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Comparative study of heat and mass exchanging materials for indirect evaporative cooling systems

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Abstract

This paper investigated several types of materials, namely metals, fibres, ceramics, zeolite and carbon, which have potential to be used as heat and mass transfer medium in the indirect evaporative cooling systems, and from the investigation, the most adequate material and structure were identified. Magnitude of heat/mass transfer rates in relation to an air-conditioning application was analysed, and the results showed that thermal properties of the materials, i.e., thermal conductivity and water-retaining capacity (porosity), have little impact on system heat/mass transfer, and therefore, these two parameters play low keys in terms of material selection. Instead, shape formation/holding ability, durability, compatibility with water-proof coating, contamination risk as well as cost, are more important concerns in this regard. Each material type was then analysed based on the above criteria and the preferable structure and configuration of this type was illustrated. A comparative analysis into different material types was carried out, and the results showed that the wick (sintered, meshes, groves and whiskers) attained metals (cooper or aluminium) are the most adequate structure/material over the others. Wick-attained aluminium sheet is much cheaper than cooper with the same structure and therefore more suitable for this application.
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Keywords: Heat and mass exchange; Material; Thermal conductivity; Porosity; Shape formation; Durability; Compatibility; Contamination risk; Cost

1. Introduction

Direct evaporative cooling systems can lower the temperature of air using the latent heat of evaporation. As a result, warm dry air is changed into cool moist air, but the energy in the air remains the same. Existing direct evaporative cooling systems are 70–95% effective in terms of the incoming air's wet bulb temperature [1,2], and only suitable for use in dry, hot climates, or rooms needing both cooling and humidification.

Indirect evaporative cooling systems have the advantage of being able to lower the air temperature without adding moisture. Thermodynamically, an indirect evaporative air cooler passes the primary (product) air over the dry side of a heat/mass exchanging wall, and the secondary (working) air over its opposite wet side. The wet side absorbs heat from the dry side by evaporating water and therefore cooling the dry side, while the latent heat of vaporising water is given to the wet side air. Under the ideal operating condition, i.e., the product air travelling in a counter-flow manner to the working air and the two airstreams having a good balance of flow rates and an infinite contact area, the product air temperature on the dry side of the sheet will reach the wet bulb temperature of the incoming working air and the temperature of the working air on the wet side of the sheet will increase from its incoming dry bulb temperature to the incoming product air dry bulb temperature and be saturated. However, practical systems are far from this ideal. It has been suggested that only 50% of the incoming working air wet bulb temperature can be achieved for a typical indirect evaporative cooling system [1,3].

The properties of the heat/mass exchanging medium (wall material) are important as these would affect the cooling efficiency and performance of indirect evaporative cooling systems. A wide range of materials can be used for this purpose, and may be classified as metal, fibre, ceramics, zeolite and carbon type. Metal type includes metal forms, metal wools, sintered metals and wicked metal plates/tubes. Fibre type includes paperboard, cloth (wood

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Nomenclature

h	convective heat transfer coefficient (product air side) (W/m^2 °C)
k	thermal conductivity (W/m °C)
q	heat transfer rate (W/m^2)
r	porosity (%)
t	temperature (°C)
U_s	heat transmittance coefficient (m^2 °C/W)
w	evaporation rate of the water on the wet surface of the wall (g/s)
Wr	water-retaining capability of the wall (g/m^2)
Δt_m	logarithmic average temperature difference (°C)
Δt_{max}	maximum value of the temperature difference between the product air and the opposite working air (°C)

Δt_{max}	minimum value of the temperature difference between the product air and the opposite working air (°C)
δ	thickness of the heat/mass transferring wall (m)
γ	latent heat of water vaporisation (J/g)

Subscripts

1	inlet
2	outlet
m	material of the wall
p	product air
w	water
wb	wet bulb
w,s	wet surface of the wall

or glass) fibres. Ceramic type includes SiC/SiC composites, zirconia ceramic, zirconia toughened aluminium, Z_rO_2, Al_2O_3, and aluminium nitride and polystyrene composites. Zeolite type includes porous ceramics, molecule sieves and synthetic polymers, and carbon fibre refers to carbon–carbon composites and activated carbon.

