Application of Thermally-Enhanced Thermoplastics to Seawater-Cooled Heat Exchangers

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Abstract

In this study, the potential benefits of using thermally-enhanced polymers in high-performance seawater heat exchangers are assessed. The thermal and mechanical properties of commercially available, thermally-conductive resins are reviewed and compared with those of polymer heat exchangers described in the literature, as well as those of metals commonly used in compact heat exchangers, including in seawater-based cooling systems (i.e., Cu-Ni alloys, stainless steel, and titanium). This survey reveals that engineered thermoplastics have sufficiently high thermal conductivities to compete with their metal counterparts.

The thermo-fluid performance of a conceptual, doubly-finned plate liquid-liquid heat exchanger module, is analytically evaluated using the ε-NTU method. The heat transfer rate and coefficient of performance (COP) of this heat exchanger are parametrically assessed for various fin spacings, wall thicknesses, and a near 3 orders-of magnitude range of wall thermal conductivities. This analysis shows that the thermal conductivities achievable with enhanced thermoplastics, 20 W/mK, can provide approximately half the heat transfer rate of an aluminum heat exchanger operating under the same conditions, and 80% of the heat transfer rate provided by a corrosion-resistant, metallic heat exchanger. This study indicates that thermally conductive thermoplastics offer a promising alternative to the use of conventional and/or corrosion-resistant metals in compact, high performance heat exchangers in seawater-cooled applications.

1. Introduction

While conventional metal heat exchangers are generally incapable of providing reliable long-term service with seawater (and other corrosive fluids), to date the cost, complexity, and the restricted availability of exotic corrosion-resistant materials have limited the use of seawater as the ultimate heat sink for energy conversion processes. Currently available polymer heat exchangers, fabricated with thermally un-enhanced thermoplastics, are an alternative option, but are limited to relatively low heat transfer rates.

In this study, the potential benefits of using thermally-conductive polymers in high-performance seawater heat exchangers are assessed. These advanced materials could provide reduced weight, greater resistance to corrosion and fouling, and reduced energy of formation and fabrication, as well as greater geometric flexibility and ease of manufacturing, relative to the conventional material technologies in use today. On the premise that such materials have the required thermal and mechanical performance characteristics, they could facilitate the development of seawater heat exchangers for the power industry, naval applications, and coastal petroleum refineries.

In this paper, commercial, prototype, and research polymer heat exchangers described in the literature are firstly discussed, with an emphasis on their performance limits and physical characteristics. A review of commercially available, thermally-conductive resins is then presented, with a comparison of their thermal and mechanical properties to those of metals commonly used in compact heat exchangers, including in seawater-based cooling systems (i.e. Cu-Ni alloys, stainless steel, and titanium). Based on this review, the thermo-fluid performance of a notional, doubly-finned plate liquid-liquid heat exchanger module is analytically evaluated using the e-NTU method. The heat transfer rate and coefficient of performance (COP)[1] of this heat exchanger are assessed for various fin spacings, wall thicknesses, and a near 3 orders-of magnitude range of wall thermal conductivities.

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[1] The coefficient of performance in this study is defined the ratio of total heat transfer rate to pumping power.

2. Thermally Un-enhanced Polymer Heat Exchangers

Polymer heat exchangers were first introduced in 1965 by DuPont (Miller *et al.*, 1979). These exchangers consisted of shell-and-tube configurations made with flexible Teflon tubing, and were adopted for many industrial applications, such as pickling in steel manufacturing, heating of agitated reactor vessels, and heating/cooling of distilled water. The wide availability and versatility of polymers has since driven the interest of the research community toward the use of these materials in a range of heat exchange applications.

Two notable government-funded research programs have contributed to the adoption of such materials. In 1976, the US Department of Energy commissioned two studies on the feasibility of developing state-of-the-art plastic heat exchangers. One study, reported by Hart *et al.* (1979) focused on ocean thermal energy conversion (OTEC), with the intent to replace corrosion resistant metal alloys with cost effective plastics for low temperature marine applications. In the second study, Miller *et al.* (1979), reviewed incentives for the development of enhanced-property materials, fabrication techniques, and innovative design of polymer heat exchangers. Also, particular environments where polymer heat exchangers are better suited than conventional units were identified.

Both studies considered the enhancement of the thermal conductivity of polymers through the use of fillers. Miller *et al.* (1979) described the types of fillers and treatments to enhance properties, and methods to predict properties of composite materials. Hart *et al.* (1979) measured an improvement of 22% in the thermal conductivity of HDPE filled with 15% by weight of acetylene black, relative to the non-enhanced material (0.24 W/m-K). Extrapolating the data to 34% filling would yield a 50% improvement in thermal conductivity. However, this improved conductivity is still two orders of magnitude less than that of corrosion resistant metallic materials. Consequently, this would not be sufficient to permit the replacement of corrosion resistant metallic materials by those enhanced polymers, since their conductivity improvement is not sufficient. Other fillers should therefore be sought to enhance polymer thermal conductivity, which are addressed in a later section of this paper.

