

Investigation of the Performance of a Low-cost Fibre Air-to-Air Heat/Mass Exchanger

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ABSTRACT: This study examines the performance of a novel air-to-air heat/mass exchanger using a fibre paper coated with a solid desiccant material. Theoretical analysis and experimental testing were carried out to determine the ability of the heat and mass transfer across the heat exchanger (i.e., between fresh air entering the room and exhaust air out of the room). Two sets of operating conditions, representing summer and winter operations, were examined and for each of these a range of airflow rates was used. Results showed that the efficiency of the heat exchanger could be as high as 87% in winter condition and 86.83% in summer. The efficiency was found to decrease with decreasing enthalpy difference between the two airstreams, and increased with increasing flow rates of both airstreams. Under the condition of equal fresh/exhaust airflow rates of 905m³/h, about 3.4kW of energy in winter and 2.5kW in summer can be recovered through use of the exchanger. The investigation indicates that the fibre heat exchanger has the advantages of being cheaper and more efficient than with conventional heat exchangers.

Keywords: Heat Exchanger, Efficiency, Energy Recovery; Solid Desiccant, Fibre, Thermal Performance

NOMENCLATURE

t	Temperature [°C]
c_p	Specific heat capacity of air [J/kg·K]
$c_{\min}$	Smaller of $m_f c_{pf}$ and $m_s c_{ps}$ [J/K]
d	Moisture content [kg/kg (dry air)]
h'_f	Convective heat-transfer coefficient [W/m ² ·K]
h	Enthalpy of dry air [kJ/kg (dry air)]
h_{pf}	Latent heat of evaporation [kJ/kg]
k	Thermal conductivity [W/m·K]
k'_f	Convective mass-transfer coefficient [m/s]
k_{mass}	Mass-transfer coefficient through the fibre paper membrane [m/s]
m	Mass of air [kg/m ³]
$m_{\min}$	Smaller of m_f and m_s [kg]

m_w	Transferred moisture [kg·m ² /s]
p	Vapour pressure [kPa]
ρ	Density of air [kg/m ³]
δ	Fibre paper membrane thickness [m]
$\epsilon_{sensible}$, ϵ_{latent} and ϵ_{total}	Sensible, latent and total exchange efficiency
Subscripts	
f	Fresh air form the environment
s	Supply air to the room
e	Exhaust air out of the room

1.0 Introduction

Due to the increased demand of air conditioning systems in resident and public buildings, the deployment of highly efficient cooling devices is important. In the traditional cooling/heating and dehumidification/humidification process heat and moisture transfer occur simultaneously when the coil surface temperature is below/over the dew point

temperature of the air being cooled [1]. However, in the fibre paper exchanger, the heat and mass exchange never stop unless there is no enthalpy difference between the fresh air entering the room and exhaust air.

Liquid and solid desiccant cooling and dehumidification systems have recently been widely investigated. In particular liquid desiccant cooling and dehumidification systems driven by low grade waste heat or solar energy have attracted a great deal of attention. However, the problems associated the low coefficient of the performance (COP), low specific cooling power and poor heat/mass transfer have limited the widespread applications [2]. In this investigation, a novel fibre paper exchanger is used for both the desiccant dehumidification and liquid regeneration. The COP of the liquid desiccant cooling and dehumidification system can be improved to 5.9 [3]. This is due to the improvement of system design and the use of a highly efficient fiber & desiccant coated exchanger. The energy recovery can be up to 85% and the temperature of the fresh air can be reduced 97.3% close to the exhaust air temperature.

Solid desiccant materials have been used for the moisture absorption in air conditioning for many years but in the conventional solid desiccant systems such as desiccant wheels and desiccant pads need to be regenerated using temperatures about 80°C [4]. In this investigation, a solid desiccant, LiCl was coated on the fibre exchanger and there is no requirement of the regeneration of the absorbent. The solid desiccant acts as the medium between the fresh air and exhaust air. Moisture in gas state can not penetrate through the fibre sheet, whereas the liquid water can pass through the fibre sheet interstices easily. Under this situation, large numbers of micro energy exchange (MEE) circles between the two airstreams are processed as shown in Figure 2. The details of the MEE circles have been

analyzed from thermodynamics and dynamics theory aspects.