In general, a good heat/mass transfer material should have high thermal conductivity (TC) and large capillary force, which allow a large amount of heat to be conducted from the dry side of the wall to the wet side, and an adequate amount of water to be retained on the wet surface of the wall. The heat conducted is intended to vaporise the water attained on the wet surface, thus maximising the cooling efficiency of the system. Also the material should have the advantages of being cheap and suitable for shaping into various geometries. Furthermore, it should be ease of cleaning and replacement and able to avoid bacterial growth on the wet surface.

An investigation into the selected materials is carried out to determine the favourite materials suitable for serving as the heat and mass exchanging mediums (wall) in indirect evaporative cooling systems. Magnitude of heat/mass transfer rates in relation to an air-conditioning application was analysed, and the results were used to judge the viability of heat and moisture transfer of the wall materials. A number of criteria, including TC, water-retaining capability, shape formation/holding ability, durability, compatibility to water-proof coating, contamination risk as well as cost, were applied for material selection, and final choice of the material would be able to offer enhanced cooling effect with reasonable durability, low contamination risk and acceptable cost.

2. Quantitative analyses of the heat/mass transfer magnitude and its relevance to material thermal properties

Fig. 1 indicates the heat and mass transfer process occurring in an indirect evaporative cooling system. When the product air (P) flows through the dry channel, it loses heat through the wall due to the temperature difference between the dry and wet sides. As a result, the temperature of the product air falls by a few degrees and its state varies from p_1 to p_2. In the meantime, water placed on the wet side of the wall will evaporate by absorbing the sensible heat from air in the dry/wet channels and the vapour generated will be removed away by the airstreams across the wet channel. As a result, the moisture content of the working air rises gradually until a saturated state is achieved (W_1 to $W_{1,w}$). Thereafter, the working air continues to attract moisture and its temperature goes up as well, while its state moves along the saturation line (from $W_{1,w}$ to W_2), as shown in Fig. 2.

The cooling efficiency of the indirect evaporative cooling system is defined as

$$\eta = \frac{t_{p_1} - t_{p_2}}{t_{p_1} - t_{w_{1,w}}}. \tag{1}$$

The cooling efficiency will largely depend on the logarithmic average temperature difference (Δt_m) between the two airstreams. The larger the Δt_m, the higher the cooling efficiency will be. The definition of Δt_m can be expressed as follows:

$$\Delta t_m = \frac{\Delta t_{max} - \Delta t_{min}}{\ln \Delta t_{max}/\Delta t_{min}}. \tag{2}$$
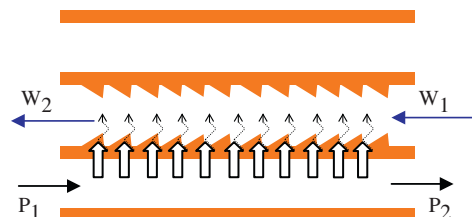

Fig. 1. Indication of heat and moisture transfer in an indirect evaporative cooling system.
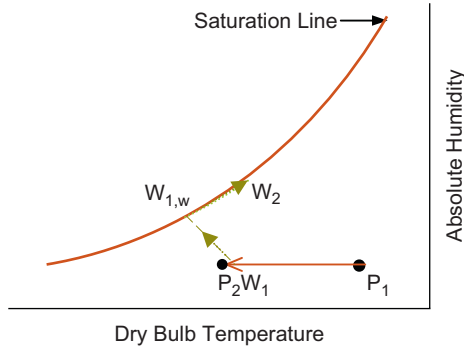
Fig. 2. Psychrometric diagram indication of the heat and moisture transfer in an indirect evaporative cooling system.

At any position in the channels, heat transfer from the dry airstream to the wet surface of the wall can be expressed as

$$q = U_s(t_p - t_{w,s}), \tag{3}$$

$$U_s = \frac{1}{(1/h) + (\delta/k)}. \tag{4}$$

Combining Eq. (3) and Eq. (4) yields

$$q = \frac{t_p - t_{w,s}}{(1/h) + (\delta/k)}. \tag{5}$$

As mentioned previously, the heat from the dry side is partly used for vaporising the water on the wet side of the wall, and the rest for increasing the temperature of wet channel working air. However, if the heat from the dry side is completely used to vaporise the water on the wet side of the wall with no sensible heat transfer between the product and working airstreams, the system will achieve its maximum cooling efficiency, as the logarithmic average temperature difference between the two airstreams reaches the highest. In that case, the working air temperature will remain constant along its path way, which is equal to wet side surface temperature $(t_w = t_{w,s})$, but its moisture content will rise along the flow path. For this particular circumstance, the evaporation rate on the wet side surface can be expressed as

