

Polymer Composite Heat Exchangers

Heike Glade, Dirk Moses and Thomas Orth

Abstract The innovative development of polymer composite tubes exhibiting high thermal conductivities for use in heat exchangers, various aspects for implementing these tubes and designing polymer composite heat exchangers are presented. Polymer composite grades based on polypropylene and polyphenylene sulphide filled with graphite have been developed by Technoform Kunststoffprofile GmbH (Lohfelden, Germany). A special extrusion process allows high filler loadings of up to 60 vol% and the orientation of filler particles in the polymer matrix to reach enhanced thermal conductivities in the radial direction. Thermal and mechanical properties, chemical resistance to various acids and alkaline media, lifetime behaviour, heat transfer performance and fouling behaviour were studied for composites with 50 vol% graphite. The extruded polymer composite tubes have a thermal conductivity of about 13–20 W/(m K) which is around 50–100 times higher than that of standard polymers and is comparable to stainless steel grades. The excellent chemical resistance, low weight, good processability as well as highly promising initial test rig results in fouling studies compared to corrosion-resistant metals open up cost-efficient opportunities for heat exchangers in various industries such as chemical, petrochemical, oil and gas, food and beverage, and seawater desalination industries. Important design aspects such as various possibilities of mounting the polymer composite tubes in the tube plates and the maximum unsupported tube span for avoiding tube failures by flow-induced vibrations are discussed. A potential enhancement of heat transfer by shaping polymer composite tubes other than circular plain tubes and the construction of fully polymer-based heat exchangers will be in the focus of future development.

H. Glade (✉)

Technische Thermodynamik, Fachbereich Produktionstechnik, Universität Bremen,
Badgasteiner Straße 1, 28359 Bremen, Germany
e-mail: heike.glade@uni-bremen.de

D. Moses · T. Orth

Technoform Kunststoffprofile GmbH, Otto-Hahn-Straße 34, 34253 Lohfelden, Germany
e-mail: dmoses@tkp.biz

T. Orth

e-mail: torth@tkp.biz

List of Symbols

Latin Symbols

A	Heat transfer surface area (m^2)
A	Dimensionless tube axial stress multiplier
A	Pre-exponential factor (1/s)
c	Concentration (mol/m^3)
C	Dimensionless constant in Eq. (11)
C_L	Dimensionless lift coefficient
CF	Cleanliness factor
d	Tube diameter (m)
D	Dimensionless parameter in Eq. (10)
E_a	Activation energy (J/mol)
E_t	Modulus of elasticity (Pa)
f_n	Natural frequency (1/s)
h	Heat transfer coefficient ($\text{W}/(\text{m}^2 \text{ K})$)
I	Second moment of area (m^4)
k	Thermal conductivity ($\text{W}/(\text{m K})$)
k_{deg}	Rate constant of polymer degradation (1/s)
L	Unsupported tube span (m)
L_t	Tube length (m)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{Q}$	Heat transfer rate (W)
R	Universal gas constant ($R = 8.314 \text{ J}/(\text{mol K})$) ($\text{J}/(\text{mol K})$)
R_a	Arithmetic mean roughness (μm)
R_f	Fouling resistance ($\text{m}^2 \text{ K}/\text{W}$)
R_z	Mean roughness depth (μm)
s	Tube wall thickness (m)
S	Salinity (g/kg)
t	Time (s)
T	Temperature (K)
u	Fluid flow velocity (m/s)
U	Overall heat transfer coefficient ($\text{W}/(\text{m}^2 \text{ K})$)
y_{vs}	Vortex shedding amplitude (m)
y_{tb}	Turbulent buffeting amplitude (m)

Greek Symbols

α	Linear coefficient of thermal expansion (1/K)
Γ	Wetting rate ($\text{kg}/(\text{s m})$)
δ_T	Dimensionless logarithmic decrement
ϑ	Temperature ($^{\circ}\text{C}$)
ϑ_g	Glass transition temperature ($^{\circ}\text{C}$)
ϑ_m	Melting temperature ($^{\circ}\text{C}$)

ρ	Density (kg/m^3)
σ_m	Tensile strength (Pa)
ϕ	Volume fraction of filler
ω_0	Effective weight of the tube per unit length (kg/m)

Subscripts

0	Initial condition
c	Clean
C	Compound
co	Condensation
crit	Critical
ev	Evaporation
f	Fouling, fouled condition
F	Filler
i	Inner, inside
m	Mean
max	Maximum
o	Outer, outside
P	Polymer
t	At time t
W	Wall

Abbreviations

AAS	Atomic absorption spectroscopy
DVGW	German Technical and Scientific Association for Gas and Water
EDXS	Energy-dispersive X-ray spectroscopy
FEM	Finite element method
FEP	Polyfluoroethylene propylene
HDT	Heat deflection temperature
MED	Multiple-effect distillation
PA 6, PA 66	Polyamides
PB	Polybutylene
PBT	Polybutylene terephthalate
PC	Polycarbonate
PE	Polyethylene
PEEK	Polyetheretherketone
PEEK-GR	Polyetheretherketone-graphite composite
PET	Polyethylene terephthalate
PFA	Perfluoroalkoxy
PP	Polypropylene
PP-GR	Polypropylene-graphite composite
PPO	Polyphenylene oxide

PPS	Polyphenylene sulphide
PPS-GR	Polyphenylene sulphide–graphite composite
PS	Polystyrene
PSU	Polysulfone
PTFE	Polytetrafluoroethylene
PV	Photovoltaic cell
PVDF	Polyvinylidene fluoride
SEM	Scanning electron microscopy
TEMA	Tubular Exchanger Manufacturers Association, Inc.
THB	Transient hot bridge

1 Introduction

Pioneering innovations for heat exchanger materials have not been made for decades. Due to their favourable thermal and mechanical properties, metals such as stainless steel, copper, nickel and aluminium alloys, and titanium are the most common materials of construction for heat exchangers. However, metals may suffer from failure due to corrosion and erosion, especially in aggressive environments. In addition, they have disadvantages in terms of weight and cost and they are prone to fouling.

Against this background, it is a major concern of various industries to find alternative materials for heat exchangers that can overcome these disadvantages and also acquire heat exchange efficiency and can be easily manufactured. Driven by the high corrosion resistance, low density, low cost and ease of manufacture of many polymer materials, considerable attention has been dedicated to the development and implementation of polymer heat exchanger technology for the past decades (Cevallos et al. 2012). However, the major drawback of polymer materials for using them in heat exchange applications is their very low thermal conductivity.

There are two main approaches to lower the relatively high heat conduction resistance offered by polymeric walls in heat exchangers. One approach is to reduce the wall thickness leading to thin polymer films with a thickness of lower than 100 μm . The use of thin polymer films requires a new heat exchanger design. The development of conceptual design criteria for innovative polymer film heat exchangers is presented in the chapter of Bart et al. in this book. The other approach aims at filling the polymer matrix with thermally conductive material and thereby increasing the overall thermal conductivity of the composite, which allows the competitive application of polymer composites in well-known and reliable heat exchanger types, such as shell and tube heat exchangers.

The shell and tube heat exchanger is by far the most common type of heat exchanger used in various industries such as chemical, petrochemical, oil and gas, power generation and process industries (Thulukkanam 2013; Müller-Steinhagen 2010; Hewitt et al. 1994). Tubular heat exchangers are also commonly used for

evaporation and condensation duties. If polymer-based tubes with a low thermal conductivity were used in evaporators and condensers with very high heat transfer coefficients on the evaporation and condensation side, the high thermal resistance of the tube wall would be the dominating thermal resistance leading to very low overall heat transfer coefficients and poor thermal performance of the heat exchanger. Thus, a high thermal conductivity of polymer-based tubes is especially important in evaporation and condensation applications.

Polymer matrix composite materials open up new opportunities to create a huge number of new material systems with enhanced thermal properties or other unique characteristics that cannot be obtained using a single monolithic material. Composite materials hold tremendous promise for heat exchanger materials which can be tailored to meet the specific requirements of an application (Chen et al. 2016b; T'Joel et al. 2009).

The prices of the highly corrosion-resistant metals typically used for heat exchanger tubes such as copper–nickel, aluminium brass and titanium have increased enormously throughout the past few decades, and the accompanying strong price fluctuations present a high risk for cost calculations. Furthermore, the high demand for some metals on the global market can lead to serious delays in delivery. As an example, Fig. 1 displays the high and fluctuating costs of aluminium brass, a commonly used tubing material. Polymer composites can be a promising alternative. In comparison, polypropylene and graphite, which can be used as filler, had lower and less fluctuating prices in the last years.

Despite the growing interest in thermally conductive polymer composites, which is clear from recent comprehensive reviews (e.g. Burger et al. 2016; Chen et al. 2016a), the manufacture of polymer composite tubes with enhanced thermal conductivities by extrusion processing has been scarcely investigated and little attention has been paid in the literature.

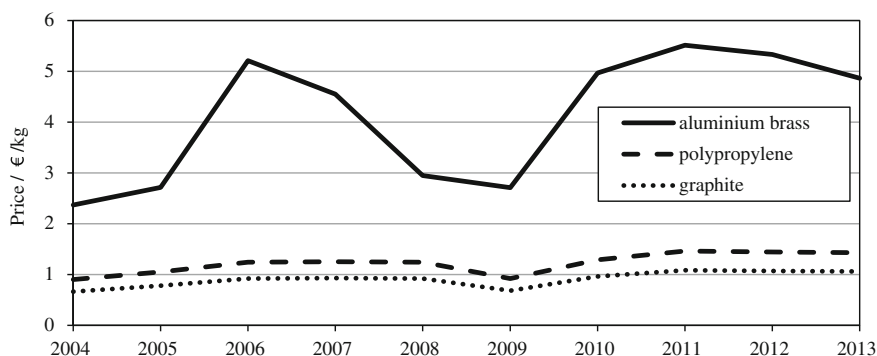


Fig. 1 Material prices for aluminium brass, polypropylene and graphite over time (price of aluminium brass is based on the prices of the main alloying elements assuming 76% copper, 22% zinc, 2% aluminium) (The London Metal Exchange 2014; Kunststoff Information 2014)

For the extrusion of thermally conductive polymer composite tubes, both advanced polymer compounds and an advanced extrusion process are necessary. Technoform Kunststoffprofile GmbH in Lohfelden, Germany, has developed polymer composite tubes exhibiting high thermal conductivities for use in heat exchangers.

After a short overview of the state of research and development of polymer-based heat exchangers, the innovative development of high-performance polymer composite tubes for use in heat exchangers, various aspects for implementing these tubes and designing polymer composite heat exchangers are presented. In Sect. 3.1, the selection of the appropriate polymer matrix and the filler material is shown. The enhanced thermal conductivity of the composite tubes is due to filler orientation during the advanced extrusion process which is described in Sect. 3.2. Thermal and mechanical properties of the polymer composites, which are important for the design of heat exchangers, are presented in Sects. 4.1 and 4.2. Studies of the lifetime behaviour are presented and discussed in Sect. 4.3. Furthermore, the chemical resistance of the novel polymer composites to various acids and alkaline media is discussed in Sect. 5. In the course of the development of the thermally conductive polymer composite tubes, heat transfer was studied in a horizontal tube falling film evaporator at pilot plant scale at the University of Bremen in order to test the tubes under process conditions which are close to those in industrial plants. Furthermore, the fouling propensity of the novel polymer composite tubes was studied in a stirred vessel test rig and in the horizontal tube falling film evaporator and compared to that of metal tubes. In Sect. 6, experimental results are shown for two different test solutions, namely calcium sulphate solution and seawater. Furthermore, important design aspects such as various possibilities of mounting the polymer composite tubes in the tube sheets and the maximum unsupported tube span for avoiding tube failures by flow-induced vibrations are described and discussed in Sects. 7.1 and 7.2. As the polymer extrusion process offers a high degree of freedom in design, a future perspective to a potential enhancement of heat transfer by forming polymer composite tube shapes other than circular plain tubes is given in Sect. 7.3. Potential applications for polymer composite heat exchangers are summarized in Sect. 8.

2 Polymer-Based Heat Exchangers

In the following, the main differences between polymers and metals which are relevant for the use in heat exchangers are described. A short overview of polymer heat exchangers and polymer composites and their applications is given. As the formation of deposits on heat transfer surfaces is a severe problem in heat exchangers and the construction material plays a major role in the fouling process, research studies comparing fouling on polymer and metal surfaces are reviewed below.

2.1 Comparison of Polymers with Metals for Use in Heat Exchangers

Polymers which are currently used in heat exchanger applications are mainly thermoplastics. The macromolecules in thermoplastic polymers are held together by relatively weak intermolecular forces. Unlike thermosets and elastomers, the chains are not cross-linked. Thus, thermoplastics can be repeatedly softened by heating and solidified by cooling as long as the material is not thermally damaged by overheating. Thermoplastics have a wide range of applications because they can be formed and reformed in many shapes and demonstrate a high level of modification potential. They are typically used to produce parts by various polymer processing techniques such as injection moulding and extrusion (Halary et al. 2011; Osswald et al. 2006).

If thermal, mechanical and chemical properties of polymer materials are compared with those of metals, crucial differences can be found.

Polymers have a very low density between 800 and 2200 kg/m³ compared to metals and metal alloys commonly used in heat exchangers with densities between 2700 and 9000 kg/m³ (Halary et al. 2011; Osswald et al. 2006). In conjunction with lower cost per unit mass, polymer lightness is the main factor that was responsible for the development of polymers over the recent decades (Halary et al. 2011). If the heat transfer surface material has a low weight, wall thicknesses of the supporting elements, e.g. tube sheets, stiffener in the shell, might be reduced as well leading to further weight and cost savings. Moreover, the advantage of the low weight reduces the handling and transportation costs and CO₂ emissions compared to metal heat exchangers (Chen et al. 2016b).

The most striking difference between polymer and metal materials for use in heat exchangers is the thermal conductivity. Conventional polymers have thermal conductivities in the range of 0.1–0.5 W/(m K) (Chen et al. 2016a) which are between 100 and 1000 times lower than those of most metals used in heat exchangers. However, in heat exchanger applications with corrosive fluids only corrosion-resistant metals, e.g. copper–nickel alloys or titanium, can be used. These metals can be very expensive. In order to compare polymers with metals for the application in heat exchangers, it is worth considering the thermal conductivity, the weight per unit heat transfer surface and the costs of the materials (Chen et al. 2016b). Zaheed and Jachuck (2004) compared these parameters for a reference heat exchanger and concluded that a tube bundle of polyvinylidene fluoride (PVDF) has to be six times larger than a tube bundle made of nickel–chromium–molybdenum (Ni–Cr–Mo) alloy, but the weight of the Ni–Cr–Mo tube bundle will be around five times larger. They concluded that the Ni–Cr–Mo alloy will cost 2.5 times as much as a PVDF tube bundle, if all other conditions remain equal.

Metals have very high melting points (>1000 °C). However, the maximum allowable stress and the maximum allowable internal pressure decrease with increasing temperature. Thus, the operating limits are assumed to be 180 °C for aluminium brass, 300 °C for copper–nickel 90/10 and 370 °C for copper–nickel 70/30 (Shinko 2017). A corrosive environment further reduces the operating limits for

metal tubes. High-temperature heat exchangers require costly materials such as nickel-based alloys which can be used up to temperatures in the range of 750 °C (Sunden 2005). Characteristic temperatures which determine the application limits of a polymer are the heat distortion or heat deflection temperature (HDT) and the service temperature. The heat deflection temperature of a polymer is the temperature under which a deflection of 0.2% is achieved under a specific bending stress, e.g. 1.8 MPa for the frequently used HDT-A procedure. The deflection temperature provides an indication of the maximum temperature in use for mechanically loaded components.

The service temperature of a polymer provides information about the thermal stability. The maximum long-term service temperature is the maximum temperature above which the properties of the polymer are significantly degrading. There is a wide range of polymers with maximum long-term service temperatures between about 60 and 260 °C (Osswald et al. 2006). The short-term service temperature is the peak temperature which the polymer can tolerate over a short period (from minutes to occasionally hours) without being damaged. The long-term service temperature of the polymer has to be higher than the operating temperature of the heat exchanger. Additionally, heat stabilizers, modifiers and other additives in the polymer material can influence the service temperature.

In combination with the operating temperature of the heat exchanger, thermal expansion is also important. The linear coefficient of thermal expansion, which is defined as the fractional change in length per degree of temperature change, is inversely proportional to the bond strength of the material and, thus, to the melting point of the material. Polymers with weak intermolecular bonds (low melting points) have very high expansion coefficients, whereas metals with high melting points (strong bonding) have low thermal expansion coefficients. The linear coefficients of thermal expansion of polymers are in the range of 40×10^{-6} to 250×10^{-6} 1/K (Osswald et al. 2006), while those of metals are in the range of 9×10^{-6} to 24×10^{-6} 1/K (Müller-Steinhagen 2010). Thus, polymers tend to thermally expand about 2–28 times more than metals. The linear coefficient of thermal expansion is of interest to design engineers, because a thermal expansion difference leads to internal stresses in the polymer which allows premature failure to occur. Therefore, thermal expansion can have a significant influence and should be considered in the design of polymer heat exchangers.

The yield tensile strengths of polymers and metals show significant differences. The maximum yield tensile strength of unfilled polymers is about 95 MPa for polyetheretherketone (PEEK) which is notably lower than the yield tensile strength of corrosion-resistant metals, for example 276–448 MPa for titanium grade 2 and 103 MPa for copper–nickel 90/10 (MatWeb 2017). The relatively low strength of the thermoplastic polymers might limit the minimum thickness that could be achieved to minimize the heat conduction resistance of the wall without compromising the physical integrity of the heat exchanger structure (Chen et al. 2016b).

Most importantly, many polymers exhibit a high corrosion resistance to acids, alkaline media, solvents and corrosive fluids, whereas metals suffer from corrosion and erosion. Moreover, in conventional heat exchangers, dissimilar metals are often coupled and exposed to an electrolyte and, thus, damage by galvanic corrosion

might occur. The corrosion process of metals is mainly caused by electrochemical reactions. Polymers do not experience this kind of corrosion. They are usually completely resistant to a specific corrodent within specific temperature ranges, or they deteriorate rapidly (Schweitzer 2007). Therefore, many polymers can be used under conditions where metals corrode, if the polymer is properly selected. However, polymer materials can also be attacked, for example, by ultraviolet radiation, oxidation, hydrolysis, degradation involving absorption or permeation or by thermal degradation (Schweitzer 2007).

Furthermore, polymers offer the advantages of greater geometric flexibility and ease of manufacturing (Chen et al. 2016b). One of the great advantages of polymers is the low energy required during manufacturing. Melting, shaping and solidification all take place in an integrated fashion (Osswald et al. 2006). The energy required to produce a unit mass of polymers is about two times lower than that for common metals, making them environmentally attractive (El-Dessouky and Ettouney 1999).

From an environmental point of view, there is a further disadvantage of the use of metal materials compared to polymers. Heavy metals are claimed to be a major pollutant of seawater desalination plant discharge during normal plant operation and during acid cleaning (Lattemann and Höpner 2003). Copper–nickel alloys are common heat exchanger materials in seawater desalination plants. Corrosion of these materials causes the contamination of reject streams with copper and nickel. Elevated copper concentrations in the reject streams between 15 and 100 µg/l have been reported (Lattemann and Höpner 2003). Based on rare published data, Lattemann (2010) estimated the discharge of copper of desalination plants into the Persian Gulf, which has the world's highest density of desalination plants, to be 296 kg per day (Lattemann 2010).

