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Recent Research Developments in Polymer Heat Exchangers-A Review

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Abstract: Due to their low cost, light weight and corrosive resistant features, polymer heat exchangers have been intensively studied by researchers with the aim to replace metallic heat exchangers in a wide range of applications. This paper reviews the development of polymer heat exchangers in the last decade, including cutting edge materials characteristics, heat transfer enhancement methods of polymer materials and a wide range of polymer heat exchanger applications. Theoretical modelling and experimental testing results have been reviewed and compared with literature. A recent development, the polymer micro-hollow fibre heat exchanger, is introduced and described. It is shown that polymer materials do hold promise for use in the construction of heat exchangers in many applications, but that a considerable amount of research is still required into material properties, thermal performance and life-time behaviour.

Key words: Polymer heat exchanger, review, application, heat transfer

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1. Introduction

Since the first polymer heat exchanger was introduced by DuPont¹, many attempts have been made for promoting the commercial utilization of polymer heat exchangers. The conventional heat exchanger manufactured in metal (such as stainless steel, copper and aluminium) has the disadvantages in terms of weight and cost. In addition, specially treated metal heat exchangers are needed if the working fluids are corrosive. Given these considerations, it is desirable to find an alternative material for heat exchangers that can overcome these disadvantages and also acquire comparable heat exchange efficiency and be easily fabricated. This is where the use of polymer heat exchanger comes into play. With the advantages of greater fouling and corrosion resistance, greater geometric flexibility and ease of manufacturing, reduced energy of formation and fabrication, and the ability to handle liquids and gases (i.e, single and two-phase duties), polymer heat exchangers have been widely studied and applied in the field of micro-electronic cooling devices, water desalination systems, solar water heating systems, liquid desiccant cooling systems, etc. Most importantly, the use of polymer materials offers substantial weight, space, and volume savings, which makes it more economically competitive compared with exchangers manufactured from many metallic alloys. Moreover, the energy required to produce a unit mass of polymers is about two times lower than common metals, making them environmentally attractive². Building on other published review papers^{3,4}, this paper aims to update the research progress and development in polymer heat exchangers in the last decade. In this paper, various polymer material characteristics, comparisons with metal heat exchangers and heat transfer enhancement methods are discussed. Recent developments of polymer heat exchangers including innovative application areas and various experimental and theoretical investigations of them are summarized and reported. Research progress in micro hollow fibre heat exchangers in recent years has been firstly grouped and then described.

2. Material characteristics of polymers

2.1 Material properties of polymers

A polymer is a large molecule, or macromolecule, composed of many repeated subunits. Polymers range from familiar synthetic plastics such as polystyrene to natural biopolymers such as DNA and proteins that are fundamental to biological structure and function⁵. A polymer is primarily made out of hydrogen and carbon atoms, arranged in long chains. Their consequently large molecular mass relative to small molecule compounds produces unique physical properties, including toughness, viscoelasticity, and a tendency to form glasses and semi-crystalline structures rather than crystals.

Naturally occurring polymers include wood, rubber and cotton. A great number of synthetic polymers also exist. Currently, the widely used polymer materials in heat exchanger applications are PVDF (polyvinylidene fluoride), Teflon or PTFE (polytetrafluoroethylene), PP (polypropylene), PE (polyethylene), PC (polycarbonate), PPS (polyphenylene sulphide) and PPO (polyphenylene oxide).

The thermal and mechanical properties of polymer materials are important when considering them in new heat exchanger designs. These properties include thermal conductivity, specific heat capacity, maximum operating temperature (thermoplastics soften on heating), coefficient of thermal expansion, ultimate tensile strength, tensile modulus, and density. The most commonly used polymers and their physical properties are reported in Table 1 and 2. The data were compiled using both an online database (Matweb, <http://www.matweb.com>) and

technical publications. The brief material descriptions are presented taken from technical papers^{3,4,6,7} in the following paragraphs.

Liquid crystal polymers (LCPs) are a class of aromatic polymers. They are extremely unreactive and inert, and highly resistant to fire. LCPs combine the material properties of both polymers and liquid crystals. Polymers containing rigid segments may also exhibit a liquid crystalline phase⁶. With proper processing methods, this can give rise to highly oriented solid-state structures, leading to elevated mechanical properties. Derozier and Bertolini⁶ summarized the pure LCPs properties data and concluded that LCPs have very high tensile strength and tensile modulus, high heat deflection temperature and very low coefficient of linear thermal expansion, and so are very suitable for using in heat exchangers. However, they recommended commercial LCP material, rather than the formulations with various fillers that they tested, with regard to corrosion resistance and mechanical strength.

Table 1 Thermal and mechanical properties of common polymers

Polymer	Manufacturing company	Density (g/cc)	Thermal conductivity (W/m K)	Yield tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation at break (%)	Flexural modulus (GPa)	Melting point (°C)
LCP(unfilled)	Celanese Corporation	1.82	18-20	45	2.07	3.4	12	212-280
PFA	DuPont	2.12		13.8		300	0.59	310
PC	FASCIA S	1.2	0.2	62	2.3	98	2.3	
PEEK	Quadrant	1.33	0.25	99	4.5	36.7	4.8	340
PPS	Quadrant	1.43	0.3	69	3.6	4	4.9	280
PPSU	Quadrant	1.29	0.35	72	7.2	60	2.4	NA
PP	TIMCAL	0.94	0.11	31	1.9	120	1.4	160
PS	Bapolan	1.05	0.14	44	3	6.9	2.8	NA
PSU	BASF	1.24	0.22	75	2.5	56.8	2.8	NA
PTFE	Saint-Gobain Chemfab	2.17	0.27	12	0.61	400	0.52	330
PVDF	Arkema Group	1.78	0.19	44	1.8	64.6	1.7	160

Table 2 Applications and working conditions of various commercially available polymer heat exchangers

Manufacturer	HX Materials	HX type	Dimensions	Working conditions		Applications
				Temperature	Pressure	
AB Segerfrojd www.segerfrojd.com	Extruded PP sheets	Plate	Sheet thickness from 2 to 5 mm	-40 to 90° C.	NA	Ventilation, humidifying, electronic cooling, wet flue gas recuperation

Ail Research, Inc www.ailr.com	Thermofomed plastic	Plate	Plates are made from a 5 mil (0.127 mm) film	< 148° C.	< 275 kPa	Corrosive liquid cooling
Cesaroni Technology Incorporated www.cesaronitech.com	Polyamide	Plate	28 x 42 x 7.6 cm	-40 to 115° C	<550 kPa	Chiller applications
Fluorotherm www.fluorotherm.com	Shell are PVC and CPVC. Tubing are PTFE, FEP and PFA	Shell and Tube		60 – 93 ° C	276 kPa - 172 kPa (60-100 ° C)	Semiconductor and biotechnology (ultrapure), environmental, laboratory and products finishing industries
Greenbox Co. www.greenbox.uk.com	PVC	Plate	Walls are less than 0.5 mm	-15° C to 60° C.	<1kPa	Can handle airflows with sensible and latent heat exchange
George Fischer www.us.piping.georgefisher.com	PVDF and PP	Plate, coils, shell and tube	NA	NA	NA	Heat transfer between corrosive fluids
Plastic Magen www.plasticmagen.com	PVDF and PP	Plate	Rectangular cavity transversed by 5 mm OD, 5 mm wall tubes	PVDF < 100° C. PE < 80° C	PVDF < 600 kPa. PE <200 kPa	Solar collectors for heating swimming pools
Process Technology www.processtechnology.com	Shell: PP of PVDF. Tube: PFA.	Shell-and tube, coils	0.76 mm thick wall	Tube < 120 ° C. Shell < 100° C	Tube < 241 kPa. Shell <206 kPa	Immersion heat exchanger

PTFE first discovered and manufactured by DuPont, is a white solid at room temperature, with a melting point around 320 °C. It maintains high strength, toughness and self-lubrication at low temperatures down to 5 K (-268.15 °C), and good flexibility at temperatures above 194 K (-79 °C). PTFE is chemical resistant to everything except certain alkali metals and fluorinating agents such as xenon difluoride and cobalt fluoride. It is widely used in wiring for aerospace and computer applications, and industrial applications such as plain bearings, gears, slide plates. Because of its non-stick properties it is also used for making non-stick cooking pans.

Polypropylene (PP) is non-toxic, non-staining and widely used variety of applications including packaging and labeling, textiles, stationery, laboratory equipment, automotive

components. Despite its rigid structure, PP is liable to chain degradation from exposure to heat and UV radiation such as that present in sunlight.

Polyethylene (PE) is a thermoplastic polymer consisting of long hydrocarbon chains. The melting point for average, commercial, low-density polyethylene is typically 105 to 115°C. PE has excellent chemical resistance, meaning that it is not attacked by strong acids or strong bases. It is also resistant to gentle oxidants and reducing agents. PE is slowly attacked by strong oxidising agents and some solvents will cause softening or swelling. PE is ideally suited to a wide range of laboratory apparatus, bottle handling machine parts, moving parts on weaving machines, bearings, gears, artificial joints, etc.

Polycarbonate (PC) provides good resistance to acids but has poor resistance to alkalis and solvents. PC has a service temperature between -4 and 135°C. Unlike most thermoplastics, PC can undergo large plastic deformations without cracking or breaking. As a result, it can be processed and formed at room temperature using sheet metal techniques, such as bending on a brake. PC is mainly used for electronic applications that capitalize on its collective safety features.

Polyphenylene sulfide (PPS) is famous for its excellent resistance to acid attack. It has not been found to dissolve in any solvent at temperatures below about 200 °C. PPS has the advantage of highly resistant to fouling and easy to clean. PPS can be molded, extruded, or machined to high tolerances. It is used to make filter fabric for coal boilers, papermaking felts, electrical insulation, specialty membranes, gaskets, and packings.

Polyetheretherketone (PEEK) is a semicrystalline thermoplastic with excellent mechanical and chemical resistance properties that are retained to high temperatures (over 250°C). It is highly resistant to thermal degradation as well as attack by both organic and aqueous environments. Because of its robustness, PEEK is used to fabricate items used in demanding applications, including bearings, piston parts, pumps, HPLC columns, compressor plate valves, and cable insulation.

Polysulfone (PSU) is an amorphous thermoplastic, which is rigid, high-strength, and transparent, retaining these properties between -100 °C and 150 °C. It has very high dimensional stability; the size change when exposed to boiling water or 150 °C air or steam generally falls below 0.1%. It is highly resistant to mineral acids, alkali, oxidizing agents and electrolytes.

According to Wharry⁷, because of their unique chemical structure, *fluoropolymers* can be corrosion resistant to almost all chemicals. There are mainly two types of fluoropolymer, one is *fully fluorinated polymers*, the other is called *partially fluorinated polymer*. Each fully fluorinated polymer always ends with a fluorine atom, while some of the branches of partially fluorinated polymers do not terminate with a fluorine atom. PTFE, PFA (perfluoroalkoxy) and FEP (fluorinated ethylene propylene) are fully fluorinated polymers. PVDF, ETFE (ethylene tetrafluoroethylene) and ECTFE (ethylene-chlorotrifluoroethylene) are partially fluorinated polymers. Due to this chemical difference, fully fluorinated structures offer a polymer with chemical and thermal stability under high temperature, while partially fluorinated polymers sacrifice some chemical and thermal resistance to enhance their mechanical properties at room temperature. From Table 1, we can see that the upper operating limits of PVDF, ETFE, and ECTFE are restricted while TEP and PFE have higher

temperature limits. Such temperature limits are crucial for heating applications when thermal margins of safety can be extremely important.

2.2 Comparison of polymers with metal materials used in heat exchangers

Polymer heat exchanger technologies are very advanced. However, if we compare the thermal and chemical properties of polymers in Table 1 with those of metal alloys used in compact heat exchangers (listed in Table 3), big differences can be found. As shown in Figure 1, the most significant difference between polymer and metal materials is the thermal conductivity. The thermal conductivities of most polymers listed are lower than 1W/mK, which are around 100 times lower than those of most metals. Because of this, it might appear futile to pursue polymers for heat transfer application. However, if we consider the application of heat exchangers with corrosive fluids, seawater in particular, the only possible metals will be Cu-Ni alloys and Titanium. Cu-Ni alloys offer good resistance to corrosion, polluted water, and deposit attack, but can be expensive. Recent advances in manufacturing technologies now permit the use of titanium, which is highly resistant to corrosion and provides more flexibility in the design of heat exchangers due to its low density and high strength. However, as shown in Table 3, corrosion resistant materials such as Cu-Ni alloys and titanium have low thermal conductivities compared to copper and aluminium, (17 to 50W/m K). To overcome this, the conductive thermal resistance of these materials is generally lowered by decreasing the thickness of the heat exchanger wall⁸.

In order to quantitatively assess the differences between polymers and metal alloys for the applications in the heat exchanger area, it is worth considering the following three parameters together: heat transfer coefficient, the weight of the surface per unit of heat exchanger and the costs of the materials. By comparing these three parameters, Zaheed and Jachuck³ concluded that by offering the same heat transfer rate, the heat exchanger manufactured using PVDF will cost 2.5 times less than the Ni-Cr-Mo alloy unit. The cost advantage of polymers becomes particularly strong when competing with expensive, corrosion resistant metal alloys. Moreover, by using thin walled structures, the increased heat transfer resistance of the tube walls compared with metal tubes can be reduced significantly, making polymers a better alternative

As shown in Figure 2, if we compare the yield strengths of polymers and metals, both types of material also demonstrate significant differences. The maximum yield tensile strength for polymers is 99MPa for PEEK, which is much lower than the yield strength of corrosion resistant metals (517 MPa for Titanium and 140 for Cu-Ni90/10). The relatively low strength of the thermoplastics, therefore, could potentially limit the minimum thickness that could be achieved to minimize wall conductive thermal resistance without compromising the physical integrity of the heat exchanger structure.

In terms of melting temperatures of polymers and metals shown in Figure 3, the polymers demonstrate relatively low heat deflection temperature (<300°C), while metals have very high melting points (>1000°C). But these numbers are not crucial for the heat exchanger design, as the operating temperatures of the heat exchangers are not necessarily determined by their melting temperature.

