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Review

A review on polymer heat exchangers for HVAC&R applications

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ABSTRACT

Because of their low thermal conductivity, polymers are not commonly considered as a material to construct heat exchangers, except for specific applications, e.g. heat recovery from solvent laden streams, where exotic alloys are required to prevent corrosion. In this review the material properties of polymers are examined, as well as the current state of the art of polymer matrix composites. It is shown that these materials do hold promise for use in the construction of heat exchangers in HVAC&R applications, but that a considerable amount of research is still required into material properties and life-time behavior. A successful application of polymers or polymer matrix composites is based on careful material selection and modification of the design to fully exploit the material properties, as is demonstrated through a series of examples.

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Echangeurs de chaleur en polymère pour les applications dans le chauffage, la ventilation, le conditionnement d'air et le froid : état de l'art

Mots clés : Échangeur de chaleur ; Conditionnement d'air ; Froid ; Enquête ; Matériau ; Polymère ; Additif ; Exemple ; Technologie

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1. Introduction

In air-conditioning, refrigeration, and energy-recovery applications, heat exchangers are very important to the overall efficiency, cost, and size of the system. Currently, these applications rely heavily on fin-and-tube or plate-fin heat exchanger designs, often constructed using copper, aluminum, or steel. A large amount of technical literature can be found to enhance the heat transfer of these conventional designs. However, the operating limitations of metallic heat exchangers in some applications have created the need to develop alternative designs using other materials. One of these materials is polymers. Much of the initial interest in the development of polymer heat exchangers was stimulated by their ability to handle liquids and gases (i.e. single and two-phase duties), their resistance to fouling and corrosion, and their possible use in both humidification and dehumidification systems. Perhaps most importantly, the use of polymers offers substantial weight, volume, space, and cost savings which can provide a competitive edge over heat exchangers manufactured from more exotic metallic alloys. In this review, a survey of the literature is presented describing the current state of the art on the use of polymers and polymer matrix composites (PMCs). To explore the potential of these materials, the property data are first presented and compared to the conventional materials.

2. Material properties of polymers and polymer matrix composites (PMCs)

2.1. Monolithic polymers

Polymers are large organic molecules consisting of a series of repeating units, called *monomers*, connected to each other. A polymer is primarily made out of hydrogen and carbon atoms, arranged in long chains. Naturally occurring polymers include wood, rubber, and cotton; however, a vast number of synthetic polymers also exist. These can be categorized in several different ways. One classic distinction considers the behavior of the polymer when it is heated and subsequently cooled down. *Thermoplastics* are polymers that soften when heated and become firm again when cooled. Heating and cooling may be repeated. *Thermosets* are plastics that soften when heated and can be molded, but harden permanently. They will decompose when reheated.

When considering new heat exchanger designs, both the thermal and mechanical properties are important. Standards and codes (ASTM, ASHRAE, ARI, etc.) impose minimal mechanical requirements for materials used in HVAC&R applications such as creep behavior over time to ensure a minimal life expectancy, e.g. at least 10 years (Raman et al., 2000). For many of these materials, this data are not readily available, indicating a need for further research. The most important property data include the thermal conductivity, specific heat capacity, maximum operating temperature (thermoplastics soften on heating), coefficient of thermal expansion, ultimate tensile strength, tensile modulus, and

density. A brief list of some of the commonly cited polymers and their material properties are presented in Tables 1 and 2. The data were compiled using both an online database (Matweb®, <http://www.matweb.com>) and technical publications. In the following paragraphs, brief material descriptions are presented taken from technical papers (Reay, 1989; Deronzier and Bertolini, 1997; Wharry, 2002; Zaheed and Jachuck, 2004).

Fluoropolymers are corrosion resistant to most chemicals due to their chemical structure, as discussed by Wharry (2002). The upper temperature operating limits of the polyvinylidene difluoride (PVDF) and ethylene tetrafluoroethylene (ETFE) are severely restricted. This is critical in heating applications where thermal margins of safety are important. PVDF swells in ketones, dissolves in polar solvents, and is not generally recommended for applications where it is in direct contact with bases. It is suitable, however, for heat recovery processes involving acids, processes aimed at reducing pollution emissions, and flue gas cleaning purposes. Its service temperature ranges from -1.6 to 154 °C. Teflon (PTFE) is chemically resistant to everything except molten alkali metals and fluorine. Teflon can withstand temperatures up to 204 °C. It is widely used in bromine recovery systems, metal pickling, plating solutions, and deionized water heating. Teflon is also well known for its non-stick properties, as in non-sticking cooking pans.

Liquid crystal polymers (LCPs) combine the material properties of both polymers and liquid crystals. Reay (1989) believed that these materials might be useful at temperatures in excess of 300 °C due to the self-reinforcing characteristics and the good creep resistance. Deronzier and Bertolini (1997) presented pure LCP property data showing a good chemical resistance to organic solvents, acids and bases, very high tensile strength and modulus, and a very low coefficient of thermal expansion characteristics that are attractive for heat exchanger manufacturing. By using fillers (e.g. glass fibers and silica powder), the mechanical properties can be further enhanced.

Polypropylene (PP) is non-toxic, non-staining, and exhibits excellent corrosion resistance. It has a significant application in mechanical vapor compression desalination units.

Table 1 – List of common polymers: thermoplastics and thermosets.

| Thermoplastics | Thermosets |
|----------------------------------|------------------|
| Fluoroplastics (PTFE, ETFE etc.) | Epoxy |
| Liquid crystal polymer (LCP) | Phenolic resins |
| Polyamide (PA or nylon) | Polyester resins |
| Polyethylene terephthalate (PET) | |
| Polycarbonate (PC) | |
| Low density polyethylene (LDPE) | |
| Polyetheretherketone (PEEK) | |
| Polypropylene (PP) | |
| Polystyrene (PS) | |
| Polysulfone (PSU) | |
| Polyvinyl chloride (PVC) | |
| Polyvinylidene difluoride (PVDF) | |
| Polyphenylsulfone (PPSU) | |
| Ionomer | |

Table 2 – Thermal and mechanical properties of common polymers.

| Properties | Ionomer | LDPE | Nylon-6.6 | PC | PEEK | PPS | PPSU | PP | PS | PSU | PTFE | PVDF |
|--|---------|-------|-----------|------|------|-------|------|-------|-------|------|--------|-------|
| Density, g/cc | 0.955 | 0.923 | 1.12 | 1.2 | 1.33 | 1.43 | 1.29 | 0.937 | 1.05 | 1.24 | 2.17 | 1.78 |
| Water absorption, % | 0.01 | 0.067 | 2.3 | 0.17 | 0.21 | 0.031 | 0.37 | 0.079 | 0.088 | 0.41 | 0.0042 | 0.032 |
| Moisture absorption at equilibrium, % | 0.011 | 0.01 | 2 | 0.27 | 0.46 | 0.03 | 0.85 | 0.1 | 0.089 | 0.32 | | 0.018 |
| Tensile strength, ultimate, MPa | 27.1 | 11 | 73.1 | 64 | 110 | 86.7 | 76 | 36.8 | 44.9 | 72 | 33.6 | 42.8 |
| Tensile strength, yield, MPa | 14.3 | 10.8 | 63.6 | 62 | 98.8 | 68.9 | 72 | 30.7 | 43.9 | 74.9 | 11.6 | 44 |
| Elongation at break, % | 440 | 190 | 82.8 | 98 | 36.7 | 4.1 | 60 | 120 | 6.9 | 56.8 | 400 | 64.6 |
| Tensile modulus, GPa | 0.3 | 0.21 | 2.1 | 2.3 | 4.5 | 3.6 | 7.2 | 1.9 | 3 | 2.5 | 0.61 | 1.8 |
| Flexural modulus, GPa | 0.25 | 0.27 | 2.4 | 2.3 | 4.8 | 4.9 | 2.4 | 1.4 | 2.8 | 2.8 | 0.52 | 1.7 |
| Flexural yield strength, MPa | | | 88.4 | 91.8 | 170 | 140 | 130 | 36.2 | 84.2 | 100 | | 44.2 |
| CTE, linear 20 °C, $\mu\text{m}/\text{m}\cdot\text{°C}$ | 150 | 210 | 100 | 70.2 | 44.1 | 39.2 | 55.8 | 120 | 79.8 | 60.1 | 100 | 140 |
| CTE, linear 100 °C, $\mu\text{m}/\text{m}\cdot\text{°C}$ | | | 100 | 65 | 39.2 | 170 | 55 | | | 60 | 140 | 145 |
| Thermal conductivity, W/m-K | 0.24 | 0.3 | 0.26 | 0.2 | 0.25 | 0.3 | 0.35 | 0.11 | 0.14 | 0.22 | 0.27 | 0.19 |
| Melting point, °C | 85.1 | 110 | 250 | | 340 | 280 | | 160 | | | 330 | 160 |
| Glass temperature, °C | | | | 150 | 140 | 88 | 220 | | 90.4 | 190 | | –37.6 |
| Specific heat capacity, J/g-°C | 2.4 | 2.2 | 2.2 | 1.2 | 2 | | | 2 | 2.1 | 1.2 | 1.4 | 1.5 |

Polyethylene (PE) has a comparatively low density. It is sufficiently robust to be virtually unbreakable, and at the same time, it is quite flexible. Chemically, PE is inert at room temperature although it is slowly attacked by strong oxidizing agents, and some solvents will cause softening or swelling. It may be used at temperatures up to 95 °C for short periods and at 80 °C continuously.

Polycarbonate (PC) has good chemical resistance to acids but poor resistance to alkalis and solvents. It is resistant to mineral acids, organic acids, greases and oils and dissolves in nitrile, polyamide and hot melt. It has a service temperature range of –4 to 135 °C.

Polyphenylene sulfide (PPS) is noted for its exceptional resistance to acid attack. Results of tests in 85% sulfuric acid at 120 °C for up to 5000 h suggested that PPS performs in acidic conditions better than Teflon and PVDF. PPS has also been found to be highly resistant to fouling and easy to clean.

Polyphenylene oxide (PPO) is similar in chemical composition to polyphenylene ether (PPE), and they are generally treated as equivalents. It has good heat resistance but poor chemical resistance. Nevertheless, the strength, stability, and the acceptance of flame-retardants of PPO make it desirable for machine and appliance housings. The lack of chemical resistance and color stability means that it often has to be painted in these applications. Low water absorption leads to the use of PPO in various water-handling products. Moreover, PPO can also be electroplated.