2.2 *Polymer Heat Exchangers*

Most applications of polymer heat exchangers deal with highly corrosive environments (CALORPLAST 2017; Chen et al. 2016b; T'Joel et al. 2009), such as:

- Heating and cooling of tanks and vessels in the electroplating industry;
- Heating and cooling of acids;
- Energy recovery from aggressive exhaust gases, e.g.
 - in surface technology, chemical and electronics industries,
 - ventilation of chemical plants and laboratories,
 - air conditioning in agriculture and livestock farming,
 - exhaust air treatment in electroplating,
 - cleaning and drying of biogas;
- Heating and cooling of aggressive exhaust gases from scrubbers, e.g. in drying technology, chemical metal processing, waste incineration;

- Ventilating installations in clean-room technology;
- Condensation of vapours in the chemical and pharmaceutical industries and for the recovery of solvents;
- Evaporative/desiccant cooling;
- Solar water heating systems;
- Seawater applications in marine, aqua zoos, air conditioning;
- Electronic cooling devices.

Polymers which are currently used in heat exchanger applications are mainly thermoplastics such as PVDF, polytetrafluoroethylene (PTFE), polypropylene (PP), polyethylene (PE), polycarbonate (PC), polyphenylene sulphide (PPS), polyphenylene oxide (PPO) and perfluoroalkoxy (PFA) (CALORPLAST 2017; Chen et al. 2016b).

Current research on heat transfer performance of polymer heat exchangers is mainly focused on shell and tube heat exchangers, but plate heat exchangers, finned tube heat exchangers, immersed tube heat exchangers and hollow fibre heat exchangers are also considered (Chen et al. 2016b).

The overall heat transfer coefficient obtained with polymers is usually smaller than that obtained with metals. It lies between 250 and 550 W/(m² K) depending on the type of polymer, the media and the temperatures. This disadvantage is offset by a larger surface area obtained by using many small tubes. The outside diameter of polymer tubes is often between 2 and 8 mm (Scholz 2004). Zarkadas and Sirkar (2004) proposed a polymeric hollow fibre heat exchanger for lower temperature and pressure applications. They tested the performance of the polymeric hollow fibre heat exchanger and achieved overall heat transfer coefficients between 647 and 1314 W/(m² K) for water–water systems.

Heat exchangers with unfilled polymers are applied in niche markets where only highly corrosion-resistant and very expensive metals could be used and/or where the low thermal conductivity of the polymer will not significantly reduce the overall heat transfer coefficient because the heat transfer coefficient on one side of the heat transfer surface is very low like in energy recovery systems from exhaust gases. Their lower thermal performance compared to that of metal heat exchangers has prevented the widespread use and acceptance of polymer heat exchangers.

More detailed information about polymer heat exchangers can be found in reviews by Boeck (2011), Cevallos et al. (2012), Chen et al. (2016b), T'Joel et al. (2009) and Zaheed and Jachuck (2004).

2.3 Thermally Conductive Polymer Composites and Their Applications

While polymers generally have a very low thermal conductivity limiting their use in heat exchanger applications, this drawback can be alleviated by adding a thermally conductive filler material to the polymer matrix. An overview of recent research

developments in thermally conductive polymer composite materials is given by Burger et al. (2016) and Chen et al. (2016a, b).

Both thermosetting polymers (e.g. epoxy, vinylester, polyester) and thermoplastics (e.g. polyamide, polypropylene) are used as the matrix material in polymer composites (T'Joen et al. 2009). Metallic fillers such as nickel, copper, aluminium, silver and carbon-based materials, including graphite, graphene, carbon-nanotubes, carbon fibre, and ceramic fillers such as hexagonal boron nitride, aluminium nitride, silicon nitride, silicon carbide and alumina can be used in polymer composites for improving the thermal conductivity (Chen et al. 2016a). Major fillers for polymer matrix composites are particles, flakes, fibres and laminas (Chen et al. 2016b).

The thermal conductivity of polymer composites depends on the thermal conductivity of the polymer, of the filler and the filler volume fraction (filler loading). The filler type, size and shape, the filler morphology (dispersed individual particles, aggregates, fractal clusters, percolated network, etc.), anisotropy (particularly in the case of non-spherical filler particles), adhesion between the filler and matrix, properties of filler–matrix interfaces and effects of processing history have strong influence on the thermal conductivity of polymer composites (Chen et al. 2016a). Figure 2 shows the relationship between properties of the polymer composite and filler content. Unlike the electrically conductive behaviour, there does not seem to be a clear percolation threshold for thermally conductive composites. In general, thermal conductivity of composites increases with increase in the volume fraction of the thermally conductive filler. The increase is often nonlinear (Bigg 1986). At lower filler loading levels (<35 vol%), the thermal conductivity increase can be relatively small. High thermal conductivities can only be achieved at high filler loadings, when thermally conductive pathways start to form due to filler-to-filler connections (Chen et al. 2016a).

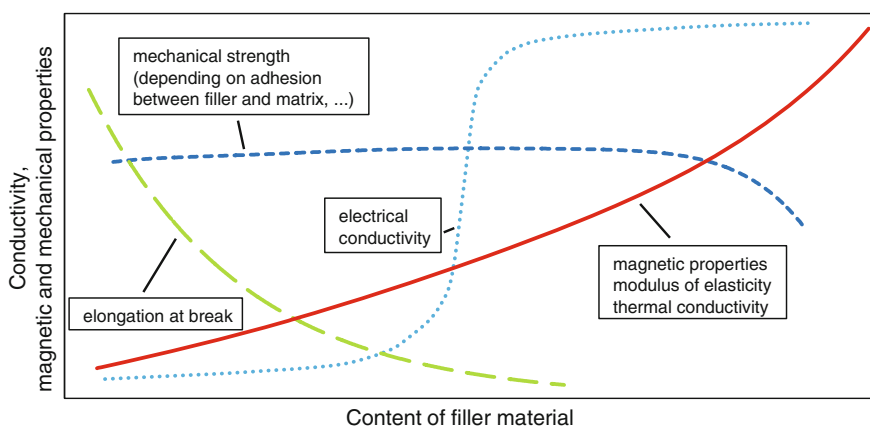


Fig. 2 Relationship between properties of polymer composites and filler content (based on Amesöder 2010 and Heinle 2012)

However, high filler loading normally causes a significant increase in the viscosity of composites and makes it more difficult for composites to be processed by conventional polymer processing techniques. Furthermore, a high filler loading level can cause the composite to be brittle (Chen et al. 2016a). Figure 2 shows that the thermal conductivity increases with the volume content of the filler, while the mechanical strength may decrease at high filler loadings; i.e., a trade-off between mechanical strength and thermal conductivity must be made.

Research and development has mainly been focussed on thermally conductive polymer composite parts produced by injection moulding for the thermal management of electronic devices, batteries and photovoltaic (PV) cells (Amesöder 2010; Amesöder et al. 2007; Burger et al. 2016; Chen et al. 2016a; Heinle 2012; Übler 2002). Performance, lifetime and reliability of electronic devices depend on their thermal management. With the miniaturization, integration and functionalization of electronics and their usage in more diverse applications such as three-dimensional chip stack architectures, flexible electronics and light emitting diodes, thermal dissipation becomes a central issue (Chen et al. 2016a). Furthermore, batteries become more powerful and are utilized in many new applications. The thermal management is one of the challenging problems in their growing use. Moreover, it is desired to remove the heat from the surface of PV cells in order to increase their conversion efficiency (Chen et al. 2016a).

However, the manufacture of polymer composite tubes with enhanced thermal conductivities by extrusion processing has been scarcely investigated and little attention has been paid in the literature. Öztürk (2012) investigated the maximum filler content in a PA 6-graphite compound for extrusion and injection moulding and found that the maximum content of graphite was about 35 vol%. The extrusion of polymer tubes with high filler loadings and the enhancement of thermal conductivities in the radial direction are challenging tasks.

Boeck (2011), Chen et al. (2016a), Lin et al. (1993) and Progelhof et al. (1976) reviewed various models for predicting the thermal conductivity k_C of thermally conductive polymer composites. For a two-component composite, there are two simple approaches assuming that the materials are arranged either in parallel or in series with respect to heat flow. In the parallel model, the thermal resistances are arranged in parallel

$$k_C = (1 - \phi) k_P + \phi k_F \quad (1)$$

with the thermal conductivity k_P of the polymer matrix, the thermal conductivity k_F of the filler and the volume fraction ϕ of the filler.

In the series model, the thermal resistances are arranged in series

$$\frac{1}{k_C} = \frac{(1 - \phi)}{k_P} + \frac{\phi}{k_F}. \quad (2)$$

Considering that the actual value of conductivity must be located somewhere between these extremes, the use of a weighted geometric mean of the thermal conductivities of the two components was proposed as

$$k_C = k_p^{(1-\phi)} k_f^\phi. \quad (3)$$

Most of the experimental results were found to fall somewhere between the parallel and the series model. The series model is usually closer to the experimental data as compared with the parallel model (Chen et al. 2016a). Nielsen (1973) took the shape of the filler particles into account. Eucken (1932) applied an approach by Maxwell (1873) for electric and magnetic properties to the thermal conductivity of spherical, non-interacting particles. The assumption of separated particles is not valid for highly filled composites where contacts are likely to occur, possibly leading to thermally conductive paths (Chen et al. 2016a). Bruggeman (1935) used a mean field approach to describe the interactions among the randomly distributed fillers. For composites with low filler loading, Maxwell–Eucken and Bruggeman models give very similar predictions. For composites with high filler loading and in those systems where thermally conductive fillers form percolated pathways, the Maxwell–Eucken model under-predicts the thermal conductivity of the composite, while the Bruggeman model can describe experimental data reasonably well (Chen et al. 2016a). Cheng and Vachon (1970) assumed a parabolic distribution of the filler. Based on experimental studies on polymer composites with carbon-based fillers, Agari and Uno (1985) developed a model using a parameter which describes the fraction of the particles forming conductive chains and a parameter which describes the effect of the particles on the structure of the polymer. The two new parameters can only be obtained by regression from experimental data.

Chen et al. (2016a) concluded that analytical models have two types of uncertainties. First, morphology in real applications is different from the idealized cases used in the models (monodisperse spherical fillers; perfectly aligned or perfectly isotropic cylinders, etc.). Secondly, the models are unable to describe effects such as interfacial thermal resistance.

2.4 Fouling on Polymer Surfaces

One of the biggest problems in heat exchangers is the unwanted deposition of materials on the heat transfer surfaces, which is called fouling. In most industrial processes, heat exchanging fluids contain dissolved or suspended material, or provide conditions favourable for the growth of biological organisms which may cause fouling (Müller-Steinhagen 2010). Since the thermal conductivity of the deposit is generally low, the fouling layer creates an additional resistance to heat transfer deteriorating the performance of the heat exchanger.

For the common case of a cylindrical tube with fouling at both the inside and outside surface, the total thermal resistance to heat transfer between the two fluid streams is given by

$$\frac{1}{U_f A} = \frac{1}{h_i A_i} + \frac{R_{f,i}}{A_i} + \frac{s}{k_w A_m} + \frac{R_{f,o}}{A_o} + \frac{1}{h_o A_o}, \quad (4)$$

where U_f is the overall heat transfer coefficient under fouled conditions, h_i is the heat transfer coefficient on the inside, h_o is the heat transfer coefficient on the outside, k_w is the thermal conductivity of the tube wall, $R_{f,i}$ and $R_{f,o}$ are the fouling resistances on the inside and outside surfaces, respectively, s is the tube wall thickness, A_i is the inner heat transfer surface area, A_o is the outer heat transfer surface area, and A_m is a mean heat transfer surface area.

The fouling resistance reduces the overall heat transfer coefficient U_c under clean conditions. Thus, it leads to a decrease of the heat duty of an existing heat exchanger or to an additional surface requirement in the design of a new heat exchanger.

The percentage of the additional surface area for a fixed heat duty increases with increasing heat transfer coefficient U_c for a clean surface, as shown in the equation

$$\frac{A_f}{A_c} = 1 + U_c R_f, \quad (5)$$

where A_f is the required heat transfer surface area under fouled conditions and A_c is the heat transfer surface area under clean conditions. Hence, the impact of the fouling resistance is more severe for heat exchangers with high overall heat transfer coefficients.

Fouling on heat transfer surfaces has a highly deleterious effect on specific energy consumption and production capacity. To account for unreliable design procedures and operational problems, heat exchangers are typically oversized by 70–80%, from which 30–50% is attributed to fouling (Müller-Steinhagen 2010). The installation of additional heat transfer surface may extend the operation time of heat exchangers, but it provides no remedy against the deposition of unwanted material. Fouling mitigation measures, e.g. the pre-treatment of the feed water, and regular cleaning will still be required in most cases (Müller-Steinhagen 2010). Furthermore, the formation of deposits on heat transfer surfaces may cause an increase in the frictional pressure drop due to restricted cross-sectional area and increased surface roughness.

Fouling mitigation methods include preventing foulants from forming, preventing foulants from adhering to themselves and to other surfaces, removing deposits from surfaces and inducing the formation of foulants on a sacrificial surface/matter (Sheikholeslami 2007). Fouling prevention can be divided into operational strategies such as limiting temperatures and concentrations, using high flow velocities, pre-treatment of the feed water by removing the foulant from the stream or by adding anti-fouling chemicals, and design strategies including

modifications to surface characteristics and to unit geometry and configuration. After being formed, fouling layers can be removed from heat transfer surfaces by chemical and mechanical cleaning methods which can be used on-line such as adding cleaning agents or using sponge ball cleaning systems or off-line such as flushing with acid or cleaning with water jets (Müller-Steinhagen 2010; Sheikholeslami 2007).

Over-sizing the heat transfer surface area, fouling mitigation measures, cleaning methods as well as production losses during plant shutdown for cleaning create considerable capital, operating and maintenance costs. Therefore, achieving effective fouling mitigation is a major concern in various industries.

The mechanisms of heat exchanger fouling are divided into five major categories with regard to the key physical/chemical processes, namely crystallization fouling, particulate fouling, chemical reaction fouling, surface reaction (corrosion) fouling and biological fouling. In industrial processes, mixed fouling occurs, i.e. two or more fouling mechanisms occur at the same time, nearly always being mutually reinforcing (Müller-Steinhagen 2010; Sheikholeslami 2007).

Crystallization fouling often occurs in heat exchangers, especially with aqueous solutions. It can be subdivided into precipitation and solidification. The most prevalent type of crystallization fouling is precipitation and deposition of dissolved salts which become supersaturated at the heat transfer surface, also referred to as scaling. The solubility of salts exhibiting an inverse solubility decreases with increasing temperature. Therefore, these salts have a tendency to precipitate on heated surfaces. Salts with a normal solubility tend to precipitate on cooled surfaces. Thus, supersaturation can be caused by heating or cooling, evaporation of solvent, mixing of process streams with different compositions and variation of pH (Müller-Steinhagen 2010).

Generally, the above fouling mechanisms occur in five consecutive steps (Müller-Steinhagen 2010): (i) induction period, (ii) mass transport, (iii) formation of deposit, (iv) removal or auto-retardation and (v) ageing.

When a new or cleaned heat exchanger is brought into operation, the initially high heat transfer coefficients may remain unchanged for a certain time. The induction period is the period of time observed before the formation of a fouled layer takes place. During this time, nuclei for crystallization are formed or nutrients for biological growth are deposited. This delay period may last from few seconds to several days (Müller-Steinhagen 2010).

There are many factors influencing fouling. They can be classified into the following three major categories (Geddert et al. 2009; Zhao and Chen 2011):

- Operating parameters (surface and bulk temperature, pressure, heat flux, and fluid dynamics such as flow velocity, flow regime);
- Solution composition (components, concentrations, pH, supersaturation, and suspended particles); and
- Heat exchanger characteristics (surface free energy, topography, surface roughness).

In addition to the selection of the heat exchanger type, the proper selection of the heat exchanger material is the second most important point (Müller-Steinhagen 2010). The main characteristics of the surface with regard to fouling are roughness, hydrophilicity and hydrophobicity, surface free energy, surface charge and chemical inertness. Thus, the choice of heat transfer surface material affects the wettability, the adhesion forces between surface and deposit as well as the induction period of fouling (Sheikholeslami 2007).

Fouling on metal surfaces has been extensively studied (e.g. Krömer et al. 2015; Müller-Steinhagen 2000; Sheikholeslami 2007; Stärk et al. 2015; Stärk et al. 2017). Although there is a growing interest in polymer materials for heat exchangers, fouling data for polymer surfaces are very limited (Wu et al. 2009). Most studies about fouling on polymer surfaces are concerned with crystallization fouling. Table 1 gives an overview of studies which compared the fouling behaviour on polymer and metal surfaces.

Förster (2001) investigated the induction period of calcium sulphate (CaSO_4) on several metal surfaces and polymer surfaces such as polyfluoroethylene propylene (FEP), PFA and PTFE. Experiments were performed in electrically heated flow channels with a rectangular and an annular geometry. Förster (2001) found that some metals have a shorter or a similar induction period, while others have a longer induction period than the polymers. He stated that the fouling curves disproved the common perception that polymers having a low surface energy are necessarily less prone to fouling than metals with a higher surface energy. The strong fouling propensity was explained by the surface topography of the polymer surfaces.

Motivated by the growing interest in the use of polymer heat exchangers and absorbers in solar heating systems, Wang et al. (2005) performed an experimental study of calcium carbonate (CaCO_3) scale formation on copper, polyamide 66 (PA 66), polybutylene (PB), PP and PTFE tubes exposed to tap water which was supersaturated with respect to CaCO_3 . Except for PA 66, the rate of CaCO_3 scale formation on the polymer surfaces was similar to that on copper. The PA 66 substrate appeared to enhance scaling which was attributed to the hydrolysis of the substrate.

An experimental study of scale formation on copper and PP tubes exposed to tap water at 40 °C and supersaturated with respect to CaCO_3 and to calcium phosphate was performed by Wu et al. (2009). The study was motivated by the interest in switching from copper to polymer materials in heat exchangers and absorbers used in solar water heaters. The quantity of Ca-rich scale was greater on copper than on PP tubes. Wu et al. (2009) concluded that the copper surface was oxidized during exposure to tap water and the oxidized copper surface was more susceptible to calcium phosphate scaling than the PP tube surface.

In another study, Wu et al. (2010) investigated the formation of calcium carbonate on the surface of PP and copper tubes by exposing the tubes to a laminar flow of distilled water at room temperature and supersaturated with regard to CaCO_3 . In contrast to their previous study (Wu et al. 2009) with supersaturated tap water containing various ions, the induction period for the PP tubes was shorter and more calcium carbonate formed on the PP tubes compared to the copper tubes.

Table 1 Overview of previous studies about crystallization fouling on polymer surfaces compared to metal surfaces

Reference	Polymers investigated	Reference material	Model solutions	Fouling parameters investigated	Fouling propensity of polymers	Explanation for fouling propensity
Förster (2001)	FEP, PFA, PTFE	Several metals	Oversaturated CaSO_4 solution	Induction period	+/o	Increased roughness of the polymers
Wang et al. (2005)	PA 66, PB, PP, PTFE	Copper	Tap water oversaturated concerning CaCO_3	Fouling rate	o/+	Hydrolysis of PA 66
Wu et al. (2009)	PP	Copper	Tap water oversaturated concerning CaCO_3 and $\text{Ca}_3(\text{PO}_4)_2$	Fouling rate	–	Surface reaction of phosphate ions on oxidized copper surface
Wu et al. (2010)	PP	Copper	Oversaturated CaCO_3 solution	Fouling rate	+	Increased roughness of polymer, surface chemistry, interfacial energy effects
Kazi et al. (2010)	PC	Stainless steel	Oversaturated CaSO_4 solution	Fouling rate	–	Decreased surface free energy and thermal conductivity of the polymer
Dreiser (2016)	PEEK, PSU	Stainless steel	Oversaturated CaCO_3 solution, oversaturated CaSO_4 solution	Induction period, asymptotic fouling resistance	o/–	Decreased roughness of the polymer, surface energy effects

Increased (+), decreased (–) or same (o) fouling propensity of the polymer surface compared to that of the metal surface

The authors assumed that the slightly higher surface roughness of the PP tubes, differences in surface chemistry and interfacial energy and the inhibition effect of copper ions released by the copper surface on CaCO_3 formation were responsible for the differences in the fouling behaviour.

