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Comparative Study of the Hydrophilic Materials for Air-to-Air Heat/Mass Transfer

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Abstract

The paper aimed to investigate the performance of several hydrophilic materials, namely metals, fibres, ceramics, zeolite and carbons, and to select the materials that are the most suitable for performing heat and mass transfer between the incoming and outgoing air-streams associated with buildings. Heat and mass transfers within the dry and wet channel airstreams were investigated, and this has provided useful suggestions on selection of the materials for heat and mass transfer membranes. It has showed that a material's thermal conductivity imposed much less impact on heat transfer than its porosity and pore size did. Besides, hardness, durability and cost of the material are also important in material selection. To enable an effective heat/mass transfer, the porosity of the material would be higher than $3.82 \times 10^{-2}\%$, and the pore size would be in the range from 2.75×10^{-10} to 3.2×10^{-7} m. The material should also be easy of shaping and durable in long-term operation. Of the selected materials, fibre and carbons indicated a higher performance in heat and mass transfer. But fibre would suggest a cheap solution to this process.

Keywords: Hydrophilic; Heat/mass recovery; Material; Membranes; Thermal conductivity; Porosity; Pore size; Durability; Cost

Nomenclature

| | | |
|----------------|--|--------------------|
| c | Specific heat capacity | J/kg K |
| d_{Pore} | Pore diameter of the porous material | cm |
| d | Moisture content of the air stream | kg/kg dry air |
| D | Equivalent diameter of the exchanger tunnel | m |
| D_{AB} | Mass diffusivity | m ² /s |
| k^{heat} | Convective heat transfer coefficient | W/m ² K |
| $k^{moisture}$ | Convective mass transfer coefficient | m/s |
| k | Thermal conductivity | W/m K |
| k_{mass} | Moisture infiltration coefficient through exchanger membrane | m ² /s |
| L | Length of the exchanger tunnel | m |
| m | Mass of materials | kg |
| M_A | Molecular weight of air (29.0) | kg/mole |
| p | Vapour Pressure | Pa |
| q | Total heat transfer | J |
| T | Absolute temperature | K |
| t | Temperature | °C |
| u | Air speed | m/s |
| δ | Thickness of the heat/mass transfer membrane | m |
| V' | Volume of material | m ³ |
| α | Thermal diffusivity of air | m ² /s |

| | | |
|-------------|--|------------------------|
| ν | Kinematic viscosity | m^2/s |
| μ | Dynamic viscosity | Ns/m^2 |
| ρ | Density | kg/m^3 |
| ϑ | Porosity of materials | % |
| λ | Free path length of the diffusing species | cm |
| κ | Boltzmann's constant (1.38×10^{-16}) | ergs/K |
| γ | Lennard-Jones diameter of spherical molecule (for air it is 3.617×10^{-8}) | cm |

Subscript Term

| | |
|-------|--|
| w | Wet (humid) air channel |
| d | Dry air channel |
| h | Hot air channel |
| c | Cold air channel |
| air | Air stream |
| b | Bulk temperature of the fluent materials in the exchanger tunnel |
| w | Wall temperature of the exchanger tunnel membrane's surface |

Superscript Term

| | |
|------------|-------------------------------|
| $heat$ | Sensible heat energy |
| $moisture$ | Condensed/evaporated moisture |

1. Introduction

The traditional enthalpy plate exchangers use activated carbon-methanol, zeolite-water, or $\text{CaCl}_2\text{-NH}_3$ covered plate or tubes. These materials have relatively higher resistance in terms of heat and mass transfer [1, 2]. Air-to-air enthalpy exchanger wheels can carry the heat/mass transfer simultaneously, but have the disadvantages of over-taking and high power-consuming for wheel driving [3~5]. The exchanger made of hydrophilic materials are able to conduct both heat and mass transfer effectively and avoid problem of over-taking and wheel-driving energy consuming. Commonly used hydrophilic materials include metals, fibres, ceramics, zeolite and carbons. However, no comparison has yet been made to these materials and therefore selection of heat exchanging medium has been based on experience and custom so far as yet know, which would lead to reduced efficiency or increased cost of the heat/mass exchanging devices.

The above hydrophilic materials could be further classified according to their structure and composition. Hydrophilic metal could be classified as metal forms, metal wools, sintered metals and wicked metal. Fibre could also be divided in terms of its material, e.g., paper, wood or glass. Ceramic type contains SiC/SiC composites, zirconia ceramic, zirconia toughened aluminium, and aluminum 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. All these materials will be investigated and their properties will be compared each other. The most adequate material for heat/mass transfer among the air-streams will be recommended as a result of the study.

2. Analyses of the heat/mass transfer within air-to-air heat/mass exchanger

2.1. Heat/mass transfer mechanism

Figure 1 indicates the heat and mass transfer occurring in the hydrophilic membrane. When the humid and hot air flows across the wet air channel, it loses heat through the membrane due to the temperature

difference between the hot and cold air streams. As a result, the temperature of the hot air falls by some degrees and its relative humidity is increased. In the meantime, the moisture content difference between the humid and dry air causes condensation of the water-vapour on the surface of wet air channel. The condensed moisture then penetrates across the membrane and re-evaporates on the dry side surface, due to the stimulation of the sensible heat transfer and moisture content difference between the two adjacent air streams. This part of vapour enters the dry air streams and is carried away with the air. To enable the moisture transfer, the material of the membrane should be hydrophilic, moisture penetrating but free of air diffusion.

The heat transfer across the membrane could be written as follow:

$$q = (t_h - t_c) / \left(\frac{1}{k_h^{heat}} + \frac{\delta}{k} + \frac{1}{k_c^{heat}} \right) \quad (1)$$

k^{heat} is the convective heat-transfer coefficient, which can be calculated using the following equation [6]:

$$k^{heat} = 1.86 \left(\frac{uD}{\nu_b} \cdot \frac{\mu_b c_b}{k_b^{air}} \cdot \frac{D}{L} \right)^{1/3} \left(\frac{\mu_b}{\mu_w} \right)^{0.14} \frac{k_b^{air}}{D} \quad (2)$$

The mass transfer across the membrane could be written as follow:

$$m = \frac{(p_w - p_d) / RT}{\left(\frac{1}{k_w^{moisture}} + \frac{\delta}{k_{mass}} + \frac{1}{k_d^{moisture}} \right)} \quad (3)$$

Whilst the mass-transfer coefficient, $k_w^{moisture}$, could be calculated using the following equation:

$$k^{moisture} = k^{heat} (\rho_b c_b)^{-1} \left(\frac{\alpha_b}{D_{AB}} \right)^{-2/3} \quad (4)$$

The mass diffusion coefficient, D_{AB} is a function of air temperature and pressure, and can be calculated using the following equation [6]:

$$D_{AB} = D_0 \frac{P_0}{P} \left(\frac{t_b + 273.15}{T_0} \right)^{3/2} \quad (5)$$

For an air-to-air exchanger in buildings, its operation is usually at the atmospheric pressure. In this case, $P_0 / P = 1$, $T_0 = 273.15$ K. This will yield a value of $2.2 \times 10^{-5} \text{ m}^2/\text{s}$ for D_0 .