Table 3 Thermal and mechanical properties of metallic materials used in heat exchangers⁹

Material	Density (10 ⁻³ kg/m ³)	Thermal conducti vity	Specifi c heat (J/kg•K)	Yield Strength (MPa)	Tensile Strength (MPa)	CTE(*10 ⁶ m /mK)	Melting Point (°C)
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		(W/m ² ·K))				
Aluminium 3003	2.71	169	921	69	179	7.2	629-652
Cu99.9	8.89	391	385	69	221	5.2	1083
Hastelloy A	8.8	17	394	303	758	3.4	1299
Inconel X	8.25	12	448	690-932	1110	3.8	1393
Stainless Steel 304	7.92	52	502	207	586	4.4	1393
Stainless Steel 316	8.08	52	502	276	621	4.9	1371
Stainless Steel 446	7.47	57	502	345	552	3.2	1399
Titanium	4.51	17	582	517	621	2.6	1691
Cu-Ni 90/10	8.9	50	377	140	320	17	1100
Cu-Ni 70/30	8.95	29	377	170	420	16	1170

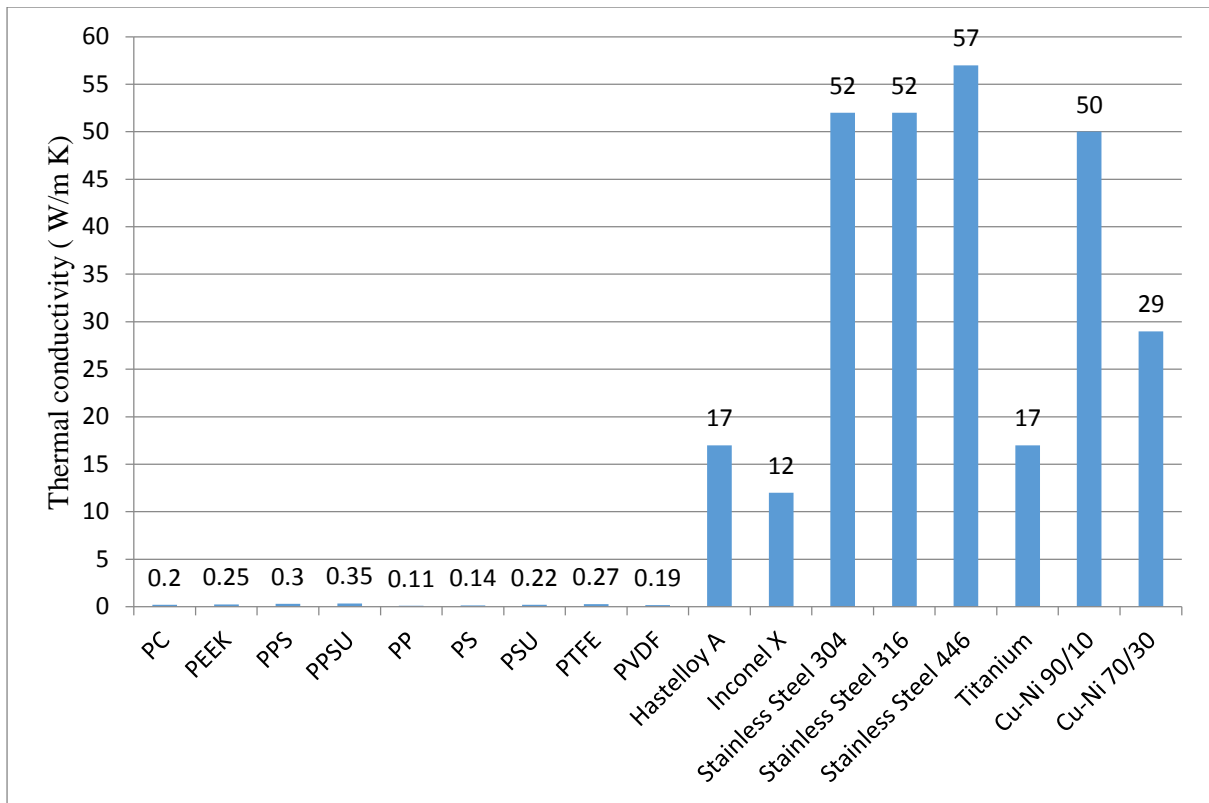


Figure 1 Comparisons of thermal conductivities for various polymers and metallic materials

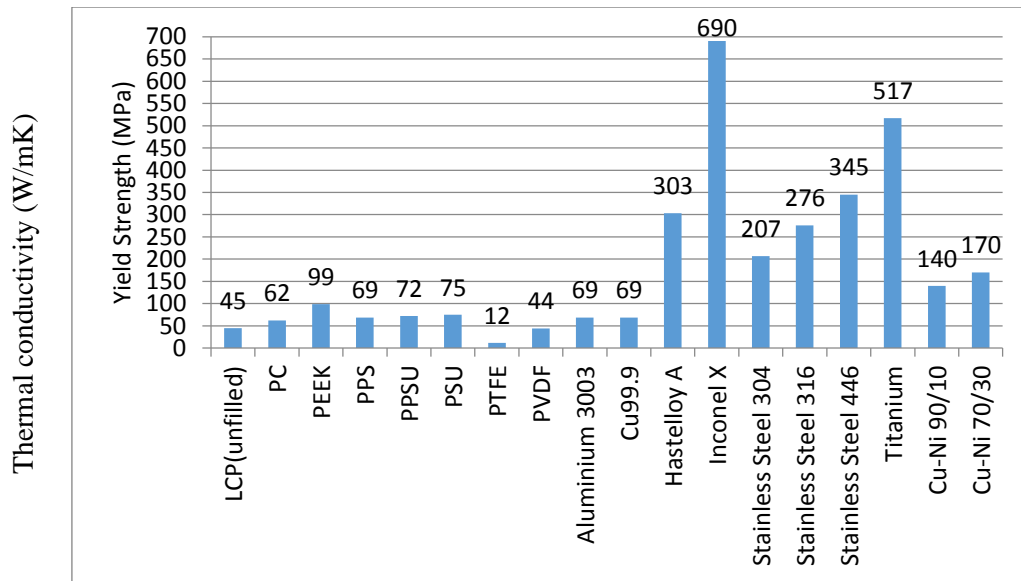


Figure 2 Comparisons of yield strengths for various polymers and metallic materials

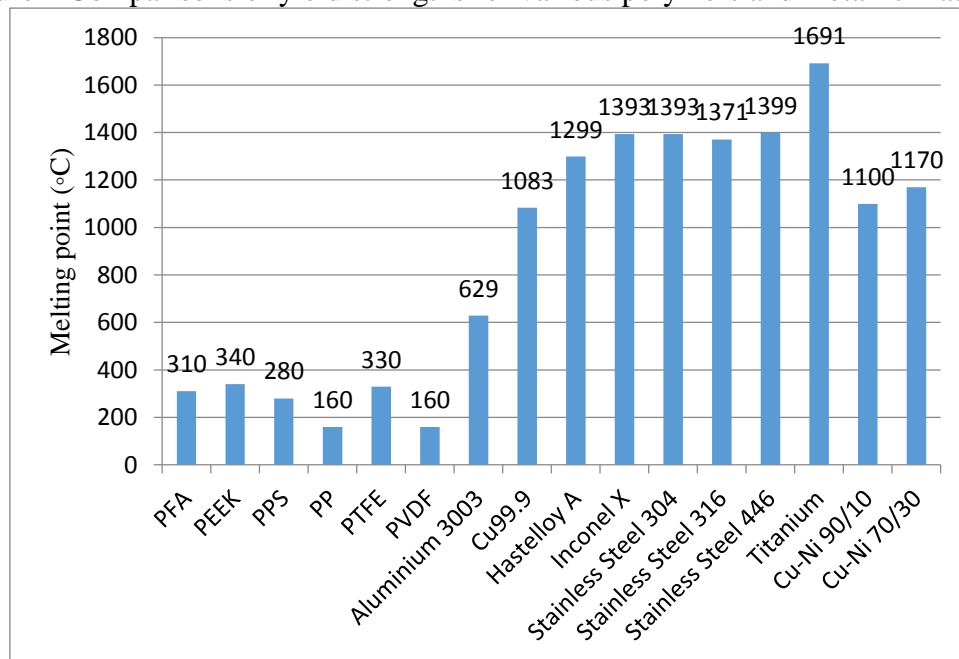


Figure 3 Comparisons of melting temperature for various polymers and metallic materials

In heat exchanger applications the low thermal conductivity of basic polymers, at best 5% of that of metals, affects their attractiveness, but this can be alleviated by using polymer composite materials, as discussed in Section 3. Additionally, the mechanical strength, service temperature, and physical considerations can be expected to limit the real application. The difference in corrosion resistance between polymers and metals are not presented in Tables 1 or 3. But as described in section 2.1, most of the polymer materials are resistant to chemical acids, solvents and corrosive fluids, whereas metals are susceptible to direct chemical dissolution. For polymers, long term exposure to sea water may only result in minor moisture-induced damage¹⁰.

In terms of the environmental aspect of polymer heat exchanger, polymers are easy to mould and the energy required to process a specific shape is low¹¹. Unlike metal units, plastic heat exchangers can be easily contoured to fit available space. In addition, most of the polymer

materials are recyclable and can be reprocessed into a new product⁴. Most importantly, the advantage of low weight reduces the handling and transportation emissions as compared to metallic heat exchangers.

3. Heat Transfer Enhancement using Polymer Composite Materials

Recent developments in material science, particularly, advances in polymer matrix composite materials, carbon nanotubes, and new fibre materials have opened up new opportunities for scientists and engineers to create new polymer materials with enhanced heat transfer properties that can not be obtained by single monolithic materials. The special chemical and physical properties of such composite polymer materials pose tremendous promise for heat exchangers which can be tailored to satisfy with the unique application requirements.

Composite materials are constructed of two or more materials, commonly referred to as 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 matrix¹².

The major fillers used in structuring composites are particles, fibres, flakes, and laminas. Figure 4 presents the different possible distributions of various fillers in composite materials. 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.

Particle-enhanced polymer composite materials often have enhanced thermal conductivities due to the fact that conductive ceramic particles like silver, aluminium, alumina, aluminium nitride and boron nitride are added into the composite materials. The most widely used fibre fillers for fibre enhanced composites include glass, carbon, and aramid fibres. Compared with particle enhanced composite, the most critical characteristic of fibre-reinforced composites is that their properties often can be tailored greatly, controlled by the chosen fibre, matrix, or processing option. Because thermal conductivity is a bulk property rather than a path dependent property, changes in the thermal conductivity of a composite are not as dramatic as those of electrically conductive composites. According to Bigg¹³, increase in the thermal conductivity of a plastic composite is limited to around 20 times that of unfilled unfilled polymers, although this brings the values closer to that of some of the metal alloys it may be competing with.

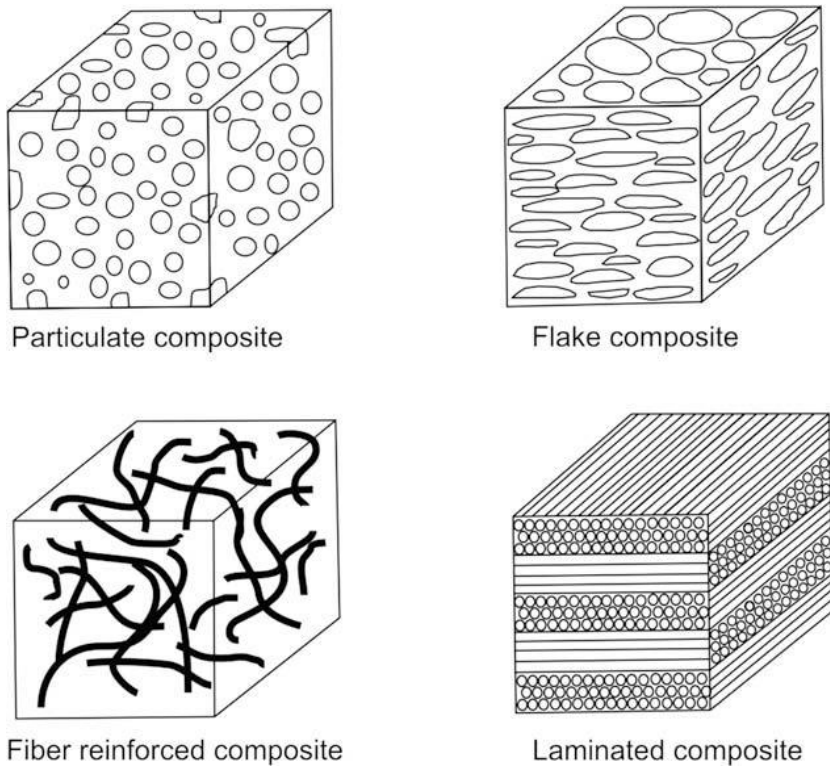


Figure 4 – Composite materials with different forms of constituents¹²

3.1 Particle-enhanced polymer composites

Metal or ceramic particles including silver, copper, aluminium and boron nitride are added into polymer composites in order to enhance the thermal conductivity of the polymers. According to Breuer et al.¹⁴, the thermal conductivity could be increased from 0.15-0.5W/mK to 20W/mK by using 60% filler content. The thermal conductivities of such particle-enhanced polymer composites are normally less than 4W/mK, although higher values are reported.

Since thermal conductivity is a bulk property, analogous to viscosity and modules, there are many theoretical and empirical models that are applied to describe the behaviour of polymer composites. Bigg¹³ examined the thermal conductivity of metal particle, mineral particle and carbon fibre filled compounds using Nielsen¹⁵'s model. The data were compared to existing models, and it was found that the Nielsen's 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. The only limitation is that this model overestimates the properties of composite when spherical and irregularly shaped particles are at high volume fractions (>0.5).

Bigg¹³ summarized that the principal factors affecting the thermal conductivity of a polymeric composite are filler conductivity, shape and concentration. For spherical and dimensionally isotropic irregularly shaped filler particles the influence of increasing filler conductivity is negligible when the ratio of filler conductivity to matrix exceeds 100:1. 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 thermally conductive PMCs can be manufactured that are electrically insulating. Such characteristics are required for some applications such as circuit boards.

Theoretical and experimental investigations on two polymers epoxy resin(ER) and poly(vinyl chloride) (PVC) filled with metal powders was presented by Mamunya et al.¹⁶. Copper and nickel powders with average size of 100 and 10 μ m were used as fillers. With filler volume content of 30%, the maximum theoretical thermal conductivity was achieved at 1.72W/mK. The results indicated that the thermal conductivity of the composites depended greatly on filler conductivity, polymer matrix conductivity and packing factor. Packing factor was showed to play more important role for the thermal conductivity of the composites. Simulation results indicated that epoxy resin composites with packing factor of 0.51 offered higher thermal conductivity than PVC composites with packing factor of 0.3.