Kazi et al. (2010) compared the rates of CaSO_4 scale formation on the outside of a polycarbonate (PC) tube and a stainless steel tube. The tubes were immersed in a stirred vessel with a CaSO_4 solution, while hot water was flowing through the tubes. The deposition rate of CaSO_4 was found to be lower on the PC tube than on

the stainless steel tube which was explained with the lower thermal conductivity and the lower surface energy of the PC tube.

For the development of a new concept of a polymer film heat exchanger, Dreiser (2016) investigated crystallization fouling of CaSO_4 and CaCO_3 on PEEK, polysulfone (PSU) and stainless steel 1.4571 surfaces. Experiments were performed in a stirred vessel. Flat samples of these materials were fixed to an electrically heated block. Dreiser (2016) found that the kinetics and the quantity of CaSO_4 fouling on the polymer surfaces were very promising compared to the stainless steel surface. No induction period was observed for the stainless steel surface. The PEEK surface showed first heat transfer reduction after 50 h. Dreiser (2016) reported that the adhesion of CaSO_4 to the polymer surfaces is 10–20 times lower in comparison with the stainless steel surface. The promising low CaSO_4 fouling affinity of the polymers was attributed to their different surface properties (roughness and surface energy) compared to stainless steel. An initially higher fouling rate and no induction period were observed for CaCO_3 fouling on the PEEK surface. The fouling Biot number, which is defined as the product of the overall heat transfer coefficient under clean conditions and the asymptotic fouling resistance, for PEEK was similar to that of stainless steel, and the fouling Biot number for PSU was found to be higher compared to stainless steel.

Several low-energy surface coatings (e.g. fluoropolymers, silicone polymers) have been developed for heat exchanger applications. Although these surfaces do accumulate fouling, the deposit is more loosely adhered and can be quite easily detached. The main reason why such coatings are not widely used is that they themselves provide a significant additional resistance to heat transfer due to their low thermal conductivity. If very thin coatings were used, the resistance against erosion or other mechanical stress would be greatly diminished. Sheikholeslami (2007) stated that PTFE, PP or glass-lined tubing can be used, if the high heat transfer resistance of the polymer tube material is not a major problem.

It is stated by Müller-Steinhagen (2010) that in polymer compact heat exchangers, which are used for low pressure operations involving corrosive gases or liquids, the low surface energy and the smooth surface of their construction materials (PP, fluoropolymer, etc.) reduce the adherence of most deposits. Since heat transfer coefficients under clean conditions are already low ($150\text{--}250 \text{ W}/(\text{m}^2 \text{ K})$), these heat exchangers are less sensitive to an additional fouling resistance compared to metal heat exchangers.

The thermal expansion of plastics can be beneficial with regard to fouling because repeated expansion and contraction of the plastic channels can lead to scale detachment (Zarkadas and Sirkar 2004).

In summary, it can be concluded that there are contrary reports on the fouling propensity of polymer surfaces compared to metal surfaces. Some reports showed that polymer surfaces are more prone to fouling, while other reports showed that polymer surfaces are less prone to fouling compared to metal surfaces. Surface roughness and interfacial energies are assumed to be decisive factors. Al-Janabi and Malayeri (2015) summarized that there is no consensus among investigators on the effect of surface energy as well as the interaction energies on fouling propensity.

However, it is generally assumed that the adhesive strength between the deposit and the heat transfer surface is lower for polymer surfaces than for metal surfaces.

3 High-Performance Polymer Composite Tubes for Heat Exchangers

Polymers are attractive materials for the construction of heat exchangers, especially in harsh chemical environments. Unfilled polymer tubes have been used in heat transfer applications for years, but their field of application is very limited due to their poor thermal and mechanical properties. To overcome these drawbacks, inert and highly thermally conductive fillers can be inserted into the polymer matrix to get acceptable thermal performance. In the following, the innovative development of high-performance polymer composite tubes for use in heat exchangers is presented.

3.1 *Material Selection*

The selection of appropriate polymer matrix materials and of a filler is shown in the following.

3.1.1 Polymer Matrix Materials

An evaluation of suitable polymers must be performed to find the best polymer material for use in heat exchangers and to meet the demands of the intended application. Over 45,000 different grades of plastics are available worldwide. These grades include additives, processing aids and other fillers. The basic components of these different grades of plastics are polymers. More than 50 different basic polymers are known. These polymers have a strong influence on the properties of the different grades. The selection of the right basic polymer is essential for the fulfilment of the material requirements. For use in heat exchangers, the polymer must be a thermoplastic polymer to fulfil the conditions regarding high filler content together with high filler orientation. Thermoplastic materials are ductile enough to realize the mechanical requirements of the composites, and they allow the orientation of the filling particles inside.

Thermoplastic polymers can be subdivided into two groups with different structures—amorphous and semi-crystalline thermoplastic polymers. The macromolecular chains in amorphous thermoplastics are completely chaotically arranged and tangled with each other. Amorphous thermoplastic polymers cannot be exposed to loads above the glass transition point. They are mostly transparent or translucent.

They show a good dimensional stability and a low tendency to creep and to warp. However, they have a low chemical resistance. Furthermore, they tend to be brittle and sensitive to stress cracking.

In semi-crystalline thermoplastic polymers, the macromolecules form a crystalline structure in some areas. Since the crystalline areas scatter the light, they are generally opaque. Due to stronger intermolecular forces, polymers with crystalline areas are generally tougher and show higher impact resistance than amorphous polymers. They are capable of withstanding mechanical loads also above the glass transition temperature. Thermoplastics exhibit good chemical resistance, fatigue resistance and sliding characteristics and are wear-resistant.

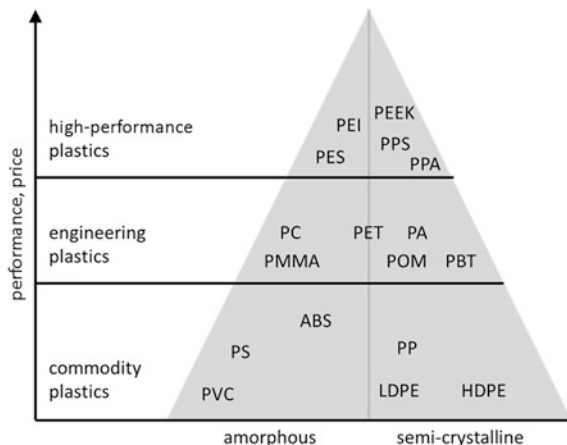
Generally, thermoplastic materials are divided into three main groups:

- Commodity plastics,
- Engineering plastics and
- High-performance plastics.

Commodity plastics such as polystyrene (PS), PP or PE have a low price and show basic mechanical properties. Engineering plastics such as polyester (PBT, PET) or polyamides (PA 6, PA 66) show enhanced mechanical properties and higher service temperatures. High-performance plastics such as PEEK or PPS exhibit the best mechanical values and the highest service temperatures. However, they have a high price and are only available in much smaller volumes than commodity and engineering plastics. Figure 3 shows the classical pyramid of polymers and the classification of common polymers.

When selecting appropriate polymers for a given heat exchanger application, the material properties must meet the thermal, chemical, mechanical and specific requirements of the application. Which of the appropriate polymers will be finally chosen at the end of the selection process also depends on the availability of the material on the market and on the price. The selection process of the polymer matrix material is illustrated in Fig. 4.

Fig. 3 Pyramid of plastics



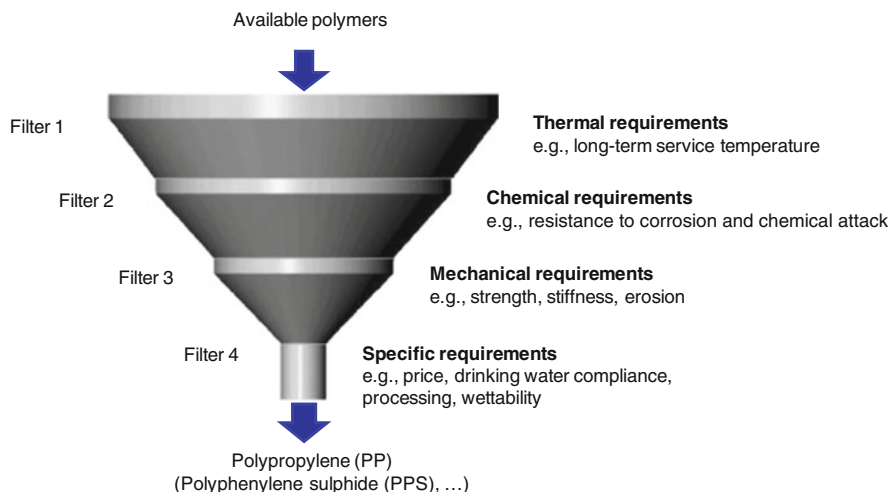


Fig. 4 Selection process of the polymer matrix

As an example, the selection of suitable polymer matrix materials for the tubes in horizontal tube falling film evaporators in multiple-effect distillation (MED) plants for seawater desalination is described. The polymer must resist a long-term service temperature of 80 °C because the top brine temperature is usually restricted to a maximum of 70 °C due to crystallization fouling and the temperature of the heating steam is some degrees higher (Boeck 2011). The material must resist these temperatures for around 20–25 years while being in contact with seawater (Boeck 2011). Thus, the material is not allowed to show a hydrolysis reaction in long-term contact with hot water that degrades the polymer chains to its monomers. Furthermore, water absorption must be low and is not allowed to tend to micro crazes (cracks at the microscopic level) under these conditions (Ehrenstein and Pongratz 2013). A softening point of the polymer lower than 80 °C is not acceptable, and deformation of the tubes during working conditions must be kept to a minimum. The polymer must be resistant to all process chemicals such as anti-foaming agents, anti-scalants and cleaning agents like hydrochloric acid. All mechanical requirements identified by finite element method (FEM) and vibration analysis must be fulfilled. Specific requirements for use in seawater desalination applications are a low price and drinking water compliance. After evaluating a wide range of polymers, polypropylene was selected as the most suitable matrix material for polymer composite tubes in MED plants for seawater desalination.

Polypropylene is a semi-crystalline thermoplastic and belongs to the group of polyolefines like polyethylene. However, it exhibits higher strength, stiffness and crystalline melting temperature at lower densities. Stiffness and hardness range between those of polyethylene and engineering plastics (see Fig. 3). The maximum service temperatures are higher than those of PE: short-term 140 °C, long-term 100 °C. Polypropylene exhibits only low water absorption and permeability.

It is chemically highly resistant due to its non-polar structure: up to 120 °C resistant to aqueous solutions of salt, strong acids and alkalis as well as brines (Osswald et al. 2006).

In addition to polypropylene, polyphenylene sulphide was identified as a suitable polymer matrix material for composite tubes in many applications due to its superior chemical, thermal and mechanical properties.

Polyphenylene sulphide is a semi-crystalline polymer in which aromatic monomer units are connected by sulphur atoms. It exhibits extremely high heat stability, high chemical resistance and strength. The long-term service temperature ranges from 200 to 240 °C, and the maximum service temperature is 300 °C. Polyphenylene sulphide is famous for its excellent resistance to acid attack. There are no known solvents below 200 °C (Osswald et al. 2006). Results of tests in 85% sulphuric acid at 120 °C for up to 5000 h suggested that PPS performs better than PTFE and PVDF in acidic conditions (T'Joel et al. 2009).

Some thermal and mechanical properties of PP and PPS are listed in Table 2. Pure PP or PPS as well as all other unfilled thermoplastics have quite low thermal conductivities between 0.1 and 0.5 W/(m K).

3.1.2 Thermally Conductive Fillers

For an efficient use in heat exchangers, filler material with a high thermal conductivity must be added to the polymers. Various metallic, carbon-based and ceramic fillers can be used (see Sect. 2.3). Thermal conductivities of some common fillers are listed in Table 3.

Table 2 Properties of unfilled polypropylene and polyphenylene sulphide (Osswald et al. 2006; Wypych 2012)

Material	Unit	PP	PPS
Density ρ	g/cm ³	0.90–0.907	1.34
Tensile strength σ	MPa	21–37	75
Modulus of elasticity E_t	MPa	1100–1300	3400
Thermal conductivity k	W/(m K)	0.17–0.22	0.25
Linear coefficient of thermal expansion α	1/K	$110\text{--}170 \times 10^{-6}$	55×10^{-6}
Specific heat capacity c_p	kJ/(kg K)	2	Not specified
Heat deflection temperature HDT/A	°C	55–70	135
Max. service temperature (short term)	°C	140	300
Max. service temperature (long term)	°C	100	200–240
Min. service temperature (long term)	°C	0 to –30	Not specified
Melting temperature ϑ_m	°C	160–170	285
Glass transition temperature ϑ_g	°C	0 to –10	85
Water absorption, equilibrium in water at 23 °C	%	0.02–0.04	0.01–0.03

Table 3 Thermal conductivities of some fillers (based on Chen et al. 2016a)

Filler	Category	Thermal conductivity k (W/(m K))
Aluminium	Metal	234
Copper	Metal	386
Silver	Metal	427
Carbon nanotube	Carbon-based	1000–4000
Carbon fibre	Carbon-based	300–1000
Graphene	Carbon-based	2000–6000
Graphite	Carbon-based	100–400
Diamond	Carbon-based	1000
β -Silicon nitride (β -Si ₃ N ₄)	Ceramics	103–200
Hexagonal boron nitride (h-BN)	Ceramics	185–300
Aluminium nitride (AlN)	Ceramics	100–300
β -Silicon carbide (β -SiC)	Ceramics	120
α -Alumina (α -Al ₂ O ₃)	Ceramics	30
Beryllium oxide (BeO)	Ceramics	270

Depending on the heat transfer application, different fillers should be considered. For applications that require both high thermal conductivity and electrically insulating properties, e.g. for electronic devices, electrically insulating fillers, such as aluminium oxide, boron nitride, aluminium nitride, can be used, while graphite and metal particles can be utilized in applications where electrical insulation is not required (Chen et al. 2016a).

Many thermally conductive fillers have anisotropic thermal conductivity. These fillers have non-spherical shape, such as plate-like boron nitride and graphite flakes. Non-spherical fillers can be oriented during processing, which usually leads to high thermal conductivity in the orientation direction, but low thermal conductivity in the direction perpendicular to the orientation direction. Due to its special crystal structure, hexagonal boron nitride shows anisotropic thermal conductivity with about 300 W/(m K) in the in-plane direction and about 2 W/(m K) in the through-plane direction (Chen et al. 2016a).

Since graphite offers the best overall performance with high heat-conducting properties, low price, low density, good availability, low wear on processing equipment and physiological as well as chemical inertness, graphite has been selected as the favourable filler for thermally conductive polymer composites.

Graphite is an allotrope of carbon in a crystalline form. It is composed of series of stacked layer planes shown schematically in Fig. 5. Within each layer plane, the carbon atom is bonded to three others, forming a series of continuous hexagons. The bond is covalent and has a high strength. The fourth valence electron is paired with another delocalized electron of the adjacent plane by a much weaker van der Waals bond (Pierson 1993). Thus, graphite is electrically conductive. However, it does not conduct in a direction at right angles to the plane. The structure of graphite

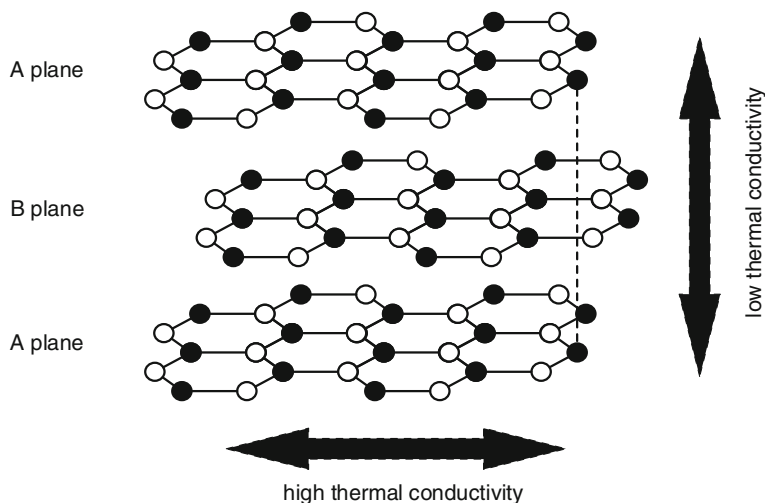


Fig. 5 Crystal structure of graphite (based on Pierson 1993)

particles has the appearance of small plates. Graphite has the advantage of being readily and cheaply available in a variety of shapes and sizes (Chen et al. 2016b).

The peculiar crystal structure of graphite results in a considerable anisotropy, especially in electrical and thermal properties. It has an exceptional high conductivity of up to 400 W/(m K) in the in-plane direction, but quite low thermal conductivity of about 2 W/(m K) in the through-plane direction (Pierson 1993), as indicated in Fig. 5. This highly anisotropic thermal conductivity of graphite has a strong impact on the performance of the polymer composite. The filler content must be high, and the orientation of the filler particles must be optimized in order to create a network of graphite particles with percolated pathways, as shown in Fig. 6, and, thus, to realize the full potential of graphite.

A reliable model for the prediction of the thermal conductivity of highly filled thermoplastics with anisotropic particles is not available so far, as described in Sect. 2.3. Modelling results give a rough estimation of the thermal conductivity of the composite at low-to-medium filler contents, but the models do not take into account the interaction of the particles as well as the orientation of particles, which is essential for high filler contents and anisotropic fillers. The simple approach in Eq. (3) may give a rough indication of the thermal conductivity of highly filled composites, but experimental results differ because of the shape and size of the filler particles and their orientation in the composite. A closer examination of the influence of the shape, size and orientation of the filler particles, the filler volume fraction as well as the interfacial thermal resistance on the thermal conductivity of the composite for anisotropic graphite particles is necessary to develop a more detailed model for the prediction of the composite conductivity.

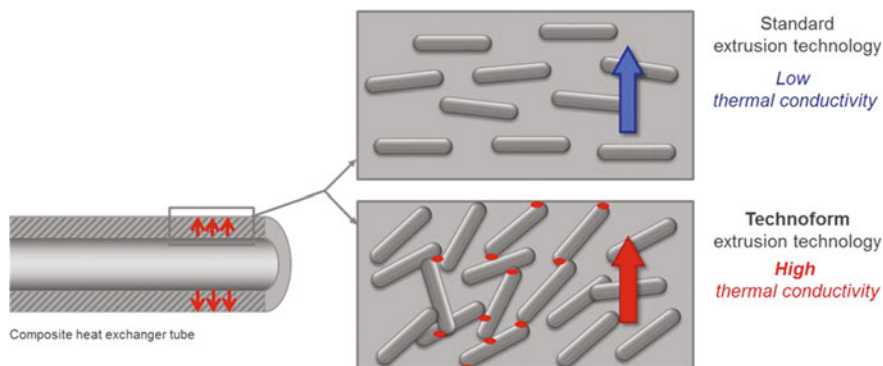


Fig. 6 Orientation of fillers in the tube wall (schematic), above: standard extrusion technology—limited filler content and longitudinally oriented particles; below: Technoform extrusion technology—high filler content and network of filler particles

Technoform Kunststoffprofile GmbH (Lohfelden, Germany) developed special polymer composite grades for use in heat exchangers. The polypropylene–graphite composite (in the following referred to as PP-GR) is filled with about 50 vol% graphite which corresponds to about 72 wt% graphite. The polyphenylene sulphide–graphite composite (in the following referred to as PPS-GR) has a filler content of about 50 vol% which corresponds to about 63 wt%. The PP-GR grade can be used in applications such as thermal seawater desalination plants, food industry heat exchangers or evaporators up to 80 °C. The PPS-GR grade can be used, for example, in some general industry sectors, wastewater applications and in heat exchangers or evaporators for acids up to 200 °C. Furthermore, other polymers such as PEEK were tested for the use in polymer composites, but the PP and PPS grades performed best for heat exchanger applications.