2.0 Describe of the novel air-to-air heat and mass exchanger structure and working principles

2.1 Fibre paper desiccant coated energy exchanger

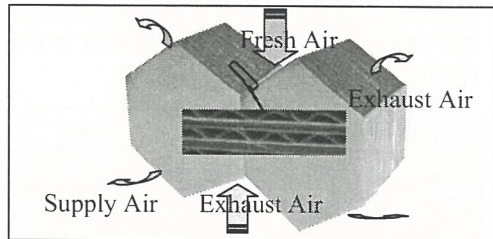


Figure 1. Structure of the fibre paper energy exchanger and amplificatory air channels

Figure 1 shows the desiccant coated fibre energy exchanger, which is the simplest method for carrying out air cooling and dehumidification/humidification. The amplificatory drawing of the energy recovery sheet shows the wave structure which supports two pieces of fibre sheets and fresh air flow through the unit. The adjacent channel is the exhaust air channel which is sealed from the fresh air side and the airflow passes in the contrary direction to fresh air. In this system, there are requirements of regeneration energy, liquid/solid desiccant to absorb moisture, spray water for humidification and pumps. Only a small amount of power is required to run the fans for circulation of the fresh air and exhaust air (which is about 25W each for air flow rate 1000m³/h). So the maximum amount of the input energy is 50W and the minimum is about 25W for an airflow rate 500m³/h.

As stated before this kind of fibre exchanger uses a solid desiccant coating and micro heat and mass transfer circles. Example, the temperature t_f and the moisture content of

the fresh air d_f are all higher than the exhaust air (t_e, d_e). When the vapour pressure p_f of the fresh air is higher than the vapour pressure p_1 of the solid desiccant coated membrane on the fresh air side, then the moisture is absorbed by the solid desiccant. The condensed water then penetrates through the fibre to another solid desiccant layer. In the exhaust air side, the infiltrated solid desorbs the moisture to the dry exhaust air.

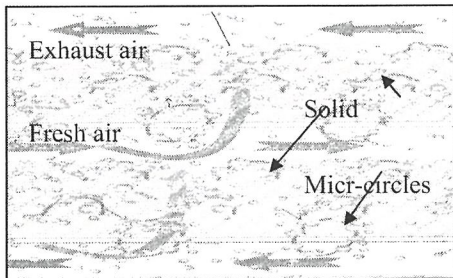


Figure 2. Micro-energy exchange circle

Simultaneity, the heat circles occur with mass circles. The condenser moisture releases the latent heat to the lower temperature exhaust air and the same time the penetrating water absorbs heat of vaporization from the fresh air. In these circles, the sensible heat exchange is also improved.

2.2 Six kinds of energy recovery conditions

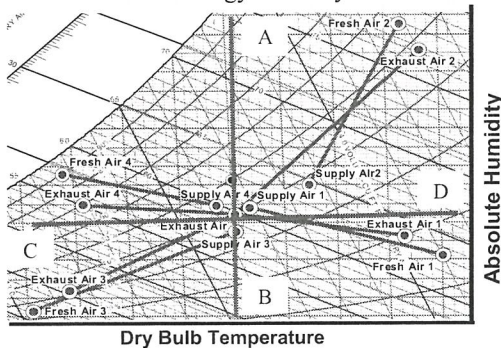


Figure 3. Six energy recovery paths in the psychrometric chart

Path A-B, $t_f = t_e$ only moisture transfer happen;

Path C-D, $d_f = d_e$ only sensible heat exchange occurs;

Area A~D, $d_f > d_e$ and $t_f > t_e$, moisture and heat transferred from the fresh air side to the exhaust air side, in this situation, the t_s can unlimited to the t_e , when the $h_f > h_e$ and the d_s is still higher than d_e ;

Area D~B, $d_f < d_e$ and $t_f > t_e$, heat transferred from the fresh air side to the exhaust air side however the moisture transferred in the contrary direction;

Area A~C, $d_f > d_e$ and $t_f < t_e$, under this winter condition, that the heat transferred from the exhaust air side to the fresh air side however the moisture transferred in the contrary direction;

Area C~B, $d_f < d_e$ and $t_f < t_e$, under this winter condition the mass and heat transferred in the same direction from the exhaust air side to the fresh air side

2.2 Heat and mass transferred principle

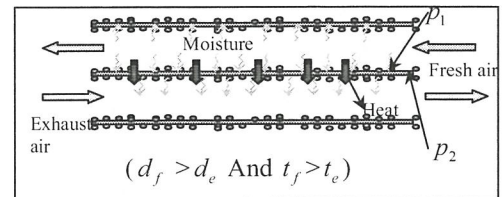


Figure 4. Model of the energy transfer

From the above statement we can see that the enthalpy difference between the fresh air and the exhaust is the force to induce the energy exchange. And the heat transfer rate at surface of the fresh can be written as:

$$q = (t_f - t_s) / \left(\frac{1}{h_f} + \frac{\delta}{k} \right) \quad (1)$$

h_f is the convective heat-transfer coefficient.