Thermal and mechanical properties of aluminium nitride (AlN) filled low density polyethylene (LLDPE) composites were reported by Gu et al.¹⁷. The relationship between the thermal conductivity of the composite and the AlN volume content was investigated experimentally. The results showed that thermal conductivity coefficient was achieved at 1.08W/mK with 30% volume fraction of AlN, which was about three times higher than that of pure LLDPE. The optimal tensile strength of the composites was 17.4MPa with volume content of 20% AlN.

Krupa and Chodak¹⁸ carried out experimental tests in terms of thermal and electrical conductivity and thermal diffusivity of high density polyethylene, polystyrene/graphite composites. Two types of graphite fillers with different distribution of the particle size, different specific surface) were identified. The experimental tests showed significant differences in conductivities dependent on the percolation concentration of the composites. The thermal conductivity increased from 0.4W/mK to 2.0W/mK when the graphite filler content rose from 0% to 30%.

An analytical modelling of the heat transfer performance of thermally conductive polymer composites filled with boron nitride particles was conducted by Leung et al.¹⁹. Polyphenylene sulphide (PPS) was used as matrix while spherical hexagonal boron (hBn) nitride was chosen as fillers. The simulation results indicated that 1.83W/mK and 1.89W/mK thermal conductivities were achieved with a PPS volume content of 25% and 60% respectively.

A CPC polymer heat sink (as shown in Figure 5) for cooling of LED lighting systems were presented by Heinle and Drummer²⁰ . The matrix materials were PA 6(ultramid B3) filled with 10% and 40% copper power. The experimental testing results indicated that it is possible to remove 0.5 to 5W of energy dissipated by LEDs with the help of polymer cooling elements.

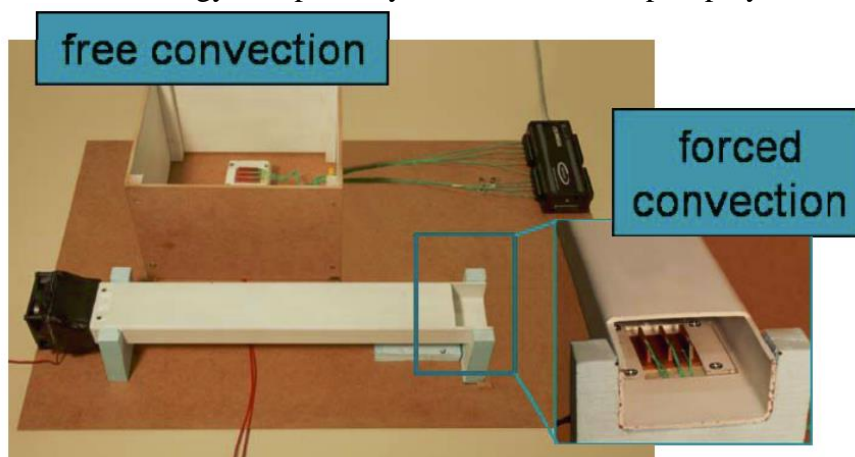


Figure 5 Set-up for variation of cooling conditions free convection (box) and forced convection (flow channel) ²⁰

3.2 Fibre-enhanced composites

Fibre fillers including glass, carbon and aramid fibres are increasingly arousing researchers' attention. These fibre enhanced composites are often successfully used to improve electrical conductivity of the monolithic, and also have relatively high thermal conductivities. The thermal conductivity enhancements with various filler volume content are summarized in Table 4, indicating about 3-4 times thermal conductivity improvements by adding particle fillers into the composites. However, metallic particle fillers have several disadvantages compared with fibre filler such as higher density and greater susceptibility to oxidation. Figure 5 summarizes the thermal conductivities for various particle-enhanced polymer composites^{16, 18} with filler content of 10% and 30%. It is clear that by changing the filler content from 10% to 30%, the thermal conductivity of polymer composites increases about 1.5 to 2.5 times.

Table 4 Thermal conductivities with various filler volume for particle-enhanced polymer composites

Type	Filler type	Matrix	Filler volume content	Thermal conductivity(W/mK)	Source
A	Copper	Epoxy(ER)	10%	0.48	Mamuya et al. ¹⁶
			30%	1.72	
B	Copper	Polyvinyl chloride (PVC)	10%	0.42	Mamuya et al. ¹⁶
			30%	1.65	
C	Nickel	Epoxy(ER)	10%	0.35	Mamuya et al. ¹⁶
			30%	1.36	
D	Graphite	Polyethylene	10%	0.65	Krupa and Chodak ¹⁸
			30%	1.8	
E	Graphite	Polystyrene	10%	0.25	Krupa and Chodak ¹⁸
			30%	0.9	
F	Spherical hexagonal boron	Polyphenylene sulphide (PPS)	25%	1.83	Leung et al. ¹⁹
			60%	1.89	
G	Nickel	Polyvinyl chloride (PVC)	10%	0.26	Mamuya et al. ¹⁶
			30%	NA	
H	Aluminium Nitride (AlN)	Low density polyethylene composites	30%	1.08	Gu et al. ¹⁷

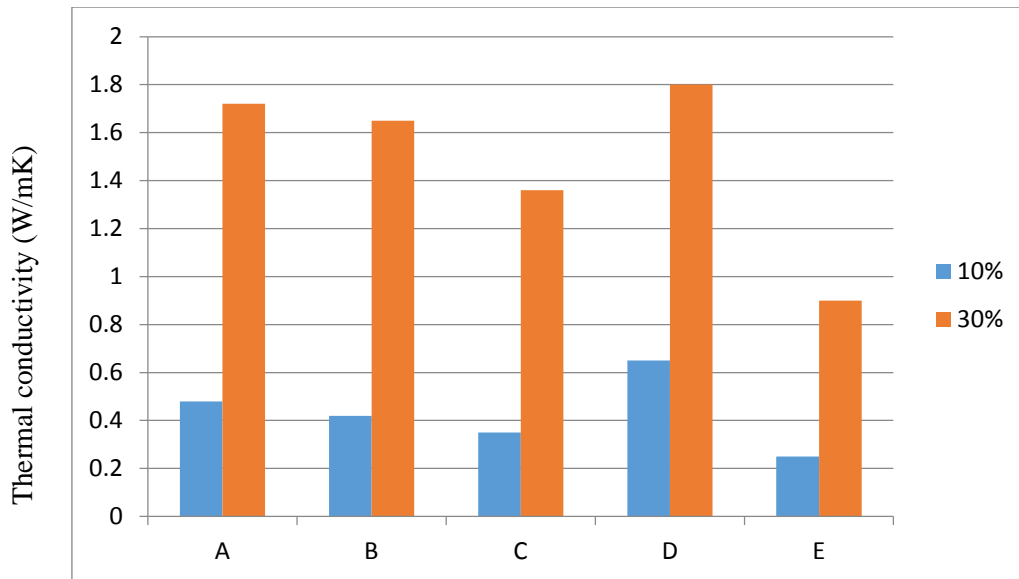


Figure 5 Comparisons of thermal conductivities for various particle-enhanced polymer composites with filler content of 10% and 30%

E-glass enhanced fibre (GF) with different fibre forms, loadings and orientation angles were introduced into wood/poly(vinyl chloride) (WPVC) composites²¹. The mechanical properties of e-glass enhanced fibre were compared with the same composites produced by two different processing methods (compression moulding or twin-screw extrusion). The experimental results showed that by using the compression moulding technique to manufacture the composite products with fibre orientation angle of 0°, the maximum mechanical properties of the GF/WPVC composites could be achieved.

Carbon is relatively inexpensive and has a higher thermal conductivity than most resins, but carbon has a lower thermal conductivity than most metals. Because carbon is too brittle and susceptible to chipping, it is not a useful material to for build heat exchanger constructions. Graphite is a crystalline and a refined form of elemental carbon. Graphite has the advantage of being readily and cheaply available in a variety of shapes and sizes. Graphite and carbon differ fundamentally in their crystalline forms and as a result of this is that graphite has a higher thermal conductivity but costs more than ordinary carbon.

Deronzier and Bertolini⁶ analysed the formulation of LCP with two types of filler glass fibre and carbon fibre. The flexural module of filler content of 40% is 6GPa for glass filler and 8.2GPa for carbon filler. The results indicated that carbon-fibre filler allowed better corrosion resistance to aggressive fluids and an improvement of mechanical properties.

The effect and interactions of carbon filler on the thermal conductivities of two polymers were studied by Weber et al.²². Two polymers (Nylon 6-6 and polycarbonate) were filled with three carbon fillers (electrically conductive carbon black, synthetic graphite particles and a milled pitch based carbon fibre). The simulation results showed that the synthetic graphite particles filled polymer offered the largest increase in the thermal conductivity. For Nylon 6-6, the thermal conductivity increased from 0.3W/mK (pure polymer) to 1.1W/mK for the composites containing 40% synthetic graphite particles.

Carbon foam is generally believed to have great potential for replacing metal fins in thermal management system. Using a low temperature (800°C) heat treatment, thermally insulating

structures are formed, while using a high-temperature treatment (3000°C) leads to highly conductive foams. High conductivity foams are being used in lightweight radiators and electronic thermal planes, while low conductivity foams are being applied for thermal protection and insulating materials. Zweben²³ has reported the bulk thermal conductivities on the order of several hundred W/mK for higher density foams (0.6g/cm³).

Another way to improve thermal conductivity of monolithic polymer is to reinforce it with vapour grown carbon fibre (VGCF) (Ting et al.²⁴). Chen and Ting²⁵ conducted an experimental study on an epoxy composite filled with VGCF. Epoxy was chosen as the matrix so that the composite had an electrically insulating surface and also there is no interfacial reaction between the fibre and matrix. With VGCF content of 56%, the thermal conductivity of the composite was estimated to be 695W/mK.

Experimental investigation of a graphite enhanced polypropylene hollow fibre heat exchanger was carried out by Qin et al.²⁶. The thermal conductivity of the composite was reported to be 0.35W/mK with graphite content of 7%. The U value of this graphite enhanced polypropylene hollow fibre heat exchanger was found to be 1229W/m²K.

Hybrid fillers are also studied by many researchers with the aim to improve the thermal performance of polymers. Chen et al.²⁷ performed modelling analysis on the thermal conductivity enhancement of polymer composite (epoxy) with hybrid filler (hybrid single walled carbon nanotubes and graphite nanoplatelets). The simulation results showed that with the mass fraction ratio of 2 for the above two fillers and the total filler content of 20%, the maximum effective thermal conductivity is equal to 9W/mK.

One drawback of carbon foams is their relatively low toughness compared with solid metal or polymers. One approach to overcome this problem is to infiltrate the open-cell foam with compounds including polymers, metals and ceramics. Bunning et al. studied experimentally the polymer-infiltrated carbon foams for application in a heat sink. The carbon foams with bulk densities of 0.14, 0.25 and 0.34g/cm³ were infiltrated with polyurethane polymers. The testing results showed that the tensile strength and modulus increased by an order of magnitude for the composites compared with unfilled foam. The higher density foams also exhibited a greater heat transfer coefficient.

3.3 Carbon nanotubes composites

The above mentioned fillers including graphite, carbon and glass fibre are polymer composites reinforced with micro-sized inclusion. The processing technology in recent years has been developed to allow the size of inclusions to go down to nanoscale. In order to be defined as nano-composite, at least on dimension of the particles must be in the range of 1-100nm²⁸. Configuration changes in the matrix can have a significant impact on the properties if the dimension of the polymer chains is of the same order as the nano particles.

Carbon nanotube (CNTs), a relatively new form of carbon, has been intensively studied by researchers during past decades. A carbon nanotube is a hexagonal network of carbon atoms rolled up into a seamless, hollow cylinder, with each end capped with half of a fullerene molecule. From unique electronic properties and a thermal conductivity higher than diamond to mechanical properties where the stiffness strength and resilience exceeds any current

material, CNTs offer tremendous opportunities for developing polymer composite CNTs materials.

For heat exchanger application, the most important parameter is thermal conductivity. The observed thermal conductivity of single-walled carbon nanotube (SWCNT) is as high as 3000W/mK at room temperature, which is higher than that of diamond²⁹. Theoretical analysis suggests that even higher values (>6000W/mK) are possible. However, CNTs in bulk have been found to have much lower thermal conductivity. For instance, 250W/mK was reported by Ekstrand et al.³⁰ for SWCNT and 20W/mK for multi-walled nanotubes (MWCNT). Xu et al³¹ investigated theoretically and experimentally the thermal behaviour of SWCNT reinforced thermoplastic polymer-matrix composites with various SWCNT volume fractions. Based on the Lewis-Nielsen model, the calculated thermal conductivity for SMCNT volume content of 40% is 232.3W/mK, while the experimental result was only 0.48W/mK for the same conditions. The authors believed that the large difference between these bulk measurements and a single tube measurement was possibly due to two reasons: one is Lewis-Nielsen model is not applicable to nanoscale reinforcement, another reason is that there are highly resistive thermal junctions between the tubes that dominate the thermal transport capabilities.

The past two decades have seen the applications of CNTs in the following fields: nano-electric devices, sensor materials, structural composites and compression-moulded plates^{31,32}. For these detailed applications, readers can find in these review paper^{14,28,33}. However, only few studies have been reported on the thermal applications of polymer CNTs composites as heat exchangers. Terao et al.³⁴ have studied the thermal properties of polyvinyl alcohol (PVA) polymer composites filled by Boron Nitride Nanotubes (BNNTs). The composites were fabricated using an electro-spinning method. The optimal thermal conductivity with BNNTs of 10% volume content was 0.54W/mK, which showed good agreement with Nielsen's model. Another attempt has been made by Zhi et al.³⁵ with a higher BNNTs fraction (>10wt%).