Polyetheretherketone (PEEK) has an estimated continuous working temperature of 250 °C, with excellent retention of mechanical properties at over 300 °C. In addition to its high resistance to chemical attack, it can be used at high temperatures (>250 °C) in steam or high pressure water environments without significant property degradation. The only common materials that attack PEEK are supposedly concentrated nitric and sulfuric acids. The material is fully resistant to aqueous solutions of 50% H₂SO₄ and 50% NaOH at room temperature.

Polysulfone (PSU) is an amorphous thermoplastic with a maximum continuous use temperature of 190 °C. It has a high creep resistance and thermal stability. It is resistant to most solvents, oils, acids, and alkalis.

If one compares the property data of the polymers in Table 2 to those of the commonly used metals, large differences can be found. Considering typical HVAC&R applications, the most striking difference is the thermal conductivity. PVDF has a thermal conductivity of 0.19 W/m-K, which is 100–2000 times lower than that of steels and other metals. At first glance, it would appear futile to pursue polymers for heat transfer. However, Zaheed and Jachuck (2004) compared a Ni–Cr–Mo (8 W/m-K) alloy tubular heat exchanger to a PVDF version of the same unit, and when considering the difference in density and in material cost, it was found that, despite being 6 times larger, the PVDF heat exchanger will cost 2.5 times less than the metal version. Moreover, by using thin-walled structures, the increased heat transfer resistance of the tube walls compared to metal tubes can be reduced considerably, making polymers a viable alternative.

Ma et al. (2002) reported on PTFE film processing conditions aimed at promoting drop-wise condensation on tubes. Condensation experiments on a single tube coated with a PTFE film showed an increase of the heat transfer rate ranging from 0.3 to 4.6 times compared to a regular brass tube. Drop-wise condensation was found to occur for more than 22,000 h. Similar experiments on a PVDF film showed the same condensation behavior and long lifetime. Brouwers and Van Der Geld (1996) found drop-wise condensation occurred within a pure PVDF plate heat exchanger. This indicates that polymer films could be used to increase the heat transfer rate in condensing applications sustaining drop-wise condensation over an extended period of time. For compact heat exchanger applications however, drop-wise condensation does not always lead to improved heat transfer rates due to the occurring blockage in the passage, as shown by Jacobi et al. (2005).

2.2. Polymer matrix composite materials

Composite materials give scientists and engineers the ability to create a limitless number of new material systems having unique properties that cannot be obtained using a single monolithic material. This approach to construction holds tremendous promise for future heat exchanger materials

which could be tailored to meet the specific requirements of an application. Composite materials are constructed of two or more materials, commonly referred to as constituents, and have characteristics derived from the individual constituents. The constituent that is continuous and which is often, but not always, present in the greater quantity in the composite is termed the *matrix*. The second constituent is referred to as the reinforcing phase, or *reinforcement* or *filler*, as it enhances or reinforces the properties of the matrix (Gurdal et al., 1999).

The major *reinforcements* used in structuring composites are particles, fibers, flakes, and laminas. Fig. 1 shows the different possible forms of composite materials. In the case of particulate composites, the particles can either be randomly dispersed within the matrix or have a preferred orientation such as flakes laid parallel to each other. For fibrous composites, a clear distinction is made between using short fibers (i.e. $l/D < 100$) and long fibers. Similar to particulate composites, the short fibers can either be randomly dispersed or have a preferred orientation. For long fibers, the fibers are dispersed in either a unidirectional or bi-directional (woven) way. A laminate composite consists of several layers each having a different fiber orientation. Because of the directionality of these long and short fibers, these composites have material properties that are highly anisotropic. Particle-reinforced composites tend to be isotropic.

An important characteristic of fiber-reinforced composites is that their properties often can be tailored greatly, controlled by the chosen fiber, matrix, or processing option. The properties of the composites depend on the manner in which the constituents are put together. The resulting composite materials may have the combined characteristics of the constituents or have substantially different properties than the individual constituents. The technologies used in the fabrication of matrices and useful structures with strong fiber reinforcement were commercialized in the two decades following 1970 (Schwartz, 1997). Along with new fibers, new matrices were developed, and new commercial fabrication

techniques were introduced. For example, thermally conductive carbon fibers are now used in the production of commercially available PMCs having a polymer, metal or carbon matrix (Zweben, 2004a,b).

The *matrix material* used in polymer matrix composites (PMCs) can be any polymer; both thermosetting polymers (e.g. epoxy, vinylester, polyester, etc.) and thermoplastics (e.g. nylon, PP, etc.) are used. The matrix material should have good resistance to environmental degradation, good toughness properties (to ensure that the composite is not too brittle), and an ability to deform at least as much as the reinforcing polymer fiber in order to realize the full mechanical potential. Good adhesion between the filler and the matrix material is essential for achieving the benefits of composite behavior.

Though these materials have been in development for decades, novel ideas such as nanoscale enhancement and new filler types drastically expand the range of PMCs. This generates a strong need for further research to understand and improve the characteristics of these materials. Some researchers have focused on developing models for PMCs in order to assess the material behavior. Bigg (1995) presented an overview of the various models to predict thermal conductivity of PMCs, showing a clear lack of validation data in some areas (e.g. through thickness thermal conductivity of short fiber filled PMCs). Ahmed and Jones (1990) presented an overview of previously published theoretical models to predict the tensile modulus and strength of particle-reinforced PMCs. It was found that both properties of a particulate composite material are affected by many parameters and that currently no general theory exists that can satisfactorily predict the modulus or tensile strength.

2.2.1. Particle-reinforced composites

The thermal conductivity of PMCs traditionally has been enhanced by addition of conductive metal and ceramic particles like silver, copper, aluminum, alumina, aluminum nitride, and boron nitride. These fillers result in composite materials with thermal conductivities that are generally less than 4 W/m-K, although higher values are reported. The thermal conductivities of these materials are still too low to be used in many commercial applications (Zaheed and Jachuck, 2004). Bigg (1986) presented a review of particulate composite materials composed of either metallic (i.e. gold, copper, and aluminum) or glass spheres. The data were compared to existing models, and it was found that the Nielsen (1974) model was accurate in predicting the thermal conductivity of these composites. At a volume fraction of 0.6 for metallic particles, the ratio of thermal conductivity of the composite to the thermal conductivity of the matrix material was found to be 7, indicating strong enhancement. For fillers with a low thermal conductivity such as glass, the thermal conductivity of the composite was almost twice that of the matrix material for a volume fraction of 0.3. Using Nielsen's model, Bigg (1986) showed that the thermal conductivity of a PMC depends only on filler volume fraction if the ratio of the thermal conductivity of the filler to that of the base polymer material is larger than 100 (as shown in Fig. 2). This means that inorganic fillers such as CaO or Al₂O₃ can be just as effective in increasing the thermal conductivity as metals. Practically, this also means that

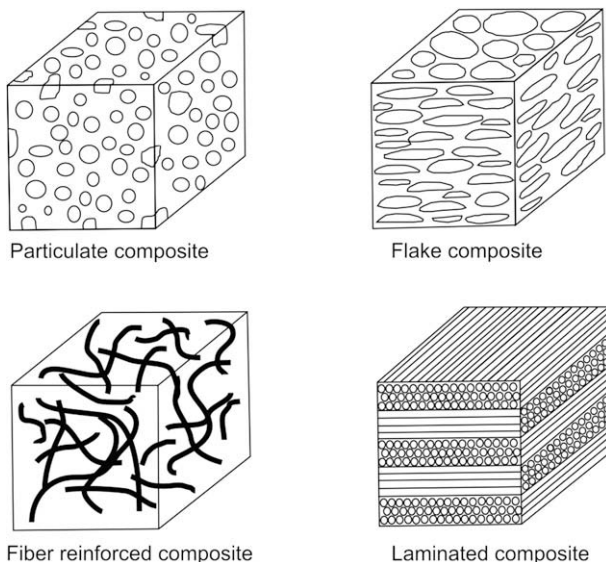


Fig. 1 – Composite materials with different forms of constituents (Gurdal et al., 1999).

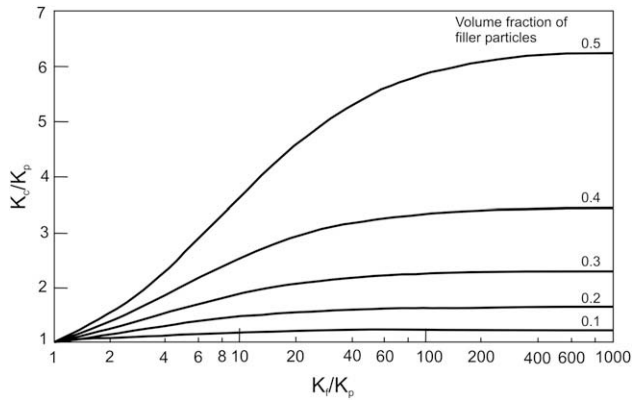


Fig. 2 – Predicted ratio of the thermal conductivity of the composite (K_c) to the thermal conductivity of the matrix material (K_p) for various volume fractions of the fillers computed using Nielsen model as a function of the ratio of the thermal conductivity of the filler material (K_f) to the thermal conductivity of the matrix material, as reported by Bigg (1986).

thermally conductive PMCs can be manufactured that are electrically insulating. Such characteristics are required for some applications such as circuit boards.

Mamunya et al. (2002) provide a description of percolation theory for conduction (electrical and thermal) in particle-filled PMCs. Percolation is a composite behavior in which a material property shows a characteristic sudden rise as the volume fraction of the filler is increased, as can be seen in Fig. 3. For conduction, this is due to the formation of particle aggregates resulting in a ‘continuous conduction path’. For metal powder-filled composites, this behavior is always observed for the electrical conductivity but never for the thermal conductivity—in order to achieve percolation-like behavior, the

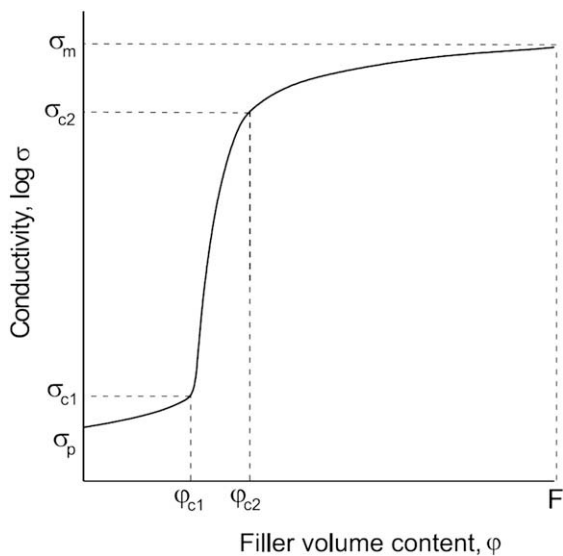


Fig. 3 – Typical representation of the electrical conductivity of a PMC using metal particles vs. the filler volume content displaying percolation behavior (Mamunya et al., 2002).

relative difference between the two conductivities of the matrix and the filler material must be at least of the order 10^5 . It was found that the maximum packing factor of the particles is a key parameter for describing percolation behavior, taking into account the phase topology and particle shape.