The thickness of the wall δ is in the range 0.1 to 0.5 mm, while its thermal conductivity, k , takes the 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 [7]:

$$k = g k_{moisture} + (1 - g) k_{materials} \quad (6)$$

Where k value of the filling moisture is about 0.6 W/m K, and k value of the wall material ranges from 0.3 to 400 W/m K, and porosity g of the material varies from 10% to 90%.

2.2. Heat Transfer Analyses

It is assumed that the air channel length (L) and equivalent diameter (D) of a fix-sized air-to-air exchanger is 0.5 m and 0.005 m, and the thickness (δ) of the membrane is 0.5 mm. The humid/hot air and cold/dry air parameters and their associated convective heat/mass transfer coefficients are also assumed as shown in Table 1.

For this case, the Reynolds number Re of the air flows is a figure smaller than 2300. This suggests that the heat and mass transfer between the adjacent flows will occur at the laminar flow condition. In this case, eqs. 2 and 4 can be applied to the heat/mass transfer analyses.

From the Table1, we can yield that value of $\frac{1}{k_h^{heat}} + \frac{1}{k_c^{heat}}$ is in the range 0.1945 to 0.09029, which is at least 60 times of value of $\frac{\delta}{k}$ ($\delta=5 \times 10^{-4}$, $k=0.3 \sim 400$ W/m K). This suggests that thermal conductivity of the material imposes very minor impact to sensible heat transfer, in comparison with convective heat transfer coefficients.

2.3. Mass Transfer Analyses

For mass transfer, $\frac{\delta}{k_{mass}}$ is associated with the thickness of membrane and its water diffusion coefficient

k_{mass} . Vapour pressure difference between the adjacent airstreams causes the condensation of vapour on the wet side of the membrane and penetration of the condensed moisture from wet to dry side. In this process, porosity and pore size of the material are the most important parameters which should be given particular consideration. Adequate porosity rate of the membrane are necessary in order to accommodate the condensed moisture. Also the pores of the membrane should have reasonable sizes that would allow the penetration of the condensed liquid but resist the cross flow (diffusion) of the two adjacent airstreams.

It is seen from Table 1 that the maximum moisture content difference between the two airstreams is 0.01528 kg/kg (dry air). Assuming that all amount of this part of moisture is condensed on the membranes surface, the required porosity rate of the membrane can be calculated using the following equation:

$$V_{moisture}' = \frac{(d_w - d_d) \pi D^2 u}{4 \rho_{moisture}} \quad (7)$$

Where the equivalent diameter, D , is 0.005 m, the maximum air flow rate is 5 m/s, and the moisture density is 1×10^3 kg/m³.

As the humid air is in contact with two sides of the wet channel, the volume of the wall transferring the moisture can be calculated using the following equation:

$$V_{wall}' = \delta\pi DL \quad (8)$$

Where the channel length is 0.5 m. Thus, the minimum porosity rate of the membrane could be obtained as follows:

$$\theta \% \geq 100 \frac{V_{moisture}}{V_{wall}} \quad (9)$$

This calculation suggests that the minimum porosity of the membrane should be $3.82 \times 10^{-2}\%$, which is value achievable by most hydrophilic materials.

Knudsen Diffusion factor is normally used to calculate the optimum pore size of the porous membranes. It has been known that the diffusion of gas molecules occurs only through very small capillary pores. If the pore diameter is smaller than the mean free path of the diffusing gas molecules, the gas molecules will collide with the pore walls more frequently than with each other, due to its low density characteristic. Knudsen number, Kn , can be expressed as follow [6]:

$$Kn = \frac{100 \lambda}{d_{pore}} \quad (10)$$

Where λ represents the free path length of the diffusing species, and d_{pore} represents the pore diameter of the porous membrane. In practice, free path length for molecules in the liquid state is very small, close to its molecular diameter. In this case, free path length of the diffused gases could be calculated using the following equation:

$$\lambda = \frac{\kappa T}{\sqrt{2} \pi \gamma^2 P} \quad (11)$$

Where κ is the Boltzmann's constant (1.38×10^{-16} ergs/K), T is the absolute temperature (290~350 K), γ is the Lennard-Jones diameter of the spherical molecule (for air it is 3.617×10^{-10} m), P is the system pressure (101.325 kPa). The free path length of air molecules is about 9×10^{-6} m.

If Kn is greater than 1, the diameter of the pore would be smaller than free path length of air molecule. Knudsen diffusivity of the air could be calculated using the following equation:

$$k_{mass} = 48.5 d_{pore} \sqrt{T / M_A} \quad (12)$$

Where M_A is the Molecular weight of the molecule. Water molecular diameter in liquid state is about 2.75×10^{-10} m, and average air molecular diameter in gas state is about 3.617×10^{-10} m [8].

For air-to-air heat/mass transfer membranes, to allow the water molecules penetrate across and stop the air molecules diffusion, the pore diameter of the porous membrane should be larger than the water molecular diameter (2.75×10^{-10} m in liquid state) and smaller than the free part length of air molecules (9×10^{-6} m). However, Eq. 6 indicated that although the pore diameter is smaller than the gaseous free part length,

there are still some air molecules passing across the membrane. By controlling the value of Knudsen diffusion, gaseous penetration through the membrane could be controlled. If reducing the Knudsen diffusion k_{mass} of the air to a level that is 1×10^{-4} times of the convective air flow rate u (0.5 m/s) in the tunnel, the air molecular diffusion across the porous membrane becomes negligible. In this case, pore diameter could be expressed as follow:

$$d_{pore} \leq \frac{u}{1 \times 10^{-4} \times 48.50 \sqrt{T / M_A}} \quad (13)$$

It can be seen from Figure 2 that to allow the moisture penetration but stop air diffusion across the membrane, the diameter of pores within the membrane would be in the range 2.75×10^{-10} to 3.2×10^{-7} m. It is also found that air temperature slightly impacts on air diffusivity.

3. Parameters considered in selecting the heat/mass transfer materials

It has been found from the previous analyses that thermal conductivity imposes a minor impact on the heat transfer due to the material's thin thickness, usually in the range 0.1 to 0.5 mm. This parameter is therefore given less consideration when selecting a material for the exchanger.

Capillary force and pore size are the key factors that affect moisture transfer across the membrane. Porosity is the parameter of a material that can represent the level of the capillary force and moisture absorbing ability. Higher porosity leads to increased moisture deposition and larger pore diameter allows for easy moisture penetration. However, pore diameter should be controlled to a certain size range in order to avoid air diffusion across the membrane.

Hardness of the material should also be taken in consideration when selecting a heat/mass transfer material. A stiff material is usually difficult to form a shape. In contrast, a soft material is easy for shaping but difficult to sustain the shape. A material with moderate hardness should be ideal for this purpose. Young's modulus is a parameter used for indicating the hardness of materials, and is defined as the ratio of the tensile stress to strain produced [9]. The Young's modulus of a porous material will degrade when it is saturated with water [10].

Durability is another factor that should be considered in material selection. This is particularly important for the porous materials used for moisture transfer. Ideally, the material selected should be able to resist rusty, deformation, oxidation, as well as bacteria growing.

Cost is also an important issue in selecting a material. This should contain two parts, i.e., cost of material itself and cost of manufacturing. Upon to meeting the requirement of heat/mass transfer, cost of the material and its manufacturing should be kept minimum.