Table 5 Thermal conductivities with various filler volume for fibre-enhanced polymer composites

Filler type	Matrix	Formulation (wt%)	Thermal conductivity (W/mK)	Source
Synthetic graphite particles	Nylon 6,6	0%	0.3(experimental)	Weber et al. ²²
		40%	1.1(experimental)	
Carbon fibre	Nylon 6,6	0%	0.3(experimental)	Weber et al. ²²
		40%	1.0(experimental)	
Vapour grown carbon fibre	Epoxy	35%	490(experimental)	Chen and Ting ²⁵
		56%	695(experimental)	
Graphite	Polypropylene	3%	0.27(experimental)	Qin et al. (2012) ²⁶
		7%	0.35(experimental)	
Hybrid filler (hybrid single walled carbon nanotubes and graphite nanoplatelets)	Epoxy	20%	9	Chen et al. (2015) ²⁷
Single walled carbon nanotube (SWCNT)	PVDF	10%	0.31(experimental)	Xu et al. ³¹
		10%	42.12(theoretical)	
		40%	0.48(experimental)	
		40%	232.3(theoretical)	

Boron Nitride Nanotubes (BNNTs)	polyvinyl alcohol (PVA)	10%	0.54 (experimental)	Terao et al. ³⁴
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4. Applications of polymer heat exchangers

In the previous sections, we presented a brief review of materials characteristics of monolithic polymers and the polymer composite materials. The following section will emphasize on the applications of polymer heat exchanger in various areas such as heat recovery system, evaporative cooling system, desiccant cooling system, electronic device cooling and water desalination system. Table 6 summarizes the working conditions, the research outcomes and conclusions from various polymer heat exchanger applications.

Table 6 Summary of polymer heat exchangers in various application fields

Application area	References	Heat exchange type	Research Methods	Working conditions	Conclusions
Evaporative cooling system	Dartnall and Giotis ³⁶	Cross flow plate heat exchanger	Experiment	Outdoor dry bulb temp: 25-26°C; outdoor air humidity ratio: 7.7-15.6g H ₂ O/Kg air	COP= 8.5
	Kachhwaha and Preahhakar ³⁷	Plate heat exchanger	Experiment	Inlet dry bulb temp: 24.8-28.4°C; air humidity ratio: 2.3-5.8g/kg; mass flow rate of 0.13, 0.2, 0.3 and 0.4g/s	Experimental testing results are in good agreement with theoretical analysis (variations:10-15%)
Cooling/Refri geration application	Bar-cohen et al. ³⁸	Doubly finned wall heat exchanger	Numerical simulation	Inlet temp of hot fresh water: 90°C; Inlet temp of cold sea water:35°C;fin height: 1mm; fin thickness: 5, 10mm; flow rate: 2m/s	COP: 1-2.5 Heat transfer rate: 250-700kW. Can provide around half the heat transfer rate of an aluminium heat exchanger under the same working conditions.
	Zarkadas and Sirkar ³⁹	Parallel flow shell and tube heat exchanger	Experiment	Coolant temp: 20-35°C; water target concentration: 0.055g/g	Using a solid hollow fibre crystallizer produced crystals of 3-4 times smaller mean size, while nucleation rates were 2-3 orders higher compared with mixed suspension mixed product removal (MSMPR) crystallizers.
	Zhao et al. ⁴⁰	PP hollow fibre heat exchanger	CFD modelling		The heat transfer coefficient : 1109w/m ² K (ID =0.6mm,OD=1mm) ;Optimized packing fraction:13-19%
Liquid desiccant cooling system	Lowenstein et al. ⁴¹	Plastic plate heat exchanger	Experiment	Lithium chloride concentrating solution: 36% - 40%; supplied hot fluid temp : 93.3°C	The COP of the regenerator : 0.93
	Alizadeh ⁴²	Cross flow plate heat exchanger	Experiment	Inlet air dry bulb temp: 31-36°C; relative humidity: 35-55%	Thermal COP:1.25, electrical COP: 6, cooling capacity:3.5kW
	Chen et al. ⁴³	Plastic finned tube heat exchanger manufactured	Experiment	Inlet air temp: 26-34°C; inlet water temp: 8-16°C;	Overall heat transfer coefficient: 34W/mK ² ; offered more than 95% of the titanium heat

		with modified PP			exchanger performance and 84% of the aluminium or copper performance at the same conditions.
	Chen et al. ⁴⁴ .	Hollow fibre membrane heat exchanger	Numerical simulation	Vapour temp: 31.7°C; absorption solution temp: 78 °C, ammonia solution : 26.8%	COP: 0.596 (increased about 14.8% compared with normal absorption system) and overall system exergy loss reduced by 26.7%.
Hot water heating system	Wu et al. ⁴⁵	Polymer tube immersed heat exchanger	Numerical simulation	Working pressure: 0.55MPa; immersed in potable water at 82 °C	Two possible failure modes (burst failure and strain failure) were analysed. The results showed that if the tubing is designed to meet the burst failure criteria, the maximum ratio of outer diameter to thickness is 13.5 for polybutylene and 16.7 for nylon
	Liu et al. ⁴⁶	Tube-in-Shell heat exchanger	Experiment	Isothermal drain-back tank temp:30°C; tube side inlet temp: 20°C	The thermal performance analysis showed that the polymer heat exchangers can provide thermal output equivalent to conventional copper heat exchangers at lower cost.
Electrical fluid heating device	Glouannec et al. ⁴⁷ , Noel et al. ⁴⁸	Tubular heat exchanger	Experiment	Inlet water temp: 28-45°C; voltage applied at the tube end: 0-200V	By using conductive polymer composites, the thermal conductivity of the heat exchanger was improved by a factor of 2 for the filler volume fraction of 25%.
Electric device cooling system	Bar-Cohen ^{49, 50}	Convection polymer pin fin heat sink (manufactured by polyphenylene sulphide (PPS))	Experiment and numerical simulation	Base temp: 10-70°C; power supply level: 1.2-7.2W	At the optimum COP array, the array heat transfer coefficient is 22W/m ² K for PPS polymer and 41W/m ² K for aluminium.
	Hoerber et al. ⁵¹	Pin fin heat sink (manufactured from polyamide 66 (PA66) polymer modified with aluminium oxide)	Experiment	Base temp:20-180°C	The thermal conductivity of 2W/mK was achieved with aluminium oxide volume content of 50%. Maximum temperature reduction could be achieved from 60°C to 25°C.
Water desalination system	Bourouni et al. ⁵²	Falling film evaporator and condenser made of 2.5 cm diameter circular PP tubes	Experiment and numerical	Inlet hot brackish water temp: 50-80°C; hot water flow rate: 0-1.4*10 ⁻⁴ m ³ /s inlet air temp:	The experimental results were compared to a model which examined the impact of the water mass flow rate and inlet temperature.

			simulation	20-45°C, humidity: 35%; liquid film flow rate: $5-25 \cdot 10^{-3} \text{ kg/m s}$	Good agreement was observed
	Song et al. ⁵³	Solid polymeric hollow fibres heat exchangers manufactured by solid PP, solid PEEK and asymmetric polyethersulfone (PES)	Experiment	Hot brine (4%NaCl) temp: 80-98°C), cold water system temp: 8-25°C and steam – cold water system temp: 8-25°C.	The experimental results indicated that the overall heat transfer coefficient of the hollow fibre heat exchanger made from solid PP was 2000W/m ² K for brine-water system and 1600-1800 W/m ² K for steam-water system.

4.1 Heat recovery application

Rousse et al.⁵⁴ presented the theoretical and experimental analysis for using plastic heat exchanger as a dehumidifier in greenhouse for agriculture industry. With the aim to recover some of the lost heat from ventilation system, the heat exchanger was designed as corrugated and flexible thermoplastic drainage tubing with four thermoplastic tubes wrapped around a central tube (as shown in Figure 6). The numerical simulation was based on Brundrett's model⁵⁵ for dehumidifiers in greenhouses. Experimental tests were then performed in a greenhouse of 576m³. The testing results indicated average efficiency of 84% and 78% for air volumetric change rates of 0.5 and 0.9 change/h.

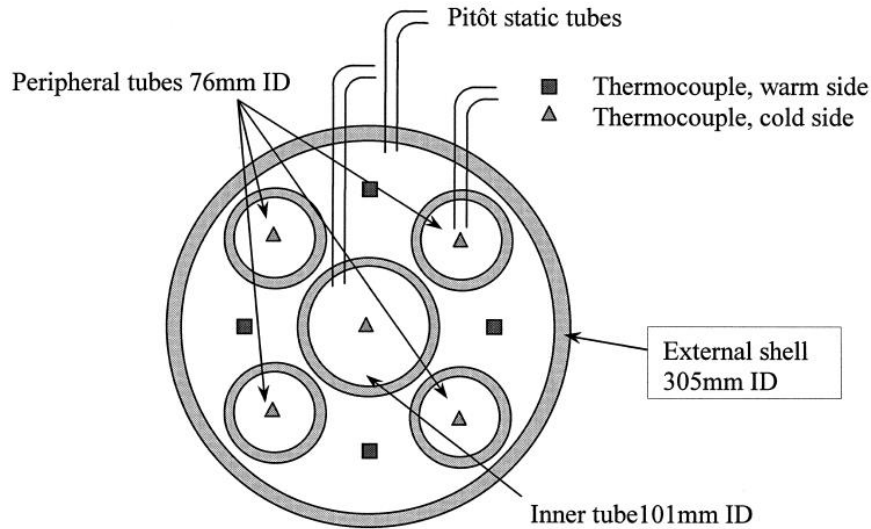


Figure 6 Plastic heat exchanger cross-section⁵⁴

Because of the corrosive resistant feature, polymer heat exchangers are also applied for flue gas recovery in power generation process. An experimental study on the heat transfer performance of wet flue gas heat recovery system using a plastic longitudinal spiral plate heat exchanger was presented by Jia et al.⁵⁶. The plastic heat exchanger was used as air preheater which avoided acid corrosion in the low temperature field for boiler using fuel containing sulphur and recover latent heat of the water vapour from the wet flue gas. The experimental results showed that of the water vapour condensation significantly improved the heat transfer performance, with the heat transfer coefficients increased about twice compared with single-phase convection transfer. Chen et al.⁵⁷ compared experimentally the heat transfer performance between PTFE tube bundle heat exchanger and fin-tube heat exchanger made of thermally conductive plastic for the heat recovery in a 1000MW power plant with a heat recovery temperature of 80°C. In order to improve heat transfer, the plastic exchanger was designed with fin-tubes as shown in Figure 7. The simulation results indicated that the PTFE bundle heat exchanger had a higher heat transfer coefficient and consumed less raw materials for manufacturing, while the fin-tube heat exchanger had smaller volume and fewer fins.

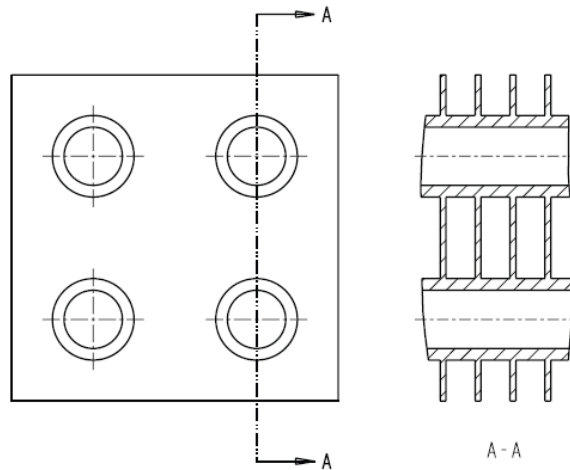


Figure 7 Structural parameters of thermally conductive plastic fin-tube heat exchanger⁵⁷

4.2 Evaporative cooling application

Pescod⁵⁸ proposed a simple design method for an indirect evaporative cooler using parallel plastic plates with small protrusions. Although the thermal conductivity of plastic is very low, the heat transfer resistance across a thin plastic plate would be less than that of the thermal resistance between the air and plate in dry conditions. Predictions of the efficiencies of Pescod's wet surface plate heat exchanger were found to be higher than experimental data. Thus incomplete wetting of plate surfaces was suspected.

An indirect evaporative cooling system using a plastic plate heat exchanger (PPHE) was proposed by Dartnall and Giotis³⁶. The heat exchanger (as shown in Figure 8) is made of multi-layered clear polymer plastic sheets, which were bound together by using a patented thermo-forming process. The outside air passed horizontally through the primary side of PPHE, where it was cooled before being supplied to conditioned space. A surprisingly high COP of 4.7 was reported from the preliminary experimental results⁵⁹ where ambient dry bulb temperature was at 27.7°C and relative humidity was 66%. The authors concluded that when coupled with conventional air conditioning system, this indirect evaporative cooling system can operate efficiently in climates with high humidity.

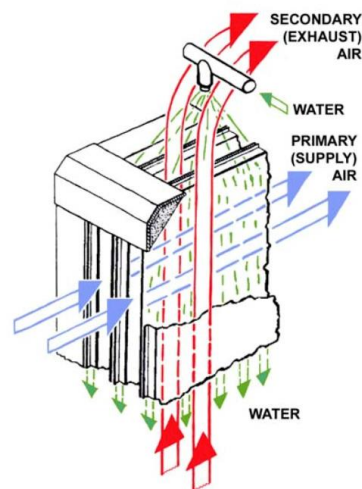


Figure 8 Section view of the plastic plate heat exchanger showing primary and secondary air flows⁵⁹

Kachhwaha and Preahhakar³⁷ analysed heat and mass transfer performance for a direct evaporative cooler using a thin plastic plate. The evaporative cooler was fabricated using a galvanized iron sheet and a rigid media cellulose (RMC) pad is attached in upstream side of the fan. The prototype was tested with inlet dry bulb temperature in the range of 24.8-28.4°C, the air humidity ratio of 2.3-5.8g/kg and mass flow rate of 0.13, 0.2, 0.3 and 0.4g/s. The experimental testing results indicated that the outlet air temperatures were between 16°C and 21°C, which was within 15% of the temperature predications of the simulation results.

4.3 Cooling/Refrigeration application

Because of the good corrosion-resistant nature and low costs of polymers, they become the alternatives for other expensive corrosion-resistant alloys which can be used in sea water cooling. A group of researcher^{11, 38, 60} from the University of Maryland conducted parametric testing on a doubly finned parallel counter-flow heat exchanger for the liquefaction of natural gas on offshore platforms. The total coefficient of performance of prototype polymer seawater- methane heat exchanger was evaluated by varying the polymer materials, geometric parameter of the heat exchangers (fin thickness of 0.1-5mm, fin spacing of 2-1000mm and fin height of 1-20mm). The results indicated that a total COP nearly doubled that of an aluminium heat exchanger and more than ten times that of titanium heat exchanger. In order to demonstrate the economic advantage of polymer heat exchanger, the manufacturing fraction of total energy consumed by metallic alloys and polymers were compared³⁸. The authors showcased that the manufacturing fraction was about 75% less for polymer heat exchangers compared with metallic heat exchangers. The group⁶¹ later considered incorporating mouldability issues with the design of the polymer heat exchangers. A mathematical model was developed to describe the variations molding cost and assembly cost as a function of the geometric parameters of the heat exchangers. The authors concluded that the optimum heat exchanger geometry is highly dependent on the values of the materials cost and labour costs. However, the optimizations between the heat transfer performance and the moulding costs were not presented.