A large number of reports on particulate PMCs’ material properties are available in the open literature. Some examples discussed below indicate the potential of these materials.

Boudenne et al. (2004) provided data on the density, thermal conductivity, specific heat capacity, crystallinity, and thermal diffusivity of polypropylene–aluminum particulate composites. Two different types of spherical aluminum particles were used having different average sizes: $8\ \mu\text{m}$ and $44\ \mu\text{m}$. For 58.7 vol% of aluminum, the thermal conductivity increased to 2.7 W/m-K for the smaller particles and 4.2 W/m-K for the larger particles. Compared to the thermal conductivity of the matrix material (0.239 W/m-K), this represents a substantial increase.

Mamunya et al. (2002) provided data on the thermal and electrical conductivity of epoxy/PVC composites filled with copper or nickel powder. The nickel particles were spherical and had a diameter of $10\ \mu\text{m}$, while the copper particles were irregular and had an average size of $100\ \mu\text{m}$. The thermal conductivity increased from 0.45 W/m-K to 1.64 W/m-K for a filler volume fraction of 0.4 Cu in a PVC matrix and from 0.52 W/m-K to 1.6 W/m-K for a filler volume fraction of 0.25 Cu in an epoxy matrix. Over the range of studied filler content, the thermal conductivity of the epoxy composites was larger than that of the PVC composites which indicates the importance of the matrix conductivity since the polymer layers between the metal particles restrict heat conduction.

Serkan Tekce et al. (2007) studied the impact of various types of copper fillers (i.e. spheres, flakes, and short fibers) in a polyamide matrix. As shown in Fig. 4, a sizeable increase in thermal conductivity was achieved from 0.21 to 11.57 W/m-K at a 60% copper flake concentration. At low concentrations (i.e. lower than 10%), the effect of particle concentration on thermal conductivity is linear, indicating no interaction between the different particles; however as the concentration rises, a sharper increase in the thermal conductivity manifests,

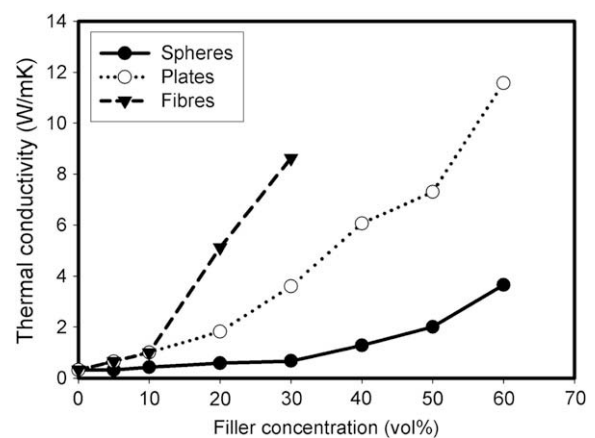


Fig. 4 – Measured thermal conductivity of a polyamide matrix with various types of copper filler (Serkan Tekce et al., 2007).

possibly as a result of particles contacting each other. Due to their shape, short fibers produce a faster rise in thermal conductivity than flakes or spheres.

Krupa et al. (2004) studied PE composites filled with graphite particles. The electrical conductivity showed percolation behavior at a volume fraction of 0.11. Thermal conductivity rose from 0.35 to 2.4 W/m-K for a filler volume fraction of 0.38. Mechanical properties were reported as well including the degree of elongation at break (decreasing two orders of magnitude for low density PE (LDPE) and three orders of magnitude for high density PE (HDPE)), tensile strength, and Young's modulus (5.5 times larger for HDPE and 7.5 times larger for LDPE), all for a volume fraction of 0.38 of graphite. This shows how a common and synthetically-created inorganic material such as graphite can have a strong impact on the thermal and mechanical properties of PMCs. In a previous paper, Krupa and Chodák (2001) also presented data on a PS matrix with two types of graphite particle filler, with different particle size distributions. The thermal conductivity showed a distinct difference between the two filler types, especially at high filler concentrations. This is most likely due to the ease of forming conductive paths between the larger particles at higher filling amount. The thermal conductivity rose from 0.2 to 1.3 W/m-K for a filler volume fraction of 0.33.

2.2.2. Fiber filled composites

The most common fibrous fillers used in PMCs are glass, carbon, and aramid fibers. The through- and in-plane thermal conductivity and coefficient of thermal expansion (CTE) are presented in Table 3.

2.2.2.1. Glass fiber reinforced polymers (GFRPs). Glass fiber reinforced polymers (GFRPs), also known as *fiberglass*, have a high specific strength and elastic modulus, good corrosion resistance, and excellent insulating properties. Glass is an inexpensive material with a high tensile strength (up to 4.1 GPa). Different glass types are used to reinforce the polymer matrix. E-glass which results in very low electrical conductivity is the cheapest and most common. C-glass imparts good chemical and corrosion resistance and is suitable for storage tanks, pipes, etc. S-glass is stronger than E-glass and is commonly used in aerospace applications. Fiberglass materials usually have a laminate structure with

different fiber orientations in the reinforcing glass layers. The concentration of glass fibers in fiberglass is normally between 40% and 70% by volume. The most popular matrix materials for manufacturing fiberglass are thermosets such as unsaturated polyesters and epoxies, and thermoplastics such as nylon, polycarbonate, polystyrene, and polyvinylchloride.

2.2.2.2. Carbon fiber reinforced polymers (CFRP). Carbon fiber reinforced polymers (CFRPs) have a very high specific (i.e. per-unit-mass) elastic modulus and strength, as well as excellent corrosion and fatigue resistance properties. The carbon fibers result in an electrically conductive material. Carbon fibers are significantly more expensive than glass fibers; however, the low density results in very high specific material properties which partially offsets this incremental cost. CFRP also have a very low coefficient of thermal expansion. Carbon fibers are very brittle, resulting in low impact resistance. Common matrix materials for manufacturing CFRPs are epoxy, polyester, and nylon (polyamide).

Nysten and Issi (1990) developed and measured twelve different unidirectional composites based on commercially available pitch-derived continuous carbon fibers (P-55, P-75, P-100, P-120). Two commercial matrices were used: thermoset polystyrene and a polyester-based resin. The best polyester composite contained 45 vol% of P-120 fibers and possessed a thermal conductivity value as high as 245 W/m-K and a density of 1.66 kg/cm³, as shown in Table 4.

A new natural graphite-epoxy composite material was developed by Norley et al. (2001) and Norley (2005). The material is lightweight, has a density of only 1.9 g/cm³, and possesses an in-plane thermal conductivity of 370 W/m-K, which is close to that of copper. This material is being used today as a fin material in combination with an aluminum or copper base to make hybrid heat sinks.

A major breakthrough was the development of injection molding compounds which use thermally conductive discontinuous carbon fibers; the reported thermal conductivities were as high as 100 W/m-K as shown in Table 4. Weber et al. (2003) performed thermal conductivity testing of carbon-filled Nylon-6.6 and polycarbonate based resins (see Table 4). The three carbon fillers investigated included an electrically conductive carbon black, synthetic graphite particles, and a milled pitch-based carbon fiber. The results showed that the largest increase

Table 3 – Properties of monolithic polymers and PMCs.

| Reinforcement | Matrix | Density, g/cm ³ | Thermal conductivity, W/m-K | | CTE, μm/m-°C | Specific thermal conductivity ^a , W/m-K | | Source |
|-----------------------------|---------|----------------------------|-----------------------------|-----------|--------------|--|-----------|---------------------|
| | | | In-plane | Thickness | | In-plane | Thickness | |
| – | Epoxy | 1.2 | 1.7 | 1.7 | 54 | 1.4 | 1.4 | Zweben (2006) |
| E-glass fibers | Epoxy | 2.1 | 0.16–0.26 | n/a | 11–20 | 0.1–0.2 | n/a | Zweben (2006) |
| Kevlar (aramid) | Epoxy | 1.38 | 0.9 | n/a | 1.4 | 0.6 | n/a | Zweben (2004b) |
| Milled glass fiber | Polymer | 1.4–1.6 | 0.2–2.6 | 0.2–2.6 | 20–40 | 0.1–1.6 | 0.1–1.6 | Zweben (2004a) |
| Discontinuous carbon fibers | Polymer | 1.7 | 10–100 | 3–10 | 4–7 | 6–59 | 1.8–5.9 | Zweben (2004a) |
| Continuous carbon fibers | Polymer | 1.8 | 330 | 10 | –1 | 183 | 5.6 | Zweben (2006) |
| Natural graphite | Epoxy | 1.94 | 370 | 6.5 | –2.4 | 190 | 3.4 | Tzeng et al. (2000) |

n/a, data not available.

a Specific thermal conductivity is defined as thermal conductivity divided by specific gravity of the material.