3.2 Advanced Extrusion Process and Particle Orientation

The polymer composite tubes for heat exchangers are produced by extrusion technology. The extrusion process is in general a simple process to form endless polymer profiles. During this process, a screw transports granulates of the polymer composite material through a heated tube, called extruder cylinder. The frictional heat and the heat introduced from outside melt the granulates, and a molten polymer mass is generated and transported to a forming die. The die forms the tube and guides the melt to a cooling section called calibration die wherein it solidifies. The cooled tubes are cut to length and packed for transportation.

Technoform Kunststoffprofile (Lohfelden, Germany) modified the standard extrusion process to handle and orient the fillers inside the polymer matrix, as shown in Fig. 6. The know-how protected, self-developed process can melt the plastic, distribute the graphite particles homogeneously in the melt and orient the graphite particles inside the tube to the optimal determined positions to maximize the thermal conductivity of the tube. By using this special extrusion process, it is possible to fill the polymers up to a filler content of 60 vol%. With standard extrusion processes, filler contents of up to 15 vol% are common. Higher filler loadings lead to rough surfaces and generate problems in the production process.

The particle orientation has a huge impact on the thermal conductivity when using anisotropic materials such as graphite. Different thermal conductivity values can be created depending on the orientation of the graphite particles. Tubes produced by an extrusion process show the natural behaviour of particle alignment in melt flow direction leading to poor thermal conductivities in radial (through-wall) direction. Hence, the particles must be aligned by special methods. Optimal particle distribution and orientation were determined. For the validation process, the extruded composite tubes were analysed by computer tomography in μm resolution. More than 60% of the particles had an angle of more than 45° towards the extrusion direction. Therefore, a relatively high thermal conductivity between 13 and 20 W/(m K) was reached in through-wall direction of the PP-GR and PPS-GR tubes with a filler content of 50 vol% (see Sect. 4.1.2).

Highly filled polypropylene-graphite tubes extruded by Technoform Kunststoffprofile are shown in Fig. 7.

Fig. 7 Polypropylene-graphite tubes with a filler content of 50 vol% developed by Technoform Kunststoffprofile GmbH



4 Material Properties of High-Performance Polymer Composite Tubes

The polymer composite materials combine the favourable properties of their polymer matrix and their graphite fillers. The composites are a new class of material. Characteristics of polymer composite tubes compared to other tube materials are summarized in Table 4.

4.1 Thermal Properties

The thermal properties of the tube materials are of utmost importance for using the tubes in heat exchangers. The thermal conductivity and the thermal expansion are presented and discussed in the following.

4.1.1 Thermal Conductivity Measurement

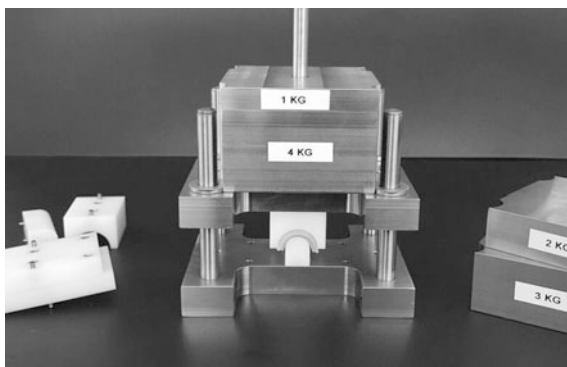
Methods for thermal conductivity measurement can be divided into steady-state methods including, for example, guarded hot plate method, axial flow method, heat flow metre method and pipe method and transient methods such as flash method

Table 4 Characteristics of tubes made of different materials

	Polymer composite tubes	Stainless steel tubes	Ceramic tubes	Aluminium alloy tubes	Polymer tubes	Graphite tubes
Thermal conductivity	+	+	–	++	– –	+
Density	++	– –	–	o	++	o
Stiffness	+	++	++	+	– –	+
Corrosion resistance	++	o	++	– –	++	++
Burst pressure	+	++	– –	+	– –	– –
Specific heat capacity	++	o	+	+	++	++
Freedom of design	++	o	– –	++	++	– –
Price	++	o	– –	o	++	– –

++ Advantage, + slight advantage, o neutral, – slight disadvantage, – – disadvantage

Fig. 8 Measurement set-up for thermal conductivity measurement of tube sections using a THB sensor



and transient hot wire method (Chen et al. 2016a). Common to all of them is the need of well-prepared flat samples.

To measure the thermal conductivity of thin-walled tubes, a modified transient hot bridge (THB) method is used. A flexible and small THB sensor (Linseis Messgeräte GmbH, Selb, THB sensor 3×3 mm) enables thermal conductivity, thermal diffusivity and heat capacity measurements on various sample geometries and materials. The foil sensor contains a printed circuit of nickel which is embedded between two polyimide sheets. The sensor consists of four identical strips. These are arranged in parallel and connected to form a Wheatstone bridge circuit. At uniform temperature, the bridge is initially balanced. The nickel wire acts as a resistance heater to induce a local change in temperature that turns the bridge into an unbalanced condition. At the same time, the nickel wire can be used as a resistance thermometer. The voltage rise in time is a measure of the thermal conductivity (Hammerschmidt and Meier 2006; Model et al. 2007).

The THB sensor allows rapid thermal conductivity measurements on solid and fluid specimens from 0.02 to 30 W/(m K). The measurement uncertainty for the thermal conductivity is better than 2% (Linseis 2017; Hammerschmidt and Meier 2006). As shown in Fig. 8, a measurement set-up was developed which provides accurate measurements of the thermal conductivity of tube sections.

4.1.2 Thermal Conductivity

The graphite-based polymer composites have a thermal conductivity of about 13–20 W/(m K) which is in a range of 50–100 times higher than the thermal conductivity of standard plastics. Thereby, these materials show comparable thermal performance to stainless steel.

During the material development of polymer composites for use in heat exchangers, the thermal conductivity has steadily increased. The optimization process was performed with respect to three main factors:

- Content of filler,
- Type of filler and
- Orientation of filler particles.

The material selection process was supported by a design of experiments (DoE) study to find the right parameters to optimize the thermal conductivity and the mechanical properties. At a limit of about 50 vol% graphite, the composites show an optimum relationship between thermal conductivity and mechanical properties for use in heat exchanger applications. Above or under this graphite content, the thermal and mechanical properties will not meet the application requirements.

Depending on the production process and the resulting orientation of the filler particles, the thermal conductivity of the PP-GR tubes with a graphite content of 50 vol% ranges between 13 and 20 W/(m K) and the one of the PPS-GR tubes with 50 vol% graphite lies between 13 and 18 W/(m K).

The optimum orientation can be found in samples which have a strong linear orientation of the fillers, for example samples produced through injection moulding with high injection forces and velocities. These samples show that the orientation of particles points significantly in the direction of injection. The measured values of the thermal conductivity of PP-GR with 50 vol% graphite in injection moulding direction were 26.6 W/(m K) and about 4.7 W/(m K) perpendicular to injection direction. These values were measured at injection-moulded samples using the laser flash method. In tubular heat exchangers, the heat flow is desired in the through-wall direction for optimum performance. However, this cannot be achieved by injection moulding.

4.1.3 Thermal Expansion

The thermal expansion is essential for the design of heat exchangers. Resulting tension and deformation may be a point of concern and should be avoided by a proper calculation of the thermally induced dimension change. The dimensions of unfilled plastics are influenced heavily by the change of temperature; e.g., pure polypropylene has a thermal expansion coefficient of $110\text{--}170 \times 10^{-6}$ 1/K (Osswald et al. 2006). In contrast to that, graphite has an extremely low coefficient of thermal expansion in the range of $1.9\text{--}2.9 \times 10^{-6}$ (Martienssen and Warlimont 2005). The mixtures of PP-GR and PPS-GR were measured in a dilatometer to determine the linear coefficient of thermal expansion. The thermal elongation of the polymer composites depends on the polymer matrix material and on the temperature range they are used in. The linear coefficients of thermal expansion of the polymer composites are summarized in Table 5.

Table 5 Linear coefficient of thermal expansion of polymer composite samples

Material	Temperature ϑ	Linear coefficient of thermal expansion α
Unit	°C	1/K
PP-GR	−20...30	15×10^{-6}
	50...100	26×10^{-6}
PPS-GR	−20...70	11×10^{-6}
	140...200	31×10^{-6}

4.2 Mechanical Properties

The mechanical properties of the polymer composite tubes are massively influenced by their high filler content. The fillers are the reason for the generally brittle behaviour. The elongation is low, but the stiffness and the strength are high. The polymeric matrix of the compound makes this material much more resilient to mechanical impact, loads or pressures compared to standard graphite tubes. Furthermore, the density is decreased compared to standard graphite tubes. Together with the possibility of greatly reducing the wall thickness compared to graphite tubes, the polymer composite tubes show excellent thermal and mechanical values together with a superior density. Typical mechanical properties of polymer composite samples based on PP and on PPS with a filler content of 50 vol% are shown Table 6.

The values shown in Table 6 were measured at room temperature. The mechanical values will decrease, if the tubes are used under hot conditions. For example, the modulus of elasticity of PPS-GR will decrease to around 10 GPa and the tensile strength to 40 MPa at 90 °C. The polymer composite tubes show favourable burst pressure values even for thin wall thicknesses. Furthermore, the tubes offer a good vibration damping behaviour. Test series with water jet cleaners

Table 6 Mechanical properties of the novel polymer composites

Property	Unit	PP-GR	PPS-GR
Density	g/cm ³	1.58	1.78
Modulus of elasticity*	MPa	7836	16523
Tensile strength*	MPa	29.1	47.9
Elongation tensile*	%	0.47	0.3
Flexural modulus*	MPa	6554	14178
Flexural strength (no yield)*	MPa	41.1	67.8
Elongation bending*	%	0.63	0.45
Roughness R_z (extruded tube)	μm	≤ 3	≤ 3
Burst strength** (@1.5 mm wall thickness)	bar	25	42
Burst strength** (@1.25 mm wall thickness)	bar	18	32

*Average values of injection-moulded samples, **tubes with an outside diameter of 24 mm

confirmed the good abrasion resistance of the tubes during mechanical cleaning. The extruded tubes have a smooth and sealed surface. The mechanical properties of the polymer tubes can be modified by changing the composition of the polymer composite material, i.e. changing the polymer matrix material and/or the filler content.

4.3 *Lifetime Behaviour*

The lifetime of a heat exchanger is an important factor that must be considered when evaluating a suitable system for an application. Since polymer heat exchangers are quite new to the market, there is not yet a sufficient database of empirical data on long-term material properties. Lifetime evaluation requires knowledge about the material behaviour under various conditions and adequate testing.

The most important factors influencing the resistance of polymers are the temperature and the chemical composition of the media in contact with the polymer. Temperature is the driving force for chemical reactions such as oxidation or chain scission effects. Degradation of the polymer is not a linear but an exponential function of temperature. Thus, the service temperature should be the first criterion to be considered when selecting an appropriate polymer.

Temperature strongly affects the chemical resistance. A material that is resistant to a specific medium at ambient temperature may not resist degradation at elevated temperatures. This applies equally to polymers and to metals. A stainless steel grade may be resistant to a solution with high chloride concentration at ambient temperature for some time. However, corrosion effects begin to show at temperatures of around 50 °C and above.

Heat ageing tests at elevated temperatures are often performed to predict the possible lifetime of polymers. Samples are exposed to different temperature levels, and the exposure time is measured until a certain decline in properties occurs. For example, a decline in the tensile strength by 50% relative to its initial value is a typical failure criterion. The procedure for the determination of time–temperature limits after prolonged exposure to heat and general ageing conditions, and procedures to be used for deriving thermal endurance characteristics are described in DIN EN ISO 2578 and in IEC 60216.

It is commonly assumed that polymer degradation follows a reaction which can be described by the Arrhenius equation (Dobkowski and Rudnik 1997),

$$k_{\text{deg}}(T) = A \exp\left(\frac{-E_a}{RT}\right), \quad (6)$$

where $k_{\text{deg}}(T)$ is the rate constant of polymer degradation, A is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant, and T is the absolute temperature.

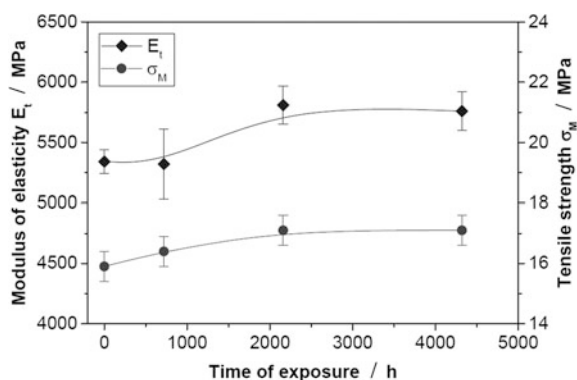
The Arrhenius equation is frequently used to assess the lifetime of polymers and to predict the combined effects of temperature and time. It is particularly useful for the accelerated testing of polymers as it allows short-term tests carried out at elevated temperatures to be used to assess long-term exposures at lower temperatures.

In tests performed by an accredited polymer testing laboratory, it was shown that the novel PP-GR composite can withstand immersion in seawater having a salinity of 65 g/kg at a temperature of 80 °C. The mechanical and fracture mechanics as well as the Fourier-transform infrared (FTIR) spectroscopy and differential scanning calorimetry (DSC) investigations revealed that neither chemical (chain scission, oxidation or alike) nor physical ageing effects could be detected after exposure of the specimens to artificial seawater at 80 °C for six months, as shown in Fig. 9. It can be assumed that none of the ions present in artificial seawater will negatively affect the morphology of the material and its properties also in the case of much higher exposure times.

To predict the lifetime more accurately, an additional test was conducted at forced ageing conditions. Due to chain scission, the exposure of PP-GR to air at 150 °C for more than one week had a negative effect on the fracture mechanics behaviour. Despite the drop in toughness (due to degradation of PP), the structural integrity of the specimens remained even after four weeks of exposure at high thermal loading. These data (one week at 150 °C) were used to carry out ordinary lifetime estimation on the basis of thermally activated molecular phenomena according to the Arrhenius equation. For chain scission, e.g. breakage of C–C bonds, one can assign an activation energy E_a which is about 350 kJ/mol for polypropylene.

The polymer testing laboratory stated a lifetime of at least 50 years at 80 °C for the PP-GR composite based on the calculations and further experiences gained in other research projects. Negative effects on the lifetime can occur at other designs, stresses, other media or concentrations than the concentrations tested. Additionally, directionally acting loads such as internal pressure or external mechanical stress were not considered in this lifetime estimation.

Fig. 9 Modulus of elasticity and tensile strength over time for PP-GR samples immersed in artificial seawater with a salinity of 65 g/kg at 80 °C



5 Chemical Resistance

Corrosion can be defined as the degradation of a material due to a reaction with its environment. Metals can suffer from many different types of corrosion, e.g. uniform attack corrosion, localized corrosion such as pitting and crevice corrosion and galvanic corrosion. Most corrosion of metals is electrochemical in nature. Polymer materials have different molecular structures compared to metals. Thus, polymer materials do not experience this kind of corrosion.

However, degradation of a material is not only caused by electrochemical processes. Degradation implies deterioration of physical properties of the material under the influence of one or more environmental factors such as cracking of a polymer due to sunlight exposure. The degradation of a material due to a reaction with its environment can happen to metals, polymers, ceramics or composite materials.

The chemical resistance of polymer materials depends on many factors. Environmental conditions such as the type and concentration of the media in contact with the polymer, exposure time, temperature, moisture, surface quality and structure, required lifetime of the structure or component and many more factors must be considered. The science of corrosion prevention and control is highly complex, exacerbated by the fact that corrosion takes many different forms and is affected by numerous outside factors.

The chemical resistance of polymers against chemical substances is usually checked in laboratory tests with defined boundary conditions for a certain period of time. However, these tests cannot mimic the real-life conditions. They can only give a first indication of the material resistance. If other influences such as stresses, temperatures, pressures, interfacial interactions occur, tests must be conducted under these conditions. The chemical resistance of materials is often listed in tables. These chemical resistance tables can give a rough indication of the material behaviour in harsh environments. The ratings in the tables are usually obtained under well-defined and controlled laboratory testing environments.

Table 7 gives a rough indication of the chemical resistance of the PP-GR, PPS-GR and PEEK-GR composites compared to metals which are commonly used in heat exchangers. It can be assumed that the chemical resistance of the composite is mainly determined by the chemical resistance of the polymer matrix material because the graphite used in the compound is inert and a negative influence of graphite on the chemical resistance is not given. Additionally, the graphite reduces the influence of chemicals on the polymers due to its inert nature. The more graphite is used, the stronger the effect is. The investigated polymers PP and PPS are resistant against the most light and medium acids at room temperature. Only aggressive acids at very high temperatures (compared to the melting point of the polymers) can induce degradation of these polymers, especially at longer exposure times. If brought in contact with these acids for short time, PP and PPS will not degrade. Due to their chemical structure, PP and PPS are more resistant than most other thermoplastic polymers such as polyamides and polyesters. Only fluorinated

polymers can have a higher chemical resistance, but the filling with graphite is limited to a low filler content and very critical during processing. Compared to the most common metals, PP and PPS have a superior resistance against acids. Only extremely expensive metals such as tantalum, zirconium or nickel alloys could fulfil these challenges.

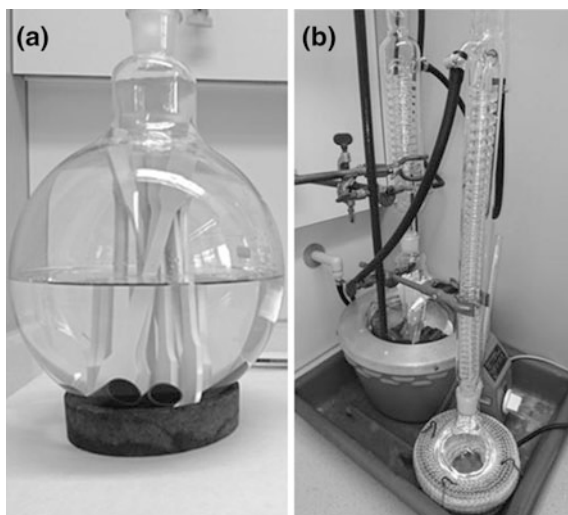
Table 7 is only intended as a rough guideline for the chemical resistance of the polymer composite materials. It is recommended to conduct tests to determine the chemical resistance in the particular application. Test rigs must be used to understand the behaviour under practical conditions. Furthermore, other concentrations

Table 7 Chemical resistance of the new polymer composites compared to common metals (e.g. Ehrenstein and Pongratz 2013; Habonim Ltd. 2013; Cole-Parmer 2017)

Medium	PP-GR	PPS-GR	PEEK-GR	Al alloy 5052	Al brass CW702R	Stainless steel 316 L	Titanium
Seawater 3.5% 60 °C	+	+	+	+	+	+	+
Seawater 3.5% 80 °C	+	+	+	o	o	o	+
Saltwater > 10% 80 °C	+	+	+	–	o	o	+
Hydrochloric acid (HCl) 2%	+	+	+	o	o	+	+
Hydrochloric acid (HCl) 37%	+	o	+	–	–	–	o
Sulphuric acid (H ₂ SO ₄) 2%	+	+	+	o	o	o	+
Sulphuric acid (H ₂ SO ₄) 80%	+	+	o	–	–	–	o
Phosphoric acid (H ₃ PO ₄) 10%	+	+	+	–	o	o	+
Phosphoric acid (H ₃ PO ₄) conc., 100 °C	+	+	+	–	–	–	o
Hydrofluoric acid (HF) 40%	+	o	–	–	–	–	–
Iron chloride Cl ₂ Fe	+	+	+	–	–	–	+
Hydrogen sulphide (H ₂ S wet)	+	+	+	o	–	o	+
Ammonium phosphate di-basic (NH ₄) ₂ HPO ₄	+	+	+	o	–	o	+

+ Resistant, o moderate resistant, – non-resistant

Fig. 10 **a** Tensile bars and tube samples in boiling phosphoric acid. **b** Test rig for sample storage in boiling acid



and temperatures or mixtures of different test fluids can be used to achieve more detailed results. For example, acid environments at higher temperatures can lead to very different results compared to lower temperatures.