4. Comparative Analyses of Potential Heat/mass Transfer Materials

4.1. Metal Type

The traditional metal heat exchanger is mainly made of aluminium, copper and their alloys, which can be shaped into a surface such as plate or tube. This kind of surface has much less capillary force to retain the condensed moisture from the humid/hot side. To increase surface capillary force, porous structure is considered to replace the smooth surface of the sheet or tube [11]. Several metal porous structures, namely, wicked metal, metal foams or wools, will be studied in this paper. Porous metals have the thermal conductivity from 29.43 to 400 W/m K, which is mainly determined by the porosity and other key characteristics of the metal [12]. Since thermal conductivity is a parameter with little impact on heat/mass transfer, porosities, pores size and membrane thicknesses are given emphasized here, and these are summarised in Table 2 [13-18].

Wickses could be one of the following structures, i.e., sintered particles, microcosmic holes, meshes, grooves or whiskers. Figure 3 shows the typical microphotography of particle-sintered porous metal and fibre-sintered porous metal [19]. As shown in Table 2, the porosities of wicked metal vary in a wide range, from 39 to 98%, depending upon their construction, density, pore size and configuration. Although the wicks porosities are enough to contain the condensed moisture, the microcosmic holes size, from 15 to 90 μm , can not match the pore diameter requirement ($2.75 \times 10^{-10} \text{ m} < d_{\text{pore}} < 3.2 \times 10^{-7} \text{ m}$) of the hydrophilic membrane.

In recent years, highly conductive foams based on copper or aluminium was used to make heat/mass exchanger membranes. Their open cell structures allow moisture/heat to be removed from the humid/hot side and added to the dry/cold side [20]. The foams can be produced in different methods, such as melts, powders, sputtering and deposition [21]. Each method covers a characteristic range of density, cell size and cell topology, thus resulting in the porosity up to 90% [22]. At present, the pore sizes ranging from 5.5 μm ~3 mm with a varying porosity from 10% to 90% have been achievable, thereby the porosity, shape information and construction expense are related to each other [21, 23~26]. Figure 4 presents the configuration of the commonly available metal foams [17]. Similar to the wicked metal, the metal foam can satisfy the porosity requirement but can not meet the demand of pore size and membrane thickness.

Metal wools are another type of porous metal mainly made of copper, aluminium and steel. The porosities are variable based on the metal fibre length, fibre diameter, and the density, from 30% to 70% [26]. It is found that the porosity of one kind of copper wools was 0.95 and the thermal conductivity of the copper reduced to 1.0~2.7 W/m K [27]. J. P. Mass et al (2006) pointed out that the porosity reduced with the decreasing of pore size and presented that when the pore size is 0.1~59 μm , the average fibre volume fraction is approximate 2% [28]. Figure 5 presents the configuration of the commonly available metal wools [29]. One kind of metal wool membrane could meet the porosity and pores size demand but its thickness induces high resistance to the heat/mass transfer. Hence, this is a challenge to develop a thin metal wool membrane with high porosity and proper pore size in the future.

The above analyses indicate that all types of metal have high thermal conductivity to carry out heat transfer and also have enough porosity to accommodate moisture. However, the pore size of metal wick, metal foam and most of metal wool are unable to meet the pore size requirement of the porous membranes.

In terms of hardness, both copper and aluminium are suitable for use as the exchanger plate, as they got adequate Young's Modulus ranging from 70 to 140 Gpa which is suitable for shaping and remaining-shape [9, 30]. Both copper and aluminium have long life span in any of its state, i.e., wick, foam and metal. In term of cost, aluminium is a better choice over the copper, as it is much cheaper compared to copper. Based on the manufacturing cost of micro-holes in the sintered metal, the metal wool and foam are better than wicked metal.

4.2. Fibre Type

It has been found that fibre materials, including paperboard, cloth, wood or glass fibre, natural fibre, all have relatively higher water affinity and lower thermal conductivity and hardness. Their thermal conductivities are in the range of 0.01 ~ 0.3 W/m K, much lower than that for metals [12, 31]. Figure 6 shows the structures of wood fibres, and Table 3 presents the porosities, pores size and membrane thicknesses of various fibre materials [31~38].

It is seen from Table 3 that woven fibre, natural random fibre and carbons fibre have the abundant level of porosity which ranges from 10% to 95%; the pore size of the various fibres change from 1.37 Å to 5 µm, which is in the range of the required membranes pore value; and most of the membranes made of fibre are thin enough to carry out the heat/mass transfer with little resistance. The natural fibre has a fibre diameter ranging from 0.1 to 205 µm with a micro lumen (less than 5 µm) and fibrillar angle (<20°), which allows the fibre materials to possess strong absorption ability. C. J. Tsenoglou (2006) carried out an experiment which showed that the clean fibre had the water penetration value of 5.35×10^{-12} m²/s under normal temperature and this could be improved if it is coated with hydrophilic materials [39, 40].

The effective thermal conductivity of a fibrous material increases with the fibre length and it approaches a stable level when the fibre length is sufficiently long. The effective thermal conductivity decreases with porosity increasing [41]. Although thermal conductivities of the fibres are lower than that of metals, porosities of most fibres listed in Table 3 are enough to absorb moisture from the humid air, and the pores size of fibre are larger than the liquid water molecular diameter, 2.75×10^{-10} m, but smaller than 3.2×10^{-7} m. Hence, the fibers membranes have the ability to conduct heat/mass transfer simultaneously, and avoid the gaseous air diffusion.

In terms of hardness, most fibre materials are not strong enough for use as the exchanger plates. However, flax or wooden fibres are the exception and have Yong's Modulus as high as 70 to 110 Gpa [32, 35~ 38]. 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. In term of cost, the fibres are extremely cheap, and so frequent replacement is affordable that could overcome the disadvantages of short life span.

4.3. Ceramics Type

Porous ceramics could be one of the potential materials used for hydrophilic membrane exchanger due to its advanced properties, i.e., high porosity, high thermal conductivity and durability. One way making porous ceramics is mixing ground vermiculite and allophone at heated condition of 600-800 °C [43]. Porous solids, such as extrude 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 and heat exchanging. Figure 7 shows the porous ceramics structure made by Kiyoshi [42~44].

The thermal conductivity of the porous ceramics depends upon the elements contained, the pore size and distribution, the porosity of the ceramics and the manufacturing processes. Thermal conductivities of the ceramics are higher than that of fibres, but lower than that of metal. It varies from 0.1 to 240 W/m K. Generally the thermal conductivity decreases with the porosity increasing [12, 45]. Table 4 shows the porosities, pores size and membrane thicknesses of a range of different ceramics [42, 43, 46~50].

All porosities of the ceramics are sufficient to retain water needed for moisture transfer. Ceramics made of different materials generally constitutes the pore size form 0.005 μm to 38 μm , hence, part of ceramics such as 8-YSZ ceramics, foamed glass ceramics and Zirconia toughened alumina, etc, can meet pore size requirement of the hydrophilic membrane [42~50]. A ceramics with higher porosity would be perfect, as it has higher moisture retaining ability and infiltration capacity that would enable moisture penetration and stop air diffusion. Water permeability of the ceramics increases with increasing of porosity and pore size. Furthermore, most ceramics could be shaped in to thin membranes and carry out the heat/mass transfer.