Table 4 – Properties of fiber reinforced PMCs.

| Reinforcement | Formulation, % (wt or V_f) | Matrix | Density, g/cm^3 | Thermal conductivity, W/m-K | | | CTE, $10^{-6} m/m/^\circ C$ | | Source |
|--------------------------------------|----------------------------------|------------------------|----------------------|-----------------------------|------|------|-----------------------------|-----|------------------------|
| | | | | x | y | z | x | y | |
| CF ^a | 40 wt | Nylon-6.6 | n/a | 16.6 | 16.6 | 0.95 | n/a | n/a | Weber et al. (2003) |
| CF | 40 wt | Polycarbonate | n/a | 12.2 | 12.2 | 0.74 | n/a | n/a | Weber et al. (2003) |
| CB ^a /SG ^a /CF | 5/30/20 | Polycarbonate | n/a | 20.1 | 20.1 | 1.99 | n/a | n/a | Weber et al. (2003) |
| 1D P-75 | 35 wt | Polystyrene | 1.34 | 59.8 | n/a | n/a | n/a | n/a | Nysten and Issi (1990) |
| 1D P-75 | 30 wt | Polystyrene | 1.34 | 95.4 | n/a | n/a | n/a | n/a | Nysten and Issi (1990) |
| 1D P-75 | 45 wt | Polyester | 1.58 | 64.5 | n/a | n/a | n/a | n/a | Nysten and Issi (1990) |
| 1D P-100 | 45 wt | Polyester | 1.64 | 104.4 | n/a | n/a | n/a | n/a | Nysten and Issi (1990) |
| 1D P-120 | 45 wt | Polyester | 1.66 | 245.0 | n/a | n/a | n/a | n/a | Nysten and Issi (1990) |
| 1D short staple VGCF | 54 V_f | Cyanate ester resin | 1.68 | 466 | 142 | 3 | -1.5 | 18 | Ting et al. (1995) |
| 2D short staple VGCF | 54 V_f | Cyanate ester resin | 1.69 | 303 | 284 | 4 | 2.0 | 6.3 | Ting et al. (1995) |
| 1D mat VGCF | 75 V_f | Epoxy | 1.87 | 661 | 37 | 9 | n/a | n/a | Ting et al. (1995) |
| 2D mat VGCF | 64 V_f | Epoxy | 1.84 | 300 | 268 | 8 | n/a | n/a | Ting et al. (1995) |
| 1D VGCF | 38 V_f | Epoxy | 1.48 | 695 | 36 | n/a | -0.11 | n/a | Chen and Ting (2002) |
| 2D VGCF | 56 V_f | Epoxy | 1.37 | 292 | 285 | n/a | n/a | n/a | Chen and Ting (2002) |

a CB signifies Kejenblack EC-600 JD, SG signifies ThermocarbTM specialty graphite, and CF signifies Thermal Graph DKD X.

of the in-plane thermal conductivity was from 0.3 to 16.6 W/m-K for nylon composites with 40 wt% carbon fiber, and from 0.23 to 20.1 W/m-K for polycarbonate composites formed from different combinations of 5 wt%, 30 wt%, and 20 wt% for carbon black, synthetic graphite, and carbon fiber, respectively. With respect to the through-thickness thermal conductivity, it was determined that, for both the Nylon-6.6 and polycarbonate-based resins, synthetic graphite particles produced the largest increase in composite thermal conductivity followed by the carbon fibers. The combination of synthetic graphite particles and carbon fiber produced the third largest increase in composite thermal conductivity.

2.2.2.3. Kevlar fiber reinforced polymers (KFRPs). Kevlar (a kind of aramid fiber) has a very high tensile strength (i.e. five times stronger per unit weight than steel), a high modulus of elasticity, a very low coefficient of thermal expansion, and very low pre-fracture elongation as well as excellent corrosion and flame resistance. The very low compressive strength and its ability to absorb moisture, together with difficulties in cutting are its main disadvantages. These fibers are excellent for absorbing impact. Different grades of Kevlar exist, developed for various applications ranging from bullet proof vests to airplane components. The most popular matrix materials for manufacturing KFRPs are epoxy, vinyl ester and phenolics.

2.2.3. Nano-composites

An emerging type of composite materials are the so called 'nano-composites' (NCs). At least one dimension of the particles must be in the range of 1–100 nm to be classified as a nano-composite. Configuration changes in the matrix can have a significant impact on the properties if the characteristic radius of the polymer chains is of the same order as the inclusions.

2.2.3.1. Inorganic clay nano-composites. Jordan et al. (2005) presented a review on this topic as well as the trends and initial tests found in previous studies. It was found that the

behavior of NCs differs from composites with larger scale inclusions. The particle size, the polymer, and particle morphology tend to play a very important role. In addition, the nature of dispersion or aggregation of particles and filler-matrix interaction affect the properties of composites significantly. Although these materials show promise, they are still in the research phase with much of the behavior still unexplained. Due to the experimental nature of the work a large range of different manufacturing techniques to create NCs was found by Jordan et al. (2005). LeBaron et al. (1999) and Ahmadi et al. (2004) presented reviews on inorganic clay composites. It was shown that, in order for clay-composite materials to have improved mechanical properties, the particles should be well dispersed within the matrix—the so-called 'exfoliated' layout (see Fig. 5). Achieving this dispersion often requires pretreatment of the clays.

Gao (2004) compared clay-polymer NCs to conventional GFRPs. In theory, the reinforcement of polymers at the nanometer scale has significant advantages over traditional fiber reinforcement. The main weakness of modern fiber-reinforced composites is the inability to fully utilize the inherent properties of these materials: e.g. CFRPs only achieve 3–4% of the theoretical strength of the aromatic sheets present within the graphite structure. In exfoliated NCs, the layers are interconnected by the polymer so that the inherent properties of the individual layers can be fully utilized. In reality, the mechanical properties of the best clay/polymer NCs (i.e. clay/nylon-6 NCs with 4 wt% clay loading) are much lower than conventional fiber reinforced composites with a high fiber volume fraction. It can be seen in Fig. 6 that clay/Nylon-6 NCs with 4 wt% clay loading cannot match Nylon-6 fiber reinforced polymers with 48 wt% chopped glass fibers. The main reason for this difference is that obtaining the exfoliated layout for the clay particles at higher loadings has proved thus far to be extremely difficult. By using large amounts of solvents, some advances have been made but at a substantial increase in cost. It is important to note, however, that when clay and fiber composites are compared in the low filler range, the clay

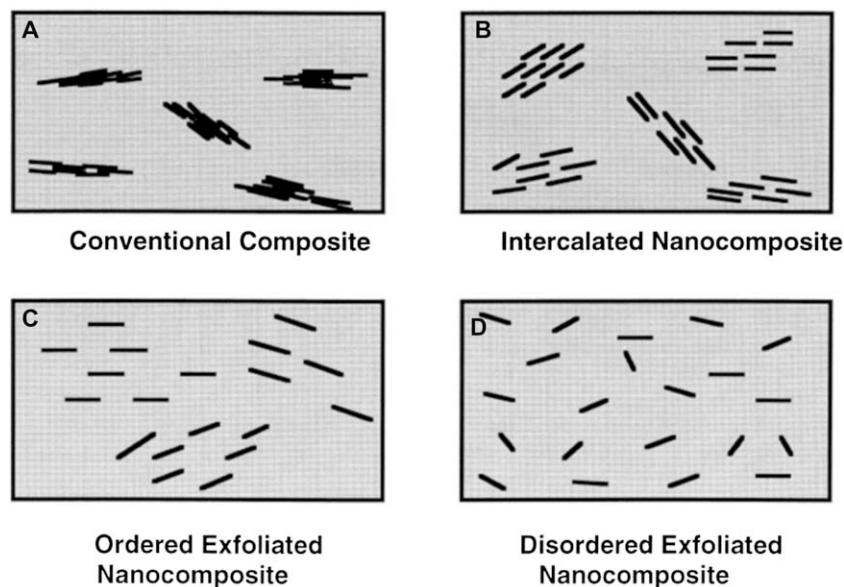


Fig. 5 – Schematic illustrations of nano-composites – A: conventional, B: intercalated, C: ordered exfoliated, D: disordered exfoliated polymer–clay nano-composite (LeBaron et al., 1999).

composites exhibit superior mechanical properties as seen in Fig. 7.

2.2.3.2. Carbon nanotube reinforced polymers (CNTRPs). A new and very promising type of fiber that can be used in the manufacture of PMCs is a carbon nanotube (CNT). These are sheets of graphite with a thickness of one or a few atoms rolled up into seamless cylinders with a diameter on the order of a nanometer. Breuer and Sundararaj (2004) and Thostenson et al. (2001) each presented reviews of the basic material properties of pure carbon nanotubes as well as the first PMCs made with these fibers. Pure carbon nanotubes have unique material properties—a tensile strength ranging from 100–600 GPa (two orders higher than regular carbon fibers) and a density of 1.3 g/cm³. Carbon nanotubes combine high stiffness with flexibility and strength. This is a great advantage compared to ordinary brittle graphite fibers. The thermal conductivity is highly anisotropic ranging from higher than diamond in the direction of the tube to insulating perpendicular to it.

In their reviews, Breuer and Sundararaj (2004) and Thostenson et al. (2001) also described various ways of producing these materials. It is clear that, while the mass production of carbon nanotubes is feasible using techniques such as chemical vapor deposition, cost-effective mass production techniques are still a long way off. Some researchers have begun describing spun nanotubes fibers which may result in a new type of carbon fiber with exceptional flexibility, stiffness and strength. Initial tests of CNTRPs revealed the importance as well as the difficulty of achieving a good dispersion of the fibers and interfacial contact between the matrix and the fibers. Injection molded CNTRPs showed a significant reduction of the coefficient of thermal expansion in the flow direction. Because CNTs are highly electrically conductive, the composites exhibit a percolation behavior. An epoxy CNTRP showed a 120% increase in thermal conductivity for a 1 wt% addition of CNTs. Xu et al. (2006) reported the thermal properties (diffusivity, specific heat, etc.) of a PVDF CNTRP and found that increasing the wt% of nanotubes decreased the coefficient of thermal expansion. For 49 wt%

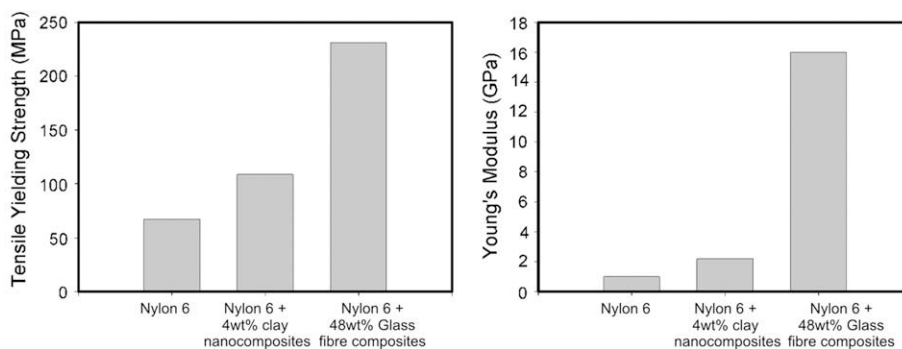


Fig. 6 – Comparison of the tensile strength and Young's modulus for Nylon-6, a 4 wt% clay composite and a 48 wt% glass fiber reinforced composite (Gao, 2004).

