

just 30 s or even 3 to 5 min of actual testing time are good enough only for a relative comparison of similar samples. Allowing much longer actual testing times will characterize samples even better and with a higher level of significance.

Translations of captions and terms to figures in the German text (cf. pp. 751/757)

Fig. 1. Characterization of melts with a mixer sensor Rheocord90: mixer tests of three PE-melts at 200 °C

Drehmoment = torque
Massetemperatur = melt temperature
Knetertemperatur = mixer temperature
Antriebsdrehzahl = rotor speed
Versuchszeit = test period

Fig. 2. Viscosity curves determined by a rod die capillary rheometer

A: apparent and true viscosity curves (hard-copy of the computer screen display)
1: apparent viscosity of PE-HD, 3: corrected/true data

2: apparent viscosity of PE-LD, 4: corrected/true data
B: Bagley diagram to determine the entrance region pressure losses
Gesamtdruckverlust = total pressure loss
Eintrittsdruckverlust = entrance region pressure loss

Fig. 3. Viscosity curves determined by a slit die capillary rheometer

A: apparent and true viscosity curves (hard-copy of the computer screen display)

1: apparent shear stress of PE-LD, 2: apparent viscosity of PE-LD, 3: true/corrected viscosity of PE-LD

4: apparent shear stress of PE-HD, 5: apparent viscosity of PE-HD, 6: true/corrected viscosity of PE-HD

B: Weissenberg/Rabinowitsch diagram to determine the shear rate correction factor
Korrektur der Schergeschwindigkeit = correction of the shear rate
Beispiel = example

Fig. 4. Direct comparison of apparent and true flow and viscosity curves of the three PE-melts
scheinbare Viskosität = apparent viscosity
scheinbare Schergeschwindigkeit = apparent shear rate
wahre Viskosität = true viscosity
wahre Schergeschwindigkeit = apparent shear rate

Fig. 5. Flow and viscosity curves determined by means of a CS-rotational rheometer

B: Combination diagram of the viscosity curves of three rheometers
Temperatur = temperature
Viskosität = viscosity
Schergeschwindigkeit = shear rate
Schubspannung = shear stress
Platte/Platte-Meßsystem = plate/plate measuring system
Platten-Durchmesser = plate diameter
Plattenabstand = plate distance
Schlitz-Kapillare = slit capillary
Rundkap. = round capillary

Fig. 6. Dynamic test results of three PE-melts
Komplexer Modul = complex modulus
Phasenverschiebungswinkel = phase shift angle
Komplexe Viskosität = complex viscosity
Module = moduli
Frequenz = frequency

Fig. 7. Creep and recovery test results with a CS-rotational rheometer
A: with variable stress loads, B: comparison of three PE-melts subjected to the same stress load

Verformung = strain
Versuchszeit = test period
Kriech-Bereich =
Rueckerholung bei Entlastung =
Last = load
Versuchstemperatur = test temperature
Platte-Platte-Meßsystem =
gemeinsame Schubspannung = joint shear stress

Fig. 8. Extrapolation of a measured recovery curve

Verformung = deformation
Versuchszeit = test time
Regressionskurve = regression curve
Last = load
Messbereich = measuring range
extrapolierter Bereich = extrapolated range
Versuchstemperatur = test temperature
Platte-Platte-Meßsystem = plate/plate measuring system

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Plastics in the Construction of Heat Exchangers

An Answer to Many Problems

Translated from *Kunststoffe* 84 (1994) 6, pp. 767/771

NOTE: For figures and literature see German text; translations of captions and terms appear at the end of this article

As contradictory as it may sound, plastics are ideal problem solvers in the construction of heat exchangers. The poor thermal conductivity of plastics, which is seemingly opposed to their use, only is an obstacle where heat is to be exchanged between two liquids.

If a gas is involved in the heat exchange, the poor heat transfer coefficient between the gas and the exchanger surface is of primary importance whereas the thermal conductivity of the plastics material (at least up to 1 mm wall thickness) is of secondary importance.

Development of the basic idea

The Ytherm heat exchanger (Fig. 1) introduced in the following is based on an idea

developed at MAN, Nürnberg, namely to put the conventional design of a heat exchanger upside down in the heat exchange between liquids and gases. The gas rather than the water is passed through the aluminium tubes [1]. Thus the water flows around the outside of the tube.