$$w = q/\gamma = \frac{t_p - t_{w,s}}{\gamma(1/h + \delta/k)}. \tag{6}$$

It is seen from Eq. (6) that both air flow condition (h, t_p, $t_{w,s}$) and material thermal properties (k, δ) have impact on the cooling performance of the system. In terms of airflow condition, increased temperature difference of the airstreams between the dry and wet channels would result in enhanced heat/mass transfer of the system. Increasing speeds of air in both dry and wet channels also help to establish this trend of potential. In terms of material thermal properties, water-retaining capability (Wr), TC (k) and wall thickness (δ) are potential factors that may impact on system performance. However, the level of impact of these parameters on cooling performance has so far not yet been studied. In light of the circumstance, an investigation into this problem is carried out as follows.

For a heat/mass exchange wall, since its thickness (δ) is usually thin, ranging 0.1–0.5 mm, its thermal resistance (δ/k) is therefore remaining low although the value of the TC (k) may vary in a wide range (between 5 and 300 W/m °C). In that case, the water-retaining ability (Wr) is a major concern that would affect the cooling effectiveness. Insufficient water retaining would result in absence of evaporation source that leads to reduction of cooling efficiency, while surplus water retaining would accumulate a water volume on the wet side of the material that retards the heat/mass transfer.

In light of air-conditioning application, the wet surface temperature, $t_{w,s}$, could be scaled down to the lowest level, i.e., the inlet working air wet-bulb temperature, which is around 15 °C for the UK climate [4]. The product air temperature, t_p, could be as high as 35 °C. Thus the $t_p - t_{w,s}$ would be about 20 °C or less, h is usually less than 20 W/m² °C for a heat exchanger [5]. While latent heat of water, γ, could be expressed as follows:

$$\gamma = 2500 - 2.387 t_{wb}, \tag{7}$$

where t_{wb} is the wet bulb temperature of the contacting surface above the water film, which may be scaled down to 15 °C. Thus γ would be 2464 J/g.

Substituting these values into Eq. (6) yields

$$w = \frac{20}{2464(0.05 + \delta/k)} = \frac{0.0081}{(0.05 + \delta/k)}. \tag{8}$$

The thickness of the wall, δ, is in the range of 0.1–0.5 mm, while TC, k, takes the weighting average of the k values of the materials and the filling water, owing to its porous structure. In that case, k value can be written as [6]

$$k = r k_{water} + (1 - r) k_{materials}, \tag{9}$$

where k value of the filling water is about 0.6 W/m °C. For the commonly used wall materials including metal, fibre, ceramics, zeolite and carbon, the k value ranges from 0.3 to 300 W/m °C, and the porosity varies between 20% and 90%, as shown in Tables 1–4.

Substituting these values into Eq. (9) yields the k value of the water-saturated wall which is in the range from 0.57 (ceramics with 90% porosity) to 270.06 W/m °C (metal with 20% porosity).

Assuming 0.5 mm of wall thickness, then the yield value of δ/k would be in the range 0.88×10^{-3}–1.85×10^{-6} m² °C/W. Substituting this into Eq. (8), the evaporation rate w can then be obtained, which is in the range 0.1592–0.16194 g/m² s, i.e., 0.57312–0.58298 l/m² h.

If these figures are applied to Eq. (6), the heat transfer rate across the wall is then obtained, which would be about 392–399 W/m².

Assuming the void space is fully filled with water, the water-retaining volume of a 0.5 mm thick wall would be in the range 0.1–0.45 l, which is able to support 0.3–1 h of evaporation for air-conditioning application.

