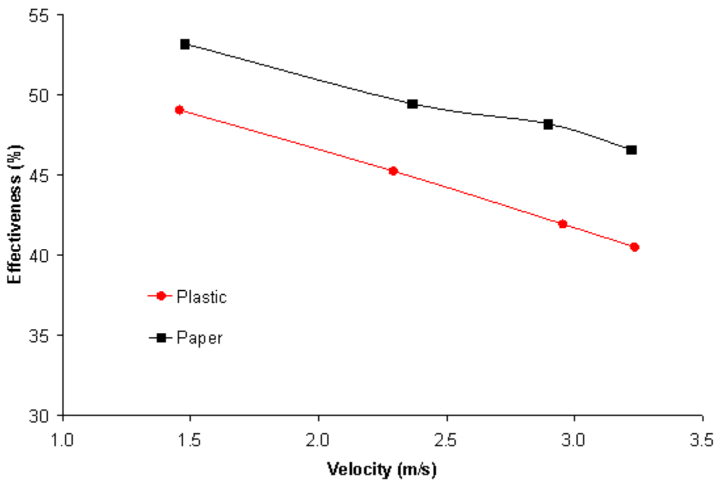

Figure 7. Paper and plastic heat exchanger sensible effectiveness.

$$q_L = \dot{m} H_{fg}(\omega_{hi} - \omega_{ci}) \qquad (11)$$

The amount of sensible energy recovered is

$$q_{sr} = \varepsilon_s q_s \qquad (12)$$

and the amount of latent energy recovered is

$$q_{Lr} = \varepsilon_L q_L \qquad (13)$$

For applications of pre-conditioning of make-up air for building ventilation the paper surface heat exchanger has the advantage of also dehumidifying the incoming air. The relative energy savings for plastic and paper heat exchanger surfaces were evaluated for the ISO13253 (1994) T1 ducted air conditioner rating conditions shown in Table 1.

Using equations 10 to 13 and the measured performance data in Figures 5 and 7 the sensible and latent energy recovery was evaluated. Table 2 shows the latent and sensible energy load conditions the air conditioner has to achieve to deliver the air with the conditions set by the ISO13253 (1994). The sensible heat transfer achieved with the plastic surface heat exchanger shown in column 4 of Table 2 was typically 40% to 50% of the required sensible load. The paper surface heat exchanger achieved a slightly higher sensible energy savings than the plastic surface system however it also provided 20% to 30% of the ISO 13253 (1994) T1 test condition latent load. The total enthalpy transfer achieved with the paper surface heat exchanger (sum of columns 5 and 6) was typically 20% to 40% of the total load depending on the air flow rate. The experimental results however, show that increasing the velocity will lead to an increase in the pressure drop, where 400 Pa pressure drop was recorded when 3 m/s air velocity was used. This means an extra 0.236 kW of fan power is needed to overcome this drop. The combination of a standard air conditioner with a paper surface heat exchanger on the make-up air will achieve significant operating cost reductions at the same time as increasing the capacity of the conventional air conditioner. This heat exchanger is a static device, which does not require maintenance and at the same time it is easy to manufacture, and made of cheap material. In addition it can recover and save a significant amount of energy

Conclusion

Paper and plastic sheet heat exchanger performance used in energy recovery systems was investigated experimentally. The results show that for the paper heat exchanger the sensible effect-

Table 1. ISO13253 ducted air conditioner T1 test conditions

Temperature	Inlet air ºC	Return air ºC
Dry bulb	35	27
Wet bulb	24	19

Table 2. Plastic and paper heat exchangers energy recovery for ISO 13253 ducted air conditioner test conditions.

Heat exchanger face velocity (m/s)	Heat load (kW)		Plastic surface sensible heat recovered (kW)	Paper surface heat recovered (kW)	
	Sensible	Latent		Sensible	Latent
1	1.84	2.16	0.96	1.017	0.75
2	3.74	4.4	1.76	1.94	1.187
3	5.78	6.8	2.35	2.76	1.53

iveness is higher than the latent effectiveness and the effectiveness decreased as air velocity is increased. The paper heat exchanger sensible effectiveness is higher than the plastic heat exchanger sensible effectiveness by approximately 5 to 7%. The difference between the plastic and paper sensible effectiveness could be attributed to the air leakage through the heat exchange surface, which carries heat across the porous paper.

Using a paper heat exchanger in an air conditioning system with ISO 13253 (1994) T1 test condition could save between 40% to 50% sensible energy and 20% to 30% of latent load. This shows that utilizing a paper surface heat exchanger in a standard air conditioner will lead to a significant cost reduction and energy savings.

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Nomenclature

A_{ht}	Heat transfer area (m^2)
C_P	Specific heat capacity at constant pressure (kJ/kg K)
h	Convective heat transfer coefficient (W/m^2K)
H	Enthalpy of air (kJ/kg)
Hfg	Enthalpy of vaporisation (kJ/kg)
k	Thermal conductivity (W/mK)
$\dot{m}$	Mass flow rate (kg/s)
NTU	Number of transfer unit
q	Heat (kW)
T	Temperature (K)
U	Sensible or latent total heat or mass transfer coefficient
ω	Moisture content of air (humidity ratio) (kg/kg)
ε	Effectiveness
δ	Thickness of the sheet

Subscript

a	Air
C	Cold
Conv	Convection
H	Hot
i	Inlet
L	Latent
Lr	Latent recovered
o	Outlet
s	Sensible
sr	Sensible recovered

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