To simulate the chemical resistance over time, accelerated testing at higher temperatures can be done (see Fig. 10). If possible, field tests under practical conditions should be performed. The material behaviour over time can help to predict a possible degradation and the lifetime of the material. Destroying tensile tests should be conducted with samples after different exposure times. Test rigs, retrofitting or application tests are excellent for this kind of chemical resistance investigation.

6 Experimental Investigations

In the course of the development of the thermally conductive polymer composite tubes, heat transfer and fouling propensity were studied at the University of Bremen, Germany, and compared with common metal tubes.

6.1 Heat Transfer in Falling Film Evaporation

Desalination of brackish water and seawater for the production of potable or process water might be one of the promising areas of application for the innovative polymer composite tubes. Multiple-effect distillation plants with horizontal tube falling film evaporators are commonly used for seawater desalination. In horizontal

tube falling film evaporators, condensation occurs inside horizontal tubes and falling seawater films evaporate outside the tubes. Falling film evaporators are known to exhibit very high heat transfer coefficients under clean surface conditions, i.e. without scale being formed on the heat transfer surface. The high heat transfer coefficients can be attributed to the thin film on the inside (film condensation) and on the outside (falling film evaporation) of the horizontal tubes.

Highly corrosion-resistant tube materials such as aluminium brass, copper–nickel 90/10, titanium grade 2, aluminium alloy 5052 and highly corrosion-resistant stainless steel grades are currently used as heat exchanger tubing material. The upper 3–5 tube rows are almost always made of titanium in order to reduce tube corrosion/erosion caused by the seawater being sprayed onto the tube bundle. In view of growing and fluctuating cost of metals, alternative materials for heat exchanger tubing are in the focus of development. Reduced corrosion problems, minimization of crystallization fouling and cleaning and maintenance simplicity are main future goals.

Heat transfer was studied in a horizontal tube falling film evaporator at pilot plant scale in order to test the tubes under process conditions which are close to those in industrial MED plants for seawater desalination.

Test Rig: A schematic diagram of the test rig is shown in Fig. 11.

The main part of the test rig is an evaporator fitted with a bank of 6 horizontal tubes. The tubes can be removed from the tube sheets in order to renew the tubes,

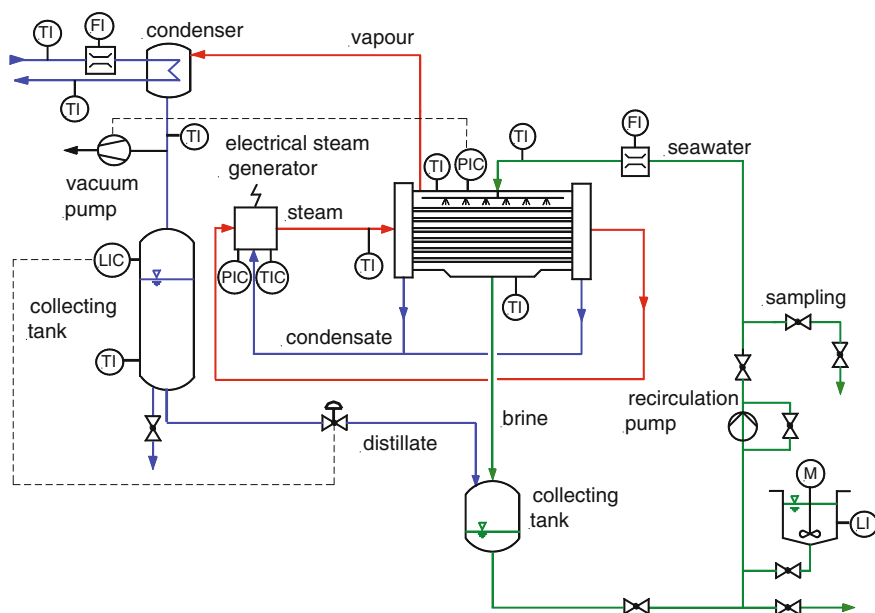


Fig. 11 Schematic diagram of the horizontal tube falling film evaporator

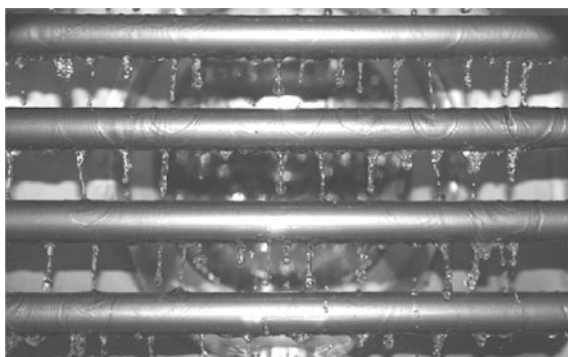
to test different tube materials and to analyse the adherent scale. Figure 12 shows a falling water film over PP-GR tubes in the horizontal tube falling film evaporator.

As shown in Fig. 11, saturated steam is provided by an electrical steam generator. The steam is introduced into the tubes and condensed under vacuum conditions. The condensate flows back to the steam generator for reuse. The test solution is evenly distributed onto the first tube by means of a toothed overflow weir and trickles down by gravity forming a thin film flow over the horizontal tubes. Inspection glasses on both sides of the evaporator shell allow for a visual observation of the wetting behaviour during the experiments. The enthalpy of condensation allows the feed water to be preheated to the boiling point on the upper tube and then part of it to be evaporated on the lower tubes. The generated vapour is condensed in a plate heat exchanger. After leaving the evaporator, the concentrated test solution flows into a collecting tank. The condensate is mixed with the concentrated solution, and the test solution is recirculated by a pump. Gases released from the evaporating test solution and ambient air potentially penetrated into the evaporator are extracted by means of a vacuum pump, which maintains the saturation pressure in the evaporator shell. The pilot plant provides conditions for CO₂ release from seawater very similar to those in industrial multiple-effect distillers. CO₂ release shifts the pH value of the seawater to higher values and influences the carbonate system.

Measurement instrumentation and automation of the test rig allow systematic studies by varying the process parameters and simulating process conditions in different stages of industrial MED plants. A detailed description of the test rig is given in previous work (Krömer et al. 2015).

Materials: In the horizontal tube falling film evaporator, artificial seawater based on salt mole fractions for standard artificial seawater as suggested in the formulation by Kester et al. (1967) was used. The composition of artificial seawater is within 1 mg/kg of natural seawater for all the major constituents (Kester et al. 1967). After mixing the salts and stirring the solution, the seawater was aerated. The aeration tended to equilibrate the solution with atmospheric gases and removed the excess CO₂ resulting from the conversion of HCO₃⁻ to CO₃²⁻.

Fig. 12 Falling water film over PP-GR tubes in the horizontal tube falling film evaporator (wetting rate $\Gamma = 0.1 \text{ kg}/(\text{s m})$)



The salinity of ocean surface waters throughout the world is fairly uniform about 35 g/kg. In areas with high levels of rainfall or river runoff, the salinity is less. In areas with higher rates of evaporation, the salinity is higher, e.g. in the Persian Gulf. In seawater, the relative proportion of the major ions compared to the salinity remains constant (Millero 2006). The pH of most surface waters in equilibrium with the atmosphere is 8.2 ± 0.1 . Therefore, the artificial seawater used in the experiments is representative for natural seawater. Experiments were performed with artificial seawater having a salinity of 65 g/kg simulating the concentrated seawater on the bottom tubes in industrial MED plants taking into account a typical concentration factor between 1.3 and 1.6.

In the experiments, PP-GR tubes with an outer diameter of 22.4 mm and a wall thickness of 1.25 and 1.5 mm were tested and compared with conventional tubes made of aluminium brass, copper–nickel 90/10 and duplex stainless steel. The Al brass and CuNi 90/10 tubes had an outer diameter of 25 mm and a wall thickness of 1.0 mm. The duplex stainless steel tubes had an outer diameter of 24 mm and a wall thickness of 0.7 mm. The effective length of the tubes was $L_t = 453$ mm. PP-GR tubes with surface treatment were used in order to improve tube wetting. Table 8 summarizes the tube data.

Test Procedure: Test series were performed at a high evaporation temperature of 75 °C exceeding the top brine temperatures currently used in industrial MED distillers in order to test the tubes under elevated temperatures. The difference between the condensation temperature ϑ_{co} inside the tubes and the evaporation temperature ϑ_{ev} outside was $\vartheta_{co} - \vartheta_{ev} = 5$ K. A typical wetting rate, which is the mass flow rate of the seawater $\dot{m}$ on one tube per unit tube length L_t ,

$$\Gamma = \frac{\dot{m}}{L_t} \tag{7}$$

Table 8 Tube data (effective tube length $L_t = 0.453$ m)

Designation Chemical designation EN designation	Thermal conductivity k (W/(m K))	Outside diameter d_o (mm)	Wall thickness s (mm)
PP-GR Polypropylene–graphite composite	15 (20 °C)	22.4	1.25/1.5
Duplex X2CrNiMoN22-5-3 1.4462	15 (20 °C) 16 (100 °C)	24	0.7
CuNi 90/10 CuNi10Fe1Mn CW352H	52 (20 °C) 60 (100 °C)	25	1.0
Al brass CuZn20Al2As CW702R	100 (20 °C) 112 (100 °C)	25	1.0

of $\Gamma = 0.1 \text{ kg/(s m)}$ was chosen. Experiments were conducted with 240 l of artificial seawater for a test period of 50 h. During the test runs, no additive (anti-scalant), which inhibits crystallization fouling, was used; i.e., the tests were performed under conditions where crystallization fouling on the outer tube surfaces may occur.

During the test runs, the temperatures and pressures of the seawater, the generated vapour, the heating steam and the volume flow rates of the feed water and the cooling water were measured. Distillate was collected at regular intervals, and the distillate volume flow rate was measured. On the basis of the measurement data, the average overall heat transfer coefficient U was determined using energy balances and overall heat transfer equations.

Results and Discussion: Figure 13 shows the average overall heat transfer coefficients obtained in the horizontal tube falling film evaporator during the test runs with seawater. The PP-GR tubes showed a good performance at the high evaporation temperature of 75°C .

Three test runs with PP-GR tubes with a wall thickness of 1.5 mm led to high overall heat transfer coefficients between $2152 \text{ W/(m}^2 \text{ K)}$ and $2316 \text{ W/(m}^2 \text{ K)}$ which is already close to the overall heat transfer coefficient of $2622 \text{ W/(m}^2 \text{ K)}$ obtained for the duplex stainless steel tubes with a wall thickness of 0.7 mm.

In addition to the continuously improving thermal conductivity of the polymer composite tubes, the decrease of the wall thickness is in the focus of development. First tests were performed with PP-GR tubes having a reduced wall thickness of

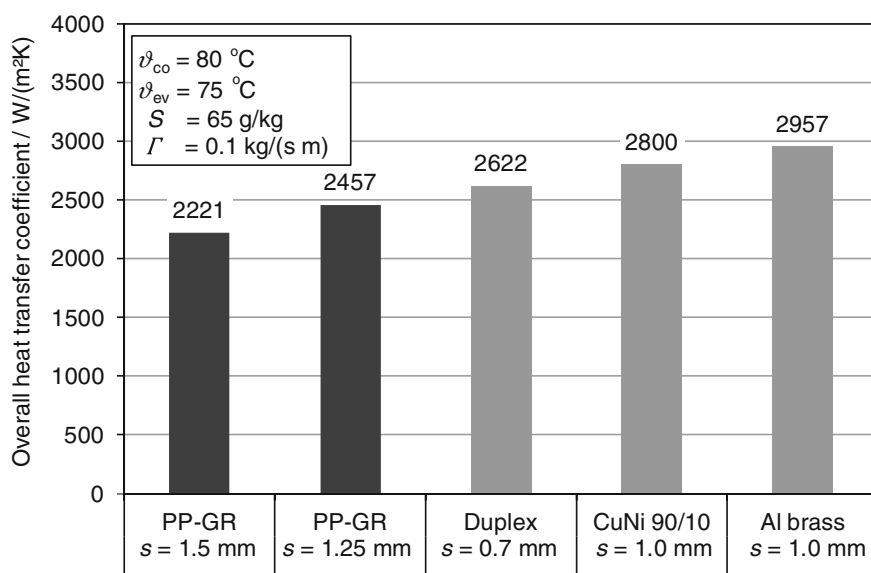


Fig. 13 Overall heat transfer coefficients for the PP-GR tubes (*black*) and common metal tubes (*grey*) measured in a horizontal tube falling film evaporator under fouling conditions with seawater

1.25 mm. The PP-GR tubes with a wall thickness of 1.25 mm resulted in a relatively high overall heat transfer coefficient of $2457 \text{ W}/(\text{m}^2 \text{ K})$. The overall heat transfer coefficient obtained with the PP-GR tubes having a wall thickness of 1.25 mm was close to that obtained with duplex stainless steel tubes with a low wall thickness of 0.7 mm under practical conditions.

Despite of the high thermal conductivities and small tube wall thickness of 1 mm, the overall heat transfer coefficients obtained with copper–nickel 90/10 and aluminium brass tubes were only 14–20% higher than the overall heat transfer coefficient obtained with the PP-GR tubes with 1.25 mm, because a notable fouling layer formed on the outsides of the metal tubes, as described in Sect. 6.2.2.

The ongoing development of the special extrusion process and of the particle orientation as well as the optimization of the tube wall thickness may lead to a further increase in the overall heat transfer coefficient.

In a previous study (Glade et al. 2014), 4-stage and 10-stage multiple-effect distillation plants for seawater desalination applying polymer composite tubes were designed with a process simulation model and compared with MED plants using aluminium brass tubes. Based on conservative calculations for polymer composite tubes with a thermal conductivity of $10 \text{ W}/(\text{m K})$, a tube wall thickness of 1.5 mm and a design fouling resistance of $0.05 \text{ m}^2 \text{ K}/\text{kW}$, the heat transfer surface area of the 10-stage MED plant was calculated to be about 33% higher than that of an MED plant with the same distillate mass flow rate using aluminium brass tubes with a thermal conductivity of $112 \text{ W}/(\text{m K})$, a tube wall thickness of 0.7 mm and a fouling resistance of $0.1 \text{ m}^2 \text{ K}/\text{kW}$. An economic analysis of the costs of water produced in the MED plants indicated the competitiveness of the novel polymer composite tubes against aluminium brass tubes.

6.2 *Crystallization Fouling on Polymer Composite Tubes*

As described in Sect. 2.4, crystallization fouling is a severe problem in most heat exchangers and a very complex phenomenon. In the course of the development of the thermally conductive polymer composite tubes, the effect of the tube material on the induction period for calcium sulphate fouling was investigated in a stirred vessel test rig. Furthermore, the fouling behaviour was studied in a horizontal tube falling film evaporator at pilot plant scale under process conditions which are close to those in industrial multiple-effect distillation plants for seawater desalination.

6.2.1 *Calcium Sulphate Fouling in a Stirred Vessel Test Rig*

Modern anti-fouling strategies are based on approaches increasing the duration of the induction period and, hence, decreasing the adhesive strength between crystals and heat transfer surface (Förster and Bohnet 2000). Sheikholeslami (2007) stated

that the best way to mitigate fouling is to prolong the induction period for the longest time possible.

Stirred Vessel Test Rig: The influence of the tube material on the induction period was studied in a stirred vessel test rig. An electrically heated tube is immersed into a solution in a stirred vessel. The solution is stirred with a 4-bladed propeller stirrer. A cylindrical heating cartridge is inserted into an aluminium cylinder which in turn is inserted into the tube with heat-conducting paste. The temperature of the aluminium block is kept constant with a PID controller, and the power is measured. The bulk temperature of the solution is controlled with a thermostat bath. Temperatures are measured in the aluminium block inside the tube and in the bulk solution with Pt100 thermometers.

Materials and Test Procedure: Experiments were performed with PP-GR, PPS-GR and duplex stainless steel tubes. The tubes had an outside diameter of 24 mm and a heated surface area of 75.4 cm². New tubes, which were not exposed to water before, were used. The tubes were employed with their typical surface topography as delivered. Surface roughness parameters were measured using a tactile stylus unit (MarSurf GD25, Mahr GmbH, Göttingen). The tube data are summarized in Table 9.

A calcium sulphate solution was prepared by mixing Na₂SO₄ and CaCl₂·2H₂O in deionised and degassed water. The solution had an initial CaSO₄ concentration of $c_0 = 0.025$ mol/l; i.e., it was supersaturated with CaSO₄ at a temperature of 42 °C. The bulk temperature was kept at 42 °C, and the heating temperature was adjusted in a way that the initial outside tube wall temperature was 72.2 °C for the tube materials. The stirrer had a rotational speed of 2 revolutions per second. The experiments were performed for a test period of 48 h.

During the process of crystallization fouling of CaSO₄ on the outside of the electrically heated tube, the heat transfer rate decreases over time. To represent the fouling process and progress, the fouling resistance R_f is determined and presented as a function of time

Table 9 Tube data (heated tube length $L_t = 100$ mm, outside heat transfer surface area $A_o = 75.4$ cm²)

Designation Chemical designation EN designation	Outside diameter d_o (mm)	Wall thickness s (mm)	Mean roughness R_a (μ m)
PP-GR PP-graphite 50 vol%	24	1.5	0.37
PPS-GR PPS-graphite 50 vol%	24	1.5	0.48
Duplex X2CrNiMoN22-5-3 1.4462	24	0.7	0.43

$$R_f = A_o \left(\frac{T_{\text{tube},t} - T_{\text{bulk},t}}{\dot{Q}_t} - \frac{T_{\text{tube},t=0} - T_{\text{bulk},t=0}}{\dot{Q}_{t=0}} \right), \quad (8)$$

whereas $T_{\text{tube},t}$ and $T_{\text{tube},t=0}$ are the temperatures measured inside the tube at the time t and at the initial time, respectively; $T_{\text{bulk},t}$ and $T_{\text{bulk},t=0}$ are the bulk temperatures at the time t and at the initial time, respectively; $\dot{Q}_t$ and $\dot{Q}_{t=0}$ are the heat transfer rates at the time t and at the initial time; and A_o is the outside heat transfer surface area of the heated tube. The heat transfer rates were set equal with the measured power outputs of the heating cartridge.

In industry, it is common to use the cleanliness factor CF given by

$$\text{CF} = \frac{U_f}{U_c} \quad (9)$$

with the overall heat transfer coefficient U_f under fouled conditions and the overall heat transfer coefficient U_c under clean conditions. The use of the cleanliness factor is helpful in comparing the condition of the heat exchanger during service to clean conditions.