In 2001, a two-year European Union funded consortium project (Brite-Euram III, 2001) was completed, which reviewed technologies for polymer forming and assembling of modular heat exchangers. The goal was to develop a prototype polymer heat exchanger evaporator, as a replacement of metallic ones, which could operate under vacuum, at over 100°C, in corrosive and fouling environments, having competitive purchase and maintenance costs.

Conventional polymers are currently used in a variety of heat exchange applications that require corrosion resistance, high manufacturability, and chemical inertness. The most commonly used polymers in heat exchangers are PVDF (polyvinylidene fluoride), PTFE (polytetrafluoroethylene), PP (polypropylene), PE (polyethylene), PC (polycarbonate), PPS (polyphenylene sulphide) and (PPO) polyphenylene oxide.

Table 1 shows a sample of commercially-available plate, immersion coil, and shell-and-tube polymer heat exchangers, including dimensions and operating limits. This summary is derived from commercial heat exchanger data, offered by vendors cited in Zaheed and Jachuck (2004), who reviewed the availability and application of polymer heat exchangers. The data in Table 1 shows that maximum operating pressures and temperatures are generally less than 700 kPa and 150°C, respectively. These upper-bound operating parameters, reflecting the low strength and glass transition temperatures of candidate polymer heat exchanger materials, could pose a significant limitation on the use of conventional polymers in heat exchanger applications. However, conventional polymers could still be suitable for a variety of relatively low temperature and pressure applications, including cooling of process air, heating and cooling of chemically aggressive or corrosive fluids, and wet flue gas recuperation.

3. Commercially-available Thermally-conductive Thermoplastics

Within the last decade, several companies have developed new composite materials, such as filler-loaded thermoplastics, that offer thermal conductivities that can be up to 100 times larger than those of conventional polymers. Zweben (2004), for example, discusses current applications and thermal conductivities of carbon fiber-filled composites. Two high volume markets have emerged for fiber-reinforced composites, namely commercial and industrial equipment, and packaging of microelectronic, optoelectronic and microelectromechanical systems (MEMS).

Table 2 summarizes the thermal and mechanical properties of current commercially-available thermally conductive thermoplastics. Thermal conductivities range from 1 to 25 W/m.K, depending on the filler type and volume fraction. However, these conductivities are generally highly orthotropic, and the figures given in Table 2 are usually the highest directional value.

Table 1. Geometrical characteristics and performance limits of a representative sample of commercially available polymer heat exchangers.

Manufacturer	HX Type	Application	Dimensions	Materials	Performance
Greenbox Co. www.greenbox.uk.com	Plate	Can handle airflows with sensible and latent heat exchange	Walls are less than 0.5 mm	PVC	Temp. -15°C to 60°C. Max. pressure 1 kPa
George Fischer www.us.piping.georgefischer.com	Plate, coils, shell and tube	Heat transfer between corrosive fluids		PVDF and PP	
Plastic Magen www.plasticmagen.com	Plate	Solar collectors for heating swimming pools	Rectangular cavity transversed by 5 mm OD, 5 mm wall tubes	PVDF and PP	PVDF can withstand 600 kPa at 100°C. PE 200 kPa at 80°C
AB Segerfrojd www.segerfrojd.com	Plate	Ventilation, humidifying, electronic cooling, wet flue gas recuperation	Sheet thickness from 2 to 5 mm	Extruded PP sheets	Temp. -40 to 90 ^{o}C. Compressive strength 188 kPa at 2.88 mm
Ail Research, Inc www.ailr.com	Plate	Corrosive liquid cooling	Plates are made from a 5 mil (0.127 mm) film	Thermofor med plastic	Temp. of up to 148°C. Pressure up to 275 kPa
Process Technology www.process-technology.com	Shell-and-tube, coils	Immersion heat exchanger	0.76 mm thick wall	Shell: PP of PVDF. Tube: PFA.	Max.pres./temp Tube: 241 kPa at 120 ^{o}C. Shell 206 kPa at 100 ^{o}C
Fluorotherm www.fluorotherm.com	Shell and Tube	Semiconductor and biotechnology (ultrapure), environmental, laboratory and products finishing industries		Shell are PVC and CPVC. Tubing are PTFE, FEP and PFA	Max. temp for shell 60 – 93 ^{o}C. Working pressure are 276 kPa at 60 ^{o}C and 172 kPa at 100 ^{o}C
Cesaroni Technology Incorporated www.cesaronitech.com	Plate	Chiller applications	(28 x 42 x 7.6 cm)	Polyamide	Operating Pressure: up to 550 kPa. Temperature Range: -40 to 115°C

Table 2. Thermal and mechanical properties of commercially available thermally conductive polymeric materials.