The ultimate temperature and cooling power of some cooling system (³He-⁴He dilution refrigerator and superfluid Stirling refrigerator) depend largely on the thermal efficiency of their counter flow heat exchanger. When the temperature is below 0.5K, the efficiency of conventional heat exchanger is very limited. In order to overcome this problem, Patel and Brisson⁶² proposed a Kapton film recuperator for sub-Kelvin use. The heat exchanger was made out of thin 127mm polymer films with a serpentine path. The detailed plastic heat exchanger design (as shown in Figure 9), construction and performance calculation were presented. However, experimental results were not presented in the paper.

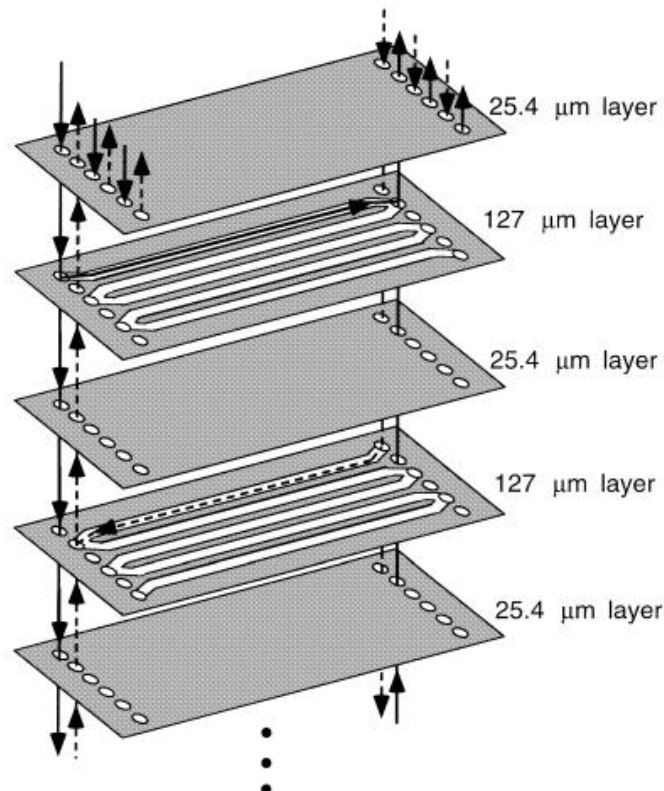


Figure 9 The arrangement of alternate layers of Kapton[®] within the recuperator to form a counter flow heat exchanger⁶²

Using hollow fibres for creation of uniform temperature in a constrained environment of sub-millimetre scale, a new cooling crystallization technique dedicated for pharmaceutical industry was proposed by Zarkadas and Sirkar³⁹. This technique was tested successfully for both aqueous (KNO₃) and organic system (salicylic acid in ethanol) with a high solubility. It was shown that the combination of a hollow fibre crystallizer with a stirred tank downstream produced crystals of 3-4 times smaller mean size, while nucleation rates were 2-3 orders of magnitude higher compared to results obtained in mixed suspension mixed product removal (MSMPR) crystallizers.

4.4 Liquid desiccant cooling application

Saman and Alizadeh⁶³ conducted a theoretical analysis of the performance of a cross-flow type plate polymer heat exchanger as an absorber in a liquid desiccant cooling system. The polymer heat exchanger (as shown in Figure 10) was designed with the dimension of 600*600*600mm³, and a thickness of 0.2mm. The liquid desiccant (calcium chloride solution) was injected into one air stream in order to dehumidify, while water is injected into secondary stream to provide evaporative cooling. The heat exchanger effectiveness was found to be 0.7 for mass flow rate of 0.1kg/s. The authors⁶⁴ later conducted experimental tests on the same system configuration. The testing results demonstrated that at a heat exchanger angle of 45°, there was an optimum value of air mass flow rate at which the effectiveness and dehumidification efficiency of the plate heat exchanger were maximized.

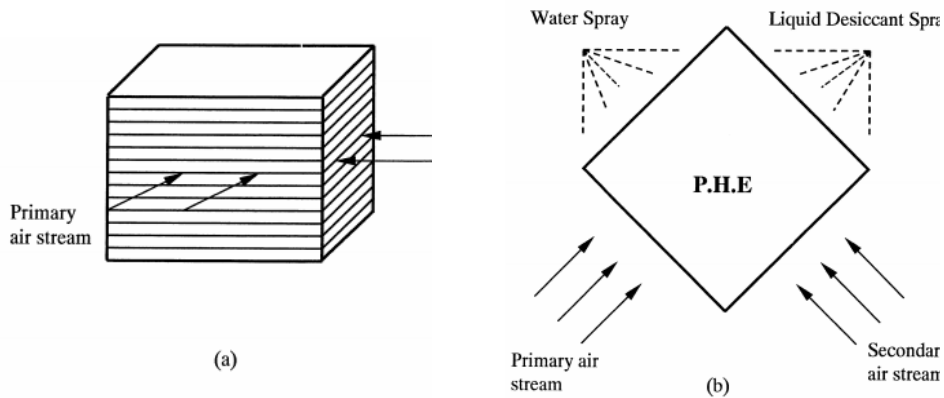


Figure 10 Schematic diagram of the cross-flow type plate heat within the absorber are the simultaneous steady- exchanger^{63,64}

Another low-flow liquid desiccant conditioner using a plastic-plate heat exchanger was presented by Lowenstein et al.⁴¹. The cross section of the plate (as shown in Figure 11) was 2.5mm by 305mm, with 110 cooling passages running the length of the extrusion. The experimental testing results indicated that this liquid desiccant conditioner offered very low droplet carryover, without the use of separate droplet filters. The COP of the regenerator was found to be 0.93 when concentrating a solution of lithium chloride from 36% to 40% and supplied with hot fluid at 93.3°C.



Figure 11 A 6,000 cfm low-flow liquid-desiccant conditioner⁴¹

When using CFC or HCFC as refrigerants in liquid desiccant cooling systems, the generator temperature has to be above 150°C. If solar energy is used as main driving force for the system, the solar collector has to be of the evacuated tube type instead of a simple flat plate collector, this will definitely lead to higher costs. Alizadeh⁴² carried out a feasibility study of a solar driven liquid desiccant cooling system (as shown in Figure 12) with a cross-flow polymer plate heat exchanger for dehumidification and cooling. A 20kW cooling air conditioner with solar collector area of 120 m² was developed and tested in Australia. The testing results indicated good agreement with theoretical models and the system efficiency of 82% could be achieved.

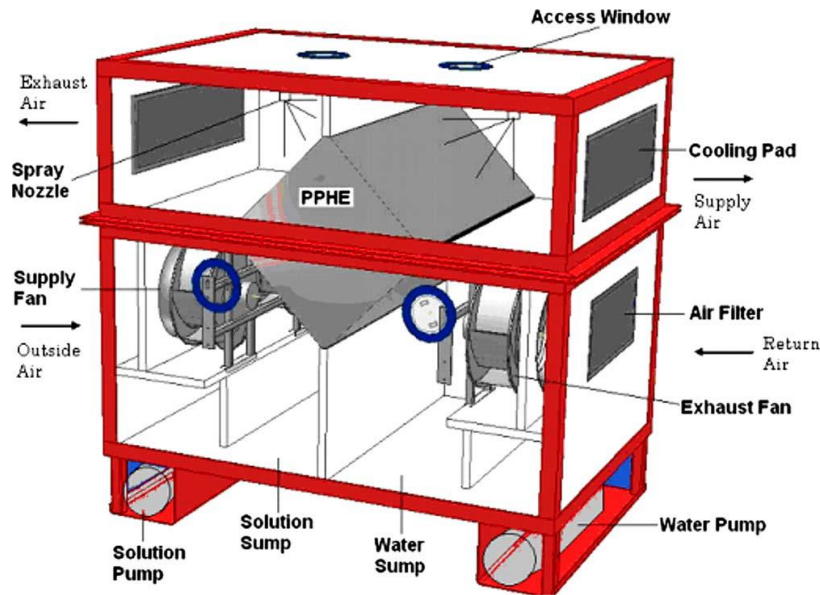


Figure 12 Three dimensional view of the liquid desiccant cooling system- absorber unit⁴²

A finned tube heat exchanger (as shown in Figure 13) was presented by Chen et al.⁴³ for a liquid desiccant cooling system. The heat exchanger is manufactured using two modified types of PP with high thermal conductivity up to 2.3W/mK and 16.5W/mK. For fabrication technologies, injection molding is used for manufacturing the finned-tube heat exchanger. Experimental testing found that the plastic finned tube heat exchanger could achieve a thermal conductivity of 16.5W/mK with overall heat transfer coefficient of 34W/m²K, which offered more than 95% of the titanium heat exchanger performance and 84% of the aluminium or copper performance at the same dimension.

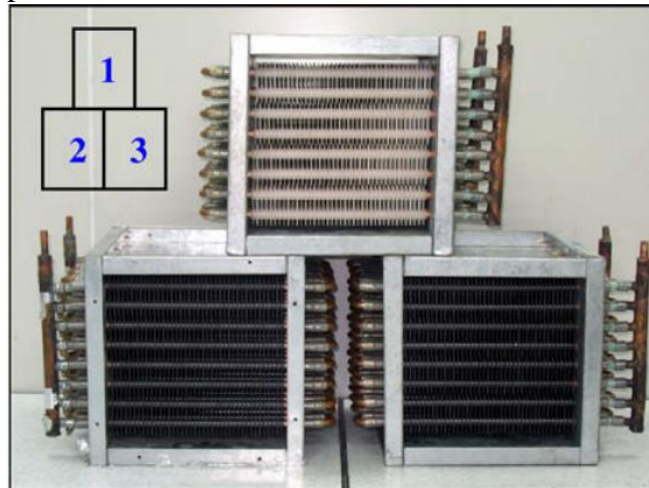


Figure 13 Plastic heat exchangers made from different PP (1 ordinary PP; 2 modified PP-a; 3 modified PP-b)⁴³

Tather and Senatalar⁶⁵ investigated the system performance of a polymeric (PTFE) heat exchanger tubes in adsorption heat pumps employing zeolite coating. The polymeric heat exchanger was chosen to replace metal heat exchangers with the aim to improve the thermodynamic efficiency. The simulation results showed that compared with the metal heat exchanger coated with zeolite, the power of the adsorption heat pumps with polymer heat exchanger remained unchanged, but the system COP increased about 1.5 to 2.5 times by easily employing relatively thinner zeolite coatings (5-100µm).

A numerical simulation of a hybrid absorber-heat exchanger using a hollow fibre membrane (HFMAE) for water-ammonia absorption cycle was conducted by Chen et al.⁴⁴. The hollow fibre membrane heat exchanger was manufactured with outer, inner fibre diameter and wall thickness of 300 μm , 240 μm and 60 μm respectively. The performance of HFMAE as an absorber in an ammonia-water absorption system was analysed and compared with a plate heat exchanger falling film type absorber (PHEFFA). The simulation results indicated that the application of HFMAE in such an absorption system allowed the increase of COP by 14.8% and the reduction of the overall system exergy loss by 26.7%.

4.5 Solar water heating application

With the attempt to replace traditional metal heat exchanger with low-cost polymer heat exchangers in solar water heating systems, a group of researchers from the University of Minnesota (Liu et al.⁴⁶) presented two types of heat exchanger: tube-in-shell and immersed tube (as shown in Figure 14). The tube-in-shell type had a shell ID of 7.5cm, and tube OD of 0.381cm. The heat exchangers were manufactured either from high temperature nylon (HTN) or cross-linked polyethylene (PEX). The thermal performance analysis showed that the polymer heat exchangers can provide thermal outputs equivalent to conventional copper heat exchangers at lower cost. The authors' preliminary works indicated that the cost of a nylon tube in shell heat exchanger was about 80% of that of a copper tube in shell heat exchanger. The design challenge remaining is how to overcome the added conduction resistance across the poor conducting polymer wall and at the same time provide sufficient strength to withstand the pressure requirement.

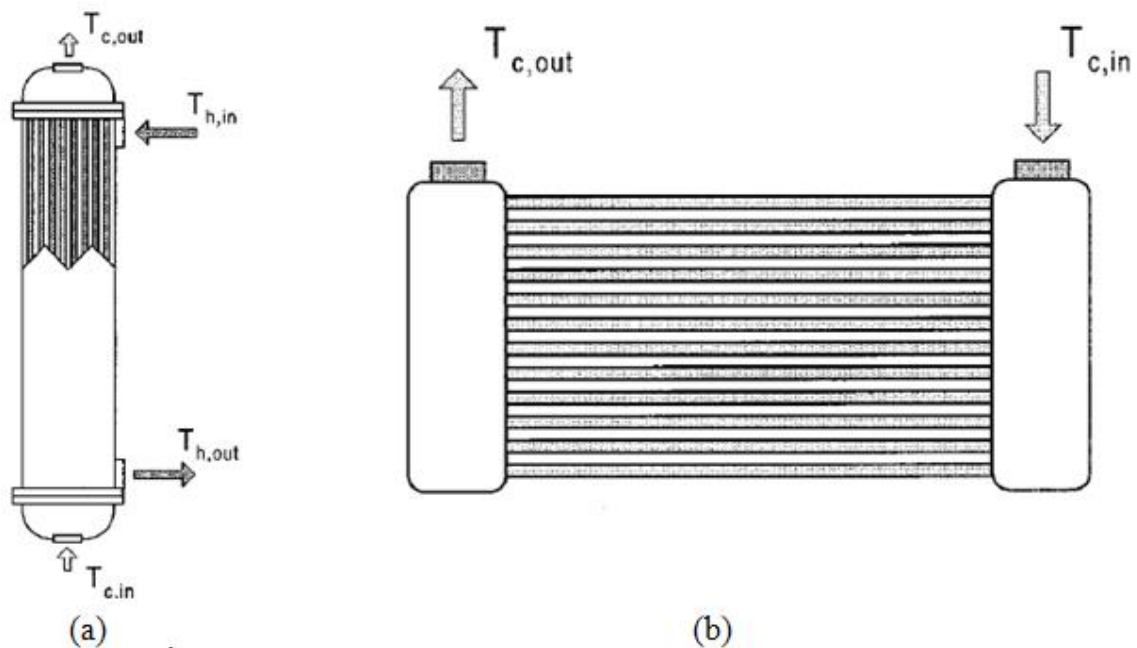


Figure 14 Two types of heat exchangers (a) tube in shell and (b) immersed tube presented in Liu et al.⁴⁶

Another aspect when considering the polymer heat exchanger for solar water heating system is its stability over the life cycle at a constant pressure. According to Wu et al.⁴⁵, the polymer tubes must be able to withstand a continuous working pressure of 0.55MPa while immersed in potable water at 82 °C for at least 10 years. In order to analyse this long term stability, the mechanical performances of two types of polymer heat exchangers made from polybutylene and nylon 6,6 were tested. Two possible failure modes (burst failure and strain failure) were

analysed. The results showed that if the tubing is designed to meet the burst failure criteria, the maximum ratio of outer diameter to thickness is 13.5 for polybutylene and 16.7 for nylon.