After the first preliminary tests had yielded positive results, the development of the system was continued with a high scientific input [2 to 8]. It culminated in the construction of an experimental cooling tower specially installed for research work. The tower had an afflux area of 36 m² and was located on the factory site of MAN, Nürnberg.

The development work then was ceased although the thermal data were excellent. Owing to the many stages of manufacture,

the tubes bent from aluminium sheet, axially welded, hexagonally expanded at their ends and provided with integrally formed channels in the cylindrical middle section were too expansive.

In addition, the system also failed because of the problem of crevice corrosion on the rear of the face-welded entrance and exit sections of the exchanger elements. As no inert gas could be used in the welding operations on the critical rear side, no solution to this problem was found.

Both these problems are in direct relation to the use of metallic materials. Much more favourable conditions result from the use of plastics. However, the basic requirement is that the use of plastics should also be acceptable in terms of thermal technology.

Consideration of thermal technology

If energy is to be transferred from a gas to another material, and if the individual materials are not to be allowed to mix, this is only possible if both material flows are completely separated. Therefore the energy must be transferred from the gas flow to a wall, transmitted through this wall and transferred to the liquid stream on the other side of the wall.

The wall material only influences the quality of the heat transfer insofar as the heat transfer coefficient depends on the surface roughness of the wall. With regard to the transfer coefficient, metallic tubes show the same behaviour as plastics tubes if, at otherwise identical conditions, they also have the same surface roughness.

According to Fig. 2, and at the orders of magnitude indicated, the heat transfer coefficient on the gas side is the parameter limiting the heat transfer. In the case of exchange between liquids, this heat transfer coefficient is higher by a factor of about 10 than between gases. In this case, therefore, the low thermal conductivity of the plastic becomes the limiting factor.

Keeping to the heat exchange with a gas flow, the heat transfer coefficient by which the exchanger efficiency is mainly determined can be considerably improved by specific reductions of the inner tube diameter (radial channels). Fig. 3 shows the heat transfer coefficients determined within the MAN development project for non-channelled and channelled tubes as a function of the air velocity. In the velocity range measured, the heat transfer can be almost doubled by channelling. Measurements made on PPE tubes at the University of Hanover confirm that the heat transfer coefficient and pressure drop with plastics material and copper are comparable (Fig. 4).

Manufacturing formed tubes...

The technological potentialities of plastics processing permit a much less costly manufacture of the heat exchangers provided with hexagonal entrance and exit sections than the solution using aluminium (cf. Fig. 1).

Using long-established extrusion methods for tubes with peripheral calibrations (on forming machines known from the manufacture of corrugated tubes), the exit tubes with the cross-sectional geometry according to Fig. 5 can be manufactured in a continuous process. A tubular melt with a circular cross section is sucked or pushed into the forming tools of the forming machine by means of an outer vacuum (vacuum technique) or an inner overpressure (blowing technique).

Fig. 6 shows the diagram of a unit based on the vacuum technique [9]. In terms of accuracy, tolerances and geometrical variety, this system on which the forming tools are fitted with vacuum bores or slits offers definite advantages compared with the blowing technique. Moreover the vacuum technique facilitates the processing of engineering thermoplastics with high temperature resistance owing

to the absence of the tow plug within the tube as required in the blowing technique.

... and welding formed tubes

No standard welding technology existed for the face welding of the hexagonal tube ends. Röhm, Darmstadt, has specially developed a modified heated-tool welding technique which enables the individual tubes to be welded together simultaneously and homogeneously on both faces of the pre-sorted loose tube bundles [10].

The specially developed heated tool contains grooves which in the entrance area precisely correspond to the face geometry of the tube bundle and which slightly taper toward the groove root. By pressing the pipe ends into the welding tool heated to welding temperature, the tube ends are melted and welded together. After a certain holding or welding time, the heated element, and thus the melt in the grooves, are cooled to below the glass transition temperature of the material. When the melt has solidified, the completely welded heat exchanger block can be released.

The same welding technique also enables correspondingly designed flanges to be integrally welded in the same welding operation [11]. Fig. 7 illustrates a swan-up heat exchanger with integrally welded flange. While in the welded section no weld is recognizable between the individual tubes any longer, a difference between the welds of the tubes and the weld of the edge tube to the flange is not noticeable either. This homogeneous welding result ensures the tightness between the media flows involved, which is especially required for recuperators.