Company	Resin	Thermal Conductivity (W/m K)	Tensile Strength (MPa)	Tensile Modulus (MPa)	Density (g/cc)	HDT @ 1.8 MPa (^{o}C)
Cool Polymers	PPS	20	45	13000	1.7	260
Cool Polymers	PP	5	25	5200	1.38	
Sabic IP	PPS	7/2.2	139	27586	1.74	270
Sabic IP	PA 6	1.1	81	10160		174
Sabic IP	PA 6/6	1.2	95	11920	2.04	216
PolyOne	PPS	10-11	100	26200	1.82	282
PolyOne	PA 6/6	10-12	60.7	14479	1.58	254
PolyOne	LCP	18-20	103.4	20684	1.82	277
PolyOne	PA 12	20-25	39.3	14479	1.68	185
RTP	LCP	18.01	45	24132	1.7	232
RTP	PPS	2.31	62	26201	1.7	260
Ovation Polymers	PC	6.10	59	6900	1.45	136
Ovation Polymers	PEEK	3.1	75	6250	1.52	206

Note: HDT = heat deflection temperature.

The material properties in Table 2 can be compared to those of metal alloys used in compact heat exchangers, which are listed in Table 3. The most common metal alloys used with corrosive fluids, seawater in particular, are Cu-Ni alloys, which offer good resistance to impingement 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 (12 to 50 W/m-K). To overcome this, the conductive thermal resistance of these materials is generally lowered by decreasing the thickness of the heat exchanger wall (Pugh, 2005). The properties of aluminum alloys and copper are also included in Table 3 for comparison purposes, but neither is suitable for corrosive fluids.

Table 3. Thermal and mechanical properties of metallic materials used in heat exchangers (Shah, 2006).

Material	Density (x 10^{-3} kg/m^3)	Specific heat (J/kg.K)	Thermal Conductivity (W/m.K)	Yield Strength (Mpa)	Tensile Strength (Mpa)	CTE (x 10^6 m/m.K)	Melting range (^{o}C)
AA3003	2.71	921	169	69	179	7.2	629-652
Cu 99.9	8.89	385	391	69	221	5.2	1083
HastelloyA	8.8	394	17	303	758	3.4	1299-1329
Inconel X	8.25	431-448	12	690-932	1100-1280	3.8	1393-1427
SS 304	7.92	502	16	207	586	4.4	1399-1454
SS316	8.08	502	16	276	621	4.9	1371-1399
SS446	7.47	502	21	345	552	3.2	1399-1482
Titanium	4.51	582	17	517	621	2.6	1691
Cu-Ni 90/10	8.9	377	50	140	320	17	1100-1145
Cu-Ni 70/30	8.95	377	29	170	420	16	1170-1240

Contrasting Tables 2 and 3, several important parameters accentuate the differences and similarities between thermally enhanced thermoplastics and metallic materials. The highest thermal conductivity values of the thermoplastics (18-25 W/m-K) are within the range of those of corrosion-resistant metals (12-50 W/m-K).

However, the yields strengths of both types of materials clearly differ. The upper limit for fiber-reinforced thermoplastics is 139 MPa, which corresponds to the lower limit for corrosion resistant metals, 140 MPa. 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.

It is not clearly discernable what the maximum operating temperatures may be from the values presented in Tables 2 and 3. Although the metals have very high melting points (> 1000 °C), and the thermoplastics have relatively low heat deflection temperatures (< 300 °C), their operating temperature is not necessarily determined by their heat deflection temperature.

The above data indicates that engineered thermoplastics have sufficiently high thermal conductivities to compete with their metal counterparts in heat exchanger applications, although mechanical strength, service temperature, and rheological considerations can be expected to limit the effective design space. Not shown in Tables 2 or 3 is the difference in corrosion resistance between polymers and metals. An electrolyte such as seawater is unlikely to chemically attack polymer-matrix composites, whereas metals are susceptible to direct chemical dissolution. For polymers, long term exposure to sea water may only result in minor moisture-induced damage (Sloan and Talbot 1992a,b). These findings motivate the analytical analysis of the thermo-fluid performance of a conceptual, thermally-enhanced polymer heat exchanger design in the following section.

4. Thermo-fluid Performance Analysis of a Doubly Finned Parallel Counterflow Heat Exchanger

The thermo-fluid performance of a notional liquid-liquid heat exchanger module, consisting of the doubly-finned plate shown in Figure 1, is assessed. Analytical models, following the ε-NTU method with established correlations for the convective heat transfer coefficient and friction factor, are used to calculate the heat transfer rate and required pumping power, as well as COP, for various fin spacings, wall thicknesses, and a near 3 orders-of magnitude range of wall thermal conductivities that represent