Table 1
Thermal conductivity of the selected metals and alloys (at 20 °C) [8,9]

Metals	Thermal conductivity (W/m K)
Copper and copper alloys	
Copper–zinc–lead brasses	115.98–159.25
Wrought copper	349.66–400
Copper–tin–bronze alloys	83.78–86.55
Wrought copper–aluminum alloys	36.35–55.93
Wrought copper–nickel alloys	29.43–45.01
Wrought copper suitable for tube	201.95–226.00
Copper suitable for pipes	158.6–340.89
Wrought high copper alloy	107.32–323.70
Aluminium and aluminium alloys	
Aluminium	229
Aluminium alloys	121–222

Table 2
Thermal characteristics of the selected fibres [19–22]

Fibres	Thermal conductivity (W/m K)	Porosity (%)
Wood fibres	0.012–0.654	54.7–63.6 (very high water penetrability)
Latex with cement	0.28–0.52	1.10–2.32 (± 0.02)
Methylcellulose with cement	0.32–0.42	2.07–2.12 (± 0.02)
Silica fume	0.33–0.36	2.97–3.14 (± 0.02)
Methylcellulose + fibre + cement	0.28–0.44	3.33–3.97 (± 0.02)
Silica fume + methylcellulose	0.28–0.36	3.14–4.36 (± 0.02)
Natural random fibrous materials (porosity = 10–58%)	0.02–0.13	Porosity = 10–58%
Cotton fibre (Sisal, Ramie and Jute)	0.176–0.351	40
Glass fibre	0.277	2.05–2.3 (± 0.02)

Table 3
The thermal conductivity of various ceramics [25,26–28]

Kinds of porous ceramics	Thermal conductivity (W/m K)
SiC/SiC composites (conventional process) (porosity = 33.0%)	0.08–15
SiC/SiC composites (chemical vapour deposition) (porosity = 33.0$\pm$0.6%)	18.5–32.5
SiC/SiC composites (polymer impregnation and pyrolysis) (porosity = 32.4$\pm$0.4%)	19–50
Zirconia ceramics (porosity = 0–100%)	0–2.2
Zirconia toughened alumina (a) (porosity = 40%)	11.09
Zirconia toughened alumina (b) (porosity = 22%)	21.67
Zirconia toughened alumina (c) (porosity = 15%)	22.79
ZrO_2	3.1
Al_2O_3	29
Aluminum nitride and polystyrene composites (porosity = 0–40%)	20–240

Table 4
Thermal conductivity and porosity of the selected carbon fibres and carbons composites [43–52]

Various carbons materials	Thermal conductivity (W/m K)	Porosity (%)
Carbon–carbon composites	55–320	31.4–46.1, 6.3–9.1
Activated carbons	0.2	80
Natural graphite + carbon composites	1–32	$\geqslant 18$
Mesophase pitch-based fibres	300–1100	1.94 ± 0.1–29.9 ± 0.5
Interplay continuous/spun hybrid carbon composites	0.68–2.24	30–40
Carbons fibres (porosity = 2.37–9.31)	175–200	2.37–9.31
3D-Hi-Nicalon Type S–CVI composites	15–108	34–40
Carbon nanotubes	4.08	35–67

rates, and therefore play low keys in material selection. The water-retaining capacity of the material is far too sufficient to support the evaporation, and therefore no dry-out would be possible to occur over the wet surface of the wall.

In addition to TC and water-retaining capability, some other criteria, such as shape formation/holding ability, durability, compatibility to a water-proof coating, contamination risk as well as cost should be taken into account. Shape formation/holding ability describes the level of difficulty in terms of shaping and shape-holding, which is evaluated by Young's modulus in Pascal (Pa). A moderate material hardness would be preferable as hard material is difficult to shaping and soft material is difficult to hold shaping. Durability indicates the time duration of the material working under the saturated condition. Compatibility stands for adaptability of the material to the other mediums, particularly a water-proof material. Since the material is intended to be wet on one side and dry on the other side, a water-proof material needs to be coated on one side of the material to prevent water penetration. To do so, the wall material should be compatible to a specific water-proof coating. It should be mentioned that the water-proof coating could be made of the same material as the wall, or some other materials which are compatible to the wall material. Contamination risk indicates the possibility of bacteria growth under wetting operation. And finally, cost of the material is also an important factor when determining the type of material.

3. Comparative analyses of potential heat/mass transfer materials and their performance

3.1. Metal type

The traditional metal heat exchanger is mainly made up of aluminium and copper and their alloys, which can be shaped into an exchanger surface such as plate or tube.

The above quantitative analyses shows that both TC and water-retaining capability (porosity) of the material have little impact on the magnitude of heat and mass transfer

This kind of surface has much less capillary force to retain water for evaporative cooling. To increase surface capillary force, porous structure is considered to replace the smooth surface at one side of the sheet or tube [7]. Several metal porous structures, namely, wicked metal, metal foams or wools, will be studied in this section. Table 1 gives the TC of the selected metals, including copper, aluminium and their alloys [8,9].