According to the Nusselt's law the heat convective enhance with the air flow rate

increased. The $\frac{\delta}{k}$ is determined by the performance of the fibre membrane. According to the Schmidt's and Fick's diffusion law, the mass transfer can be derived [5], [6]:

$$\text{Fresh air side: } m_w = \frac{(p_f - p_e) / R_w T_f}{\left(\frac{1}{k'_f} + \frac{1}{k_{mass}} \right)} \quad (2)$$

$$k'_f = h'_f / \rho_f c_p \quad (3)$$

k_{mass} is the mass transfer coefficient through the fibre paper membrane, which is decided by the character and structure of the fibre membrane. For the purpose improving the value of the k_{mass} , solid desiccant was coated on the fibre membrane. Solid desiccant has lower vapour pressure p_1 to absorber moisture from the fresh air and then on the other side, adsorptions occur from the saturated desiccant with higher p_2 to the exhaust air. k_{mass} is a steady factor when the energy exchanger is structured. The sensible effectiveness, latent effectiveness and total effectiveness are obtained from the Ref. [6]:

$$\varepsilon_{sensible} = m_f c_{pf} (t_f - t_s) / C_{min} (t_f - t_e) \quad (4)$$

$$\varepsilon_{latent} = m_f h_{pf} (d_f - d_s) / m_{min} (d_f - d_e) \quad (5)$$

$$\varepsilon_{total} = m_f (h_f - h_s) / m_{min} (h_f - h_e) \quad (6)$$

3.0 Experiments

The main physical characteristic of the paper heat exchanger is the heat and mass transfer occur simultaneously. So the energy recovery efficiency is studied, the mass and heat transfer efficiency should be considered synthetically. Enthalpy is the summation of sensible heat, latent heat and superheat between an arbitrary datum point and the temperature and state under consideration two sets of operating conditions, representing summer and winter operations, were examined and for each of these a range of airflow rates of 500m³/h, 609m³/h, 700m³/h, 808m³/h and 905m³/h were tested.

3.1 Winter conditions

In winter condition, the environment air temperature was about 14~16°C and relative humidity was 60%~70%. Inside room experiment temperature was set around 24~26 °C (35~45%). The energy recovery processes happened in the area B~C showed in Figure 3, in which area the moisture and heat are all transferred from the exhaust air to the fresh air.

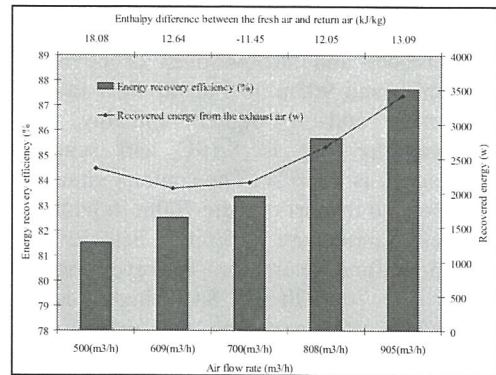


Figure 5. Energy recovery and saved energy with the air flow rate and enthalpy difference

It is obvious from Figure 5 that the energy recovery efficiency of the fibre heat exchanger is relative high; can reach about 87%, when the airflow rate is 905m³/h. The energy recovery efficiency increases with the increase of the airflow rate. The amount of saved energy in the winter is 3415W when the airflow rate is 905m³/h and the enthalpy difference is 13kJ/kg between the fresh air and return air. For an air flow rate of 500m³/h and heat recovery efficiency 81.54% the energy saving is about 2388W. Consider all testing results it can be concluded that: the higher airflow rate has higher energy recovery efficiency and save more energy at the condition that having same enthalpy and moisture difference; the energy exchange will be improved with the enthalpy difference increased at the same air flow rate.

Table I: Sensible heat recovery efficiency

Flow Rate (m ³ /h)	Fresh air (□)	Return air (□)	Increased temperature (□)	Efficiency (%)
500	14.23	24.66	8.19	73.99
609	15.29	24.92	6.86	56.29
700	16.77	25.49	6.47	48.58
801	16.33	25.89	7.08	58.48
905	14.55	24.88	7.63	66.45

Table 1 show that the sensible heat recovery efficiency increases with the increase of airflow rate for a similar temperature differences and airflow rates of 609m³/h, 801m³/h and 905m³/h. For air flow rate of 500m³/h and a higher enthalpy, the temperature rise is 8.19C and sensible efficiency is 73.99%. The contrary situation happens to the airflow rate 700m³/h with the lowest temperature difference between the fresh air and return air. However the air flow rate 700m³/h has 8.0% higher latent recovery efficiency than the airflow rate 609m³/h. Therefore higher latent recovery efficiency recovered the lower sensible heat recovery efficiency showed in the total heat recovery efficiency balance in Figure 5.