This welding technique very easily enables individual base module blocks to be welded together to form relatively large heat exchangers. As a result, any multiple of the entrance surface area of the base module can be obtained to meet the requirements of the particular application.

Owing to the continuous tube manufacture, any desired exchanger length is also easily obtainable. The hexagonal inflow and outflow geometries reduce the pressure drops as compared to conventional tube type exchangers and exit areas.

Aspect of application technology

As described above, heat exchangers made of plastics material are inexpensive and safe to construct. In addition to the technical advantages of the Ytherm system [12] under discussion, plastics based heat exchangers yield other decisive benefits. Corrosion, which often presents problems with metals, narrows the flow channels and thus reduces the air throughput and/or increases the pressure drop before complete failure occurs due to leaks. If appropriately selected, plastics offer excellent resistance to corrosion and chemicals at an extremely low price when compared with resistant high-alloy metals.

The tendency to be contaminated, which may substantially reduce the exchanger effi-

ciency, is generally lower with plastics because of a lower affinity of impurities with the plastics surface. As a result, plastics based exchangers are easier to clean.

A decisive argument for the use of plastics – especially with relatively large exchangers – is the considerable weight savings. They lead to substantially reduced costs of the overall construction since the entire supporting structure can be given a less sturdy design.

If the construction space available is limited, the small size of the heat exchanger is a particular advantage. The increase in the heat transfer coefficient by the special channelling of the tubes results in considerably smaller dimensions at equal efficiency than with conventional metal based exchangers.

The use of plastics in the construction of heat exchangers is limited. For example, service temperatures above 250 °C can be reached with plastics only in exceptional cases. The pressure range above 15 bar, too, is not permissible for reinforced thermoplastics in most cases. Normally the pressure limit is considerably lower because the service temperature is so high that the mechanical properties of the plastics material are markedly reduced.

Applications for plastics based heat exchangers

The use of plastics in the construction of heat exchangers is growing. Plastics based heat exchangers are increasingly used in heat recovering facilities. Both regenerative and recuperative systems are used in the private and industrial sectors.

In environmental technology the importance of plastics based heat exchangers is increasing on account of their outstanding chemical resistance. Primary applications in this sector are exchangers for off-heat recovery. An ideal use of plastics based heat exchangers is in recovering the off-heat of gaseous media, e.g. for utilizing the energy contained in combustion gases. After pre-cooling of the gases to a temperature acceptable for plastics, heat exchangers based on plastics prove successful on account of their excellent resistance to the gases condensing at low temperatures. They are also suitable for uses as air heaters for the indirect heating of drying facilities and as air preheaters for crude or purified gases. In the chemical industry the applications are concentrated on coolers and condensers.

In coal fired power plants plastics have stood the acid test in more than 40 gas preheaters of smoke gas desulphurization units. In Europe they have already been used for several years in low-cost, acid-resistant regenerative exchangers (Fig. 8).

Outlook

A replacement of a number of conventional materials by plastics in many applications can be forecast for the near future. On account of their special advantages plastics will also open up new applications in which conventional materials fail. However, it is a decisive requirement for successful uses of plastics based

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heat exchangers in the future that systems designed in consistency with the behaviour of plastics will be used, such as the one introduced in this report. The basis for meeting this requirement is the intensive dialogue between manufacturer and user as early as at the development stage of such heat exchanger systems.

Translations of captions and terms to figures in the German text (cf. pp. 767/771)

Fig. 1. Heat exchanger block made of profiled PPE tubes, with integrally welded flange (tube diameter 20 mm, length 280 mm)

Fig. 2. Heat flow through a heat exchanger wall in the energy exchange between a gas and a liquid

A: wall surface, d: wall thickness, Q: heat flow, T_G : gas temperature, T_F : liquid temperature, w thermal conductivity of the wall (for plastics: 0.2 W/mK, for copper: 380 W/mK), H: heat

transfer coefficient on the gas side ($20\text{W/m}^2\text{K}$), F : heat transfer coefficient on the liquid side ($200\text{W/m}^2\text{K}$)

Gas = gas
Flüssigkeit = liquid

Fig. 3. Comparison of the heat transfer coefficients on the air side for a smooth (a) and a channelled (b) tube

