PLASTIC HEAT EXCHANGERS FOR WASTE HEAT RECOVERY

Final Report

by

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Components Technology Division

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ABSTRACT

Metallic corrosion is one of the major impediments to using the large amounts of heat available in flue and exhaust gases. Our approach is to develop plastic coatings to eliminate this corrosion problem and make this waste heat available economically. The advantages of plastics and their limitations in this application are discussed. Laboratory testing in an acid-condensing environment has been performed on numerous plastics and has identified several plastics with good potential as corrosion barriers. Polyphenylene sulfide, in particular, has resisted sulfuric acid attack for over 5000 hours and can be used at temperatures up to 300°C.
Large quantities of useful thermal energy are currently being lost in flue gases throughout the industrial, commercial and residential sectors of our economy. The amount lost in just the industrial sector is > 3.7 quad/year. The goal of the work reported here is to help recover this energy by developing a heat exchanger which can survive in the very corrosive conditions usually found in such flue gases. Plastics are well suited for this task because they are

- Very corrosion resistant,
- Easy to fabricate, and
- Relatively inexpensive.

The low melting point of plastics is not a problem; corrosion occurs only below 200°C—a temperature range in which many plastics can perform well.

Our approach has been to combine plastics with metals, usually in the form of a thin plastic coating on a metal tube. The resulting heat exchanger element combines the strength and high thermal conductivity of the metal with the corrosion resistance of the plastic. A laboratory testing program has been established to evaluate both the corrosion resistance and high-temperature behavior of the plastic-coated tubes. The corrosion test exposes the samples to sulfuric-acid vapor under condensing conditions. This is representative of actual flue-gas conditions and produces concentrated sulfuric acid on the plastic surfaces. Among the plastics tested under these conditions are

- Polytetrafluoroethylene (Teflon),
- Fluorinated ethylene propylene (Teflon),
- Perfluoroalkoxy (Teflon),
- Polyvinylidene fluoride (Kynar), and
- Polyphenylene sulfide (Ryton).

The test results clearly show that complex geometries, such as fin-tubes, are difficult to coat adequately and that coatings must be at least 0.05 mm thick to give adequate protection. With these restrictions, most of the plastics performed fairly well. The best plastic tested was the Ryton, which gave good protection and showed virtually no change after more than 5000 hours of exposure. The other plastics have not performed as well, allowing slight metal corrosion or showing degradation of the coating. In the high-temperature tests, most of the plastics performed well at temperatures above 300°C. If applied to water-cooled tubes, the plastics could be used in flue-gas environments as hot as 500°C.

Rough estimates of costs for plastic heat exchangers indicate a favorable cost-to-benefit ratio. But two criteria must be met to assure economic viability: lower initial cost and proven long life. Both of these areas need emphasis in future work. Coating and fabrication techniques need to be developed to produce a reliable prototype heat exchanger. These prototypes must undergo extensive testing to demonstrate the feasibility of the plastic heat exchanger concept.
1.0 INTRODUCTION

1.1 HEAT EXCHANGER PROBLEM

The rapid rise in fuel costs in recent years has led to increased emphasis on energy conservation. One area which has enormous potential for conservation is the heat wasted in exhaust and flue gases. This heat loss occurs in residential furnaces, commercial boilers and a wide range of industrial processes. As a result, large quantities of useful thermal energy are simply discharged to the atmosphere because no economic means has been available to recover it. The problems associated with heat recovery are most severe at temperatures below 200°C for two reasons:

- The burning of sulfur-bearing fuels produces small quantities of sulfuric acid in the flue gas. As this gas is cooled in heat recovery equipment, the sulfuric acid condenses onto the cool surfaces. In conventional metal heat exchangers, this acid condensation produces severe corrosion.

- The relatively low temperature of the recovered heat limits its usefulness and lowers its economic value.

But rising fuel costs have increased the economic incentives and have encouraged the development of solutions to the corrosion problem.