3.2 Summer conditions

In the summer condition, airflow rate 609m³/h, 700m³/h, 801m³/h and 905m³/h are shown in Figure 3 area B~D and air flow rate 500 m³/h and 700 m³/h are in the area D~A. In area B~D, the sensible heat of the fresh air decreases but the latent heat increases. Dry and hot fresh air streams absorb moisture from the exhaust air as well release sensible heat to the exhaust air. However, in the area A~D, the moisture and heat transferred in the same direction which results in a higher average heat recovery efficiency in airflow rate 500 m³/h 83.71%, which is 5.67% and 0.92% higher than the airflow rate 609 m³/h, and 801 m³/h respectively.

It's obviously that the relationship between the energy recovery efficiency and the air flow rate is similar with the winter condition besides the air flow rate 700 m³/h, of which

the heat recovery efficiency is nearly to the air flow rate 801 m³/h. The reasons are the moisture and sensible heat transferred in the same direction to the exhaust air. The average heat recovery efficiency of air flow rate 700m³/h is 83.10% and 0.18% higher than the air flow rate 801m³/h. Energy recovery efficiency has direct proportion with the enthalpy difference in all the exchange processes. The highest recovery efficiency is 86.83% for an airflow rate of 700m³/h and enthalpy difference of 10.52kJ/kg

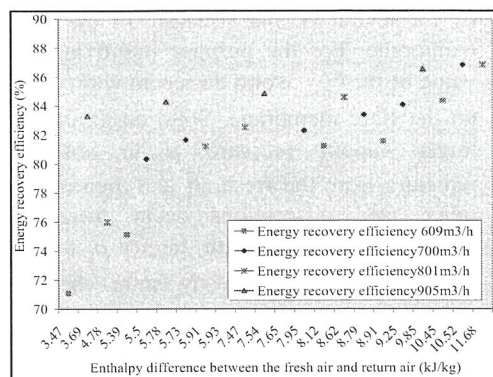


Figure 6. Energy recovery efficiency in summer conditions

Saved energy in the summer condition rises when the airflow rate and enthalpy difference increases. The maximum energy saved for the airflow rate 905 m³/h is 2769 W, which is 232W higher than when the airflow rate 801 m³/h for the same enthalpy condition.

Table II: Testing examples for air flow rate 700m³/h

Cooling and dehumidification				
		1	2	3
Fresh air	Temperature	35.476	34.504	32.99
	Moisture	10.85	10.319	9.89
	Enthalpy	63.663	61.30	58.65
Return air	Temperature	26.073	26.47	26.13
	Moisture	10.485	10.067	9.72
	Enthalpy	53.049	52.39	51.15
Supply air	Temperature	26.782	27.60	27.15
	Moisture	10.634	10.155	9.76
	Enthalpy	54.159	53.77	52.31
$\varepsilon_{sensible}$		82.25	76.16	74.91
ε_{latent}		58.14	65.04	77.74

As described in front, the process in area D~A, mass and heat transfer can occur in the same direction. Ideal process, when the supply air temperature equal to the return air but the enthalpy is still high, then the process will go down A~B, only moisture exchange in the last step. Testing results listed in table 2 displays that the supply air temperature can be 97.3% close to the return air however the moisture is still higher than the return air. The experiments proved the theory analysis. In this situation, the sensible heat recovery efficiency is relative higher. And the sensible heat transfer effectiveness increase with the temperature difference between the fresh air and return increasing. However, the latent heat transfer effectiveness decrease with the moisture content difference improved. The k_{mass} plays the most important role to the moistures transfers.

4.0 COP of the fibre energy exchange

The only input energy is the supply fans mentioned in frontal: 50W for 1000m³/h and 25W for 500m³/h. The saved energy listed in Figure 5 is 2351.56W, 2067.8W, 2148.6W and 2679.3W for five different air flow rate. The maximal input energy used in all air flow rate we can gain the COP for the winter condition are 47.01, 41.35, 42.98 and 53.6.

COP for the summer condition change with the air flow rate and enthalpy difference between the fresh air and exhaust air. It could be 54.36 under the condition set in air flow rate 700m³/h. In the area D~A, the environment such like air flow rate 700m³/h, the temperature and relative humidity can be reduced to the air condition designed condition without any additional input energy.

5.0 Conclusion

The following conclusions were drawn from theatrical analysis and experimental testing:

- The energy recovery efficiency of fibre paper exchanger is in the range 71~87%. The value is higher than the normal cross-flow heat exchangers (50~70%) [6].
- Energy recovery efficiency improves with the increase of airflow rate and enthalpy difference.
- Energy recovery efficiency is enhanced when the mass and heat transfer are in the same direction
- Little energy is required to run the system. The system is also cheap and easy to use.
- More experiments should be carried to investigate the heat and mass transfer coefficient of the fibre exchanger. Particularly the humidity environment mass transfer coefficient should be examined.

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