Wick may be one of the following structures, i.e., sintered particles, microcosmic holes, meshes, grooves or whiskers, and is attained to the tube/sheet to hold water for evaporation. The porosity of the wick varies in a wide range, from 20% to 90%, depending upon its construction, density and configuration. Fig. 3 presents a whisker-attained tube heat exchanger, which has large volume micro cavities on the external surface of the tube [10]. The density of metal whiskers covered on the tube determines the porosity of the tube surface. From the point of water-retaining view, this structure is usually better than making holes and grooves on the tube.

In recent years, highly conductive foams based on copper or aluminium have been used to make heat exchangers. These foams involve open cell structures that allow heat to be removed from or added to gases or liquids by letting them flow through the foams and cooling or heating the foams at the same time [11]. Owing to the open porosity structure, plenty of water can be contained in the structure that would allow the moisture transfer as well. The foams can be produced in different methods, such as melts, powders, sputtering and deposition [12]. Each method covers a characteristic range of density, cell size and cell topology, thus resulting in the porosity ranging 30–80%. At present, the pore sizes ranging 4.5–0.5 mm at constant porosity of 80% have been achieved, thereby the porosity, shape information and construction expense are related to each other [12]. Fig. 4 presents the configuration of the commonly available metal foams [13].

Metal wools are the other type of porous metal mainly made from copper, aluminium and steel. The porosities are various based on the metal fibre length, fibre diameter, and the density, ranging 30–95%. It is found that the porosity

of one kind of copper wools was 0.95 and the TC of this form of copper reduced to 1.0–2.7 W/m K [14]. Fig. 5 presents the configuration of the commonly available metal wools [15].

If any of the above materials is used as the exchanger panel of the indirect evaporation system, one side of the panel has to be water-proofed to prevent penetration of moisture. This can be achieved by attaching a thin solid film of the same material onto the porous metal.

An analysis was carried out by using the method given in Section 2, and the results showed that both TC and porosity of any metal structures are all high enough to deal with the heat/mass transfer involved in an air-conditioning application. This means that any of the selected metal types
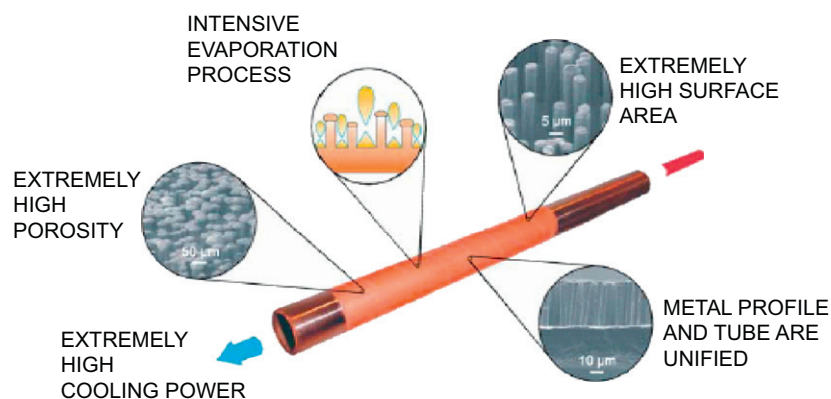

Fig. 4. Metal foams.

Fig. 5. Metal wools.

Fig. 3. The heat exchange copper tube with the micro-structured surface.

is suitable for use as the exchanger plate, and the thermal properties of the metals are the least important factors in terms of material selection.

In terms of hardness, both copper and aluminium are suitable for use as the exchanger plate, as they got adequate Young's modulus ranging 70–140 GPa, which is suitable for shaping and shape-remaining [16,17]. Both copper and aluminium are durable and compatible with the solid metal of the same material. In terms of risk of bacterial growing, the wick (sintered, meshes, grooves or whiskers) attained metal plates are better than foams and wools, as the pores on the winked plates are exposed rather than concealed, which would facilitate cleaning/hygiene treatment of the plate surface. In terms of cost, aluminium is a better choice over copper, as it is much cheaper compared to copper [18].