Note: Flows entering and exiting are denoted by subscripts i and o, respectively. Hot and cold sides are denoted by subscripts 1 and 2, respectively.
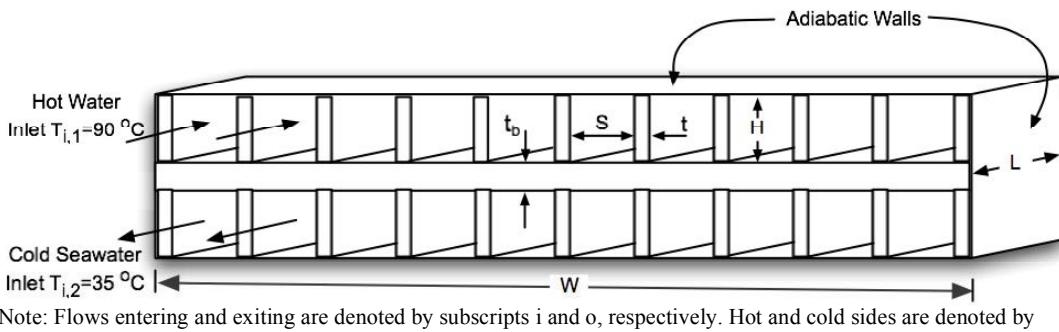
Figure 28. Doubly finned parallel counterflow heat exchanger.

different groups of materials. This range is represented by the following four thermal conductivity values:

- Conventional thermoplastics: 0.25 W/m-K
- Thermally conductive thermoplastics, and certain corrosion resistant metals such as titanium and stainless steel: 20 W/m-K
- Corrosion resistant alloys such as Cu-Ni: 50 W/m-K
- Aluminum alloys: 168 W/m-K

To assess the feasibility of using polymeric heat exchangers, as a first step, the conductive behaviour of the material is assumed isotropic, with the highest directional thermal conductivity assumed to act in the direction of fin height. This assumption can be justified on the basis that the Biot number (~ ht/2k) being small enough (< 0.4) (Bahadur and Bar-Cohen, 2006) to treat the structure as isotropic. This analysis will permit an order-of-magnitude assessment of a polymer heat exchanger performance to be made. Future work will develop a two-dimensional, orthotropic analytical conductive model for a longitudinal rectangular fin.

As shown in Figure 1, the doubly finned wall is enclosed by adiabatic surfaces. The inlet temperatures of the hot fresh water and cold seawater are 90 °C and 35 °C, respectively. Fin thickness, fin spacing, dividing wall thickness, and free-stream velocity are considered as design variables.

4.1 Heat Transfer Analysis

The heat transfer rate is calculated using the ε-NTU method for a counterflow heat exchanger:

$$\dot{q} = \varepsilon C_{min}(T_{i,1} - T_{i,2}) \tag{1}$$

The effectiveness, ε, and number of transfer units (NTU) are computed as:

$$\varepsilon = \frac{1 - \exp[-NTU(1 - C_r)]}{1 - C_r \exp[-NTU(1 - C_r)]} \quad (C_r < 1) \tag{2}$$

The heat transfer capacity, UA, is calculated through the convection and conduction thermal resistances network:

$$UA = \frac{1}{\dfrac{1}{h_1 A_b} + \dfrac{t_b}{k A_b} + \dfrac{1}{h_2 A_b}} + \frac{1}{\dfrac{1}{\eta_f h_1 A_f} + \dfrac{t_b}{k A_{fcs}} + \dfrac{1}{\eta_f h_2 A_f}} \tag{3}$$

It should be noted that thermal resistances due to fouling are not included in this network. Inclusion of a fouling thermal resistance would benefit the heat exchanger thermal resistance comparison in favor of polymers, which are less susceptible to seawater corrosion than metals as previously noted. Therefore, the present estimation of polymer heat exchanger thermal resistance can be considered as conservative.

For the fluid velocity range under analysis, the working fluids exhibit turbulent properties (15,000 < Re < 45,000). The following correlation by Gnielinski (1976) for fully developed turbulent flow is selected:

$$Nu = \frac{(Re-1000)\Pr f/8}{1.0+12.7\sqrt{f/8}(\Pr^{2/3}-1.0)} \qquad 0.5 < \Pr < 2000 \quad 3000 < Re < 5\times10^6 \tag{4}$$

where the friction factor, f, for smooth pipes is calculated using a correlation by Petukhov (1970):

$$f = (0.790\ln Re - 1.64)^{-2} \qquad 3000 \leq Re \leq 5\times10^6 \tag{5}$$

As noted by Incropera and DeWitt (2002) the *à priori* selection of a Nusselt number correlation for a given geometry is subject to some conjecture. Relations which are applicable to a wide range of Reynolds numbers, geometries, and fluids are desirable for parametric analyses, and this was the basis for the selection of this correlation. It has been reported to have an accuracy within ±20% for the conditions under which it was derived. However, its applicability is restricted to hydrodynamic/thermal entry lengths that are not significant relative to channel length. For (L/D) > 60, which is representative of the geometries under analysis, the errors incurred in the predicted Nusselt number are typically less than 15% (Incropera and DeWitt, 2002). In such conditions the average Nusselt number can therefore be approximated to that of the fully developed region. Considering that this correlation will be applied to metallic and polymeric heat exchangers having the same geometries and exposed to the same convective conditions, potential prediction errors will be the same. This therefore permits comparison of exchanger performance on a like by like basis.