In terms of hardness, most porous ceramics are suitable as exchanger plate, which has Young's Modulus ranging from 50 to 400 Gpa [50~53]. Porous ceramics are durable in use at the wetted condition. In terms of cost, it's more expensive than fibre and metal [54].

4.4. 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, ion exchange, selective separations involving gases and liquids. The industrial applications involve primarily "Linde Molecular Sieves" called LMS and Davison "Microtraps" for the obvious reasons of availability in quality 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 [55]. Figure 8 shows the diagram of three kinds of zeolite [56~58]. The porosities, pores size and membrane thicknesses of kinds of zeolites are listed in Table 5 [55~60].

The thermal conductivity of Linde molecular sieves is around 0.59 W/m K, which is much smaller than that of metals and porous ceramics [55]. However, the value is similar to the thermal conductivity of fibre.

Linde Molecular Sieves (LMS) have a high sorption capacity at low water vapour concentrations, and maintain the high sorption capacity at fixed relative humidity, which is a direct contrast to silica gel and activated alumina [61]. LMS has porosity of 4% to 80%, and its absorption capacity is even higher due to its characteristics of water affinity. LMS as the popular molecules sieving and separation materials, it has pore diameter as low as 1×10^{-10} m [55]. And the zeolite membrane is easy to be manufactured into thin films as shown in table 5. Hence it has the ability to service as the thin heat/mass recovery membranes with the proper pore size ($2.75 \times 10^{-10} \text{ m} < d_{\text{pore}} < 3.2 \times 10^{-7} \text{ m}$) and high absorption capacity.

In terms of hardness, most zeolites are adequately strong for use as exchanger plates, which have Young's Modulus ranging from 1 to 20 GPa [62, 63]. The durability of zeolites is decided by the composites. In term of the cost, they have similar prices as the ceramics.

4.5. 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 thermal conductivity of carbon fibre makes it useful in a wide variety of products [64]. Such as activated carbons are often used for desiccant, Carbon-carbon composites are used mostly in aerospace, Mesophase pitch-based carbon fibers with high preferred orientation have low density and high thermal conductivity (TC), with a TC at room temperature up to 1120 W /m K, etc, [65, 66]. Fig. 9 shows three types of carbon fibre structure [65]. Table 6 presents the porosities, pores size and membrane thicknesses of porous carbons and its composite [59, 67~71].

AC-ENG composite, acetylene black carbon, porous carbon (SiC) and carbon foam have high porosities to contain the condensed moisture from the humid air side. Besides carbon foam, all the carbons and its composites listed in Table 6 can offer the proper pore size in the range of $2.75 \times 10^{-10} \text{ m} < d_{\text{pore}} < 3.2 \times 10^{-7} \text{ m}$.

Pore diameter between carbon fibres can be as small as 6×10^{-9} m, which can allow the moisture transfer and stop air diffusion [65, 71 and 72]. Considering the membrane's thickness as well as porosity and pore size, the AC-ENG composite, CM-260, acetylene black carbon all can carry as the hydrophilic heat/mass transfer membrane.

Carbons materials have stronger capillary force than metals and better thermal conductivity than fibres, which are enough for the heat/mass transfer between two airstreams. A carbon material with high porosity and adequacy thermal conductivity is a preferable for the heat/mass transfer purpose.

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 [73].it's cheaper than metal, ceramic and zeolite but more expensive than cellulose fibre.

5. Comparison of the Material Types and Results Discussion

Table 7 summaries the level of performance of the above mentioned materials, in terms of thermal conductivity, porosity, pore size, hardness, durability and cost [74, 75]. In overall, a porous metal has relatively higher thermal conductivity and porosity than other materials. However, it is difficult to prevent air diffusion across when the moisture is transferred from one side to the other of the membranes. The porous metal is therefore not a suitable material for heat/mass transfer membranes. Fibre can carry out heat/mass transfer simultaneously without air diffusion. It is the cheapest of the above mentioned materials and can be shaped and structure easily. However, the fibre has disadvantages of low thermal conductivity and short life span. Ceramic and Zeolite are suitable materials for the heat/mass transfer membranes as these have adequate pore sizes and water retaining capacities. However, they are hard for shaping and relatively expensive. Carbon is the best selection for use as the heat/mass transfer membranes, as it has higher heat/mass transfer capacity and can be easily shaped into different geometries at the affordable prices.

In conclusion, carbon and cellulose fibre may be adequate materials for use as heat/mass transfer membranes, as they both can carry out heat/mass transfer effectively. A carbon membrane is better than a fibre membrane in terms of hardness, but its price is higher. The cheap cost of the fibre may somehow compensate its disadvantages of short life span.

6. Conclusion

The thermal conductivity of the materials is a less important parameter in material selection. Porosity, pore diameter and membranes thickness are three most important parameters which largely impact on the performance of membrane heat/mass transfer. Larger porosity represents a stronger capillary effect and moisture retaining ability. Pore sizes should be suitably selected to allow moisture penetration but stop air diffusion across the membrane. This investigation suggests that the pore sizes should remain in the range 3.75×10^{-10} m to 3.2×10^{-7} m. Besides, hardness, durability and cost should also be taken into consideration in selecting a material for heat/mass transfer membrane.

Carbon and fibres are the suitable materials for making heat/mass transfer membranes. Fibres are currently more popular in application owing to its cheaper price. However, carbons may be more attractive in terms of its durability, cleanliness and performance retaining.

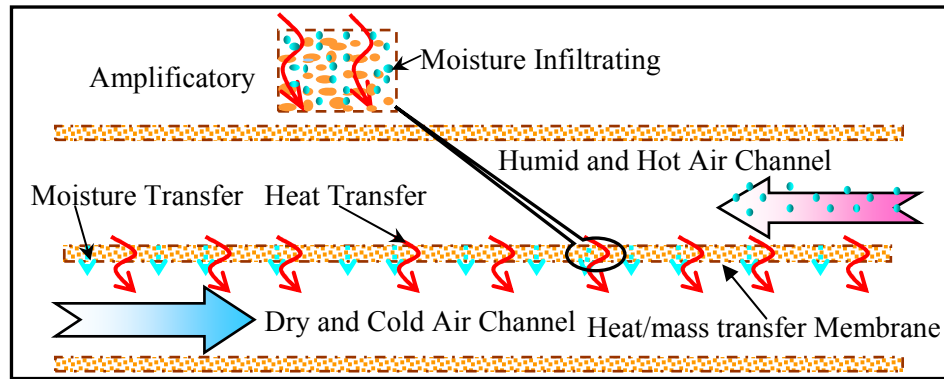


Fig.1. Schematic diagram showing the principle of the heat/mass transfer

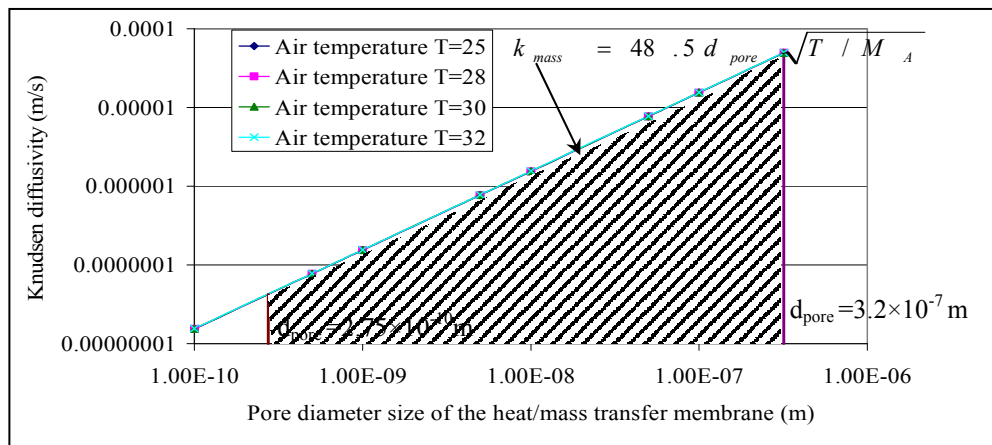


Fig.2. Pore diameter size of the heat/mass transfer membrane



Fig.3. Microphotography of particle-sintered porous metal and fiber-sintered porous metal