3.2. Fibre type

It has been found that fibre materials, including paperboard, cloth, wood or glass fibre and other fibres all have relatively high penetrability and lower TC and hardness. Fig. 6 shows the structure of a hardwood fibre, and Table 2 presents the TC of various fibre materials [19–22]. It is seen that the fibres have much lower TC than metals, ranging 0.01–0.3 W/m K [23]. Solid fibres are even worse than porous ones [22].

Table 2 also presents the porosity of a number of commonly used fibre materials. It is seen that wooden fibre, natural random fibre and glass fibre have the same level of porosity which ranges from 10% to 60%, while the rest are at much lower level range 1–5%.

The effective TC of a fibrous material increases with the fibre length and it approaches a stable level when the fibre length is sufficiently long. The effective TC decreases with porosity increasing [24].

Although TCs of the fibres are much lower than that of metal, an analysis using the method given in Section 2 indicated that the figures are still high enough to deal with the heat/mass transfer needed in an air-conditioning application. Also porosities of fibre are sufficient to retain water needed for moisture transfer. It would be preferable to choose a fibre with low porosity, as this kind of fibre has less water-retaining capacity that would enable enhanced sensible heat transfer. The most fibres presented in Table 3, except for wood and cotton fibres, are suitable for use as the exchanger material.

In terms of hardness, most fibre materials are not strong enough for use as exchanger plates. However, flax or

wooden fibres are the exception and have Yong's modulus as high as 70–110 GPa. The life span of the fibre exchanger is short as it is easy to be deformed or damaged when being soaked by water, except for flax or wooden fibre. The fibre is compatible to polyethylene, which is a water-proof material to be coated on one side of the fibre to avoid water penetration [29]. Fibre surface is ease of growing bacteria when being soaked, and therefore is not a perfect material for evaporative cooling. In terms of cost, the fibres are extremely cheap [29], and so frequent replacement is affordable that would overcome the difficulties of short life span and contamination risk.

3.3. Ceramics type

Porous ceramics could be one of the potential materials used for evaporative cooling due to its advanced properties, i.e., high capacity force, high TC, water-proof, and durability. Porous solids, such as extruded monoliths with parallel channels and thin walls, are made of various oxide and non-oxide ceramics, ceramics foams and metal structure, which can perform both moisture retaining and heat exchanging. Fig. 7 presents the porous ceramics structure made by IKTS [25].

The TC of the porous ceramics depends upon elements contained, the pore size and distribution, the porosity of the ceramics and the manufacturing processes. It varies from 0.1 to 240 W/m K. Generally the TC decreases with the porosity increasing [30]. Table 3 shows the TC of a range of different ceramics [25–28].

Water-retaining capacity (permeability) of the ceramics increases with increasing porosity and pore size. One way to make porous ceramics is mixing ground vermiculite and allophone at heated condition of 600–800 °C [31].

TCs of the ceramics are higher than that of fibres, but lower than that of metal. This level is good enough to deal with the heat/mass transfer needed in an air-conditioning application. Also porosities of ceramics are sufficient to retain water needed for moisture transfer. A ceramics with low porosity would be a preferable, as it has less water-retaining capacity that would enable enhanced sensible heat transfer. Aluminium nitride and polystyrene composites could be made into low porosity level, such as 1% or below, and therefore, may be suitable for use in this application.

A porous ceramic may be combined with a thin film made of the same material to avoid penetration of moisture when being used in indirect evaporation systems.

In terms of hardness, most porous ceramics are suitable as exchanger plate, which has Young's modulus ranging 50–400 GPa [32–35]. Porous ceramics are durable in use at the wetted condition, and its compatibility with the solid film of the same material is high. Porous structure is likely to grow bacteria at the wetted condition, as the pores are concealed inside the structure that increases the difficulty of cleaning/hygiene. In terms of the cost, it is about twice the price of the metal plate of the same material [36].
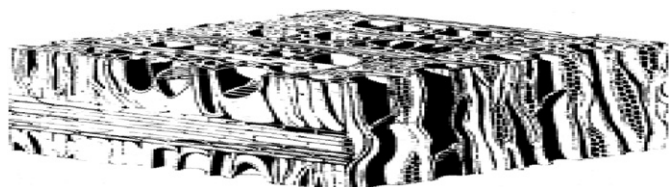

Fig. 6. Fibre structure of hardwood.

Fig. 7. Ceramic structure overview.