4.2 Pumping Power Analysis

The pumping power is defined as the product of the pressure drop and the volumetric flow rate:

$$P = \Delta p \cdot \dot{\forall} = \Delta p\, N u_m SH \tag{6}$$

where the pressure drop, Δp, is the sum of the friction and dynamic (entrance and exit) losses:

$$\Delta p = \left(f\frac{L}{D_h} + K_{L,entry} + K_{L,exit}\right)\left(\frac{1}{2}\rho u_m^2\right) \tag{7}$$

4.3 Parametric Analysis

The coefficient of thermal performance, COP, is defined as the ratio of the heat transfer rate to the pumping power incurred:

$$COP = \frac{\dot{q}}{P} \tag{8}$$

Using the thermal and pressure drop analyses presented in sections 4.1 and 4.2 the following parametric analysis was undertaken for the geometry given in Figure 1 with the analysis parameters shown in Table 4.

Table 4. Analysis parameters for assessment of doubly finned heat exchanger heat transfer rate and COP.

Run	t (mm)	t_b (mm)	H (mm)	$u_1 = u_2$(m/s)	S (mm)	Results
1	1, 2, 4	1	10	2	1 – 12	Figures 2 and 3
2	1, 2, 4	1	5 – 30	2	5	Figures 4 and 5

W = L = 1 m, k = 0.25, 20, 50, 168 W/m.K.

Figure 2 shows that at large fin spacings, the heat transfer rates are becoming less sensitive to both fin thickness and material conductivity. Although the convective area is reduced with increasing fin spacing, the mass flow increases (since fluid velocity is fixed within the passages), thereby reducing bulk heating of the flow.

More importantly, the results in Figure 2 reveal that the thermal conductivity achievable with enhanced thermoplastics, i.e. 20 W/mK, can provide approximately half the heat transfer rate of an aluminum heat exchanger operating under the same conditions, but almost 80% of the heat transfer rate provided by heat exchangers made of corrosion resistant Cu-Ni alloys having thermal conductivities of 50 W/m.K. Figure 2 also shows that the conductivity of conventional plastics (0.25 W/m.K) can provide very limited thermal performance, thereby motivating the need for thermally enhanced polymer materials. At such low conductivity, the addition of fins produces no visible improvement in the heat transfer rate, mainly because of the fins having a high conductive resistance.

In Figure 3, the COP increases with fin spacing, which indicates that pumping power is dropping faster than heat transfer rate. Considering that the reduced sensitivity of the heat transfer rate with increased fin spacing (Figure 2), it is therefore possible to provide the same heat transfer rate at a higher COP. This might be the preferred design solution for polymeric heat exchangers. Therefore, if higher values of COP need to be achieved but without a significant loss in heat transfer rate, the thermal performance gaps between fin thermal conductivity and thickness diminish.

Figure 4 reveals almost the same performance gaps between material thermal conductivities as Figure 2. Figures 2 and 3 show that fin spacing values close to 5 mm yield a heat transfer rate and COP close to their maxima. For this reason, 5 mm is chosen as an apparent optimum spacing. In addition, Figures 4 and 5 demonstrate that improvements in heat transfer rates come at the cost of lower COP values. Thus in
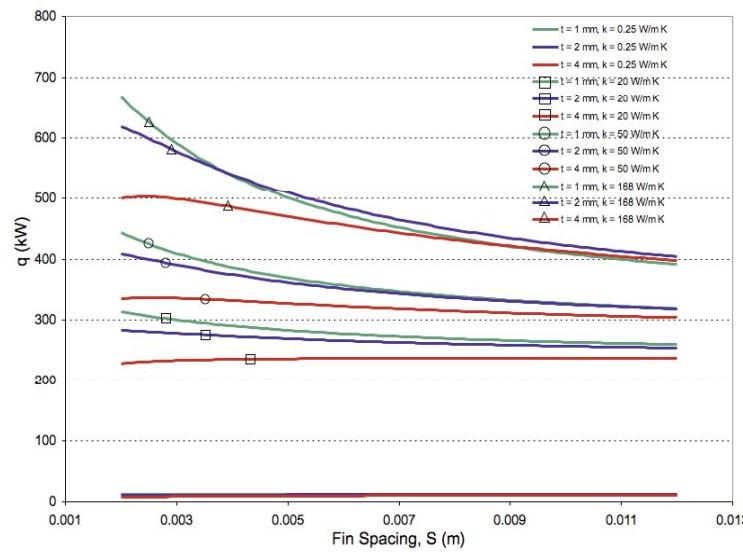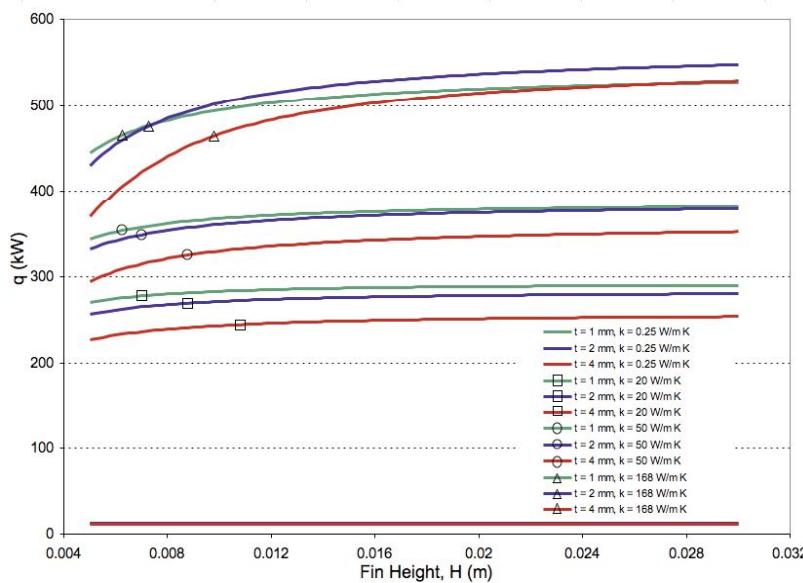