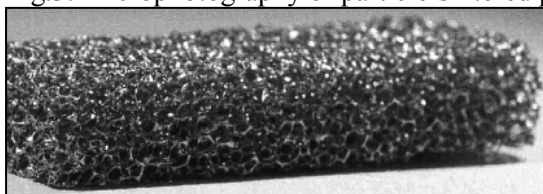


Fig.4. Metal foams

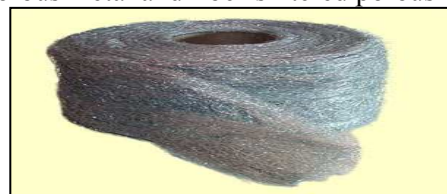


Fig.5. Metal wools

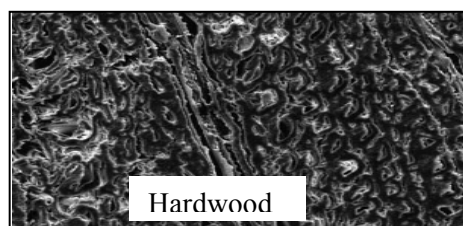
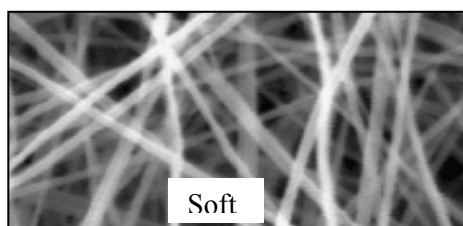


Fig.6. Fibre structures of soft fibre and hardwood fibre

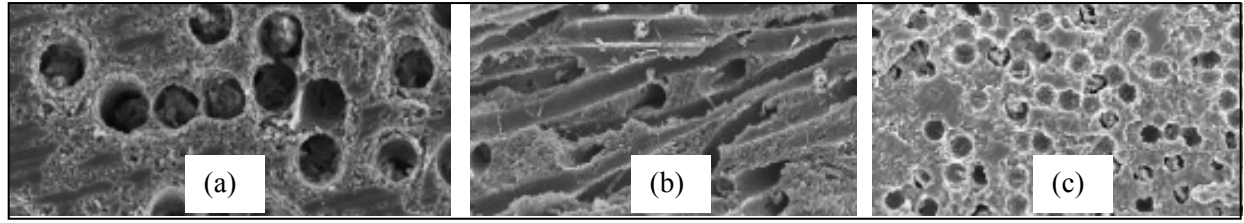


Fig. 7. Structure diagram overviews of alumina ceramics prepared by methods: (a) extrusion; (b) parallel to the extrusion; (c) conventional

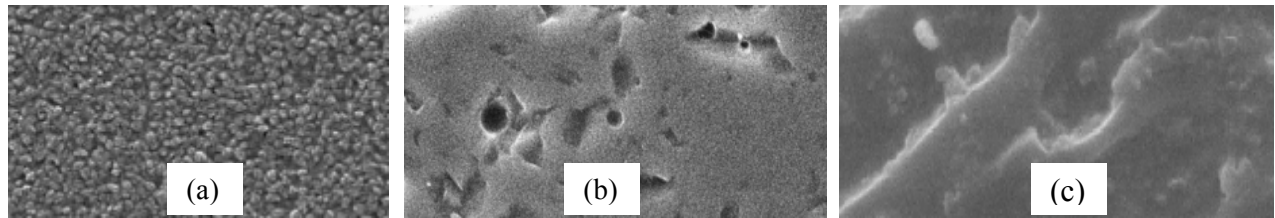


Fig.8. Structure diagram of zeolite: (a) Spin-on zeolite; PVA-CMS-06 film; (c) Celsian sintered glass

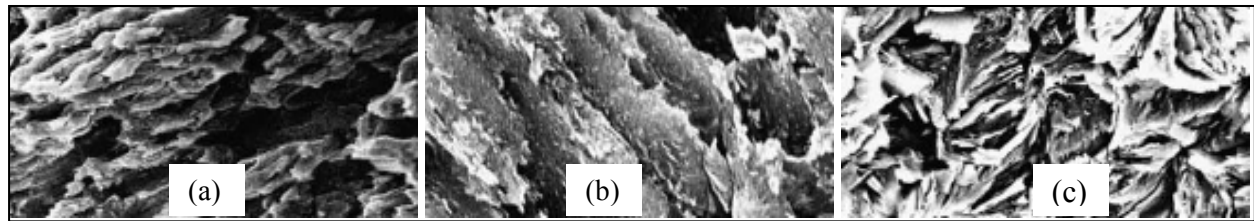


Fig.9. Textures of the carbon materials prepared from (a) RMPF-180; (b) CM-260; (c) CM-260-round

Table 1 Air parameters and calculated Re

| | Temperature (°C) | Relative humidity (%) | Moisture content (kg/kg dry air) | Air flow rate (m/s) | Convective heat- transfer coefficient (W/m ² K) | Convective mass- transfer coefficient (m ² /s) | Reynolds Number ($Re = \frac{uD}{v_b}$) |
|------------------|---------------------|-----------------------------|---|---------------------------|--|--|---|
| Humid/hot Air | 35 | 70 | 0.02516 | 0.5~5 | 10.2430~22.067 | 0.0089~0.0191 | 148~1480 |
| Dry/cold Air | 25 | 50 | 0.00988 | 0.5~5 | 10.3215~22.237 | 0.0086~0.0186 | 157~1565 |

Table 2 Porosities, pores size and membranes thicknesses of wicked metal, metal foams and wools

| Porous metal | Pore size ($\times 10^{-6}$ m) | Porosity (%) | Membranes thickness (mm) |
|-------------------------------------|---------------------------------|--------------|--------------------------|
| Open Cell metal foam | 2300 | 92 | 2.0 |
| AI metal foam | 2000 | Up to 90 | 550 |
| Whisker-attained tube | 3 | 40 | 1.0 |
| Metal bronze sintered (wicked) | 30~90 | 80~98 | 0.1~10 |
| Sintered (wicked) metal | 15~30 | 39 | 1.6 |
| Amorphous metal foams | 20 ~3000 | <90 | 2~10 |
| Bulk metallic glasses metal foam | 25~250 | 15~22 | 7~10 |
| Metal fibre (wool) in foam | >5.5 | >50 | 2.0 |
| Metal wool | 0.1~10 | 85 | 3.2 |
| Sintered Power | < 20 | Average 31.5 | 0.7 |
| Sintered metal wool | 3~59 | 65~87 | 0.17~0.82 |