Wärmeübergang der Luft = heat transfer of the air

Geschwindigkeit der Luft im Rohr = air velocity in the tube

Fig. 4. Comparison of the heat transfer coefficients for a channelled plastics tube (a) and a smooth metal tube (b)

Wärmedurchgangskoeffizient = heat transmission coefficient

Reibungsdruckverlust = frictional pressure drop

Werkstoff = material

Durchmesser = diameter

Wanddicke = wall thickness

Länge = length

Kupfer = copper

Wasser = water

Fig. 5. Geometry of a plastics tube for a Ytherm type heat exchanger

Fig. 6. Diagram of the extrusion technique for manufacturing profiled heat exchanger tubes [8]

a: extrusion die, b: melt stream, c: casting die with included mould geometry, d: application of the vacuum, e: vacuum duct, f: machine table

Fig. 7. Plastics based heat exchanger sawn up in the entrance and flange sections

Fig. 8. Plastics based heat exchanger in the gas preheater of a smoke gas desulphurization unit

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Fibre-Reinforced Phenol Resin Materials for Plant Construction

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NOTE: For figures and literature see German text; translations of captions and terms appear at the end of this article

Besides metals and inorganic materials, thermoplastics and glass fibre-reinforced thermosetting plastics based on unsaturated polyester, vinyl ester, and epoxy resins also lend themselves to use for plant construction [1]. Materials based on phenol resins occupy a special position in this respect. These materials offer outstanding thermal stability and corrosion resistance to acids and, due to their advantageous processing properties, make it possible to create large-volume components with complicated shapes [2, 3]. Originally, production used to be limited to short fibre-reinforced phenol resin moulding materials. Long fibre-reinforced types with improved mechanical properties have also been available for some time.

Phenol resin, fibres, fillers, and additives

Resol resins with a molar phenol : formaldehyde ratio between 1 : 1.3 and 1 : 1.8 and a mean molecular weight of less than 1500 are used as phenol resins.

Owing to the high degree of cross-linking, phenol resins are known to be hard and brittle after hardening. Attempts to render phenol resins more flexible by adding oils, other resins, or other organic substances soon meet with certain limits. This is because flexibilization also reduces the thermal stability

and the corrosion resistance of the material. Still, several substances that react with phenol resin [4] and finely dispersed caoutchouc types, which form a second phase in the phenol resin matrix, have gained particular importance [5].

To a certain extent, the hard brittle character of phenol resins may be subdued in the presence of additives:

- Inorganic fibres, especially glass and carbon fibres, meet the requirement for constant stability and rigidity up until about 200 °C. In terms of corrosion resistance, carbon fibres are to be preferred. Their high price, however, limits their application.
- Mineral fillers and carbon-based fillers with a layered structure, such as graphite, are interesting because of their effective barrier effect to any penetrating medium.
- Various additives enhance the processing properties and control the hardening rate. Polycondensation of the phenol resin during hardening affords a close three-dimensional network, which is responsible for the good chemical stability and thermoforming resistance of the material (Fig. 1).

The more demanding autoclave process, which affords a better property spectrum, is usually to be preferred over the technique of hardening phenol resins at reduced temperature without external pressure in the presence of acids.

Processing and properties of short fibre-reinforced types

Kneadable, plastic masses containing short fibres with a length of less than 5 mm are employed for components made of short fibre-reinforced phenol resins. The former are homogenized in primarily discontinuously operating twin-sigma blade kneaders. At low pressure, this creates a particularly dense texture.

For the production of phenol resin components, usually individual parts, the moulding material, contained in wooden or steel moulds, is applied to vertical and horizontal surfaces, including upside-down ones, pressed into cavities, or wound around mandrels. Layer thicknesses of 50 mm or more may be realized in one operation. The wall thickness is commonly between 10 and 30 mm. Pipes are made on lathes by applying the moulding material onto steel mandrels and obtaining the desired pipe wall thickness by repeated rolling.

Certain series-produced components may be pressed. Moulded pipes, loose flanges, as well as cones, hoods, and overflow cones for bubble plates for columns, for instance, then harden in the mould inside a pressurized autoclave at about 140 °C. The excess pressure prevents evaporation of volatile portions and, after hardening, creates a material with a dense texture.