3.4. Zeolite type

Zeolites include natural and synthetic crystalline zeolites. The crystalline zeolites can be used for a wide variety of purposes include static, dynamic drying, iron exchange, selective separations involving gases and liquids. The industrial applications involve primarily "Linde Molecular Sieves (LMS)" called LMS and Davison "Microtraps" for the obvious reasons of availability in quantity and cost. The synthetic zeolites are attractive for drying and separation owing to their affinity for water and other small diameter molecules and also their ability to reject large diameter molecules [37].

The TC of LMS is around 0.59 W/m K, which is much smaller than that of metals and porous ceramics [37]. However, the figure is still high enough to deal with heat transfer needed in air-conditioning applications.

LMS have a high sorption capacity at low water vapour concentrations, and maintain the high sorption capacity at elevated relative humidity, which is a direct contrast to silica gel and activated alumina [38]. LMS has porosity of 40–80%, however, its absorption capacity is even higher due to its characteristics of water affinity. This water-retaining potential is good enough to take the moisture transfer duty in air-conditioning applications.

A zeolite material is compatible to polyethylene or wax [39,40], which is coated on one side of the exchanging wall to prevent moisture penetration when being used in indirect evaporation systems.

In terms of hardness, most zeolites are adequately strong for use as exchanger plates, which have Young's modulus ranging 1–20 GPa [41]. Since the pores are concealed inside, zeolites structure is also likely to grow bacteria when being soaked with water. In terms of the cost, they have ever higher prices than ceramics [36].

3.5. Carbon type

Carbon fibres have become an important reinforcement material in composite materials because of its low density, high strength (up to 7 GPa) and tensile modulus up to 600 GPa. In addition, high electrical and TC of carbon fibre makes it useful in a wide variety of products [A. Hoque]. Activated carbons are often used for desiccant; Carbon–carbon composites are used mostly in aerospace; Mesophase pitch-based carbon fibres with high preferred orientation have low density and high TC, with a TC at room temperature up to 1120 W/m K, etc. Fig. 8 shows three types of carbon fibre structure [42–44].

Activated carbons present very low TC (0.2 W/m K) responsible for severe thermal limitations inducing low overall adsorption and desorption kinetics as well as secondary reaction products or hazards in industrial applications. The in situ activation of various precursors within a consolidated expanded natural graphite matrix led to composites of high TCs (from 1 to 32 W/m K) and high effective adsorbent level (80 wt%) [45]. The type of carbon fibres in the composites plays an important role in the thermal conduction behaviour of carbon/carbon composites and the highly graphitic flat-layered structured fibres are conducive to conduction in the direction parallel to fibre axis [42]. Table 4 presents the TC and porosity of the selected carbon fibre materials [43–52].

An analysis carried out using the method given in Section 2 indicated that thermal properties of carbon materials are good enough to transfer both sensible and latent heat in air-conditioning application. A carbon material with low porosity would be preferable, as it has less water-retaining capacity that would enable enhanced sensible heat transfer. Carbon fibres or mesophase pitch-based fibres could be made into low porosity level, such as 1% or below, and therefore, may be suitable for use in this application.

A carbon fibre is also compatible to polyethylene or wax, which is coated on one side of the carbon made exchanging wall to prevent moisture penetration when being used in indirect evaporation systems [53,54].

In terms of hardness, carbon fibres are strong enough for making heat/mass transfer element, which have Young's modulus ranging from 1 to 220 GPa [41]. Since the pores are concealed inside, carbon fibre structure is likely to grow bacteria when being soaked with water for a long duration. In terms of the cost, they have similar prices as metals [36].

3.6. Comparison of the material types and result discussion

Table 5 summaries the level of performance of the above mentioned materials, in terms of TC, porosity, hardness, compatibility to the coating material, contamination risk and cost.

It has been known that thermal properties of the selected material types are all good enough to take the duty of heat/
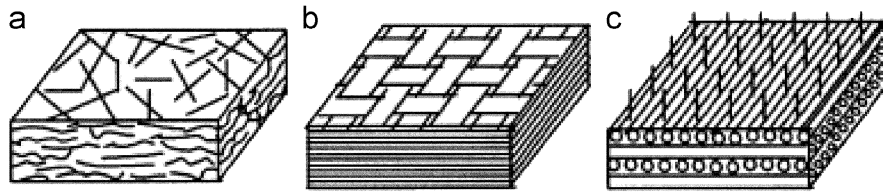
Fig. 8. Three types of carbon fibre structures: (a) laminated short fibre felt; (b) laminated carbon cloth felt; and (c) needle picked long fibre felt.