Results and Discussion: Figure 14 shows the fouling resistance over time for the polymer composite tubes and the duplex stainless steel tube. The fouling resistance shows an asymptotic behaviour over time. The rate of deposit growth can be regarded as the difference between the deposition and removal rates. If the removal process becomes significant, the net deposition approaches zero at later stages and therefore asymptotic behaviour will be obtained. As shown in Fig. 14,

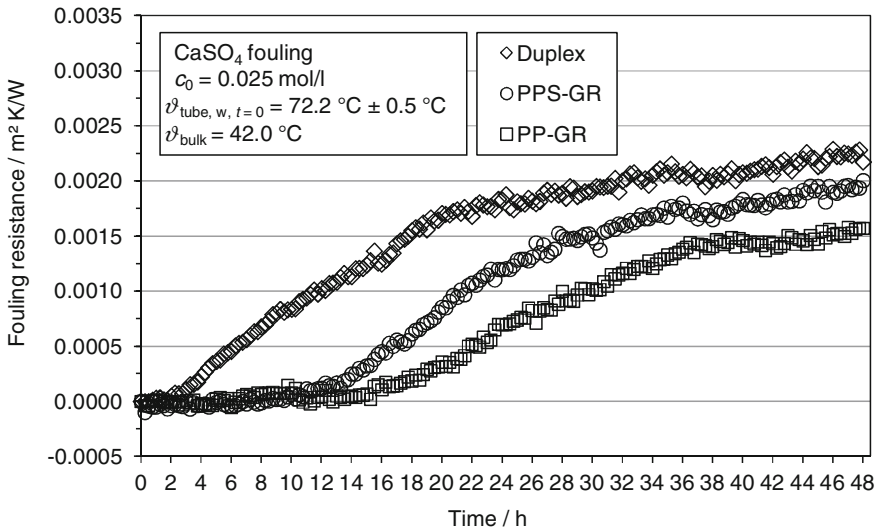


Fig. 14 Fouling resistance over time measured in the stirred vessel test rig

the induction periods of fouling were different for the tube materials. The induction period of the duplex stainless steel was found to be only 2 h, while the induction periods of the polymer composite surfaces were considerably higher, namely about 10.5 h for PPS-GR and 15 h for PP-GR. The asymptotic fouling resistance was higher for duplex stainless steel than for PPS-GR, and it was the lowest for the PP-GR tube.

Surface roughness is believed to enhance nucleation and to increase the contact surface area which in turn increases adhesion (Sheikholeslami 2007; Müller-Steinhagen 2010). Both PP-GR, which had a slightly lower surface roughness than Duplex, and PPS-GR, which had a slightly higher surface roughness than Duplex, showed a significantly higher induction period. It can be assumed that there are further surface characteristics such as energetic properties lowering the adhesive strength and increasing the induction period for the polymer composite materials. An overlap of surface roughness and energetic effects complicates a simple interpretation. As summarized in Sect. 2.4, there is not yet any consistent picture that can explain the influence of surface energy components on fouling propensity (Al-Janabi and Malayeri 2015). Therefore, it is not attempted here to derive a general relation between the surface energy data and the fouling propensity.

The cleanliness factor is depicted in Fig. 15. After a short induction period of 2 h, the overall heat transfer coefficient obtained with the duplex stainless steel tube

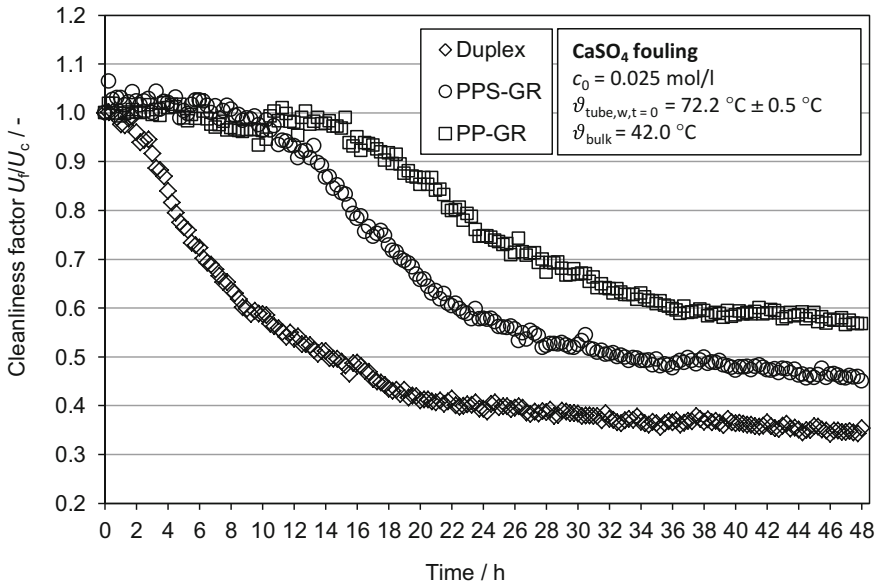


Fig. 15 Cleanliness factor over time measured in the stirred vessel test rig

decreased rapidly to only 35% of the initial overall heat transfer coefficient under clean conditions. For PPS-GR and PP-GR, the overall heat transfer coefficients started to decrease after 10.5 and 15 h (induction periods), respectively, and dropped down to 46 and 57% of their initial values, respectively.

Under special circumstances, where the surface is initially smooth and the deposit formation increases the surface roughness, the convective heat transfer can be enhanced. The increase in roughness may actually reduce the net system resistance, and one may encounter negative values for the fouling resistance during the initial period (Sheikholeslami 2007). Slightly negative values for the fouling resistance and, thus, slightly positive values for the cleanliness factor during the initial period can be seen in Figs. 14 and 15.

6.2.2 Mixed Salt Fouling in a Horizontal Tube Falling Film Evaporator

Crystallization fouling on the surfaces of the metal tubes is one of the biggest problems in horizontal tube falling film evaporators which are commonly used in MED plants for seawater desalination. Since seawater is a multi-component electrolyte solution, scale formation is caused by co-precipitation of different calcium- and magnesium-containing salts such as calcium carbonate, magnesium hydroxide and calcium sulphate. The solubility of these salts decreases with increasing temperature. The scale formed on the outside of the tubes reduces the overall heat transfer coefficient. Thus, the efficiency decreases and, above a certain limit, the distillate mass flow rate declines. In order to allow for scale formation, an additional thermal resistance on the outside tube surface (fouling resistance $R_{f,o}$) is assumed in the design of MED plants as given in Eq. (4). The fouling resistance $R_{f,o}$ is assumed to be between 0.1 and 0.15 m² K/kW up to 0.3 m² K/kW for the design of horizontal tube falling film evaporators for seawater desalination. Assuming a dense scale layer of calcium carbonate with a thermal conductivity in the order of 1.5–2.9 W/(m K) (Müller-Steinhagen 2000, 2010), a layer thickness of only 150–290 μm would result in a fouling resistance of 0.1 m² K/kW. The deleterious effect of scaling is of particular significance in a falling film evaporator. Deposit accumulation causes a considerable reduction in heat transfer due to the relatively high heat transfer coefficient achieved by film flow under clean surface conditions.

With increasing salinity, the amount of calcium-containing scale significantly increases. An increase in temperature and a decrease in wetting rate result in an increase in scale formation (Krömer et al. 2015; Stärk et al. 2017). However, the effects of tube material on scale formation in horizontal tube falling film evaporators commonly used for seawater desalination have been scarcely investigated.

Experimental: The experimental study was performed in the horizontal tube falling film evaporator which is described in Sect. 6.1. Crystallization fouling was studied on PP-GR and PPS-GR tubes and compared with conventional tubes made of aluminium brass (CW702R) and duplex stainless steel (1.4462). PP-GR and PPS-GR tubes with surface treatment were used in order to improve tube wetting.

Test series were performed at a high evaporation temperature of 75 °C exceeding the top brine temperatures currently used in industrial MED distillers in order to test the tubes under more extreme conditions. The difference between the condensation temperature ϑ_{co} inside the tubes and the evaporation temperature ϑ_{ev} outside was $\vartheta_{co} - \vartheta_{ev} = 5$ K. A typical wetting rate of $\Gamma = 0.1$ kg/(s m) was chosen. Experiments were conducted with 240 or 300 l of artificial seawater for a test period of 50 or 140 h. In previous experiments, different volumes of test solution and time periods were tested. Experiments with 240 or 300 l of test solution and time periods of 50 and 140 h were found to be favourable because time periods are long enough to find differences in scale formation and supersaturation levels are still sufficiently high.

The scale layers formed outside the tubes of the falling film evaporator were analysed by various methods to obtain chemical, structural and quantitative information. The scale of the fourth tube was dissolved in diluted acid, and the concentrations of Ca^{2+} and Mg^{2+} ions in the solution were measured using atomic absorption spectroscopy (AAS). The fifth tube was analysed using scanning electron microscopy (SEM) in combination with energy-dispersive X-ray spectroscopy (EDXS) to provide qualitative information on structural and chemical characteristics of the scale.

Results and Discussion: The scanning electron micrographs in Fig. 16 show that the surface of the aluminium brass tube was covered with a two-layer scale comprising a thin, flaky magnesium-rich and calcium-free base layer underneath a thick layer of calcium carbonate crystals in the form of aragonite. The results suggest that the Mg-rich base layer forms in the early stages and its growth ceases and aragonite crystals start to precipitate once the tube surface is completely covered with the Mg-rich scale layer.

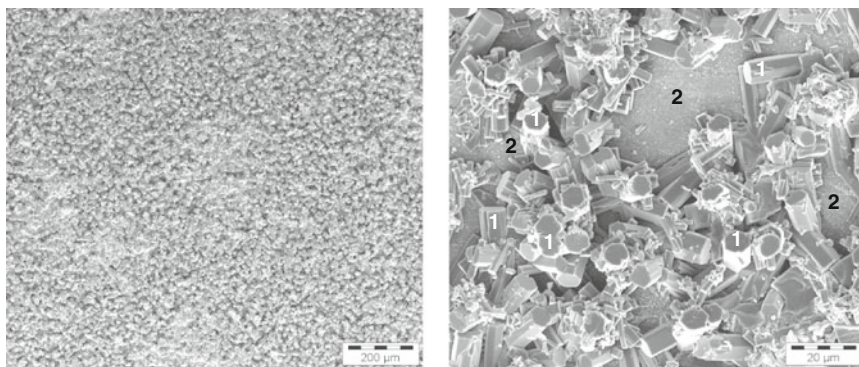


Fig. 16 SEM images of the Al brass tube surface after 50 h, artificial seawater $S = 65$ g/kg, $\vartheta_{ev} = 75$ °C, $\vartheta_{co} = 80$ °C, $\Gamma = 0.1$ kg/(s m), $t = 50$ h: 1 CaCO_3 (aragonite), 2 Mg, O-containing scale (Stärk et al. 2014)

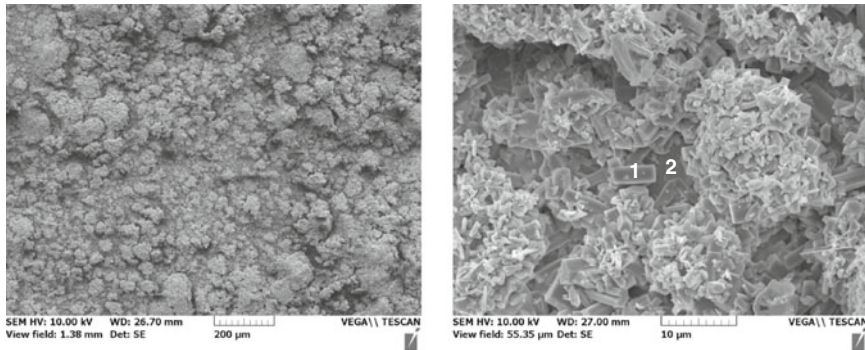


Fig. 17 SEM images of the duplex stainless steel tube surface after 50 h, artificial seawater $S = 65$ g/kg, $\vartheta_{ev} = 75$ °C, $\vartheta_{co} = 80$ °C, $\Gamma = 0.1$ kg/(s m), $t = 50$ h: 1 CaCO_3 (aragonite), 2 uncovered tube surface

As shown in Fig. 17, the surface of the duplex stainless steel tube was densely covered with a crystalline scale layer after a test period of 50 h. CaCO_3 crystals grew on the tube surface. Only some single spots were uncovered.

The surface of the PPS-GR tube was partly densely and partly weakly covered with deposits after 50 h, as shown in Fig. 18. Few CaCO_3 crystals, which were partly covered with a Ca, C, O, Mg-containing scale, were found on the tube surface. In some spots, the tube surface was still uncovered.

The scanning electron micrographs in Figs. 19 and 20 show that the surfaces of the PP-GR tubes were only weakly covered with scale after 50 and 140 h. A very thin Ca, Mg, O-containing scale was found on the tube surface, whereas many spots on the tube surface were uncovered. Only few calcium carbonate crystals in the modification of aragonite grew on the tube surface and were covered with a Ca, Mg, O-containing scale.

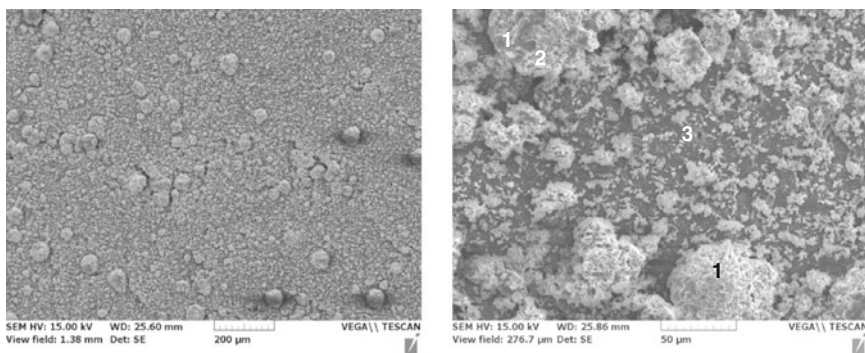


Fig. 18 SEM images of the PPS-GR tube surface after 50 h, artificial seawater $S = 65$ g/kg, $\vartheta_{ev} = 75$ °C, $\vartheta_{co} = 80$ °C, $\Gamma = 0.1$ kg/(s m), $t = 50$ h: 1 CaCO_3 (aragonite), 2 Ca, C, O, Mg-containing scale, 3 uncovered tube surface

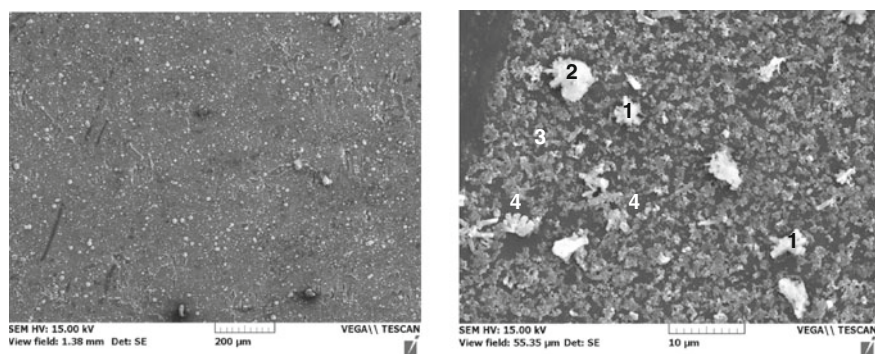


Fig. 19 SEM images of the PP-GR tube surface after 50 h, artificial seawater $S = 65$ g/kg, $\vartheta_{ev} = 75$ °C, $\vartheta_{co} = 80$ °C, $\Gamma = 0.1$ kg/(s m), $t = 50$ h: 1 CaCO_3 (aragonite), 2 Ca, Mg, O-containing scale, 3 Ca, Mg, O-containing scale, 4 uncovered tube surface

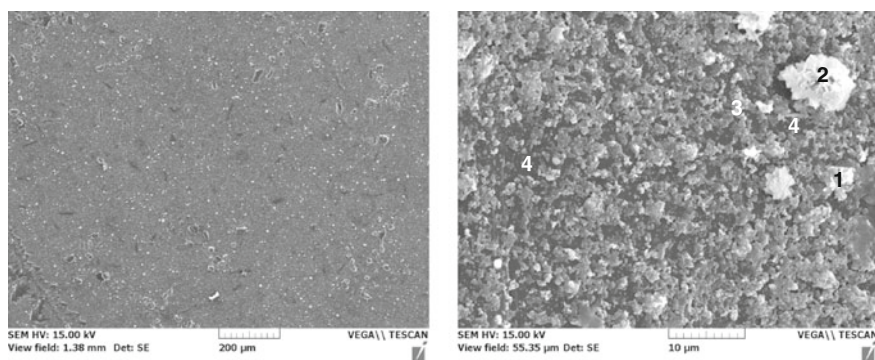


Fig. 20 SEM images of the PP-GR tube surface after 140 h, artificial seawater $S = 65$ g/kg, $\vartheta_{ev} = 75$ °C, $\vartheta_{co} = 80$ °C, $\Gamma = 0.1$ kg/(s m), $t = 140$ h: 1 CaCO_3 (aragonite), 2 Ca, Mg, O-containing scale, 3 Ca, Mg, O-containing scale, 4 uncovered tube surface

Figure 21 shows the calcium content and the magnesium content in the scale on the PP-GR, PPS-GR, duplex stainless steel and aluminium brass tubes after a test period of 50 and 140 h, respectively. In accordance with the SEM images in Figs. 16, 17, 18, 19 and 20, the calcium and magnesium contents on the polymer composite tubes were considerably lower than those on the duplex stainless steel and aluminium brass tubes.

In previous experiments (Krömer et al. 2015) with copper–nickel 90/10 tubes, it was found that the calcium content on the tubes notably increased between 50 and 90 h. As shown in Fig. 21, the calcium and magnesium masses on the PP-GR tubes per unit surface area slightly increased between 50 and 140 h, but even after 140 h the calcium and magnesium contents in the fouling layer were very low compared to those on the metal surfaces.

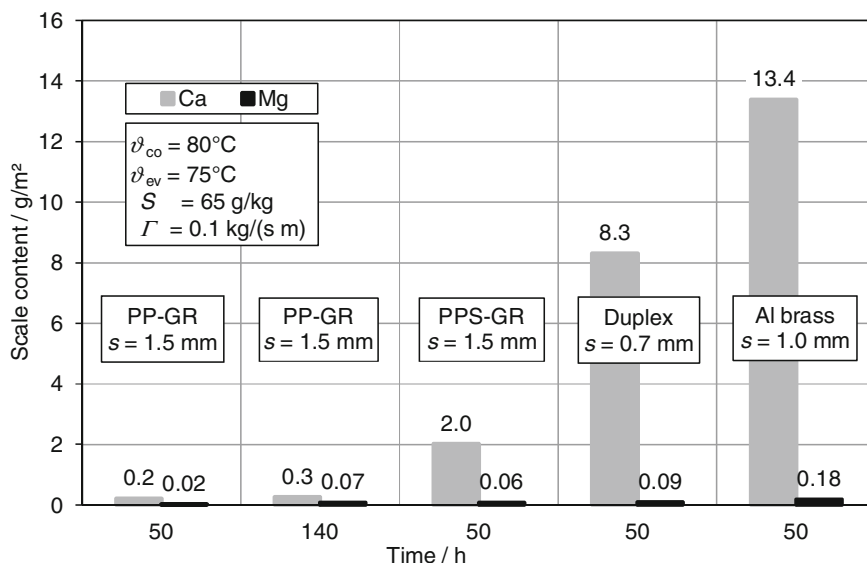


Fig. 21 Scale quantity (masses Ca and Mg per unit tube surface area) on the PP-GR and PPS-GR tubes compared to duplex stainless steel and aluminium brass tubes in the horizontal tube falling film evaporator with artificial seawater

The results suggest that the crystallization fouling propensity of the PP-GR and PPS-GR tube surfaces in contact with seawater is lower than that of the metal surfaces under the test conditions. As for the CaSO_4 crystallization fouling in the stirred vessel test rig (see Sect. 6.2.1), the PP-GR tubes showed a lower fouling propensity than the PPS-GR tubes.

Since the surface roughness of the metal tubes was slightly lower than the roughness of the polymer composite tubes, the surface roughness is most likely not the decisive factor for the stronger scale formation on the metal tubes. The scale layer can be detached more easily from the polymer tubes than from the metal tubes. Thus, it is assumed that the adhesive strength between scale layer and substrate surface is lower for the polymer composite tubes, which would increase the induction period.

The variety of fouling mechanisms, the multitude of factors influencing fouling and the complexity of the fouling processes do not allow a general answer to the question if a specific tube material or heat transfer equipment is more or less prone to fouling. Instead, the specific fouling situation must be considered separately for each application. Various test rigs have been installed at the University of Bremen to study fouling with different test solutions in order to get an indication of the fouling behaviour and to develop fouling mitigation measures.