Table 3 Porosities, pores size and membranes thicknesses of various fibres

| Fibres | Pore size ($\times 10^{-6}\text{m}$) | Porosity (%) | Membrane thickness (mm) |
|--|--|--------------|-----------------------------|
| Woven fibre | 0.3~2.5 | >50 | 0.86 |
| Randomly oriented ultra-fine fiber | 0.2~0.4 | 52~83 | 0.15~0.3 |
| Carbons fibres | > 0.000137 | 0~95 | 1.6 |
| Hardwood fibre | 2~5 | 63~71 | <15 |
| Si-Al-C fibres | 0.1 | >10 | 0.394~0.706 |
| Porous paper | 0.05~0.1 | <90 | $0.2\sim 2.0\times 10^{-3}$ |
| Pigment-filled polymer coated paperboard | 0.08~0.14 | >70 | 0.3 |
| Paper board | 0.01~0.06 | 30~95 | 0.012~0.5 |
| Natural fibre (Banana, Pineapple, Sisal, etc.) | 0.1~5 | <50 | 0.015~0.5 |

Table 4 Porosities, pores size and membranes thicknesses of porous ceramics

| Porous ceramics | Pore size ($\times 10^{-6}\text{m}$) | Porosity (%) | Membrane thickness (mm) |
|------------------------------|--|--------------|-------------------------|
| Zirconia toughened alumina | 0.25 | 60~80 | — |
| Porous alumina ceramics | 8.5 to 38 | 39~43 | 0.5~3 |
| Porous SiC ceramics | 0.31~1.39 | 45.7~49.8 | <3 |
| AlN ceramics | 21~38 | 40 | 0.2~0.24 |
| 8-YSZ ceramics | 0.01~0.05 | 45~75 | 0.08 |
| Alumina ceramics | 0.5 | 45~70 | 0.08 |
| Foamed glass ceramics | 0.005~0.01 | 37~90 | 5 |
| MgO-ZrO ₂ ceramic | 10~20 | 37~60 | 1~2 |
| SiC/SiC composites | 0.7~3.2 | <90 | 0.03 |

Table 5 Porosities, pores size and membranes thicknesses of porous zeolite

| Porous zeolite | Pore size ($\times 10^{-6}\text{m}$) | Porosity (%) | Membrane thickness (mm) |
|--------------------------------------|--|--------------|-------------------------|
| Zeolite P-C, P-W, P-R | 0.0003 | 1~4 | <0.5 |
| Gram activated zeolite | 0.0006~0.001 | 50 | <0.5 |
| ZSM-3 | 0.00143 | 38.1 | <0.5 |
| Natural zeolite | About 0.00044 | 20~60 | <0.5 |
| LMS-Type 4A | 0.00042~0.0011 | 14 | <0.5 |
| PSZ MEL zeolite | 0.002~0.05 | 20.3~64.8 | <0.5 |
| Molecular sieve filled vinyl alcohol | 0.00053~0.001 | 20~80 | 0.08 |
| Sodium ion zeolite | 0.000098 | <50 | <0.5 |

Table 6 Porosities, pores size and membranes thicknesses of porous carbons

| Porous carbons | Pore size ($\times 10^{-6}\text{m}$) | Porosity (%) | Membrane thickness (mm) |
|-------------------------------|--|--------------|-------------------------|
| C-C/Al composites. | 0.1~4 | 31.4~33.8 | 3 |
| CM-260 | 0.02~5 | 2~30 | 0.0057 |
| spun hybrid carbon composites | 0.1~5 | <40.7 | 5 |
| AC-ENG composite | 0.0006~0.0026 | 80 | <0.5 |
| Carbon nanotube/silica | 0.018~0.02 | 10~45 | <1 |
| Acetylene Black carbon | 0.001 | 70 | <0.1 |
| Carbon foam | 310~643 | 67~89 | <1 |
| Porous carbon (SiC) | 0.03~2.58 | 35~67 | 3 |

Table 7 Summaries of the properties of the selected material types [72], [73], [74]

| Materials | Thermal conductivity (W/m K) | Porosity (%) | Pore size (μm) (approximate) | Hardness (shaping ability) | Durability | Cost (£)* |
|-----------|------------------------------|--------------|---|----------------------------|------------|------------|
| Metal | High | 20-90 | $15\sim 3\times 10^3$ | High | Long time | 30 to 100 |
| Fibre | Low | 1 - 60 | $1.3\times 10^{-4}\sim 5$ | Low | Short time | < 5 |
| Ceramic | Variable | 1 - 80 | $5\times 10^{-3}\sim 38$ | High | Long time | 150 to 250 |
| Zeolite | Low | 40 - 80 | $9.5\times 10^{-5}\sim 5\times 10^{-2}$ | Medium | Medium | 150 to 250 |
| Carbon | Variable | Variable | $6\times 10^{-4}\sim 643$ | Medium | Medium | 30 to 80 |

Cost per sheet 100 x 100 x 0.5 (mm \times mm \times mm)