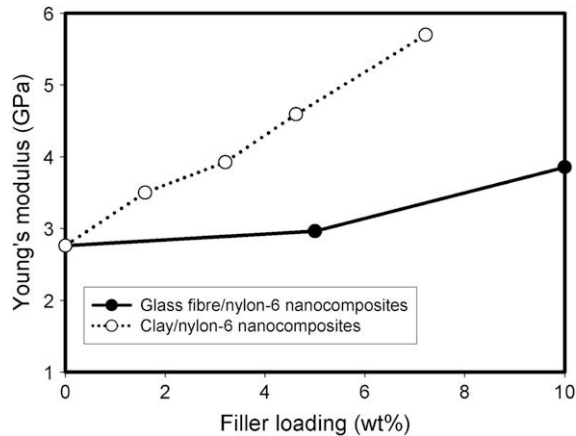


Fig. 7 – Comparison of Young's modulus for Nylon-6 clay composite and a glass fiber reinforced composite at low filler loadings (Gao, 2004).

addition of nanotubes, the thermal conductivity was increased to 0.8 W/m-K; however, this value fell far short of model predictions. Xu et al. (2006) attributed this to the large amount of junctions between carbon nanotubes involved in forming a conductive path and the exceptionally low thermal conductance at the interface.

Chen and Ting (2002) and Ting et al. (1995) fabricated epoxy composites based on vapor grown carbon fiber (VGCF) and analyzed the room temperature thermo-physical properties of these VGCF/epoxy composites. An unusually high thermal conductivity of 695 W/m-K for a 1-D polymer matrix composite was obtained for a 56% volume fraction of VGCF (see Table 4). The density of all the composites was lower than 1.5 g/cm³. In addition, the coefficient of thermal expansion (CTE) for the polymer matrix was significantly reduced by the incorporation of VGCF.

2.2.4. Composites with polymer fillers, based on a non-polymer matrix

In the previous composite materials, the matrix was a polymer. However, polymers can be used as fillers in combination with a different matrix material such as carbon foams and graphite. Some examples are presented below.

Schou et al. (1997) investigated the effect of orientation, manufacturing process, and impregnation content on the thermal conductivity of six different grades of polymer-impregnated graphite. The thermal conductivity of non-impregnated, extruded graphite showed significant and uniform anisotropy, ranging from 140 to 100 W/m-K parallel and perpendicular to the direction of extrusion, respectively. Impregnation of extruded graphite with pitch increased the thermal conductivity at all angles by approximately 20 W/m-K, while still maintaining its uniform anisotropy. Both vibration-molded and isostatically pressed graphite exhibited little anisotropy. The thermal conductivity of vibration-molded graphite with and without a synthetic resin impregnate was determined to be approximately 103 and 97 W/m-K, respectively. For isostatically pressed graphite, the thermal conductivity was significantly lower—approximately 56 and

63 W/m-K for the non-impregnated and resin-impregnated cases, respectively.

Bunning et al. (2003) investigated thermal and mechanical properties of polyurethane (PU)-infiltrated carbon foams of three different densities. The higher density foams showed the best heat transfer performance in a set of experiments that used a heat source and a heat sink. As a result of PU infiltration, the mechanical properties of the carbon-filled foams were substantially improved. Both the tensile strength and the modulus increased by an order of magnitude for the composite foam as compared to the unfilled foam, while the compressive and shear strengths and modulus of the composite foams approached values typical of pure polyurethane. The in-plane thermal conductivity was as high as 210 W/m-K. Resin infiltrated carbon foam matrix composites (i.e. infiltrated CFOAM) represent a significant improvement over conventional carbon foams (Chang and Lucas, 2005). These materials have significant cost and manufacturing advantages. While full resin infiltration enables the infiltrated CFOAM to be more isotropic, partial infiltration can also be used for selective reinforcement.

3. Application of polymers in heat exchangers

In the previous section, a brief overview of the material properties of monolithic polymers and PMCs has been presented. The use of these materials in heat exchanger design will be discussed in the subsequent paragraphs according to the intended application of the heat exchanger (i.e. liquid-liquid, liquid-gas, gas-gas, etc.). In their reviews, Zaheed and Jachuck (2004) and Reay (1989) present an overview of existing polymer heat exchangers. Most presented applications deal with corrosive applications such as immersion coils for electroplating, cooling and heating of acids, and heat recovery from a solvent laden air stream.

3.1. Liquid-to-liquid heat exchangers

Morcos and Shafey (1995) presented heat transfer and pressure drop data for a PVC shell and tube heat exchanger for varying tube and shell side Reynolds numbers. The unit (Fig. 8) consisted of 1.3 m long circular tubes with an outer diameter of 34 mm and a wall thickness of 5 mm. Five baffles were placed within the shell. The wall thickness was found to limit

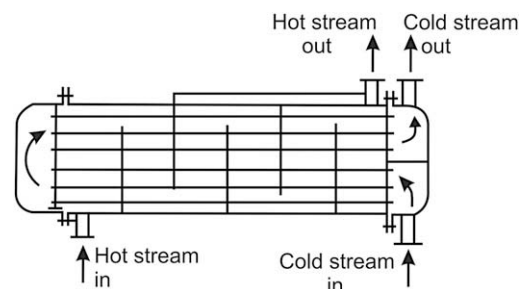


Fig. 8 – PVC shell and tube heat exchanger studied by Morcos and Shafey (1995).

the overall heat transfer coefficient to a maximum of 90 W/m²-K; reducing the thickness would result in a higher maximum value. To enhance the heat transfer rate, double conical PVC turbulators (Fig. 9) were introduced in the tubes. These were held in place using wires. Heat transfer enhancement factors of up to 3.5 were recorded without pressure drop penalty. This is probably due to high dominating pressure drops at the headers.

The solar energy research group at the University of Minnesota has worked extensively towards creating a low cost solar water heater (Davidson et al., 1998; Liu et al., 2000; Li et al., 2004; Raman et al., 2000; Wu et al., 2004; Freeman et al., 2005; Wang et al., 2005). In a review of the use of polymers in liquid- to- liquid heat transfer, Davidson et al. (1998) employed a three- level screening to determine which polymers were suitable for the application. First, NSF (National Sanitation Foundation) standards were checked to determine which polymers met potable water requirements. These polymers were then assessed for their mechanical retention and water compatibility. As for most polymers, no mechanical data were available for hot water or hot propylene glycol interaction, and therefore data from hot air measurements were used. Using criteria based on glazing temperature, thermal index, and heat distortion temperature at 1.8 MPa, the set of suitable polymers was reduced. In a final screening the remaining polymers were ranked according to strength, stiffness, cost, and thermal conductivity. The aim of this screening was to study the polymer's response to mechanical and thermal static or cyclic loads. The material properties were all combined into a single figure of merit, the ratio of the thermal conductance to the cost per unit area. For the tubes, high temperature nylon (HTN), cross- linked polyethylene (PEX) and polypropylene (PP) were found to be the best candidates. For the headers, glass fiber reinforced polymers were preferred, with HTN, PP, and PPS being the recommended types. More details on this screening can be found in Raman et al. (2000). These reviews indicated a lack of data on the long term mechanical behavior of polymer tubing in hot water environments. To fill this gap, an experimental study was conducted about the creep compliance, tensile strength, and strain at failure for PSU, PB, and Nylon-6.6 at 82 °C and in hot chlorinated water (Freeman et al., 2005 and Wu et al., 2004). For applications with mineral-containing water, scaling in these polymer tubes was studied by Wang et al. (2005). It was found that Nylon-6.6 had a more pronounced scaling rate compared to HTN, PB, PP, and copper.

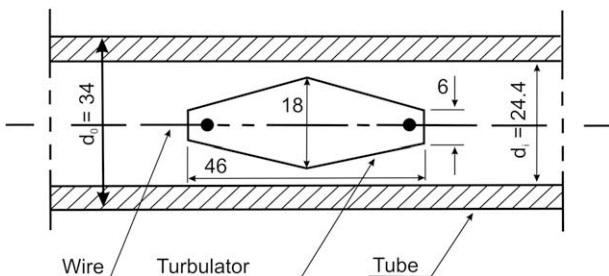


Fig. 9 – Turbulator introduced within the heat exchanger tube by Morcos and Shafey (1995).

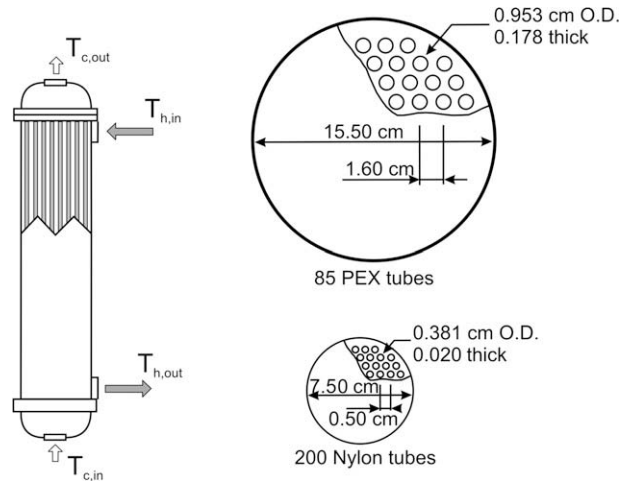


Fig. 10 – Polymer shell and tube heat exchanger studied by Liu et al. (2000).