Table 5
Summary of the properties of the selected material types

Material type	Index					
	Thermal conductivity (W/m K)	Porosity (%)	Hardness (shaping ability)	Compatibility with coating	Contamination risk	Cost (£) per sheet [36] 100 mm × 100 mm × 0.5 mm
Metal	High	20–90	High	Compatible with the solid metal	Low (sintered metal)	30–100
Fibre	Low	1–60	Low	Compatible to polyethylene	High	<5
Ceramic	Variable	1–80	High	Compatible with the solid metal	High	150–250
Zeolite	Low	40–80	Medium	Compatible to polyethylene or wax	High	150–250
Carbon	Variable	Variable	Medium	Compatible to polyethylene or wax	High	30–80

mass transfer occurring in air-conditioning application. Therefore there is no need to consider impact of TC and porosity on system thermal performance when selecting a material for a heat/mass exchanger. In that case, hardness, compatibility, contamination risk as well as cost are the most important factors to be considered. In terms of compatibility with coating materials, all the selected materials are compatible with a specific coating and therefore they have comparable performance. In terms of geometry shaping/retaining ability (hardness), metal and ceramic are better choices, followed by Zeolite, carbon and fibre. In terms of contamination risk, the wick (sintered, meshes, grooves or whiskers) attained metal is the most adequate material and the rest are somehow contagious. From the cost point of view, fibre is the cheapest material, followed by metal and carbon. The ceramics and zeolite are the most expensive types and therefore not cost-effective.

In summary, to achieve a durable and healthy air-conditioning system, wick (sintered, meshes, grooves or whiskers) attained metals (copper or aluminium) are the most preferable option for heat/mass transfer materials. They are cheaper than ceramics and zeolites, about the same price as carbons, but more expensive than fibres. This price level is acceptable if the other benefits of metals have been taken into account.

4. Conclusions

Heat and mass transfer materials have five major types, namely metal, fibre, zeolite, ceramic or carbon. Each material type has its own best configuration that would allow the best performance when being used as heat/mass transfer medium in indirect evaporative cooling systems. The metal type refers to wick (sintered, meshes, grooves or whiskers) attained copper or aluminium sheet; fibre type refers to wooden or flax fibres with low porosity; ceramic refers to a metal based structure with small porosity; zeolite and carbon prefer a structure with low porosity and high TC.

Investigation into heat and mass transfer occurring in the heat/mass exchangers for air-conditioning applications was carried out. It is found that the heat transfer rate is in the range 392–399 W/m^2, and moisture evaporation rate is between 0.57 and 0.58 l/m^2 h. These rates are relatively low so that the thermal properties of the selected materials, i.e., TC and porosity, impose very little impact onto the process. In that case, these two parameters play low keys in selecting heat and mass exchanging materials. Instead, shape formation/holding ability, durability, compatibility with coatings, contamination risk as well as cost become more important concerns in this regard.

As indirect evaporative cooling requires product air to be cooled somehow but no moisture added, a water-proof coating is needed on one side of the exchanging sheet. The selected materials have their own compatible coatings and therefore these have no distinct difference in terms of coating compatibility.

As micro channels are arranged to allow dry or wet airstreams pass through alternatively, a fixed channel structure should be established easily and could remain

for a long duration. For this regard, metal and ceramic are better than zeolite, carbon and fibre.

As the wet channels are always soaked with water, there would be a high chance to come up with bacterial growth within the porous structure, particularly interior pores. To avoid this, exposed pore structure would be preferable and a material allowing frequent cleaning and sterilisation is desirable. A wick (sintered, meshes, grooves or whiskers) attained metal (copper or aluminium) is exactly the wanted material in this regard.

In terms of cost, fibre is obviously cheaper than any other materials. Metals and carbons cost more than fibres but less than ceramics and zeolites.

In summary, wick (sintered, meshes, grooves or whiskers) attained metals (cooper or aluminium) are the most adequate structure/material over the others. Wick-attained aluminium sheet is much cheaper than the cooper sheet with the same structure and therefore more suitable for this application.

Acknowledgement

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