Scaling can be another issue for solar water heat system using polymer heat exchangers. In the solar water heat systems, particularly in absorber rise tubes and heat exchangers, long term scaling can dramatically reduce the heat transfer due to the additional conductive resistance across the calcium carbonate layer. Wang et al.⁶⁶ conducted experimental study of the growth scale of heat exchangers made from copper, nylon 6,6, semiaromatic high performance nylon, polypropylene, polybutylene, and Teflon tube. Due to the hydrophilic nature of polymers, nylon 6,6 showed the higher scaling rates than other materials. Copper did not demonstrate any major enhanced tendency to scale compared with other materials.

Antar et al.⁶⁷ proposed using a conductive polymer nanocomposite (CPC) for the solar absorber design. Polylactic acid (PLA) and poly (amide 12) (PA12) filled with carbon nanotube were selected to replace the traditional copper absorbers. Several parameters including thermal performance, electrical resistivity, light absorption and thermal conductivity were analysed. The thermal conductivities of PLA and PA12 were reported to be 0.28W/mK and 0.26W/mK, with 5 wt% of carbon nanotube. However, these values were still too low to be used in solar absorber applications (normally needing values of between 1W/mK and 1.5W/mK).

4.6 Electrical fluid heating device

A tubular heat exchanger (as shown in Figure 15) manufactured using conductive polymer composites (CPC) were used for fluid heating, as presented by Glouannec et al.⁴⁷. Two types of polypropylene tubes were filled with carbon black and carbon fibres respectively to improve the thermal conductivity. The experimental testing results showed that the thermal conductivity of CPC heat exchanger was improved by a factor of 2 for the filler volume fraction of 25%.

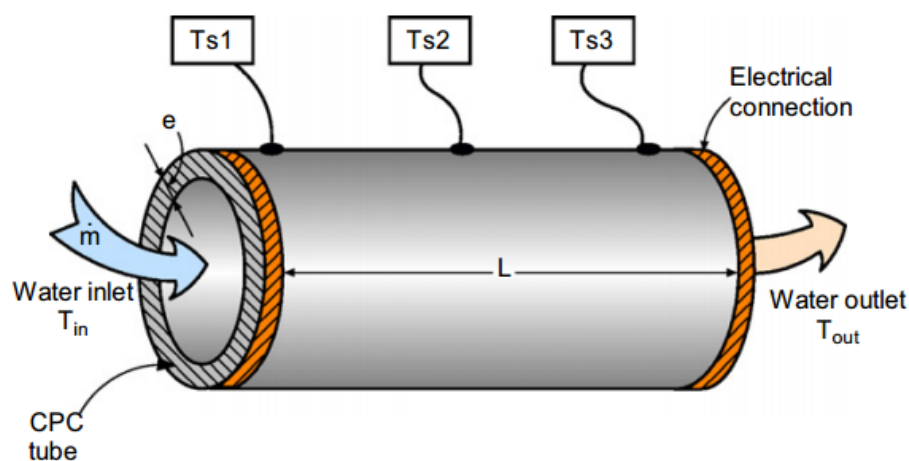


Figure 15 Conductive polymer composites tube⁴⁷

A similar electrical liquid heater using a current passage tube made of CPC tubes was presented by Noel et al.⁴⁸. The CPC materials were insulating polymer matrix combined with electrical conductive fillers (carbon black, carbon fibres or metal particles). Power dissipation of the heating device was observed when an electrical current is passed through the charged polymer matrix. The experimental recordings indicated a thermoelectric efficiency of higher than 90%. This agreed well with the numerical simulations.

4.7 Electric device cooling application

Pin fin arrays relying on natural convection, as well as radiation, heat transfer, can be effectively used as heat sinks for various electronic cooling applications. The availability of thermally conductive polymers raises the possibility of lighter, more energy efficient, mouldable plastic heat sinks. More importantly, the energy required to produce a unit mass of polymer heat sink at some 100MJ/kg, is about one third of the energy required to form the comparable mass of aluminium, making it a most attractive materials for achieving the aim of sustainability⁶⁸.

The thermal performance of staggered pin fin arrays manufactured using polyphenylene sulphide (PPS) in relation to pin fin length, pin diameter, horizontal spacing, and pin fin density was analysed by Bahadur and Bar-Cohen^{49, 50}. The coefficient of performance which related to the cooling capability to the energy required in the formation of the heat sink was determined and compared with conventional aluminium heat sinks. The authors concluded that the PPS polymer heat sinks offered comparable thermal performance to those achieved with aluminium heat sinks with fin length of 5cm, but yielded 50% higher mass-based heat transfer coefficients.

Hoerber et al.⁵¹ conducted experimental tests on an electronic heat dissipation device (as shown in Figure 16) manufactured from polyamide 66 (PA66) polymer modified with aluminium oxide. The thermal conductivity of 2W/mK was achieved with aluminium oxide volume content of 50%. The cooling performance was experimentally tested and compared with a heat sink manufactured by neat PA 66, and significant temperature reductions could be achieved by PA 66 with 50 wt% volume content. However, the cooling capacity and coefficient of performance of the device were not presented.

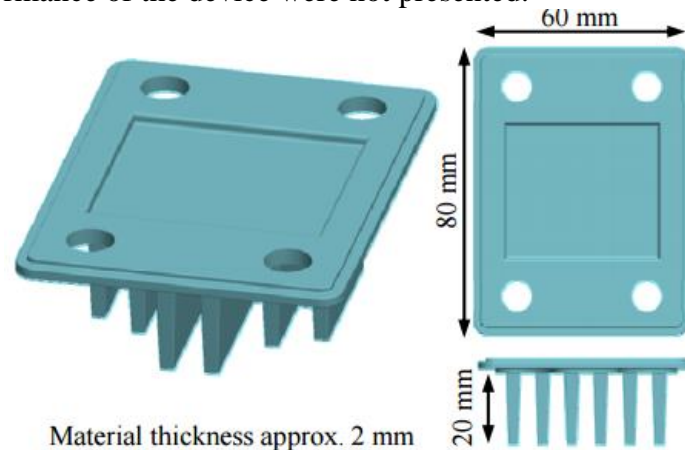


Figure 16 Heat sink device presented by Hoerber et al.⁵¹

A CFD design optimization and thermal efficiency analysis of a staggered pin fin heat sink made of CPC was carried out by Kasza et al.⁶⁹. The temperature rise, array coefficient and mass coefficient were analysed in relation to the pin fin height in the range of 20-40mm. The most effective heat sink design was optimized and selected based upon CFD modelling results.

4.8 Water desalination/distillation application

Because of the limited availability of fresh water sources around the world, the industrial process of desalination of the sea water and brackish water remains a hot topic. Most of the

water desalination processes rely mainly on expensive construction material (such as high steel alloys, copper-nickel alloys and titanium) for manufacturing various metallic heat exchangers. The attempts to replace the metal heat exchangers with polymers have been made by many researchers during past decades.

Bourouni et al.⁵² presented experimental data on a falling film evaporator (as shown in Figure 17) 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 results were compared to a model which examined the impact of the water mass flow rate and inlet temperature, and good agreement was observed. By considering the capital recovery charges, operating and maintenance costs and total energy costs, the economic analysis was also performed in this paper. The authors concluded that by using the geothermal power source as the driving force for the proposed system, the cost of one cubic meter evaporated water was \$1.2/m³, which was only ¼ for the same system driven by fuel.

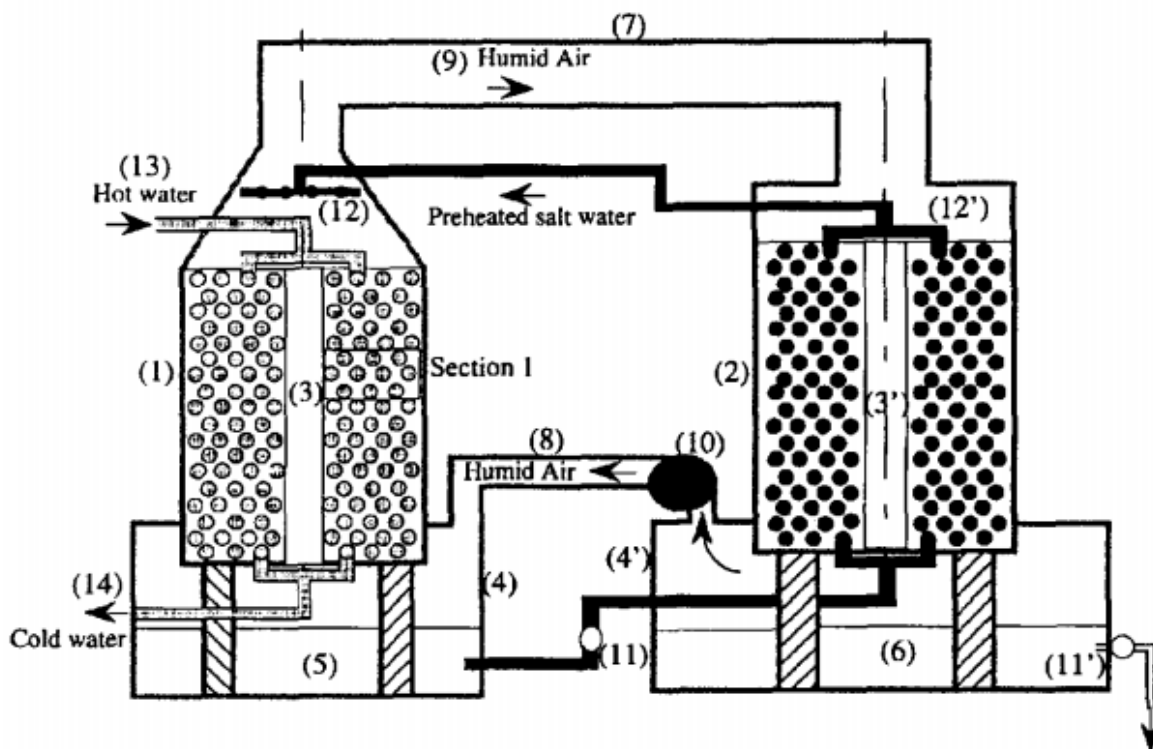


Figure 17 A falling film evaporator (1) and condenser (2) used in an ‘aero-evapo-condensation process’ for desalination⁵²

Plastic and compact heat exchangers made from PTFE for single-effect desalination system was proposed by El-Dessouky et al.². In the model, thin walled polymer tubes and plates were studied (tube diameter of 0.05-0.1mm), indicating a need for spacers to prevent the structure from collapsing and for very fine filtering, should this unit ever be constructed. The heat transfer areas with respect to hot brine boiling temperature for a heat exchanger made from PTFE were studied and compared to these made from metals (titanium, high alloy steel, and Cu-Ni alloys). The results indicated that heat transfer area of the PTFE preheaters and evaporator was 2–4 times larger than that of the metal heat exchangers with varying boiling brine temperature. However, the polymer heat exchanger had the lowest cost.

Christmann et al.^{70, 71} studied a falling film plate evaporator (as shown in Figure 18) made from high performance PEEK for multi-effect distillation (MED) plants. The experimental

testing results showed the mean overall heat transfer coefficients for evaporation in the range of 3182 to 3765 W/m²K, which were comparable to literature values of metallic falling film heat exchangers. The heat transfer simulations were also presented in this paper, and a good agreement between theoretical and experimental data was achieved.

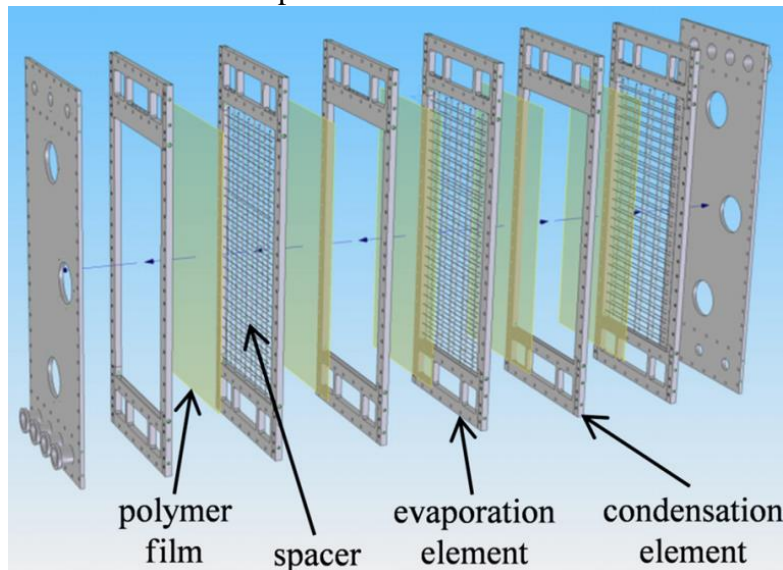


Figure 18 Exploded assembly drawing of the falling film plate heat exchanger with PEEK film heat transfer surfaces and spacers⁷⁰

A similar multi-effect distillation system was designed and fabricated by Scheffler and Leao⁷². Polyolefins such as high density polyethylene (HDPE) and PP were chosen because of their high heat transfer performance and low cost. The U values of HDPE and PP were about 71-105% of equivalent cupro-nickel tubes. The authors presented details about the material selection criteria and manufacturing process of this system, however, the experimental testing results were not well disclosed.