Having analyzed the material properties and having selected polymers of choice for the solar heater, Liu et al. (2000) studied the feasibility of both a shell-and-tube heat exchanger and an immersed unit numerically. The arrangement and the number of tubes, shell dimensions, flow rate of the liquids, and the required heat transfer rate in an external tube-in-shell heat exchanger were fixed and the required length of the tube was calculated. Figs. 10 and 11 show the dimensions and layouts of the polymer shell-and-tube heat exchanger and the immersed

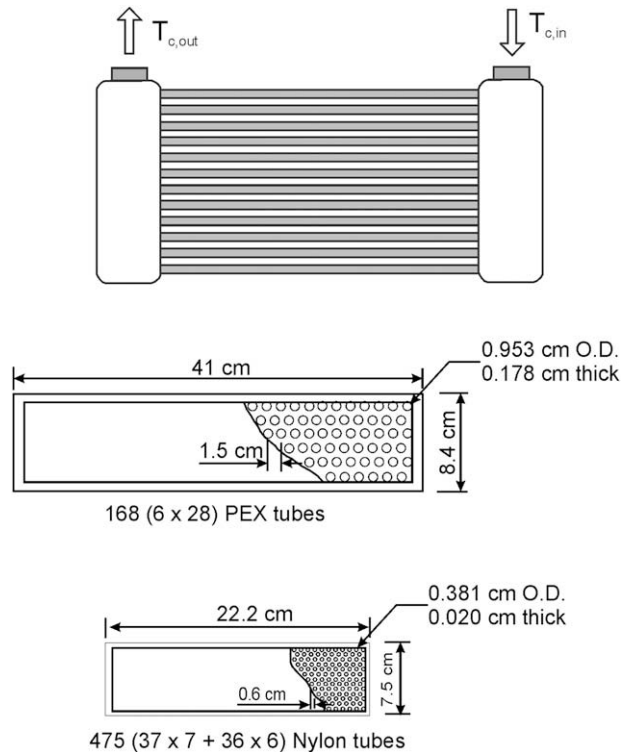


Fig. 11 – Immersed heat exchanger studied by Liu et al. (2000).

heat exchanger, respectively. Two kinds of polymer tubes were analyzed: PEX and nylon. The thermal conductivities for PEX and nylon were similar, with PEX being slightly more conductive (~ 0.38 W/m-K) as compared to nylon (~ 0.31 W/m-K). The PEX heat exchanger used a standard PEX tube with outer diameter 9.53 mm with a wall thickness of 1.78 mm, while the nylon heat exchanger used smaller tubes of outer diameter 3.81 mm and only 0.2 mm thick walls, as shown in Fig. 10. The analysis highlighted the fact that the thermal resistance of the wall was a dominant limitation of the PEX heat exchanger, while it was not so for the nylon one. Liu et al. (2000) noted that at a typical water flow rate of 5.7 L/min, the ratios for tube inside, outside, and wall thermal resistance were 24%, 34%, and 42%, respectively of the total heat transfer resistance for the PEX heat exchanger, and 49%, 26%, and 25%, respectively for the nylon counterpart. Also, the required lengths of the tube for the nylon heat exchanger were $\sim 75\%$ less than the PEX heat exchanger. This is mostly due to decreased thermal resistance due of thinner walls in nylon heat exchanger. An analysis of a copper heat exchanger, with tubes of outer diameter 6.35 mm and wall thickness 0.5 mm, showed that its wall thermal resistance was negligible and its performance was limited only by the flow inside the tubes. The inside, outside and wall thermal resistance contribution at the same water flow rate of 5.7 L/min were found to be 76%, 24% and 0.04% respectively. A comparison of the polymer heat exchanger with the copper one is given in Table 5. It is interesting to note that the thin-walled nylon heat exchanger has a very similar thermal performance as the copper heat exchanger.

The immersed heat exchanger (Fig. 11) has a bundle of horizontal tubes laid in a water tank with liquid flowing through the tubes only. There is no flow in the tank, only natural convection. The outer diameters and wall thicknesses of the tubes for PEX and nylon immersed tube-bank configuration were the same as those for the tube-in-shell configuration. The results of the analysis were very similar to the tube-in-shell configuration as summarized in Table 6. Here the copper immersed heat exchanger was modeled as a single 15.88 mm outside diameter tube. Again, it is clear from the results that heat transfer areas in the nylon and copper heat exchangers are significantly lower than the PEX heat exchanger. Thus in liquid-to-liquid heat exchangers, thin walls in polymer designs are necessary to achieve thermal performance levels comparable to their metallic counterparts.

To reduce exterior pressure drop Li et al. (2004) numerically studied different extruded shaped tubes: lenticular, teardrop and oval (Fig. 12). In each case, the inner flow passage was circular. The analysis showed that adding material to the base tube to form these shaped tubes reduces the heat transfer

Table 5 – Total exterior heat transfer surface areas for shell and tube heat exchanger at 5.7 L/min (Liu et al., 2000).

| Heat transfer capacity | PEX | Nylon | Copper |
|------------------------|---------------------|---------------------|---------------------|
| 3000 W @ 5.7 L/min | 1.78 m ² | 0.50 m ² | 0.50 m ² |
| 6000 W @ 5.7 L/min | 7.78 m ² | 2.16 m ² | 2.19 m ² |

Table 6 – Total exterior heat transfer surface areas for immersed heat exchanger (Liu et al., 2000).

| Heat transfer capacity | PEX | Nylon | Copper |
|------------------------|---------------------|---------------------|---------------------|
| 3000 W @ 5.7 L/min | 4.21 m ² | 1.89 m ² | 1.10 m ² |
| 6000 W @ 5.7 L/min | 11.4 m ² | 8.42 m ² | 2.03 m ² |

rate, due to low thermal conductivity of the material. The analysis introduced ‘shaped tube efficiency’, comparing the added material to a longitudinal fin. It was also found that increasing the thermal conductivity of the polymer to 1 W/m-K will make the use of these shaped tubes even more practical.

Zakardas et al. (2005) presented a novel design of polymer heat exchanger for liquid-to-liquid or condensing-fluid-to-liquid heat transfer: hollow fiber heat exchangers. The heat exchanger consists of thin hollow fibers connected between two headers (Fig. 13). It is basically a shell-and-tube heat exchanger without baffles, but on a different length scale, operating in either cross or parallel flow. In the constructed heat exchangers thin PP (425/575 μ m ID/OD) and PEEK fibers (150/360 μ m ID/OD) were used. Three different designs were tested. These units showed a very high compactness achieving 1500 m² of exterior surface in an 11.8 cm long shell with a diameter of 2.3 cm. Overall heat transfer coefficients up

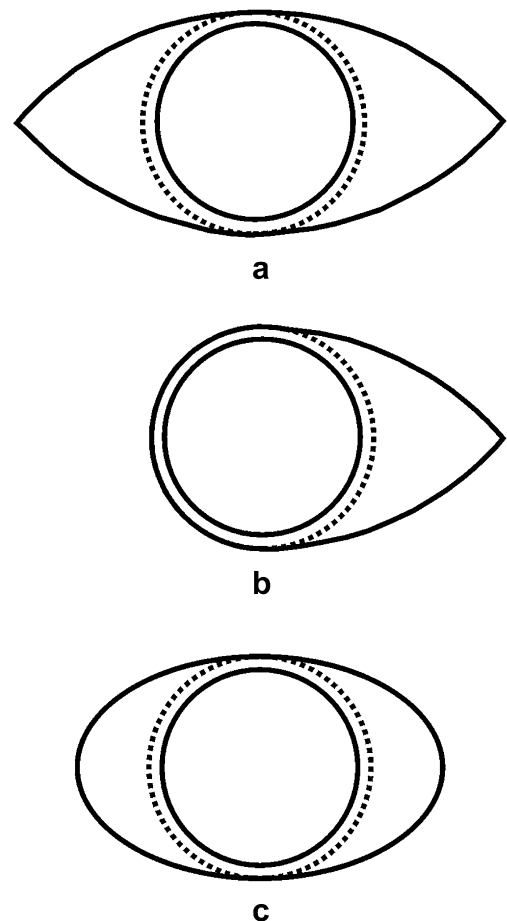


Fig. 12 – Different tube shapes studied by Li et al. (2004): (a) lenticular, (b) teardrop, and (c) oval.

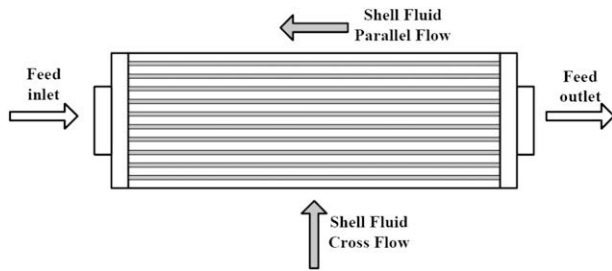


Fig. 13 – Concept of a hollow fiber heat exchanger as proposed by Zakardas et al. (2005).

to $1360 \text{ W/m}^2\text{-K}$ were reported, based on the total exterior surface area. The unit '41939' was found to be able to transfer up to 5.3 kW with a volume which is over 250 times smaller than a conventional design. Two figures of merit were defined: the overall conductance per unit volume and the pressure drop per NTU. Comparing unit '41939' to a conventional shell-and-tube design and a plate heat exchanger, it was found that even for fouled conditions the unit achieved similar performance, while having a lower overall pressure drop. This type of heat exchanger could be an excellent replacement for the conventional metal designs.

Patel and Brisson (2000) studied a polymer kapton heat exchanger for cryogenic applications. The heat exchanger was made out of thin $127 \mu\text{m}$ polymer films with a serpentine path. The aim was to exchange heat between a superfluid for a Stirling cycle and a $\text{He}_3\text{-He}_4$ dilution. Polymer materials clearly offer some advantages for very low temperature applications using the Kapitza limit.

Leigh et al. (1989) studied the possibility of dramatically lowering the first costs of absorption chillers by reducing the amount of required material and the use of lower cost materials, primarily in the heat exchangers which make up the bulk of the operating components of these systems. They identified and tested a set of polymeric and metallic materials appropriate to particular components to meet the cost goals. They also developed conceptual designs and a simulation model which indicated this design will operate with a COP of 1.0 for a directly fired, double effect unit. They determined that the second effect generator and one or both recuperators were viable candidates to be manufactured from PEEK but that the permeability of all polymers rendered them unsuitable for the evaporator, absorber, or condenser, since they would allow oxygen into the chiller from the circulating water. The additional load on the chiller's purge system would be unacceptable, and the chiller's performance would be significantly degraded.

A novel design for a plastic thin-film heat exchanger was developed and tested by Lowenstein and Sibilia (1993, 1999). This investigation proved the feasibility of designing and producing evaporators and absorbers from thin plastic films. A laminated film composed of Mylar/PVDC/adhesive/polyethylene-EVA demonstrated excellent seal strength in bursts tests of single tubes. Based on tests of the long-term creep characteristics of a HDPE film, the projected life of this heat exchanger made from HDPE and operating at 25 psi/100 °F (172 kPa/38 °C) would be 20 years.