7 Design Aspects

Various aspects for the implementation of the novel polymer composite tubes and for the design of polymer composite heat exchangers are presented in the following. Diverse possibilities of mounting the polymer composite tubes in the tube sheets and the maximum unsupported tube span for avoiding tube failures by flow-induced vibrations are described and discussed.

7.1 Mounting of Polymer Composite Tubes in Tube Plates

There are numerous possibilities of connecting polymer composite tubes with a tube plate to enable functionality in a heat exchanger system, as shown in Fig. 22.

To select the most reliable connection technology for a new application, the boundary conditions must be considered carefully. The selection depends on various factors, such as material of the tube plate, operating pressure, temperature, spacing between the tubes, use of chemicals, lifetime of the system and forces acting on the tube/tube plate system. The connection technologies with their advantages and disadvantages are summarized in the following.

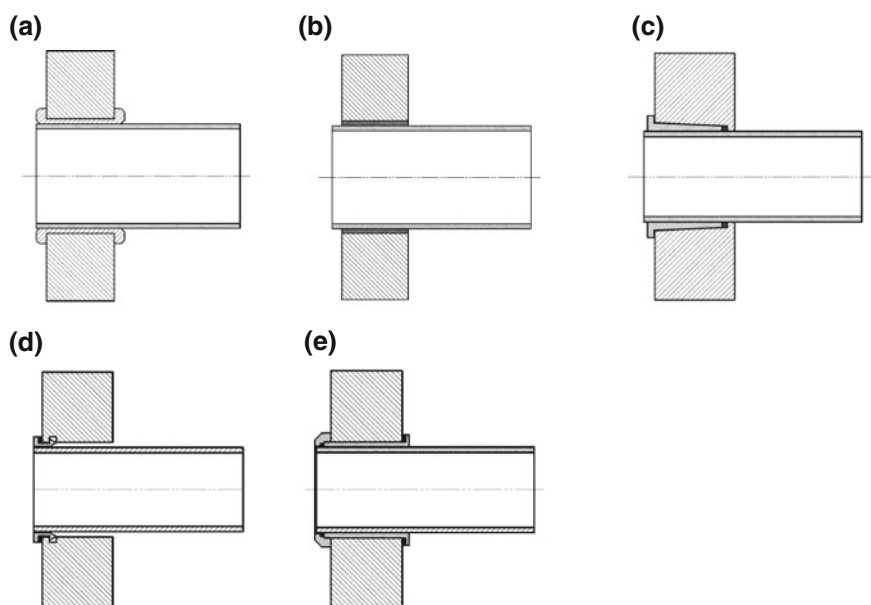


Fig. 22 Different tube/tube plate connection technologies: **a** rubber grommets, **b** bonding, **c** self-locking cone, **d** snap lock, **e** screw lock

Rubber Grommets: The use of rubber grommets is a straightforward way of connecting heat exchanger tubes with tube plates. The rubber grommets are plugged into the mounting holes of the tube plate. The tubes are pushed through the grommets, and sealing is provided by compressing the rubber material. The sealing properties and reliable hold depend on various parameters, e.g. materials, surface quality, applied temperature and chemicals. Therefore, the material selection of the grommets must be carefully considered for every application.

Advantages:

- Economic solution (low price and uncomplicated fast mounting).
- Flexible connection, compensation of thermal expansion.
- Damping of vibration.
- Detachable connection.
- Applicable to any material combination (tube/tube plate).

Disadvantages:

- Maximum pressure is limited by the force that the rubber can withstand between tube and tube plate.

Bonding: Connecting the tubes and the tube plates via bonding provides a sealing over the full mounting hole in the tube plate leading to a high pressure resistance. Depending on the type of glue, bore holes can be wide (for rubber-like glues) or must be very precise (for contact adhesives). Moreover, the applied temperature, chemicals and types of material for tubes and tube plates require suitable types of cement.

Advantages:

- Tight sealing even for high pressure.
- Flexible glue can compensate a small thermal elongation.

Disadvantages:

- Time-consuming pre-treatment (such as degreasing, priming).
- Selection of adhesive depends on material combination (tube/tube plate) and surrounding conditions (chemicals, temperature).
- Curing time.
- Manual application requires much training to be fail-safe, automated glue applicator may be necessary.

Welding: By applying heat locally to the tube and the tube plate, the material melts and gives a substance-to-substance bond with high strength. However, welded connections are only possible when using compatible materials for tubes and tube plates. Welding of polymer composite tubes into the tube plates requires the usage of polymer-based tube plates.

Advantages:

- Tight sealing.
- Resistance to pressure depends on the weld seam and the material of tube and tube plate.
- No special preparation necessary.

Disadvantages:

- No compensation of thermal expansion.
- Welding might be complicated and unsafe for narrow tube distances.
- Special equipment for plastic welding in narrow space is needed.

Self-Locking Cone: Mounting with a self-locking cone is a fast and easy way to establish a reliable connection. An O-ring seal is applied in a conically shaped mounting hole in the tube plate. The plastic cone is pushed into the hole with adequate force. Sealing is provided through the squeezed O-ring and the stuck cone. Since it is a purely mechanical method of connection, this method does not have special requirements to the surrounding materials. The plastic must resist the surrounding chemicals and temperature.

Advantages:

- Fast and fail-safe mounting.
- Economic connection.
- Reversible connection.
- Applicable to any material combination (tube/tube plate).

Disadvantages:

- Maximum pressure is limited.
- Preparation of tube plates is slightly more complicated (drilling of cones).

Snap Lock: A snap-in ring connector is plugged into the mounting hole with inner notches. Two gaskets provide sealing: one between ring connector and tube plate, another one between ring connector and tube. After snapping in, the connection is very tight with a controllable force to the sealing. The plastic must resist surrounding chemicals and temperature.

Advantages:

- Fast and fail-safe mounting.
- Economic connection.
- Applicable to any material combination (tube/tube plate).

Disadvantages:

- Sealing must be provided on more than one area.
- Maximum pressure is limited by sealing material.
- Preparation of tube plates is slightly more complicated (cutting of inner notch).

Screw Lock: A sleeve with thread at the end and a sealing are inserted into the mounting hole from one side. Then, the tube is pushed through it and is fixed by a screwed-on cap, also equipped with a sealing, from the other side. Since the connection is screwed together, it resists high pressure but can be unlocked again any time. The plastic must resist surrounding chemicals and temperature.

Advantages:

- Fast and fail-safe mounting.
- Tight mechanical connection, resistant to high pressure.
- Reversible connection.
- Applicable to any material combination (tube/tube plate).

Disadvantages:

- Connection parts must be inserted from two sides.
- More complex connection parts, less economic.

7.2 *Flow-Induced Tube Vibrations*

Vibration of tubes in heat exchangers is an important limiting factor in the durability of the heat exchangers. In many shell and tube heat exchangers, cross-flow of gases, liquids or gas–liquid mixtures occur. Optimum heat exchanger performance often requires high flow velocities, while reduced structural support is desirable in order to minimize pressure drop and manufacturing costs.

High flow velocities and reduced structural support can lead to flow-induced vibrations which may cause short-term damage, such as tearing the tubes from the tube plates or causing the tubes to impact against each other, or long-term damage, such as material fatigue when long-term vibrations exceed the fatigue strength of the material and/or fretting wear failures due to friction and impact between the tubes and the support baffles (Gelbe and Ziada 2010).

Proper material selection, vibration tests and vibration analysis are important in the design process of tubular heat exchangers in order to avoid tube failures due to vibrations.

7.2.1 *Reverse Bending Cycle and Vibration Tests*

The polymer composite tubes were tested according to the standards of the German Technical and Scientific Association for Gas and Water (DVGW) for pipe systems in drinking water installations. A combination of the reverse bending cycle test according to DVGW worksheet W 534, paragraph 12.9, and the vibration test according to DVGW worksheet W 534, paragraph 12.7, was performed with the polypropylene–graphite composite tubes, as shown in Fig. 23.

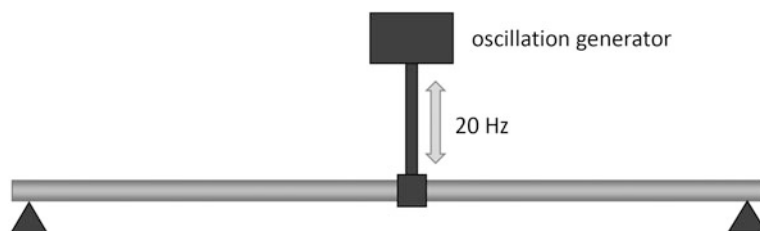


Fig. 23 Reverse bending cycle and vibration test (schematic)

The vibration resistance of the PP-GR tubes was tested with a fixing distance of two metres and the force applied in the middle. An internal pressure of 2 bars was used for leakage detection. The PP-GR tubes passed without failure for

- 1×10^6 cycles with an amplitude of 10 mm at 20 Hz air filled,
- 2×10^6 cycles with an amplitude of 1 mm at 20 Hz water filled.

7.2.2 Maximum Unsupported Tube Span

The tubes in a shell and tube heat exchanger tend to vibrate under the influence of single-phase or two-phase cross-flows (Thulukkanam 2013). The effect of the axial flow outside the tubes or the flow inside the tubes is often negligible, except in the case of tubes with large spacings between the support plates and small stiffness (Gelbe and Ziada 2010).

Tube failure as a consequence of flow-induced vibrations is a serious problem which has to be considered within the design process of a shell and tube heat exchanger. Four different excitation mechanisms are responsible for vibrations (Thulukkanam 2013):

- Vortex shedding;
- Turbulent buffeting;
- Fluid elastic instability and
- Acoustic resonance.

If the amplitude of the vibration exceeds a certain threshold, mechanical failure in various forms can arise. Damage patterns are divided into the following types (TEMA 1999):

- Collision damage: impact of the tubes against each other.
- Baffle damage: tubes hit against the baffle holes causing thinning of the tube wall.
- Tube plate clamping effect: stresses due to lateral deflection have maximum values at the tube plate.
- Material defect propagation: vibrations with very small amplitude in combination with flaws in the tube material propagate tube failure.
- Acoustic vibration: harmful when the acoustic resonant frequency approaches the tube natural frequency.

The Tubular Exchanger Manufacturers Association, Inc. (TEMA 1999) has developed standards for flow-induced vibration analysis which have achieved worldwide acceptance. In order to prevent damaging tube vibration in heat exchangers, support plates are installed along the tubes. The support plate configuration as well as the unsupported tube span has to be adjusted with regard to shell-side flow conditions (TEMA 1999).

The vibration evaluation procedure involves the estimation of certain parameters for each excitation mechanism. The estimated parameters are compared to defined threshold values to check whether or not damaging tube vibration occurs (Thulukkanam 2013).

In order to evaluate the phenomena of fluid elastic instability, the critical velocity

$$u_{\text{crit}} = \frac{D f_n d_o}{12} \quad (10)$$

is calculated in ft/s, where d_o is the outside diameter of the tubes in inches, D is a dimensionless parameter which is a function of several fluid, geometric and material values, and f_n is the fundamental natural frequency in cycles/s (TEMA 1999).

The fundamental natural frequency can be calculated from:

$$f_n = 10.838 \frac{A C}{L^2} \left(\frac{E_t I}{\omega_0} \right)^{1/2} \quad (11)$$

in the case of straight tubes, where A is the dimensionless tube axial stress multiplier, C is a dimensionless constant depending on the edge condition geometry, L is the unsupported tube span in inches, E_t is the modulus of elasticity of the tube material in psi, I is the second moment of area of the tube cross section in inches⁴, and ω_0 is the effective weight of the tube per unit length in lb/ft (TEMA 1999). It must be ensured that the cross-flow velocity at every point in the tube bundle is less than the critical velocity u_{crit} .

Vortex shedding is evaluated by determining the respective amplitude. The vortex shedding amplitude y_{vs} in inches can be defined by:

$$y_{\text{vs}} = \frac{C_L \rho_o d_o u^2}{2\pi^2 \delta_T f_n^2 \omega_0}, \quad (12)$$

where C_L is the dimensionless lift coefficient, ρ_o is the density of the fluid outside the tube in lb/ft³, u is the cross-flow velocity in ft/s, and δ_T is the dimensionless logarithmic decrement (TEMA 1999). Harmful tube vibration is prevented when

$$y_{\text{vs}} \leq 0.02 d_o \quad (13)$$

is valid (TEMA 1999).

The threshold in Eq. (13) is universal. Thus, the vibration amplitude y_{tb} as a consequence of turbulent buffeting

$$y_{tb} = \frac{C_L \rho_o d_o u^2}{8\pi \delta_T^{1/2} f_n^{3/2} \omega_0} \quad (14)$$

has to be below this value (TEMA 1999), where C_L is the dimensionless lift coefficient and y_{tb} is calculated in inches.

In order to evaluate the suitability of PP-GR and PPS-GR composites as tube materials in heat exchangers, their vulnerability to flow-induced vibration has to be investigated. Therefore, the maximum unsupported tube span was determined by using the TEMA Standard Guideline (TEMA 1999) and compared to other common metal tube materials for a reference horizontal tube falling film evaporator. The reference evaporator represents one stage of a large MED plant for seawater desalination. The design and process parameters are listed in Table 10.

Table 11 shows the examined tube specifications. PP-GR and PPS-GR are compared to titanium grade 2, aluminium brass (EN CW702R) and duplex stainless steel (EN 1.4462). Each tube material is taken into account with its commonly applied wall thickness.

For the analysis of the flow-induced vibrations, three different vapour velocities are assumed in a practical range, amounting to 10, 20 and 30 m/s. The results for the maximum unsupported tube span for the three most important excitation mechanisms are presented in Table 12.

The results reveal that turbulent buffeting and fluid elastic instability are negligible within the considered vapour velocity range, since in all cases the maximum unsupported tube span is restricted by vortex shedding. Therefore, the discussion will focus on the results for vortex shedding.

With rising vapour velocity, the maximum unsupported tube span decreases due to the fact that excitation by vortexes increases. Therefore, support plates in the heat

Table 10 Main design and process parameters of the reference horizontal tube falling film evaporator for vibration analysis

Parameter	Unit	Value
Tube length	mm	7000
Tube sheet thickness	mm	20
Pitch configuration	–	Triangular
Pattern	°	60
Tube pitch	mm	33.78
Tube outer diameter	mm	25.4
Temperature shell-side	°C	55
Temperature tube-side	°C	60
Pressure shell-side	bar	0.158
Pressure tube-side	bar	0.199
Wetting rate	kg/(s m)	0.1
Seawater salinity	g/kg	45

Table 11 Tube specifications for vibration analysis

	Unit	PP-GR	PPS-GR	Titanium grade 2	Al brass CW702R	Duplex stainless steel 1.4462
Tube wall thickness	mm	1.25	1.25	0.5	0.7	0.7
Elastic modulus	MPa	7836	16,523	105,000	110,000	200,000
Density	kg/m ³	1580	1780	4510	8350	7800

Table 12 Results of the flow-induced vibration analysis

		PP-GR	PPS-GR	Titanium	Al brass	Duplex
	Vapour velocity u	Maximum unsupported tube span L				
Unit	m/s	m				
Vortex shedding	10	3.37	3.47	3.75	3.93	4.30
	20	2.05	2.11	2.28	2.39	2.62
	30	1.51	1.56	1.69	1.77	1.94
Turbulent buffeting	10	16.13	17.07	18.63	24.03	25.95
	20	9.70	10.26	11.20	14.45	15.60
	30	7.09	7.51	8.20	10.57	11.41
Fluid elastic instability	10	20.27	20.89	22.58	23.63	25.91
	20	12.33	12.71	13.74	14.38	15.76
	30	9.12	9.40	10.16	10.63	11.65

exchanger have to be placed in a shorter distance to each other and consequently in a larger number, which results in higher investment costs.

As shown in Table 12, the maximum unsupported tube spans for PP-GR and PPS-GR are very similar in the reference evaporator. The maximum unsupported tube spans for PP-GR and PPS-GR tubes are slightly smaller than those for the established metal tubes. For example, the unsupported tube spans for the PP-GR tubes are only about 14% lower than those for aluminium brass tubes at vapour velocities between 10 and 30 m/s in the reference evaporator. The results undeniably illustrate the competitiveness of the novel polymer composite tubes against established metal tubes.

7.3 Tube Geometries

During extrusion, a polymer melt is forced through a shaping die and formed into a profile. This profile can be a plate, a tube or any other desired form (Osswald et al. 2006). The polymer extrusion process is very versatile. Products with complex

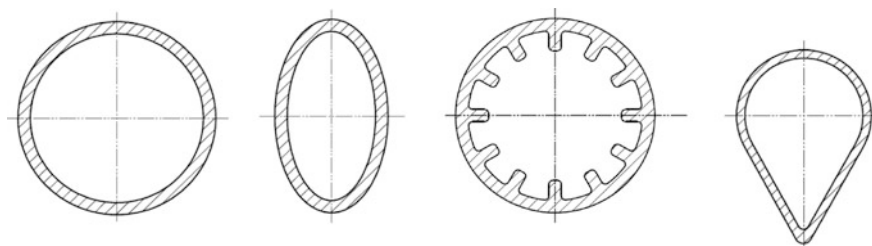


Fig. 24 Possible contours of polymer composite tubes

shapes can be created. As the polymer extrusion process offers a high degree of freedom in design opposed to the manufacturing process of metal tubes, shapes other than circular plain tubes can be easily produced. Some examples of tube shapes are shown in Fig. 24.

Ophir and Gendel (2007) reported that experiments indicated a significant increase in heat transfer when utilizing corrugated oval tubes in horizontal tube falling film evaporators for seawater desalination. Hasan and Siren (2004) studied the performance of evaporative coolers with plain circular and plain oval tubes and concluded that the oval tubes have good heat and mass transfer characteristics and better characteristics regarding pressure drop, so that the combined thermal–hydraulic performance of oval tubes is favourable in evaporative coolers. Numerical and experimental studies by Khan et al. (2005) and Ota et al. (1984) of fluid flow and heat transfer around elliptical tubes show that they offer less flow resistance and higher heat transfer rates than circular cylinders. Moreover, a very effective way of enhancing heat transfer is to provide heat exchanger tubes with structured surfaces. Finned tubes, spirally fluted tubes, corrugated tubes and dented tubes have been used (Naik 2004; Geißler and Szech 2004).

Various polymer composite tube geometries optimized with regard to fluid flow, heat transfer and available space and adapted to the specific application might offer further benefits in future heat exchangers.