Reference

- [1] R. Z. Wang, J. Y. Wu, Y. X. Xu, Y. Teng and W. Shi, Experiment on a continuous heat regenerative adsorption refrigerator using spiral plate heat exchanger as adsorbers, *Applied Thermal Engineering* 18 (1998) 13-23,
- [2] A. Hachemi, Experimental study of thermal performance of offset rectangular plate fine absorber-plates, *Renewable Energy*, Vol. 17 (1999) 371-384
- [3] Sankar Nair, Samir Verma, S. C. Dhingra, Rotary heat exchanger performance with axial heat dispersion, *International Journal of Heat and Mass Transfer*, Vol. 41 (1998) 2857-2864
- [4] L.A. Sphaier and W.M. Worek Analysis of heat and mass transfer in porous sorbents used in rotary regenerators, *International Journal of Heat and Mass Transfer*, Vol. 47 (2004) 3415–3430
- [5] (S. Nair, et al 1995 and L.A. Sphaier and W.M. Worek 2004).
- [6] Welty J. R., Wicks C. E., Robert E. Wilson, Gregory L. Rorrer, *Fundamentals of Momentum, Heat, and Mass Transfer*, John Wiley & Sons, Inc (2001) 723–724.
- [7] J.E. Parrott and Audrey D. Stuckes, *Thermal conductivity of solids*, Pion Limited, 1975, P 92,123,144
- [8] <http://www.lsbu.ac.uk/water/molecule.html>
- [9] Michael Piggott, *Load Bearing Fibre Composites*, 2ed Edition, KLUWER ACADEMIC PUBLISHERS, 2002
- [10] Ana Espert, Francisco Vilaplana, Sigbritt Karlsson, Comparison of water absorption in natural cellulosic fibres from wood and one-year crops in polypropylene composites and its influence on their mechanical properties, *Composites: Part A*, Vol. 35 (2004) 1267–1276
- [11] L. Tadrist, M. Miscevic, O. Rahli, F. Topin, About the use of fibrous materials in compact heat exchangers, *Experimental Thermal and Fluid Science*, Vol. 28 (2004) 193-199
- [12] X. Zhao, Shuli Liu, S.B. Riffat, Comparative study of heat and mass exchanging materials for indirect evaporative cooling systems, *Building and Environment*, Vol. 43 (2008) 1902–1911
- [13] A. Schulz, G.N. Akapiev, V.V. Shirkova, H. Rösler, S.N. Dmitriev, A new method of fabrication of heat transfer surfaces with micro-structured profile, *Nuclear Instruments and Methods in Physics Research B*, 236 (2005) 254–258,
- [14] Z. Y. Zhao, Q. Z. Wu, M. Shao, Y. Y. Li, Study on Porosity of Sintered Metallic porous material, *Powder Metallurgy Industry, China*, Vol.15 (2005) 4-10
- [15] Kenneth L. Rubow, Louise Stange and Billy Huang, *Advances in Filtration Technology Sintered Metal Filters, Application in Textiles*, China, Vol. 180 (9) (2005) 23-29
- [16] W. Jinhu and W. Yang, Study on an Integrated Sintered Metal Screen Moving Granular Bed Filter, *Chinese J. Chem. Eng.* Vol. 12 (3) (2004) 458-462
- [17] K. Boomsma, D. Poulikakos, and F. Zwick, Metal foams as compact high performance heat exchangers, *Mechanics of Materials* Vol. 35 (2003) 1161–1176
- [18] L. Gu, S. T. Qiu, Y. Zhao, The Review on Sinter Metal Porous Filter Element, *Liquid Mechanism, China*, Vol. 30(2) (2002) 30-37
- [19] Kazuhisa YUKI, Jun ABEI, Hidetoshi HASHIZUME, Saburo TODA, Super-High Heat Flux Removal Using Sintered Metal Porous Media, *Journal of Thermal Science* Vol. 14 (2005) 272-280
- [20] John Banhart, *Manufacture, characterisation and application of cellular metals and metal foams*, *Progress in Materials Science*, Vol. 46 (2001) 559–632
- [21] T.W. Clyne and F. Simancik, *Metal Matrix Composites and Metallic Foams*, EUROMAT-Volume 5, Weinheim. New York. Chichester, 2000
- [22] W. Azzi, W.L. Roberts, A. Rabiei, A study on pressure drop and heat transfer in open cell metal foams for jet engine applications, *Materials and Design*, Vol. 28 (2007) 569–574
- [23] J. F. Despois, et al, Influence of the infiltration pressure on the structure and properties of replicated aluminium foam, *Materials Science*, A 462 (2007) 68-75
- [24] A.H. Brothers, D.C. Dunand, Amorphous metal foams, *Scripta Materialia*, Vol. 54 (2006) 513–520
- [25] A.H. Brothers, R. Scheunemann, J.D. DeFouw, D.C. Dunand, Processing and structure of open-celled amorphous metal foams *Scripta Materialia*, Vol. 52 (2005) 335–339
- [26] E.J. Minay, P. Veronesi, V. Cannillo, C. Leonelli, A.R. Boccaccinia, Control of pore size by metallic fibres in glass matrix composite foams produced by microwave heating, *Journal of the European Ceramic Society*, Vol. 24 (2004) 3203–3208

- [27] Lacroix C, Ramany Bala P, Feidt M. Evaluation of the effective thermal conductivity in metallic porous media submitted to incident radiative flux in transient conditions. *Energy Conversion and Management*, Vol. 40 (1999) 1775–81.
- [28] J. P. Masse, et al, Influence of relative density on the architecture and mechanical behaviour of a steel metallic wool, *Scripta materialia*, Vol. 54 (2006) 1379-1383
- [29] http://cai.tongji.edu.cn/wanluokecheng/p03/ch08/example/exa08_09_01
- [30] H.Pelletier, Predictive model to estimate the stress-strain curves of bulk metals using nanoindentation, *Tribology International*, Vol. 39(2006) 593-606
- [31] James R. Gaier, Yvonne YoderVandenberg, Steven Berkebile, Heather Stueben , Frederick Balagadde, The electrical and thermal conductivity of woven pristine and intercalated graphite fiber–polymer composites, *Carbon*, Vol. 41 (2003) 2187–2193
- [32] Chang Seok Ki, Eun Hee Gang, In Chul Um, Young Hwan Park, Nanofibrous membrane of wool keratose/silk fibroin blend for heavy metal ion adsorption, *Journal of Membrane Science*, Vol. 302 (2007) 20–26
- [33] Kiyoshi Itatani, Tsuyoshi Tanaka, Ian J. Davies, Thermal properties of silicon carbide composites fabricated with chopped Tyranno Si-Al-C fibres, *Journal of the European Ceramic Society*, Vol. 26 (2006) 703–710
- [34] Li-Wu Fan, Ya-Cai Hu, Tian Tian, Zi-Tao Yu, The prediction of effective thermal conductivities perpendicular to the fibres of wood using a fractal model and an improved transient measurement technique, *International Journal of Heat and Mass Transfer*, Vol. 49 (2006) 4116–4123
- [35] Thomas Schuman, Anders Karlsson, Johan Larsson, Magnus Wikström, Mikael Rigdahl, Characteristics of pigment-filled polymer coatings on paperboard, *Progress in Organic Coatings*, Vol. 54 (2005) 360–371
- [36] Mitsuhiro Murayama, Shigeru Nagasawa, Yasushi Fukuzawa, Takashi Yamaguchi, Isamu Katayama, Orthotropic effect and strain dependency of paperboard on load characteristic of center bevel cutter indented on paperboard, *Journal of Materials Processing Technology* , Vol.159 (2005) 199–205
- [37] Yun M. Chung, Min J. Jung , Kyung H. Nam , Jeon G. Han , Seung H. Baeg , Se H. Yang, A study on formation of Al and Al₂O₃ on the porous paper by DC magnetron sputtering, *Surface and Coatings Technology*, Vol. 171 (2003) 65–70
- [38] N. C. Gallego and D. D. Edie, Structure-property relationships for high thermal conductivity carbon fibres, *Composites: Part A* 32 (2001) 1031-1038
- [39] M. Idicula, et al, Thermophysical properties of natural fibre reinforced polyester composites, *Composites Science and Technology*, Vol. 66 (2006)2719-2725
- [40] C.J.Tsenoglou, et al, Evaluation of interfacial relaxation due to water absorption in fiber-polymer composites, *Composites science and technology*, Vol. 66 (2006)2855-2864
- [41] Moran Wang, Jihuan He, Jiangyong Yu and Ning Pan, Lattice Boltzmann modelling of effective thermal conductivity for fibrous materials, *International Journal of Thermal Science*, (2006)
- [42] Kiyoshi Okada, Shaunsuke Matsui, Toshihiro Isobe, Yoshikazu Kameshima, Akria Nakajima, Water-retention properties of porous ceramics prepared from mixtures of allophone and vermiculite for materials to counteract heat island effects, *Ceramics international*, Vol. 34 (2008) 345-350
- [43] Okada K, Matsui S, Isobe T, Kameshima Y, Nakajima A. Waterretention properties of porous ceramics prepared from mixtures of allophone and vermiculite for materials to counteract heat island effects. *Ceramics International*, Vol. 10 (2006)1–6
- [44] Toshihiro Isobe, Yoshikazu Kameshima, Akira Nakajima, Kiyoshi Okada, Yuji Hotta, Gas permeability and mechanical properties of porous alumina ceramics with unidirectionally aligned pores, *Journal of the European Ceramic Society*, Vol. 27 (2007) 53–59
- [45] B.Nait-Ali, K.Haberko, H.Vesteghem, J.Absi, D.S.Smith, Thermal conductivity of highly porous zirconia, *Journal of the European Ceramic Society*, Vol. 26 (2006) 3567–3574
- [46] B. Nait-Ali, K. Haberko, H. Vesteghem, J. Absi, D.S. Smith, Preparation and thermal conductivity characterisation of highly porous ceramics Comparison between experimental results, analytical calculations and numerical simulations, *Journal of the European Ceramic Society*, Vol. 27 (2007) 1345–1350
- [47] M.Luga, F. Raether, FEM simulations of microstructure effects on thermoelastic properties of sintered ceramics, *Journal of the European Ceramic Society*, Vol. 27 (2007) 511–516