3.2. Liquid-to-gas heat exchangers

Bigg et al. (1989) studied the use of polymer tubes and polymer-coated metal tubes for a condensing heat exchanger placed in the flue gas channel of a gas fired boiler. The aim of the study was to assess the lifetime of the polymer tubes and coatings. Commercial 1.27 cm diameter tubes of PTFE, PP, and PPS and 1.9 cm diameter tubes of PSU and PEI (polyetherimide) were tested. Aluminum tubes of 1.9 cm diameter were covered with an epoxy or vinyl ester coating of 0.1 mm thickness or a thicker coating of 0.5 mm of FEP (fluorinated ethylene propylene). After 100 days of exposure, none of the full polymer tubes showed any degradation (as indicated by local hardness measurement and infrared scans); however the epoxy and vinyl ester coating had failed. Due to the difference in thermal expansion between the metal and the coating, small cracks had appeared, allowing the corrosive gas to attack the base metal. A coating mixed with aluminum flakes (to increase the thermal conductivity) showed degradation where the flakes made contact with the surface. Previous studies had shown that thin coatings can fail due to pinhole effects, indicating the need for thicker extruded coverings.

El-Dessouky and Ettouney (1999) presented a numerical model for PTFE plate preheaters and a shell-and-tube evaporator for a single-step mechanical vapor compression unit. This is a typical desalination application, where the hot brine is very corrosive towards metals. In the model, thin walled polymer tubes and plates were studied ($40\text{--}150 \mu\text{m}$), indicating a need for spacers to prevent the structure from collapsing and for very fine filtering, should this unit ever be constructed. The results were compared to metal heat exchangers made of titanium, high alloy steel, and Cu-Ni alloys. The heat transfer area of the PTFE preheaters and evaporator was 2–4 times larger than that of the metal heat exchangers with varying top brine temperature. However, the polymer heat exchanger had the lowest cost. Bourouni et al (1997) presented experimental data on a falling film evaporator and condenser made of 2.5 cm diameter circular PP tubes (wall thickness of 5 mm) used in an 'aero-evapo-condensation process' for desalination. The

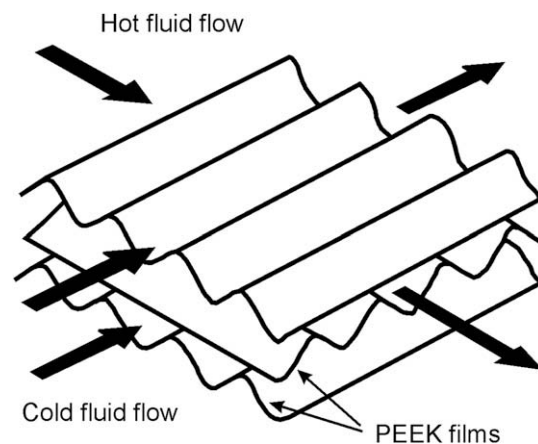


Fig. 14 – Corrugated PEEK films used by Zaheed and Jachuck (2004).

results were compared to a model which examined the impact of the water mass flow rate and inlet temperature. Good agreement was observed, but economic analysis indicated that the unit would only be viable if cheap heat was available, such as a geothermal power source.

Burns and Jachuck (2001) presented a compact plate heat exchanger made of thin wavy (100 μm) PEEK films with a mean thickness of 53 μm and amplitude of 1 mm. Seven sheets, 13.5 cm wide by 13.5 cm long, were stacked each rotated 90° to one another to provide a cross-corrugated layers for fluid flow, as can be seen in Fig. 14. PEEK was selected for its high chemical and fatigue resistance, high working temperature (up to 220 °C), and thermal stability. The hydrophobic and very smooth surface, combined with the thermal expansion properties can help resist fouling. The constructed unit showed remarkable mechanical stability withstanding pressures up to 10 bar at atmospheric conditions. The typical capacity of these units ranged from 10 to 400 W for a heat transfer area of 0.125 m². Experimentally measured pressure drops on the liquid side were below 400 Pa for a flow rate up to 500 ml/min and on the gas side below 4.3 kPa for a flow rate up to 10 m³/h. Overall heat transfer coefficients ranged from 60 to 370 W/m²-K with drop-wise condensation on the gas side. It was found that a significant volume of liquid condensate remained within the gas layer which decreases as the gas flow rate was increased.

Cheng and Van Der Geld (2005) studied a PVDF plate-fin heat exchanger experimentally using air-water or air/steam-water as fluids. The heat exchanger geometry is presented in Fig. 15. The overall heat transfer coefficients of air to water ranged from 80 to 130 W/m²-K; and from 150 to 600 W/m²-K for air/steam to water. As expected, an increase in the inlet steam mass fraction increased the overall heat transfer coefficient. The rise in heat transfer coefficient in the case of heat transfer from air/steam to water was due to drop-wise condensation on the air side, even in the presence of high amounts of non condensable gas. Very high local gas side heat transfer coefficients were found for air/steam to water heat transfer.

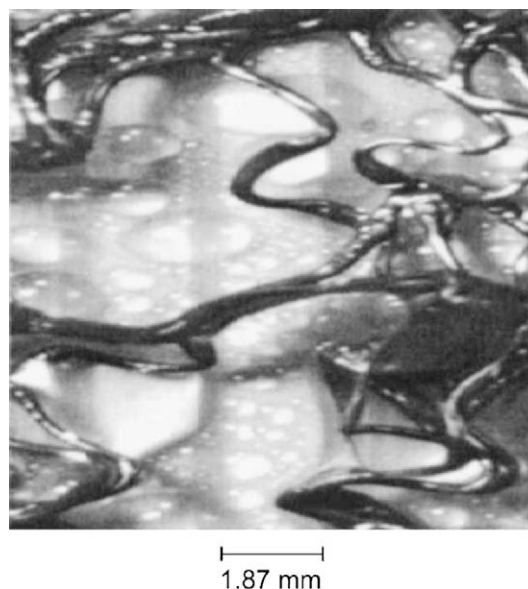


Fig. 16 – Nylon inserts as used by Van Der Geld et al. (2001).

Van Der Geld et al. (2001) studied a similar design as that by Cheng and Van Der Geld (2005). The aim was to improve the heat transfer rate without making drastic modifications to the design. It was found that, by inclining the heat exchanger mildly and changing the locations of the spacers, the heat transfer rate increased by 7%. This was due to enhanced drainage of the condensate. Another interesting approach was to add either HDPE or Nylon inserts between the plates (Fig. 16). These random fiber-like structures resulted in a considerable increase in the heat transfer rate. This may be due to a limited fin effect (low thermal conductivity), a large increase of the exterior surface area (159% extra for the HDPE inserts) and an increase of the velocity between the plates.

Harris et al. (2002) studied a micro cross-flow plate heat exchanger made of nickel and PMMA (Fig. 17). The overall

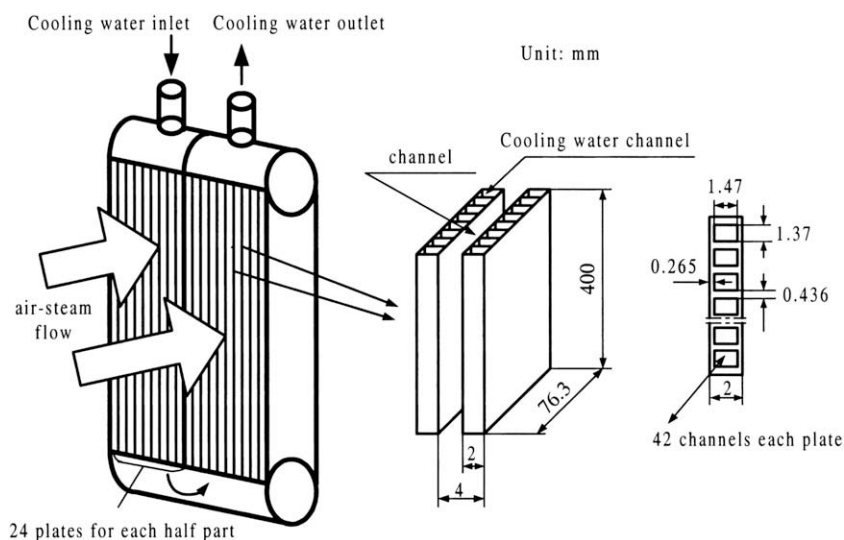


Fig. 15 – Heat exchanger geometry studied by Cheng and Van Der Geld (2005).

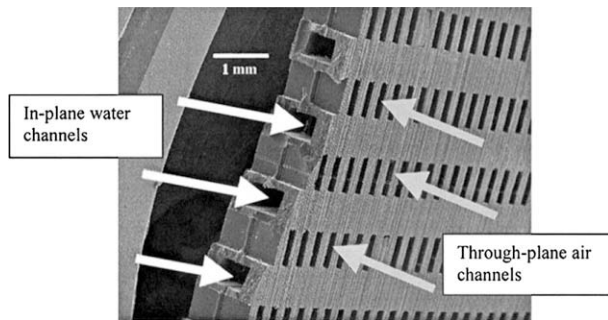


Fig. 17 – PMMA micro cross flow heat exchanger, Harris et al. (2002).

dimensions of the polymer heat exchanger were 5 mm by 5 mm by 1.8 mm. An analytical model was derived for the micro cross-flow heat exchanger combined with finite element simulations to predict the performance. Good agreement was found between the predictions and the measured results. The results are presented in Table 7. The first two rows show the experimental data of the PMMA and nickel heat exchanger. Three figures of merit were introduced: the heat transfer rate Q was divided by the temperature difference between the fluids entering the heat exchanger ΔT and then divided as well by either the frontal surface A , the volume V , or the mass m . The performance of the fabricated nickel heat exchanger is significantly better than the fabricated PMMA heat exchanger in terms of heat transfer/frontal area, while the PMMA heat exchanger outperforms the nickel heat exchanger on heat transfer/mass basis, due to the low density of the polymer. The final row of Table 7 contains data on a conventional scale radiator showing good performance based on the frontal area and not too much worse than the micro-heat exchangers on a heat transfer/mass basis.