Figure 2. Doubly finned counterflow heat exchanger heat transfer rate as a function of fin spacing and fin thickness (t_b = 1 mm, H = 10 mm, W = L = 1 m, $u_1 = u_2 = 2$ m/s, turbulent flow).
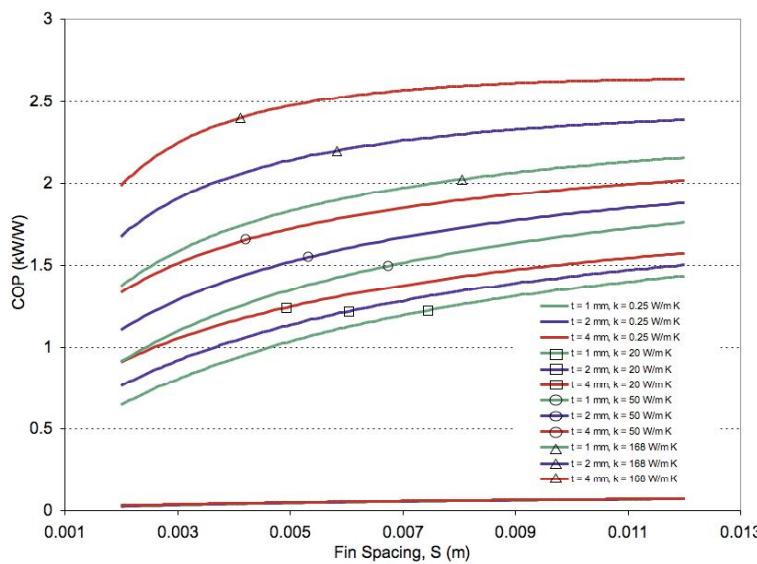
Figure 3 Doubly finned counterflow heat exchanger COP as a function of fin spacing and fin thickness (t_b = 1 mm, H = 10 mm, W = L = 1 m, $u_1 = u_2 = 2$ m/s, turbulent flow).

Figure 4, increasing fin height yields higher values of heat transfer rate up to a certain point, but the pumping power increases with the higher flow rate, as can be seen by the sharp decrease in COP as fin height increases (Figure 5).

Focusing on the thermo-fluid performance of a thermally enhanced thermoplastic (20 W/mK), the surface plots shown in Figures 6 and 7 illustrate the combined effect of fin spacing and fin height on the heat transfer rate and COP, respectively. Figure 6 shows that maximum values for heat transfer rate occur for tall fins, having small spacing. Conversely, maximum values of COP occur for short fin heights with higher fin spacing. It is evident therefore that optimization of these performance metrics comes with a compromise between them.

Figure 4. Doubly finned counterflow heat exchanger heat transfer rate as a function of fin height and fin thickness (t_b = 1 mm, S = 5 mm, W = L = 1 m, u_1 = u_2 = 2 m/s, turbulent flow).
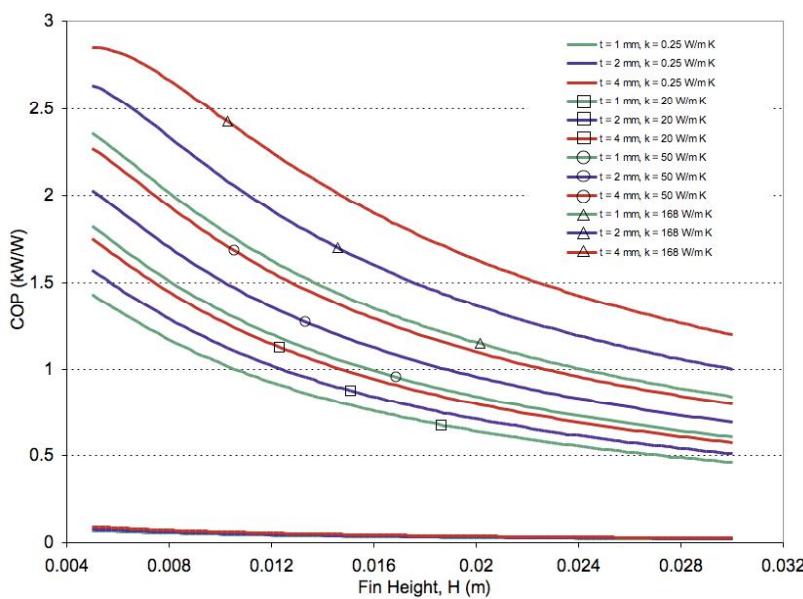