- [48] Yan Ma, Qing-Song Ma, Jun Suo, Zhao-Hui Chen, Low-temperature fabrication and characterization of porous SiC ceramics using silicone resin as binder, *Ceramics International*, Vol. 34 (2006) 253–255
- [49] Taguchi T, et al. Effect of thick SiC interphase layers on microstructure, mechanical and thermal properties of reactionbonded SiC/SiC composites. *Journal of Physics and Chemistry of Solids*, Vol. 66 (2005) 576–80
- [50] G. Krauß, J. Kübler, E. Trentini, Preparation and properties of pressureless infiltrated SiC and AlN particulate reinforced metal ceramic composites based on bronze and iron alloys, *Materials Science and Engineering A337* (2002) 315 –322
- [51] Pabst W, et al. Elasticity of porous ceramics—a critical study of modulus–porosity relations. *Journal of the European Ceramic Society*, Vol. 26 (2006) 1085–97
- [52] Douglas E.Burkes, Guglielmo Gottoli, John J.Moore, Mechanical properties of porous combustion synthesized $\text{Ni}_3\text{Ti-TiC}_x$ composites, *Composites Science and Technology*, Vol. 66 (2006) 1931–1940
- [53] Hyunjo Jeong and David K.Hsu, Quantitative estimation of material properties of porous ceramics by means of composite micromechanics and ultrasonic velocity, *NDT&E International*, Vol.29.No.2(1996) 95–101
- [54] http://www.coleparmer.co.uk/catalog/Product_Index.asp?search=Aluminum+nitride
- [55] Hersh CK. In: *Molecular sieves*. New York, London: Reinhold Publishing Corporation; Chapman & Hall Ltd.; 1961.
- [56] Mark Johnson, Zijian Li, Junlan Wang, Yushan Yan, Mechanical characterization of zeolite low dielectric constant thin films by nanoindentation, *Thin Solid Films*, Vol. 515 (2006) 3164–3170
- [57] V. Cannillo, T. Manfredini, A. Motori, F. Patuelli, A. Saccani, A. Sola, Technological properties of celsian reinforced glass matrix composites, *Ceramics International*, Vol. 33 (2006) 1597–1601
- [58] Honglei Sun, Lianyu Lu, Fubing Peng, Hong Wu, Zhongyi Jiang, Pervaporation of benzene/cyclohexane mixtures through CMS-filled poly(vinyl alcohol) membranes, *Separation and Purification Technology*, Vol. 52 (2006) 203–208
- [59] X. Py , E. Daguerre, D. Menard, Composites of expanded natural graphite and in situ prepared activated carbons, *Carbon* , Vol. 40 (2002) 1255–1265
- [60] Robert F.Gould, *Molecular Sieve Zeolites-I*, American Chemical Society, Washington. D. C, 1971, 110
- [64] Jeong J, Mumma SA. Practical thermal performance correlations for molecular sieve and silica gel loaded enthalpy wheels. *Applied Thermal Engineering*, Vol. 25(2005)719–40.
- [65] J. Lin, X.F. Shu, T, J.X. Dong, The experimental determination of mechanical properties of zeolite ferrierite crystal, *Materials Letters*, Vol. 59 (2005) 1595– 1597
- [63] D. Metin, F. Tihminlioğlu, D. Balköse, S.Ülkü, The effect of interfacial interactions on the mechanical properties of polypropylene/natural zeolite composites, *Composites: Part A*, Vol.35 (2004) 23–32
- [64] A. Hoque, M. K. Alamb, G. G. Tibbetts, Synthesis of catalyst particles in a vapor grown carbon fiber reactor, *Chemical Engineering Science*, Vol. 56 (2001) 4233–4243
- [65] Zhaokun Ma, Jingli Shi, Yan Song, Quanguo Guo, Gengtai Zhai, Lang Liu, Carbon with high thermal conductivity, prepared from ribbon-shaped mesophase pitch-based fibers, *Carbon*, Vol. 44 (2006) 1298–1352
- [66] Zhenyi Liu, Guoding Zhang, Hong Li, Jinliang Sun, Musu Ren, Al infiltrated C–C hybrid composites, *Materials and Design*, Vol. 26 (2005) 83–87
- [67] Ramasamy Sivakumar, Shuqi Guo, Toshiyuki Nishimura and Yutaka Kagawa, Thermal conductivity in multi-wall carbon nanotube/silica-based nanocomposites, *Scripta Materialia*, Vol. 56 (2007) 265–268
- [68] X.L. Wang, H.M. Zhang, J.L. Zhang, H.F. Xu, Z.Q. Tian, J. Chen, H.X. Zhong, Y.M. Liang, B.L. Yi, Micro-porous layer with composite carbon black for PEM fuel cells, *Electrochimica Acta*, Vol. 51 (2006) 4909–4915
- [69] Tae Jin Kang, Seung Jun Shin, Kyunho Jung, Jong Kyoo Park, Mechanical, thermal and ablative properties of interplay continuous/spun hybrid carbon composites, *Carbon*, Vol. 44 (2006) 833–839

- [70] A.G. Straatman, N.C. Gallego, B.E. Thompson, H. Hangan, Thermal characterization of porous carbon foam—convection in parallel flow, *International Journal of Heat and Mass Transfer*, Vol. 49 (2006) 1991–1998
- [71] Yanxiang Wang, Shouhong Tan, Dongliang Jiang, The effect of porous carbon perform and the infiltration process on the properties of reaction-formed SiC, *Carbon*, Vol. 42 (2004) 1833–1839
- [72] N.A. Eltekova , D. Berek , I. Novak , F. Belliardo, Adsorption of organic compounds on porous carbon sorbents, *Carbon*, Vol. 38 (2000) 373–377
- [73] Metin D, et al. The effect of interfacial interactions on the mechanical properties of polypropylene/natural zeolite composites, *Composites: Part A*, Vol. 35 (2004)23–32
- [74] [http:// www.ifam-dd.fraunhofer.de/fhg/ifam_dd/EN/gebiete/schaum/index.jsp](http://www.ifam-dd.fraunhofer.de/fhg/ifam_dd/EN/gebiete/schaum/index.jsp)
- [75] <http://www.briwax-online.com/GMTStainless.html>