3.3. Gas-to-gas heat exchangers

Rousse et al. (2000) presented an experimental study of a PE shell-and-tube heat recovery unit for greenhouses. This trial unit was not very compact (i.e. only $27 \text{ m}^2/\text{m}^3$) and was solely aimed at demonstrating proof of concept to greenhouse owners. Five corrugated PE tubes (shown in Fig. 18) with a wall thickness of 1 mm were placed within a single shell. Experimental data agreed well with the proposed model. The designed unit met the requirements: low cost (3-year pay back period); ease of assembly, repair, maintenance, and operation; corrosion resistance and satisfactory performance under

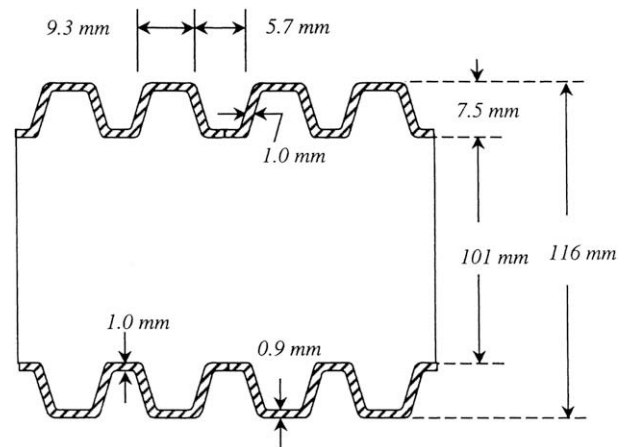


Fig. 18 – Corrugated PE tubes as used in a shell and tube heat exchanger (Rousse et al., 2000).

frosting conditions. In operation, efficiencies up to 84% were measured, with latent heat contributing about 40% of the total heat transfer in some cases. The efficiency was defined as the ratio of the temperature difference between inlet and outlet of the inlet air to the maximum temperature difference. The inlet air passed through the tubes while the shell carried the moist air.

Jia et al. (2001) provided experimental data on a PTFE plate heat exchanger used as a flue gas heat recovery unit. The channels were made of 1.5 mm thick PTFE sheets spaced 1 cm apart. The heat exchanger served as a SO_2 scrubber through condensation. Experimental data were provided with and without condensation as well as a correlation for this type of heat exchanger.

An interesting idea proposed by Dobbs and Freihaut (2006) consists of a plate heat exchanger using ionomer membranes made of sulfonated or carboxylated polymers. This heat exchanger is intended to be used as 'energy recovery units' in HVAC&R, recovering not only heat but also moisture, as it can pass through the membranes, in contrast to regular 'heat recovery units' made of metals. No experimental data was presented.

Saman and Alizadeh (2001, 2002) presented a numerical and experimental study of a polymer plate heat exchanger aimed at dehumidification and cooling (Fig. 19). A liquid desiccant is injected into one air stream in order to dehumidify, while water is injected into the secondary stream to provide evaporative cooling. Thin PE sheets (0.2 mm) separate both streams. The numerical results were compared with measured data and good agreement was found. Various parameters were studied: the injection angle, air mass flow rate, temperature and humidity. However, in a case study, the unit was not able to achieve desired summer comfort level conditions in Brisbane, Australia and additional HVAC&R systems were required.

3.4. Heat sinks

Heat sinks are a possible application for polymer materials. Their low weight and electrically insulating properties make

Table 7 – Figures of merit for various configurations as presented by Harris et al. (2002).

| Heat exchanger | Δp air | $\frac{Q}{A \cdot \Delta T}$ | $\frac{Q}{V \cdot \Delta T}$ | $\frac{Q}{m \cdot \Delta T}$ |
|----------------|----------------|------------------------------|------------------------------|------------------------------|
| PMMA | 175 | 0.58 | 400 | 692 |
| Nickel | 175 | 1.30 | 1036 | 440 |
| Webb-radiator | 179 | 3.12 | 123 | 283 |

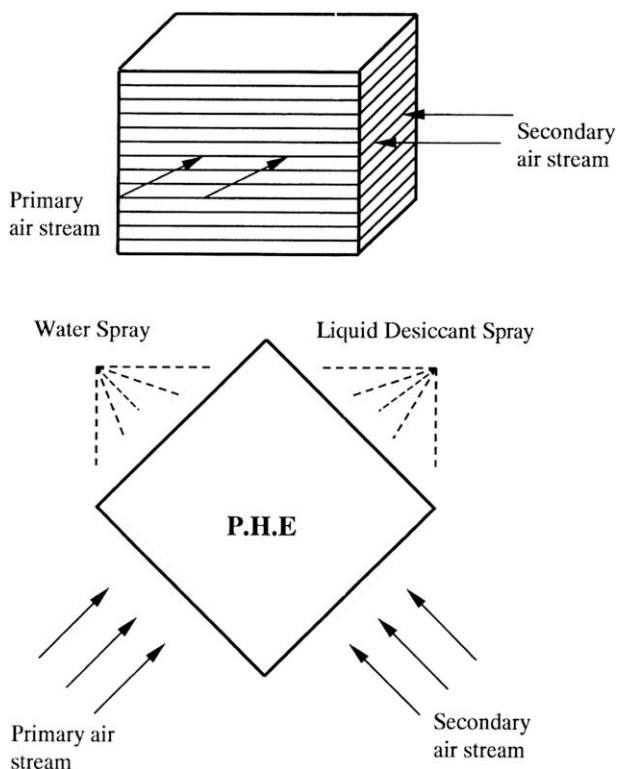


Fig. 19 – Plate heat exchanger for dehumidification and cooling studied by Saman and Alizadeh (2001).

them an interesting and safe option for portable applications such as laptops. Miller (2003) states that the ‘Apple Powerbook’ uses polymer components made of PMCs with a high thermal conductivity. It can be argued that a minimal thermal conductivity of 1 W/m-K is required to create an economically viable heat sink thus eliminating conventional polymers. However, composites are a suitable option as shown by Bahadur and Cohen (2004). In this work, a natural convection pin fin heat sink made of fiber-filled polyphenylene sulfide (20 W/m-K) had a similar performance as an aluminum design for small fin heights.

The thermal performance of a graphite–epoxy composite is significantly better than aluminum (and even approaches copper), but at only 70% and 21% of the weight of aluminum and copper, respectively. A heat sink made of such a composite can perform like copper but at a fraction of the weight. Norley et al. (2001, 2003) developed a novel improved heat sink by using a new natural graphite-based/epoxy composite material with an in-plane thermal conductivity of ~ 370 W/m-K and through-thickness thermal conductivity values of 7 W/m-K (Nysten and Issi, 1990). Because this material is naturally graphitized, anisotropic heat-spreaders with high thermal conductivity can be manufactured without using traditional carbon fiber-based additives.

The design and manufacturing of heat sinks from an anisotropically conductive material is a great challenge, especially for the heat sink base. Norley and Chen (2002) studied the influence of different orientations in the base of a heat sink by CFD analysis. Perhaps intuitively, the results showed that the

worst orientation for the base plate was when the lowest thermal conductivity was in the through-thickness orientation.

Marotta et al. (2003) developed a bonded-fin graphite/epoxy heat sink for high performance servers using this natural graphite-based/epoxy material. The heat sinks were manufactured in both cases using pre-molded graphite–epoxy fins and spacers bonded together. Because these materials are relatively soft, some form of mechanical protection is often required. One solution is to use aluminum end plates to provide edge protection to the heat sink with metal stiffeners inserted into the base to enhance the structural integrity. A variety of mechanical attachment methods were evaluated for joining the graphite to the copper heat spreader. The bonded-fin graphite/epoxy heat sink has demonstrated thermal performance comparable to a copper heat sink of similar geometry but at only 21–25% of the mass.

However, when the heat source area is smaller than the heat sink, the previously described laminated graphite/epoxy heat sinks perform poorly. For this situation, Shives et al. (2004) developed a hybrid heat sink composed of graphite/epoxy fins bonded to a copper base. The design of this hybrid heat sink compared to the laminated graphite/epoxy heat sink is shown in Fig. 20. A lead tin solder, a standard industrial epoxy and a thermally conducting epoxy were each used to bond the fins to the base. The performance of the hybrid and laminated graphite/epoxy heat sinks was then compared with equivalent aluminum and copper heat sinks using CFD and experiment. It was found that the best performance was obtained from the soldered all-copper heat sink, but the hybrid heat sink made with graphite/epoxy fins bonded to a copper base with a thermally conducting epoxy adhesive had a thermal resistance that was on average only 0.015 °C/W higher than that of the all-copper heat sink and its weight was 40% lower. The thermal resistance of the all-copper heat sink ranged from 0.32 °C/W to 0.18 °C/W for a mean inlet air velocity ranging from 1 m/s to 3 m/s. In addition, the soldered fins performed better than the fins attached with epoxy for the hybrid heat sink, but this effect was very slight. Therefore, the hybrid heat sink offered the best combination of weight, thermal performance, and ease of manufacturing.

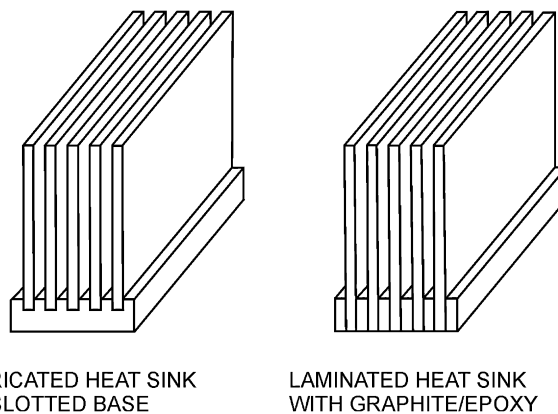


Fig. 20 – Comparison of hybrid and laminated graphite/epoxy heat sinks (Shives et al., 2004).

4. Conclusions

Historically, the interest in polymer materials for heat exchanger applications has been driven by their high chemical stability and corrosion resistance. It was shown that through the use of a polymer coating or polymer tubing, heat recovery from solvent-laden streams is possible. However, because of the low thermal conductivity of polymers, using polymers in a standard design configuration will likely result in a dominating heat transfer resistance by the polymer walls. But by using very thin polymer structures, both plate and tubular heat exchangers can be successfully designed, constructed, and tested with their performance being comparable to conventional units at lower cost and reduced weight. By using polymer matrix composites, light weight heat sinks have been built that achieve similar performance as the copper equivalent. If one considers the advances made in composite materials, as well as the new emerging technologies such as nanoscale composites, it is clear that, through careful material selection and design modification, the incorporation of polymer materials into HVAC&R applications has a bright future.

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