Figure 5. Doubly finned counterflow heat exchanger COP as a function of fin height and fin thickness (t_b = 1 mm, S = 5 mm, W = L = 1 m, u_1 = u_2 = 2 m/s, turbulent flow).

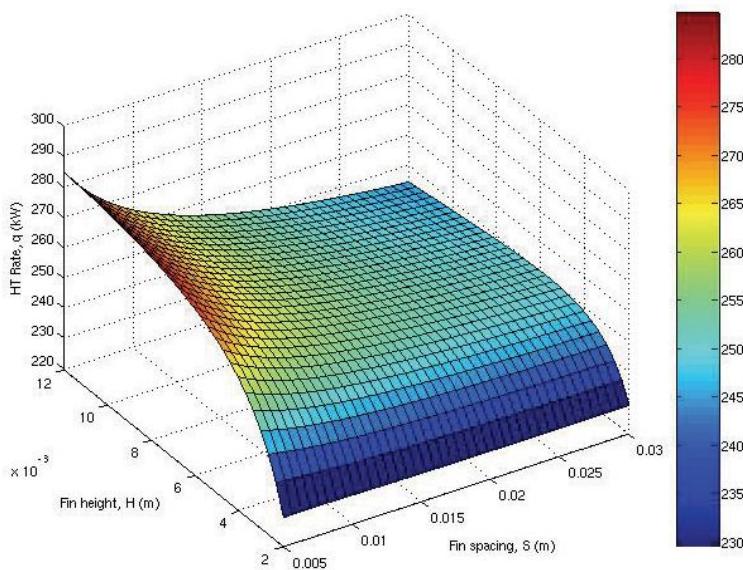Figure 6. Doubly finned counterflow heat exchanger heat transfer rate as a function of fin spacing and fin height ($k = 20$ W/m-K, $t_b = 1$ mm, $W = L = 1$ m, $u_1 = u_2 = 2$ m/s, turbulent flow).
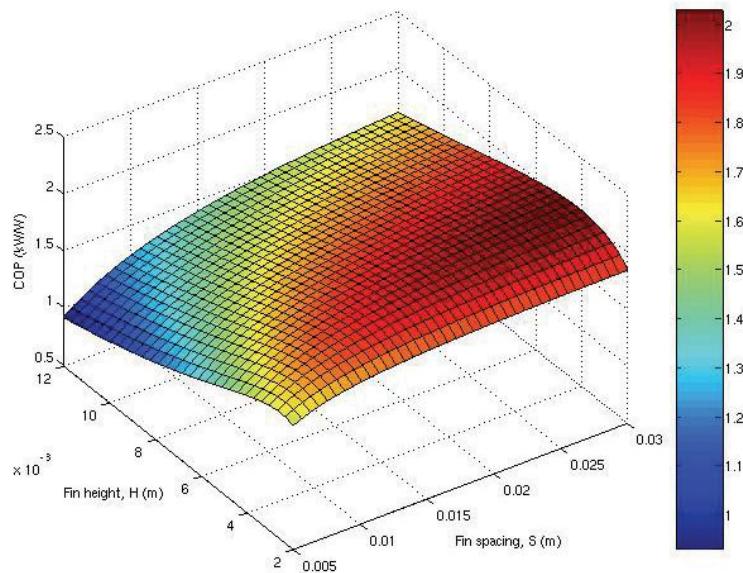

Figure 7. Doubly finned counterflow heat exchanger COP as a function of fin spacing and fin height ($k = 20$ W/m-K, $t_b = 1$ mm, $W = L = 1$ m, $u_1 = u_2 = 2$ m/s, turbulent flow).

5. Conclusions

The use of conventional plastics to fabricate heat exchangers has increased significantly since their introduction to this market more than forty years ago. The physical properties of polymers make them ideal candidates for applications involving highly corrosive or chemically aggressive fluids. While the mechanical strength, service temperature, and rheological considerations of new thermally enhanced thermoplastics could limit the effective design space for polymer heat exchangers, these materials offer thermal conductivities that can be up to 100 times larger than those of conventional plastics, and comparable to those of corrosion-resistant metal alloys.