In applications where seawater and other streams where fouling might occur, the use of polymers has added benefits due to their relative ability (a) to be cleaned, or (b) the characteristics of the polymer surface that inhibit foulants sticking. This has running cost benefits – lower cleaning costs and pumping power.

4.9 Polymer micro-hollow fibre heat exchanger

The relatively low overall heat transfer coefficients achieved in plastic heat exchangers can be improved and reach values comparable to metal heat exchangers, if the polymer tube thickness is kept below 100µm⁷³. Several researches have been focused on the heat transfer mechanism of polymer micro-hollow fibre heat exchangers. Such polymer micro hollow fibre normally has a relatively smaller inside and outside diameter (ID and OD < 0.1mm).

Zarkadas and Sirkar^{74, 75} reported polymeric hollow fibre heat exchangers (PHFHE) for low temperature (up to 150-200°C) and low pressure applications (test rig as shown in Figure 19). Polypropylene (PP), polyetheretherketone (PEEK) and asymmetric polyethersulfone (PES) hollow fibres have been used to manufacture heat exchangers. The overall heat transfer coefficients for the water-water, ethanol-water, and steam-water systems reached 647-1314, 414-642, and 2000 W/(m²K), respectively. The experimental test results of PHFEH presented in this paper indicated that PHFHE can achieve high thermal effectiveness (up to 95%), large

number of transfer units (NTU), and a very small height of a transfer unit ($HTU=6\text{cm}$, 20 times less than the lower limit for shell-tube heat exchangers) if correctly designed. If the PHFHE is designed like commercial membrane contactors, they can achieve up to 12 transfer units in a single device with length less than 70cm. The authors concluded that PHFHE could offer comparable heat transfer performance with reduced weight and cost compared with metal heat exchangers.

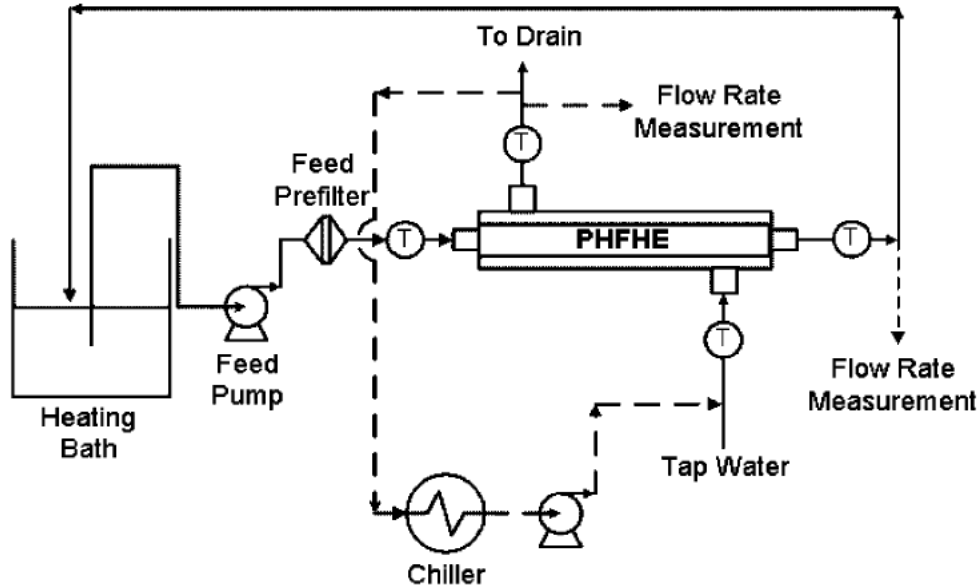


Figure 19 Experimental testing rig for heat transfer measurement of PHFHE⁷⁴

An olefin/paraffin distillation system using hollow fibre structured packings (HFSP) (as shown in Figure 20) was proposed by Yang et al.⁷⁶. Several commercially available hollow fibres, such as PP, polysulfone and PVDF were conceptually demonstrated. The model showed that, with small inner diameter, thin wall and small pore size, Celgard PP hollow fibres was the best candidate for HFSPs application. This group of researchers recently scaled up the experiment and long-term operational testing results were obtained and reported (Yang et al.⁷⁷). The results demonstrated that the HFSPs technology could provide high separation efficiency and column capacity in iso-/n-butane distillation for 18 months. After long-term exposure to light hydrocarbon environments ($\leq 70^\circ\text{C}$), the mechanical properties of the PP polymer did not degrade significantly. However, the commercially available Teflon and PVDF fibres are not applicable for this system, as they have larger pore size and thicker walls. Therefore, some R&D effort should be dedicated to fabricate the fibres with smaller dimensions and pore sizes to extend this technology to broader chemical streams.

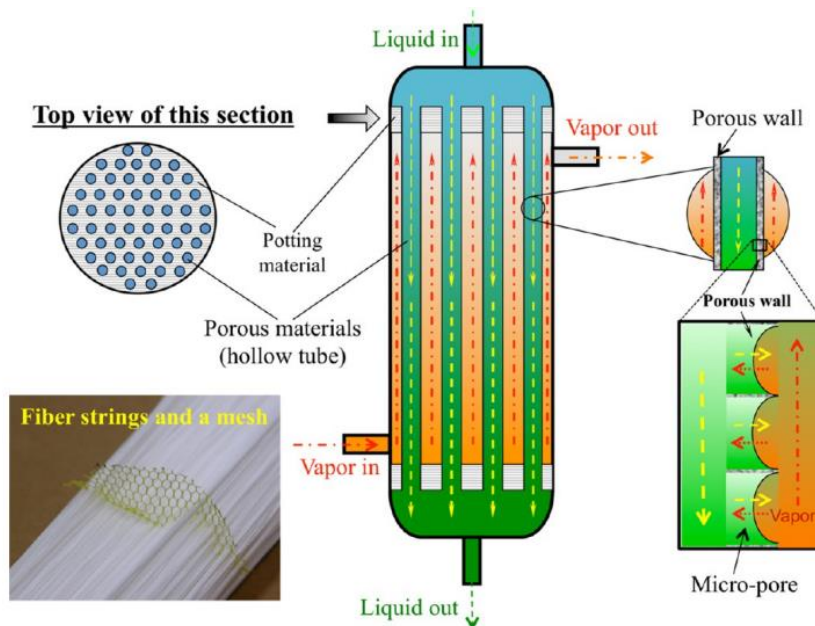


Figure 20 Conceptual illustration of HFSPs module used as a distillation column⁷⁶

Astrouski I. et al.⁷⁸ studied the fouling effect of polymeric heat exchanger made from PP (inner and out fibre diameter of 0.461mm and 0.523mm respectively) for the purpose of cooling TiO₂ suspension. The experimental test results showed a very high overall heat transfer coefficient, with up to 2100W/m²K for clean conditions and 1750W/m²K for dirty conditions at the flow velocity of 0.05m/s. The experimental results were presented as second-order polynomials and the fouling coefficient was correlated into one function. However, this correlation was not enough to characterize the fouling coefficient, as it was only validated for Re numbers in the range of 800-1600.

Zhao et al.⁴⁰ presented a numerical analysis of a novel PP hollow fibre heat exchanger for low temperature applications. A 3D model of a tube-and-shell application of hollow fibre heat exchangers was simulated using the CFD modelling tool FLUENT. The impacts of velocities and packing factors in the tube-side and shell-side on total heat transfer coefficients were studied parametrically. The heat transfer coefficient of PP fibres was predicted to be achieved at 1109W/m²K with inside and outside fibre diameters of 0.6mm and 1mm respectively. An optimal packing fraction of 13-19% was concluded by the authors.

Song et al.⁵³ proposed experiments and numerical simulation of solid polymeric hollow fibres heat exchangers (PHFHE) for thermal desalination process. Three types of polymeric hollow fibres (as shown in Figure 21) including solid PP, solid PEEK and asymmetric polyethersulfone (PES) with nonporous coatings were used to produce the heat exchangers. The heat transfer performances of these devices were studied for a hot brine (4%NaCl, 80-98°C)-cold water (8-25°C) system and a steam –cold water (8-25°C) system. Compared to metallic heat exchangers, these polymer heat exchangers have an order of magnitude larger surface area per unit volume. The results indicated that the overall heat transfer coefficient of the hollow fibre heat exchanger made from solid PP (wall thickness of 75µm and outside diameter of 575µm) was 2000W/m²K for brine-water system and 1600-1800 W/m²K for steam-water system.

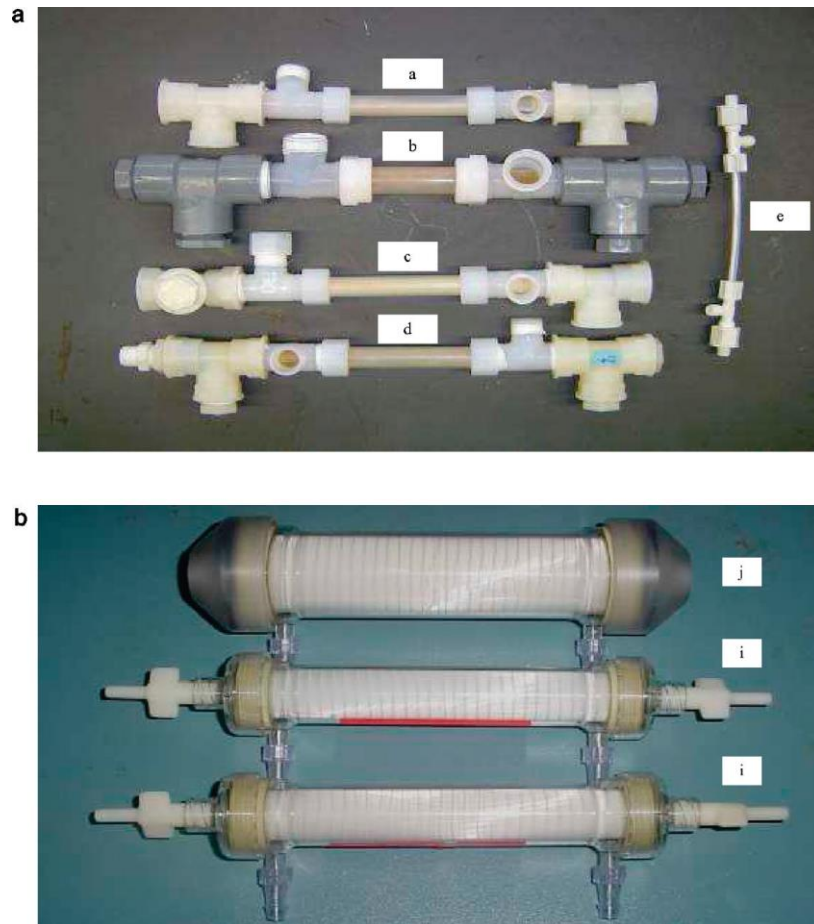


Figure 21 (a) Cross/parallel flow test modules developed at NJIT: (a) module with 79 PP hollow fibres; (b) module with 400 PP hollow fibres; (c) module with 200 hollow fibres; (d) module with 79 PEEK hollow fibres; (e) module with six asymmetric UltraPES fibres. (b) Modules developed at Membrana, Charlotte, NC (Celgard Inc.): (i) modules with 950 PP solid hollow fibres; (j) module with 2750 PP solid hollow fibres.⁵³

4.10 Experimental results summary

One advantage of the polymer heat exchanger is the possibility with some variants to achieve very high surface area/volume ratios. Table 7 summarizes the experimental test results for polymer heat exchangers. The major data include the overall heat transfer coefficient and the surface area to volume ratio, which is a measurement of the compactness of the heat exchanger. Comparison of the surface area/volume ratio between PHFHEs based on commercial membrane contactors (Liqui-Cel Extra-flow 10*28, Celgard, Charlotte, NC) and commercial metal heat exchangers are conducted by Kakac et al.⁷⁹. The PHFHE membrane contactor presents a surface area/volume ratio based on total volume up to $3900 \text{ m}^2/\text{m}^3$. This value is slightly more than an order of magnitude higher than shell-and-tube or plate heat exchangers, higher than plate-fin heat exchangers and inferior only to periodic-flow (matrix surfaces) heat exchangers and rotary regenerators⁷⁹. However, if we compare this surface area/volume ratio with the data summarized in Table 8, it is interesting to observe that most of the surface area/volume ratios obtained from the experimental tests are below $1000 \text{ m}^2/\text{m}^3$, which is much lower than the results reported by Kakac et al.⁷⁹. It would be helpful to obtain more experimental testing results on different heat exchanger types to compare and validate these existing results. Nevertheless, owing to the high surface area/volume ratio, the thermal

performance of some types of polymer heat exchanger is superior on a volumetric basis compared to metal shell-and-tube or plate heat exchangers, making them an obvious choice for lower temperature and pressure applications.