8 Potential Applications

The novel polymer composite heat exchangers offer opportunities in many fields of applications, especially in applications that require a high corrosion resistance such as thermal desalination, flue gas cooling and thermal processes in the chemical industry. The outstanding resistance of the polymer matrix and graphite against salt solutions and acids in even high concentrations makes the thermally conductive composite materials the perfect fit for the applications shown in Table 13. Additionally, the low fouling propensity and the favourable cleaning possibilities

Table 13 Potential applications for polymer composite heat exchangers

Industry	Applications and requirements	Heat exchanger	Advantages of polymer composite heat exchangers
Chemical industry	– Cooling of water circuits – Condensation of exhaust vapours – Condensation and tempering of solvents – Cooling and heating of acids and caustic solutions – Flue gas cooling Requirements: high efficiency and heat transfer capacity, ease of repair, low pressure drop, abrasive wear protection, excellent drainage properties	– Heater – Cooler – Evaporator – Condenser – Absorber – Gas cleaner	– High chemical resistance to acids, aggressive flue gases – Lightweight design – High robustness – Low fouling propensity – Easy and fast to clean – High thermal conductivity
Petrochemical, oil and gas industry	– Heating and cooling – Processing – Gas cooling and condensing – Gas sweetening – Gas dehydration – Wastewater treatment – Crude oil dehydration – Stabilization – Regasification Requirements: energy efficiency, maximum heat recovery	– Heater – Cooler – Evaporator – Condenser	– High chemical resistance – Low fouling propensity
Heating, ventilation, air conditioning and refrigeration	– Air conditioning – Heating and cooling – Desiccation – Refrigeration – White goods (refrigerators, washing machines) Requirements: economic use of energy	– Heater – Cooler – Heating panel – Condenser – Boiler	– Frost-proof – Resistance to freezing agents – Resistance to hydrocarbons
Food and beverage	– Food processing/dried fodder production – Dairy processing – Beverage processing – Pasteurization – Brewing and malting Requirements: low cost, energy efficiency, corrosion resistance, food safe	– Heater – Cooler – Evaporator – Condenser – Chiller	– Low fouling propensity – Chemical resistance – Food grade quality

(continued)

Table 13 (continued)

Industry	Applications and requirements	Heat exchanger	Advantages of polymer composite heat exchangers
Pulp and paper	– Heating of clear filtrate and liquids – Cooling of wastewater – Heat recovery – Cooling of hydraulic oil – Heating of process water – Cooling of wash water and backwash water Requirements: production efficiency, maximum heat recovery	– Heater – Evaporator – Boiler	– Low fouling propensity – Low costs
Power generation	– Condensation – Cleaning and cooling of biogas – Cooling of lube oil – Cooling of motor cooling water – Flue gas cooling – Solar heating Requirements: safe operation, efficiency	– Shell and tube heat exchanger – Air cooled condenser (dry cooling) – Wet cooling tower – Hybrid cooling tower – Preheater – Solar absorber	– Corrosion resistance – Low fouling propensity – Erosion resistance – Lightweight design – Long life
Thermal desalination	– Multiple-effect distillation – Evaporation with vapour compression – Multi-stage flash evaporation Requirements: corrosion resistance, chemical resistance to cleaning acids, low fouling propensity, low cost	– Evaporator – Condenser	– Corrosion resistance – Low fouling propensity – Erosion resistance – Lightweight design – High robustness – Long life – High thermal conductivity – Low cost

open the door for the novel polymer composite tubes to many markets. Restrictions are the maximum temperature limit of about 200 °C and the brittleness compared to metal tubes.

9 Conclusions and Future Prospects

Unfilled polymer tubes have been used in heat transfer applications for years, but their field of application is very restricted due to their poor thermal and mechanical properties. Thermally conductive polymer composite materials are very promising, but research and development has mainly been focussed on polymer composite parts produced by injection moulding for the thermal management of electronic devices such as light emitting diodes, batteries and photovoltaic cells. However, the extrusion of polymer tubes with high filler loadings and the enhancement of thermal conductivities in the radial direction are challenging tasks.

Technoform Kunststoffprofile GmbH in Lohfelden, Germany, has developed polymer composite tubes exhibiting high thermal conductivities for use in heat exchangers by applying a special extrusion process. Polymer composite grades based on polypropylene and polyphenylene sulphide filled with graphite have been devised. The special extrusion process can handle high filler loadings up to 60 vol% and orient the filler in the polymer matrix in order to reach enhanced thermal conductivities in the radial heat flow direction. Thermal and mechanical properties, chemical resistance to various acids and alkaline media, lifetime behaviour, heat transfer performance and fouling behaviour were studied for PP- and PPS-based composites with 50 vol% graphite.

The thermally conductive polymer composites produced by extrusion are a new class of material, which can bridge the gap between polymers and metals and replace metals in many applications. The polymer composite materials combine the favourable properties of their polymer matrix and their graphite fillers. The extruded polymer composite tubes have a thermal conductivity of about 13–20 W/(m K) which is about 50–100 times higher than the thermal conductivity of standard polymers and comparable to stainless steel grades. Heat transfer was studied in a horizontal tube falling film evaporator under conditions close to those in industrial plants. When using the polymer composite tubes with a wall thickness of 1.25 mm or 1.5 mm, overall heat transfer coefficients near to those obtained with stainless steel tubes having a wall thickness of 0.7 mm were reached.

The novel polymer composite tubes showed a lower crystallization fouling propensity compared to common metal tubes. The induction period was longer, and the reduction of the overall heat transfer coefficient over time was lower compared with stainless steel tubes in a stirred vessel test rig with a CaSO_4 solution. In the horizontal tube falling film evaporator, the scale quantity formed on the polymer composite tubes in contact with artificial seawater was significantly lower than the scale quantity on common metal tubes under the same process conditions.

The excellent chemical resistance to strong acids and alkaline media, low weight, good processability and highly promising initial test rig results in fouling studies compared to corrosion-resistant metals offer benefits and open up cost-efficient opportunities for heat exchangers in various industries such as chemical, petrochemical, oil and gas, food and beverage, and seawater desalination industries. The polymer composite tubes with enhanced thermal conductivity are of

particular interest for evaporators and condensers with high heat transfer coefficients on the evaporation and condensation side in which a low thermal resistance of the tube wall is important to maintain a high overall heat transfer coefficient and thermal performance.

In the course of further development of the polymer composite tubes for specific applications, their properties and characteristics, such as thermal conductivity, chemical resistance and fouling behaviour, can be tested and compared to other materials with the developed test equipment. Thereby, it is possible to show advantages and disadvantages of this new class of material for a specific application compared to tube materials which are commonly used.

Various possibilities of mounting the polymer composite tubes in the tube plates were described. An analysis of flow-induced vibrations in a horizontal tube falling film evaporator with vapour cross-flow showed that the maximum unsupported tube spans for the PP- and PPS-based composite tubes are only slightly smaller than those of the established metal tubes underlining the competitiveness of the novel composite tubes.

The polymer extrusion process offers a high degree of freedom in design. A potential enhancement of heat transfer by shaping polymer composite tubes other than circular plain tubes offers promising future prospects. Furthermore, the construction of fully polymer-based heat exchangers will be in the focus of future development. The low weight of the polymer composite tubes may allow the construction of tube plates, support plates and other structural elements from polymer-based materials leading to further weight and cost savings and reduced corrosion problems in harsh environments. Thermoplastics with glass fibre or carbon fibre reinforcement may offer the required stiffness and strength for parts with low-to-medium mechanical loads.

Acknowledgements The authors are very grateful to M.Sc. Christoph Gatz, M.Sc. Sebastian Schilling, M.Sc. Alexander Stärk and M.Sc. Maximilian Waack for supporting the development of the polymer composite tubes with experimental and theoretical studies at the University of Bremen, Germany.

References

- Agari Y, Uno T (1985) Thermal conductivity of polymer filled with carbon materials: effect of conductive particle chains on thermal conductivity. *J Appl Polym Sci* 30:2225–2235
- Al-Janabi A, Malayeri MR (2015) A criterion for the characterization of modified surfaces during crystallization fouling based on electron donor component of surface energy. *Chem Eng Res Des* 100:212–227
- Amesöder S (2010) Wärmeleitende Kunststoffe für das Spritzgießen. Dissertation, Universität Erlangen-Nürnberg
- Amesöder S, Heinle C, Ehrenstein GW, Schmachtenberg E (2007) Injection moulding of thermally conducting polymers for mechatronic applications. In: Proceedings of the polymer processing society 23rd annual meeting, Salvador, 27–31 May 2007

- Bigg DM (1986) Electrical properties of metal-filled polymer composites. In: Bhattacharya SK (ed) Metal-filled polymers. Marcel Dekker, New York, pp 165–226
- Boeck K (2011) Zum Einsatz polymerbasierter Werkstoffe in Mehreffekt-Verdampfern für die Meerwasserentsalzung. Dissertation, Universität Bremen. Shaker Verlag, Aachen
- Burger N, Laachachi A, Ferriol M, Lutz M, Toniazzo V, Ruch D (2016) Review of thermal conductivity in composites: mechanisms, parameters and theory. *Prog Polym Sci* 61:1–28
- Bruggeman DAG (1935) Berechnung verschiedener physikalischer Konstanten von heterogenen Substanzen. I. Dielektrizitätskonstanten und Leitfähigkeiten der Mischkörper aus isotropen Substanzen. *Ann Phys* 416:636–664
- CALORPLAST Wärmetechnik GmbH (2017) CALORPLAST Wärmetechnik - Corrosion resistant heat exchangers for critical media. <http://www.calorplast-waermetechnik.de/en>. Accessed 28 Feb 2017
- Cevallos JG, Bergles AE, Bar-Cohen A, Rodgers P, Gupta SK (2012) Polymer heat exchangers—history, opportunities, and challenges. *Heat Transfer Eng* 33(13):1075–1093
- Chen H, Ginzburg VV, Yang J, Yang Y, Liu W, Huang Y, Du L, Chen B (2016a) Thermal conductivity of polymer-based composites: fundamentals and applications. *Prog Polym Sci* 59:41–85
- Chen X, Su Y, Reay D, Riffat S (2016b) Recent research in polymer heat exchangers—a review. *Renew Sustain Energy Rev* 60:1367–1386
- Cheng S, Vachon R (1970) A technique for predicting the thermal conductivity of suspensions, emulsions and porous materials. *Int J Heat Mass Transf* 13:537–543
- Cole-Parmer Instrument Company, LLC. (2017) Chemical Compatibility Database. <https://www.coleparmer.com/Chemical-Resistance>. Accessed 1 Mar 2017
- Dobkowski Z, Rudnik E (1997) Lifetime prediction for polymers via the temperature of initial decomposition. *J Therm Anal* 48:1393–1400
- Dreiser C (2016) Falling liquid film enhancement, fouling mitigation and conceptual design of polymer heat exchangers. Dissertation, Technische Universität Kaiserslautern. Shaker Verlag, Aachen
- Ehrenstein GW, Pongratz S (2013) Resistance and stability of polymers. Carl Hanser, Munich
- El-Dessouky HT, Ettouney HM (1999) Plastic/compact heat exchangers for single-effect desalination systems. *Desalination* 89:122–271
- Eucken A (1932) Die Wärmeleitfähigkeit keramischer feuerfester Stoffe. Ihre Berechnung aus der Wärmeleitfähigkeit der Bestandteile, *Forschungsheft/Verein Deutscher Ingenieure* 353
- Förster ML (2001) Verminderung des Kristallisationsfouling durch gezielte Beeinflussung der Grenzflächen zwischen Kristallen und Wärmeübertragungsfläche. Dissertation, Technische Universität Braunschweig
- Förster M, Bohnet M (2000) Modification of molecular interactions at the interface crystal/heat transfer surface to minimize heat exchanger fouling. *Int J Therm Sci* 39:697–708
- Geddert T, Bialuch I, Augustin W, Scholl S (2009) Extending the induction period of crystallization fouling through surface coating. *Heat Transfer Eng* 30:868–875
- Geißler S, Szezech D (2004) Tubes with structured surfaces. In: Mitrovic J (ed) Heat exchanger and condenser tubes—tube types, materials, attributes, machining. Publico Publications, Essen, pp 116–124
- Gelbe H, Ziada S (2010) Vibration of tube bundles in heat exchangers. In: VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen (ed) VDI Heat Atlas. Springer, Berlin, pp 1553–1585
- Glade H, Stärk A, Bart H-J, Krätz L, Dreiser C, Zöllmer V, Haberkorn A (2014) Entwicklung polymerbasierter Wärmeübertrager für den Einsatz in Meerwasserentsalzungsanlagen. Final Report, IGF Research Project 16959N. http://www.veu.de/files/abschlussbericht_16959.pdf
- Habonim Ltd. (2013) Chemical Compatibility Guide. <http://habonim.com>. Accessed 1 Mar 2017
- Halary J-L, Lauprêtre F, Monnerie L (2011) Polymer materials—macroscopic properties and molecular interpretations. Wiley, Hoboken
- Hammerschmidt U, Meier V (2006) New transient hot-bridge sensor to measure thermal conductivity, thermal diffusivity, and volumetric specific heat. *Int J Thermophys* 27(3):840–865

- Hasan A, Siren K (2004) Performance investigation of plain circular and oval tube evaporatively cooled heat exchangers. *Appl Therm Eng* 24:777–790
- Heinle C (2012) Simulationsgestützte Entwicklung von Bauteilen aus wärmeleitenden Kunststoffen. Dissertation, Universität Erlangen-Nürnberg
- Hewitt GF, Shires GL, Bott TR (1994) *Process heat transfer*. CRC Press, Boca Raton
- Kazi SN, Duffy GG, Chen XD (2010) Mineral scale formation and mitigation on metals and polymeric heat exchanger surface. *Appl Therm Eng* 30:2236–2242
- Kester DR, Duedall IW, Connors DN, Pytkowicz RM (1967) Preparation of artificial seawater. *Limnol Oceanogr* 12:176–179
- Khan WA, Culham JR, Yovanovich MM (2005) Fluid flow around and heat transfer from elliptical cylinders: analytical approach. *J Thermophys Heat Transfer* 19(2):178–185
- Krömer K, Will S, Loisel K, Nied S, Detering J, Kempter A, Glade H (2015) Scale formation and mitigation of mixed salts in horizontal tube falling film evaporators for seawater desalination. *Heat Transfer Eng* 36(7–8):750–762
- Kunststoff Information (2014) *Kunststoff Information Verlagsgesellschaft mbH*, Bad Homburg. <https://www.kiweb.de>. Accessed 20 June 2014
- Lattemann S, Höpner T (2003) *Seawater desalination—impacts of brine and chemical discharge on the marine environment*. Desalination Publications, L'Aquila
- Lattemann S (2010) *Development of an environmental impact assessment and decision support system for seawater desalination plants*. Dissertation, Delft University of Technology
- Lin F, Bhatia GS, Ford JD (1993) Thermal conductivities of powder-filler epoxy resins. *J Appl Polym Sci* 49:1901–1908
- Linseis GmbH (2017) THB—transient hot bridge—thermal conductivity meter, specifications. <https://www.linseis.com/en/our-products/thermal-diffusivity-thermal-conductivity/thb-transient-hot-bridge>. Accessed 1 Mar 2017
- Martenssen W, Warlimont H (2005) *Springer handbook of condensed matter and material data*. Springer, Berlin
- MatWeb, LLC. (2017) *Material property data, online database of engineering materials*. <http://www.matweb.com>. Accessed 28 Feb 2017
- Maxwell JC (1873) *A treatise on electricity and magnetism*, vol I. Clarendon Press, Oxford
- Millero FJ (2006) *Chemical oceanography*. CRC Press, Boca Raton
- Model R, Stosch R, Hammerschmidt U (2007) Virtual experiment design for the transient hot-bridge sensor. *Int J Thermophys* 28(5):1447–1460
- Müller-Steinhagen H (2010) Fouling of heat exchanger surfaces. In: VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen (ed) *VDI Heat Atlas*. Springer, Berlin, pp 79–104
- Müller-Steinhagen H (2000) Modellierung der Ablagerungsbildung in Wärmeübertragern. *Berichte zur Energie- und Verfahrenstechnik BEV*. Ed. A. Leipertz, ESYTEC Energie- und Systemtechnik GmbH, Erlangen
- Naik G (2004) Industrial power tubes—structured surface tubes. In: Mitrovic J (ed) *Heat exchanger and condenser tubes—tube types, materials, attributes, machining*. Publico Publications, Essen, pp 104–115
- Nielsen LE (1973) Thermal conductivity of particulate-filled polymers. *J Appl Polym Sci* 17:3819–3820
- Ophir A, Gendel A (2007) Latest developments in MED and MVC thermal desalination processes. In: *Proceedings of IDA World Congress on desalination and water reuse*. Maspalomas, 21–26 Oct 2007
- Osswald TA, Baur E, Brinkmann S, Oberbach K, Schmachtenberg E (2006) *International plastics handbook*. Carl Hanser, Munich
- Ota T, Nishiyama H, Taoka Y (1984) Heat transfer and flow around an elliptic cylinder. *Int J Heat Mass Transf* 27(10):1771–1779
- Öztürk G (2012) *Hochgefüllte Graphit-Polymer-Compounds für Einsätze im Wärmemanagement*. Dissertation, Technische Universität Darmstadt
- Pierson HO (1993) *Handbook of carbon, graphite, diamonds and fullerenes*. Noyes, Park Ridge

- Progelhof RC, Throne JL, Ruetsch RR (1976) Methods for predicting the thermal conductivity of composite systems: a review. *Polym Eng Sci* 16:615–625
- Scholz F (2004) Heat exchangers made of plastic pipes. In: Mitrovic J (ed) *Heat exchanger and condenser tubes—tube types, materials, attributes, machining*. Publico Publications, Essen
- Schweitzer PA (2007) *Corrosion of polymers*. CRC Press, Boca Raton
- Sheikholeslami R (2007) *Fouling in membranes and thermal units—a unified approach—its principles, assessment, control and mitigation*. Desalination Publications, L'Aquila
- Shinko Metal Products Co., Inc., Japan (2017) Copper alloy tubes for heat-exchanger. Brochure <http://www.shinkometal.co.jp/catalog/copperalloy-en-sc.pdf>. Accessed 1 Mar 2017
- Stärk A, Krömer K, Loisel K, Odiet K, Nied S, Glade H (2017) Impact of tube surface properties on crystallization fouling in falling film evaporators for seawater desalination. *Heat Transfer Eng* 38(7–8):762–774
- Stärk A, Loisel K, Odiet K, Feßenbecker A, Kempter A, Nied S, Glade H (2014) Wetting behaviour of different tube materials and its influence on scale formation in multiple-effect distillers. Paper presented at the conference desalination for the environment, clean water and energy, Limassol, Cyprus, 11–15 May 2014
- Stärk A, Loisel K, Odiet K, Feßenbecker A, Kempter A, Nied S, Glade H (2015) Wetting behaviour of different tube materials and its influence on scale formation in multiple-effect distillers. *Desalination and Water Treatment* 55:2502–2514
- Sunden B (2005) High temperature heat exchangers (HTHE). Proceedings of fifth international conference on enhanced, compact and ultra-compact heat exchangers: science engineering and technology. In: Shah RK, Ishizuka M, Rudy TM, Wadekar VV (eds) *Engineering conferences international*, Hoboken, NJ, USA
- The London Metal Exchange (2014) World centre for industrial metals trading. <https://www.lme.com>. Accessed 20 June 2014
- Thulukkanam K (2013) *Heat exchanger design handbook*. CRC Press, Boca Raton
- T'Joene C, Park Y, Wang Q, Sommers A, Han X, Jacobi A (2009) A review on polymer heat exchangers for HVAC&R applications. *Int J Refrig* 32:763–779
- Tubular Exchanger Manufacturers Association (TEMA) (1999) *Standards of the tubular exchanger manufacturers association*. Tubular Exchanger Manufacturers Association, Inc., New York
- Übler W (2002) *Erhöhung der thermischen Leitfähigkeit elektrisch isolierender Polymerwerkstoffe*. Dissertation, Universität Erlangen-Nürnberg
- Wang Y, Davidson JH, Francis LF (2005) Scaling in polymer tubes and interpretation for use in solar water heating systems. *J SolEnergy Eng* 127:3–14
- Wu Z, Francis LF, Davidson JH (2009) Scale formation on polypropylene and copper tubes in mildly supersaturated tap water. *Sol Energy* 83:636–645
- Wu Z, Davidson JH, Francis LF (2010) Effect of water chemistry on calcium carbonate deposition on metal and polymer surfaces. *J Colloid Interface Sci* 343:176–187
- Wypych G (2012) *Handbook of polymers*. ChemTec Publishing, Toronto
- Zaheed L, Jachuck RJJ (2004) Review of polymer compact heat exchangers, with special emphasis on a polymer film unit. *Appl Therm Eng* 24:2323–2358
- Zarkadas DM, Sirkar KK (2004) Polymeric hollow fiber heat exchangers: an alternative for lower temperature applications. *Ind Eng Chem Res* 43:8093–8106
- Zhao X, Chen XD (2011) A critical review of basic crystallography to salt crystallization fouling in heat exchangers. In: *Proceedings of international conference on heat exchanger fouling and cleaning*, Crete Island, 5–10 June 2011

Innovative Heat Exchangers

Bart, H.-J.; Scholl, S. (Eds.)

2018, X, 394 p. 242 illus., 100 illus. in color., Hardcover

ISBN: 978-3-319-71639-8