A parametric thermo-fluid performance analysis of a conceptual doubly-finned plate heat exchanger module, presented in this study, reveals that that the thermal conductivities achievable with enhanced thermoplastics, i.e. 20 W/mK, can provide approximately half the heat transfer rate of an aluminum heat exchanger operating under the same conditions, and 80% of the heat transfer rate provided by a corrosion-

resistant, metallic heat exchanger. It may thus be concluded that thermally conductive thermoplastics offer a most promising alternative to the use of conventional and/or corrosion-resistant metals in compact, high performance heat exchangers in seawater-cooled applications.

Acknowledgments

References

Bahadur, R., and Bar-Cohen, A., 2005, "Thermal Design and Optimization of Polymer-Based Pin Fin Natural Convection Heat Sinks," IEEE Transactions on Components and Packaging Technologies, Vol. 28, No. 2, pp. 238-246.

Bahadur, R., and Bar-Cohen, A., 2006, "Analysis and Design of a Least Material Orthotropic Pin Fin Heat Sinks," Tenth **Intersociety Conference on** Thermal and Thermomechanical Phenomena in Electronics Systems, San Diego, CA, USA, May 28-31, pp. 305-313.

Brite-Euram III, 2001, Design of New Heat-Exchangers made of Polymer (Project BRST985337) [Online]. Available at http://cordis.europa.eu/data/PROJ_BRITE/ACTIONeqDndSESSIONeq6

9132005919ndDOCeq342ndTBLeqEN_PROJ.htm [accessed 24 November 2007].

Cool Polymers, Inc., 2007, Thermally Conductive Polymers [Online]. Available: http://www.coolpolymers.com [accessed 24 November 2007].

GE Plastics, 2007, Engineering Resins [Online]. Available at http://www.geplastics.com [accessed 24 November 2007].

Gnielinski, V., 1976, "New Equation for Heat and Mass Transfer in Turbulent Pipe and Channel Flow," International Journal of Chemical Engineering, Vol. 16, pp. 359-368.

Hart, G. K., Lee, C-O., Latour, S. R., 1979, Development of Plastic Heat Exchangers for Ocean Thermal Energy Conversion, DSS Engineers, Inc., Fort Lauderdale, FL, USA. Technical Report ORO-5165-1.

Incropera, F.P., and DeWitt, D.P., 2002, *Fundamentals of Heat and Mass Transfer*, Fifth Edition, John Wiley & Sons, Inc., New York.

Kern, D. Q., and Kraus, A. D., 1992, *Extended Surface Heat Transfer*, McGraw-Hill, New York.

Miller, D., Holtz, R. E., Koopman, N., Marciniak, T. J., and MacFarlane, D. R., 1979, Plastic Heat Exchangers: A State-of-the-Art Review, ANL-79-12, July 1979.

Ovation Polymers, 2007, Thermally Conductive Compounds [Online]. Available at www.opteminc.com [accessed 24 November 2007].

Petukhov, B. S., (1970), "Heat Transfer and Friction in Turbulent Pipe Flow with Variable Physical Properties," Advances in Heat Transfer, Hartnett, J. P., and Irvine, T. F., (Eds), Vol. 6, Academic Press, New York.

PolyOne, 2007, Specialized Polymer Materials [Online]. Available at http://www.polyone.com [accessed 6 June 2007].

Pugh, S. J., Hewitt, G. F., Müller-Steinhagen, H., 2005, "Fouling During the Use of Seawater as Coolant - the Development of a User Guide," Heat Transfer Engineering, Vol. 26, No. 1, pp. 35-43.

RTP Company, 2007, Engineered Plastic Compounds, [Online]. Available at http://www.rtpcompany.com [accessed 24 November 2007].

Shah, R.K., 2006, "Advances in Science and Technology of Compact Heat Exchangers," Heat Transfer Engineering, Vol. 27, No. 5, pp. 3-12.

Sloan, F. E., and Talbot, J. B., 1992a, "Corrosion of Graphite-Fiber-Reinforced Composites: I -Galvanic Coupling Damage," Corrosion, Vol. 48, No. 10, pp. 830-838.

Sloan, F. E., and Talbot, J. B., 1992b, "Corrosion of Graphite-Fiber-Reinforced Composites: II - Anodic Polarization Damage," Corrosion, Vol. 48, No. 12, pp. 1020-1026.

Zaheed, L., and Jachuck, R. J. J., 2004, "Review of Polymer Compact Heat Exchangers, with Special Emphasis on a Polymer Film Unit," Applied Thermal Engineering, Vol. 24, No. 16, pp. 2323-2358.

Zweben, C. 2004, "Emerging High-Volume Applications for Advanced Thermally Conductive Materials," Proceedings of the 49th International SAMPE Symposium and Exhibition, Long Beach, CA, USA, May 16-20, pp 4061-4072.

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