Table 7 Summary of the experimental results of polymer heat exchanger

Heat exchanger type	Material(s)	Overall thermal transfer coefficient (W/m ² K)	Fibre diameter (ID/OD: mm) (ID: inside, OD: outside)	Surface area/volume ratio (m ² /m ³)	Applications	Reference
Shell and tube, immersion coil	Teflon	30-570		<340	Gas to gas, liquid to liquid, steam heating	Githens et al. ¹
Shell and tube, immersion coil	FEP, resin Q	341-567	OD:2.54-9.53mm	NA	Liquid to liquid, bath heating, corrosive media	Wharry ⁸⁰
Shell and tube	PP, PVDF, PPS,	50-500		<600	Liquid to liquid	Bandelier et al. ⁷³
Shell and tube	PVC	90-150	OD=34mm, ID=24.4mm	NA	Water to water	Morcos and Shafey ⁸¹
Plate, triangular channel	PE, PVDC	80-90	Triangle cells: 14*10mm	651	Gas to air	Hetsroni, G. and Mosyak ⁸²
Plate, rectangular channel	PP, PVDF	55	Rectangular channel: 1.6*1.6mm	500	Air to water	Brouwers and Van Der Geld ⁸³
Plate in shell, rectangular channel	SPER 12	150-230	OD=140mm ID=136mm	64	Gas to gas, gas to liquid	Deronzier and Bertolini ⁶
Plate, cross flow, irregular channel	PEEK	60-900	Channel width: 2mm; Height: 1mm; thickness: 100 µm	<1140	Gas to gas, air to water, water to water	Burns, and Jachuck ⁸⁴⁻⁸⁶
Shell and tube	PP	170	OD=25mm ID=24mm	42	Evaporator, condensers	Bourouni et al. ⁵²
Shell and tube	High temperature nylon (HTN)	1100	OD=3.41mm ID=3.81mm	NA	Water to water, solar water heating system	Liu et al. ⁴⁶
	Cross-linked polyethylene (PEX)		OD=5.97mm ID=9.53mm	NA		
Shell in tube	Carbon fibre	15.8-16.9	OD=9.3mm ID=7.8mm	NA	Water heater	Glouannec et al. ⁴⁷

	polymer composite					
Finned tube	PP	33-40	OD=10mm ID=14mm	NA	Water to air	Chen et al. ⁴³
Shell and tube	PP	1750-2100	OD=0.461mm ID=0.523mm	670	Liquid to liquid, TiO2 cooling	Astrousand Raudensky ⁷⁸
Shell and tube	PP	320-1314	OD=0.42mm ID=0.575mm	1394	Water to water	Zarkadas et al. ⁷⁴
	PP	414-642	OD=0.42mm ID=0.575mm	358	water to ethanol	
Shell and tube	PP	430-1360	OD=0.425mm ID=0.575mm	300	Water to 4% NaCl	Zarkadas et al. ⁷⁵
	PEEK	306--394	OD=0.15mm ID=0.36mm	70		
Shell and tube	PP	319-2076	OD=0.425mm ID=0.575mm	531-1345	Thermal desalination	Song et al. ⁵³
	PEEK	535-1929	OD=0.700mm ID=1mm	537		
	PES	804-2109	OD=0.42mm ID=0.57mm	730		

Note: SPER 12: Super Polymer EniRicerce with 40% glass fibre or 40% silica

5. Summary of Heat Transfer Studies on Polymer Heat Exchanger

5.1 Effect on Geometry

The relatively low overall heat transfer coefficients achieved in polymer heat exchangers can be improved and reach values comparable to metal heat exchanger, if the tube thickness is kept below 100 μ m.⁷³ Mechanical strength consideration, on the other hand, imposes a minimum wall thickness to diameter ratio of about 10%⁸⁷.

The polymer tube diameter is found to be closely related to the heat transfer efficiency (Wharry⁷). It becomes difficult to gain heat transfer efficiency in tubing above 12mm. diameter. The wall thickness required to provide structural strength of tubing with diameter larger than ½ in. reduces the thermal efficiency considerably. Generally speaking, the smaller diameter tubes are suitable only for clean fluids. Larger chemical process units normally require larger diameter tubes, where the dirty process fluids can flow easily inside the heat exchanger.

Pressure drop along the polymer heat exchangers are another important parameters analysed by many researchers. The pressure capabilities of the various fluoropolymer materials are very much related to the temperature of the application and the upper temperature capabilities of the various polymers (Wharry⁷). Most manufacturers of polymer materials follow a similar rule. Tubing is typically manufactured with a so called 10% wall. In other words, the wall thickness is 10% of the diameter of the tubing. Following this 10% rule for wall thickness, all tubing within this size range (less than ½ in. diameter) has more or less similar temperature/pressure capabilities.

Morcos and Shafey⁸¹ conducted experimental tests on plastic shell and tube heat exchangers with tube internal diameter of 24.4mm, outside diameter of 34mm and length of 1.3m. With the purpose of improving the overall heat transfer in the heat exchanger, a total of 78 conically-shaped plastic turbulators (as shown in Figure 22) arranged in six groups were fabricated and inserted in the heat exchangers. The overall heat transfer coefficients were obtained in the range of 90 to 150W/m²K, which were 1.5 to 3 times higher than that without turbulators.

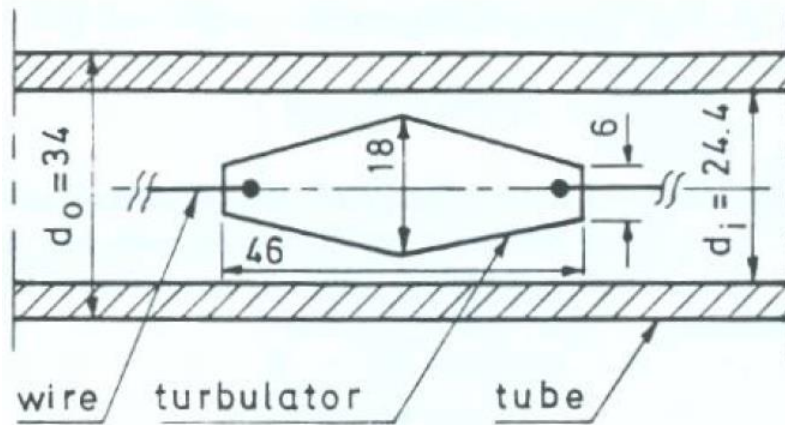


Figure 22 Turbulators inside tube⁸¹ (dimension:mm)

As we discussed in the previous section, adding metallic particles or carbon nanotubes into polymer materials yield an increase in the bulk thermal conductivity. However, the increase in the bulk thermal conductivity is not isotropic but primarily in the longitudinal rather than the radial direction. In order to reduce the conductive resistance of the polymer wall and maintain acceptable pressure drops, researchers have focused on the efforts to develop polymer tube bundles with small diameter and thin wall tubes. The fluid dynamic and thermal performance of using the unique shaped polymer tubes in bundles comprised of small diameter tubes (as shown in Figure 23) was conducted by Li et al.⁸⁸. The outer surface of the tube was streamlined into oval shapes to reduce form drag and the inner flow passage was kept circular to maintain pressure capability. The numerical analysis revealed that such geometry changes improved convective heat transfer with Re numbers in the range of 2000 to 20,000 and a Biot number less than 0.3.

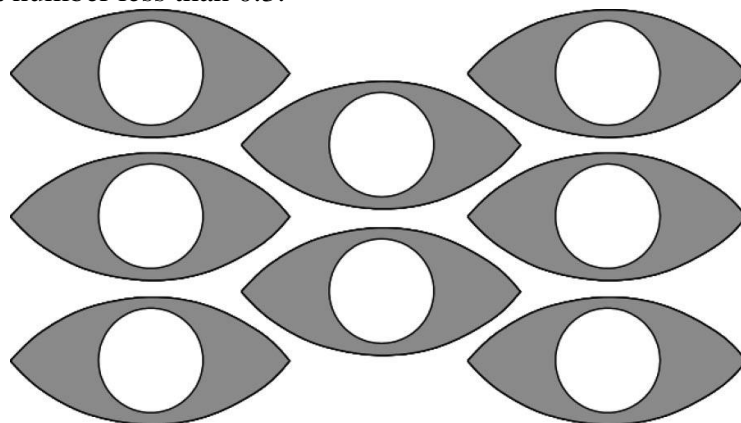


Figure 23 Tube bundle of 'shaped' polymer tubes⁸⁸

Park and Jacobi⁸⁹ proposed an analytical method to model the polymer heat exchanger tube bundle geometry. The tube core mass/ volume ratio, facial area ratios were tuned according to

various heat transfer rate, pumping rate and pumping power. It was found that all the geometrical parameters had monotonic effects on the selected figures of merit.

The geometric features including the tube inside and outside diameters, tube length, and tube shapes proved to have special importance of the heat transfer performance of polymer heat exchangers. For more detailed fluid flow maldistribution, fouling, pressure drop and thermal analysis in the design and optimization phase of the heat exchanger, CFD simulation and Artificial neural networks (ANN) analysis methods are extensively studied by researchers as well, for more details readers can be referred to ^{90,91}.

5.2 Study of Polymer Heat Exchanger with Drop Wise Condensation

Condensation heat transfer has been extensively studied for more than on hundred years. Dropwise condensation (DWC) demonstrates significantly higher heat transfer performance than filmwise condensation. The use of polymer coatings to maintain DWC has aroused great attentions for industrial applications. Two difficulties remains before the polymer coating approach can be widely applied: one is to form a film that adheres well to the substrate with few voids and sufficiently high mechanical strength; the other is to make the film thin enough to not excessively increase the conduction heat transfer resistance in the film. Another challenge is to ensure DWC is maintained over the life of the heat exchanger.

Burns and Jachuck⁸⁴ conducted experimental testing on a cross-corrugated polymer film compact heat exchanger. The heat exchanger (as shown in Figure 24) is made from thin wavy (100 mm) PEEK films with a mean thickness of 53 μm and amplitude of 1 mm. Seven sheets with the dimension of 13.5cm*13.5cm were stacked each rotated 90° to one another to provide a cross-corrugated layers. PEEK was chosen because of its high working temperature (up to 220°C) and the capability of being formed into a 100 μm thick film. 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 400W for a heat transfer area of 0.125m². 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 10m³/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.

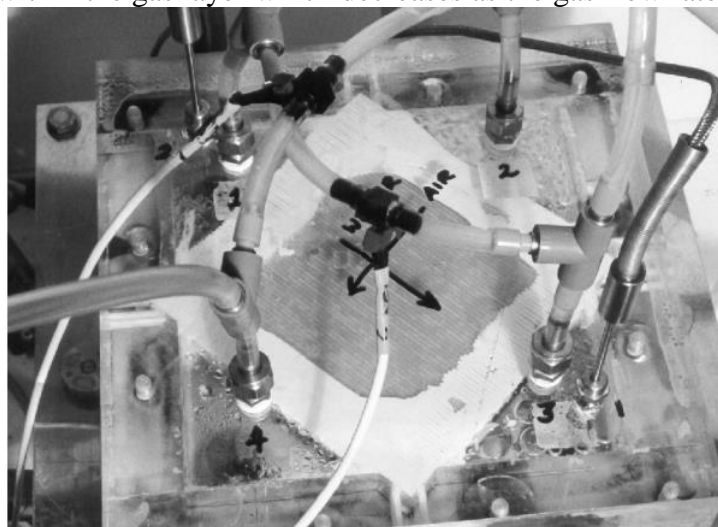


Figure 24 Heat exchanger made from thin wavy (100 mm) PEEK films⁸⁴

In order to promote dropwise condensation with the help of polymer materials, Cheng and Van Der Geld⁹² studied experimentally the heat transfer and pressure drop characteristics of air/water and air-steam/water heat exchanger (as shown in Figure 25) made from PVDF. The inlet air temperature was in the range of 50-90°C, with mass flow rate of 0.25-0.38kg/s. The inlet temperature of the cooling water is 24-25°C, with flow rate of 2.5m³/h. The experimental results revealed that 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. Due to dropwise condensation on the air side, increasing the inlet steam mass fraction resulted in the increased overall heat transfer coefficient.

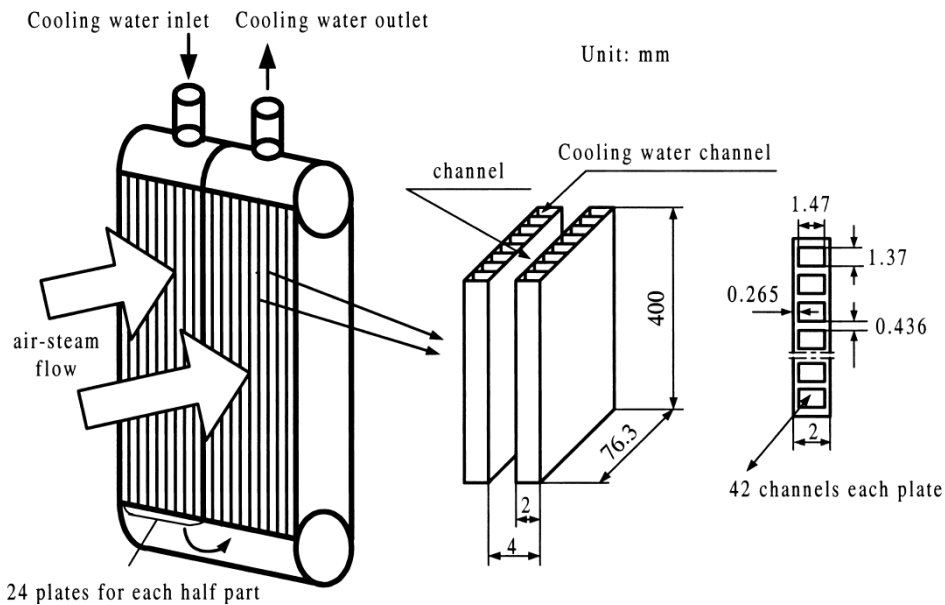


Figure 25 Heat exchanger configuration studied by Cheng and Van Der Geld⁹²

6. Conclusions

In the present work, the merits and drawbacks of various polymer materials and filler enhanced polymer composite materials are reviewed in detail. Based on the review, recent successful applications of polymer heat exchangers in a wide range of applications have been summarized, which includes heat recovery systems, evaporative/desiccant cooling systems, and solar water heating systems, water desalination systems and electronic cooling devices. In recent years, special research interests have been placed on the thermal performance and application of polymer hollow fibre heat exchangers. Despite polymer materials' low thermal conductivities (0.1-0.4W/mK, which is 100-300 times lower than metals), by using hollow polymer fibres with the diameters less than 100µm, the surface area/volume ratio of polymer hollow fibre heat exchangers can be very high. This makes them extremely efficient with superior thermal performance. Taking into considerations of the potential lower cost, light weight, low fouling coefficients and corrosive resistant features, polymer heat exchangers should be seriously considered as substitutes for metal heat exchangers.

Current research on the heat transfer performance analysis of polymer heat exchanger is mainly concentrated on shell and tube polymer heat exchangers, with very few experimental and theoretical results published for other types of heat exchangers (such as plate heat exchanger, finned tube exchangers). Moreover, the applications of heat exchangers in various fields are mostly presented by theoretical simulation. For the very few experimental works of polymer heat exchanger applied in various heat recovery and cooling systems, the emphasis have been laid on the overall system performance, while the actual thermal performance of

polymer heat exchangers are hardly revealed. Therefore, a considerable amount of research is still required to fully analysis the thermal performance of various types of polymer heat exchangers, as well as the manufacturing cost in comparisons with metal counterparts. Further research is needed to experimentally tailor the structure configurations and obtain the thermal performance of polymer heat exchangers in a wide range of industrial and mechanical applications. Since the thermal conductivity and wall resistance of polymer heat exchangers are quite different from metallic heat exchangers, the procedures/parameters applied for polymer heat exchanger design could be unique as well. Besides, a disinclination of the industry to depart from well-established metal heat exchanger practices remains a big barrier to the commercialization of polymer heat exchangers. In order to overcome this and ensure a good penetration of polymer heat exchanger in the commercial market in the future, research cooperation with industrial partners is strongly recommended.

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