1.2 APPROACH

Our project at Argonne National Laboratory is aimed at developing a corrosion-resistant heat exchanger based on the use of plastics.¹ In many ways, plastics are nearly ideal for this application, combining corrosion resistance, low cost, and ease of fabrication. And the recent development of high temperature engineering plastics has greatly expanded the temperature range in which such heat exchangers can be considered. It is expected that plastics will play a significant role in the development of heat exchangers for waste heat recovery. This paper describes the results of the work at Argonne with several promising plastics.

2.0 BACKGROUND

2.1 WASTE HEAT SOURCES

A recent report on industrial waste heat in the U.S.² provides valuable data on potential applications for plastic heat exchangers. The data are given by type of waste-heat stream for all major U.S. industries. Table 1 gives a summary of the types of waste-heat streams and the estimated heat content of each.

The waste-heat streams most suitable for plastic heat exchangers are those that are very corrosive and in the moderate temperature range (< 200°C). This applies to categories 4 and 5 in Table 1, boiler and furnace exhausts. These streams represent a substantial amount of wasted heat, > 3.7 quad/year. But only part of this heat can be recovered with a plastic heat exchanger, because many of the exhaust streams are initially at
temperatures too high for plastics. Precooling of the exhaust in a conventional heat exchanger can be used to lower temperatures to ~ 200°C. Then an estimated 2.1 quad/year is still available for recovery from these streams by a plastic heat exchanger which cools the gas to ambient temperature. Because this moderate temperature range is where corrosion typically occurs, it is the range where the plastic heat exchanger is very well suited.

Table 1. Waste-Heat Streams*

<table>
<thead>
<tr>
<th>Type of Stream</th>
<th>Waste Heat Content quad/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.  Condenser Cooling Water</td>
<td>1.10</td>
</tr>
<tr>
<td>Avg. Temperature 45°C</td>
<td></td>
</tr>
<tr>
<td>2.  Contaminated Process Water</td>
<td>1.68</td>
</tr>
<tr>
<td>Avg. Temperature 50°C</td>
<td></td>
</tr>
<tr>
<td>3.  Steam Condensate</td>
<td>0.16</td>
</tr>
<tr>
<td>Avg. Temperature 80°C</td>
<td></td>
</tr>
<tr>
<td>4.  Boiler Stack Exhaust</td>
<td>0.96</td>
</tr>
<tr>
<td>150-320°C</td>
<td></td>
</tr>
<tr>
<td>5.  Furnace Exhaust</td>
<td>2.75</td>
</tr>
<tr>
<td>250-550°C</td>
<td></td>
</tr>
<tr>
<td>6.  Heat Rejected with Product or Process</td>
<td>4.02</td>
</tr>
<tr>
<td>(streams and temperatures not defined)</td>
<td></td>
</tr>
</tbody>
</table>

TOTAL HEAT REJECTED 10.67

* From Ref. 2
** 1 quad = 10^15 Btu = 1.06 x 10^18 joule.

2.2 FLUE-GAS PROPERTIES

Flue gases can have a wide range of properties, depending on such variables as the fuel used, amount of excess air, combustion parameters, and amount of heat recovery. For this study, we are considering flue gases produced by the combustion of high-sulfur fuel. Then, in addition to the usual flue gas constituents of N₂, CO₂, H₂O and O₂, there will be significant levels of SO₂ and SO₃ formed. It is this SO₃ content of the flue gas that is responsible for the corrosion that occurs in heat recovery equipment.
2.2.1 Acid Dew Point

Most of the sulfur in the fuel is converted to SO₂ and does not contribute significantly to the corrosion problem. However, ~ 1% of the SO₂ is oxidized further to SO₃, the ratio depending on combustion conditions and the presence of certain catalysts such as vanadium. Vanadium can be a significant component in fuel oils, as was found by Dietz et al. in a recent study of a condensing economizer.³ As a result, industrial flue gases can have SO₃ levels as high as 500 ppm by volume.⁴ This SO₃ quickly combines with the water vapor that is present to form sulfuric acid vapor, H₂SO₄. When the flue gas is cooled sufficiently, the sulfuric acid vapor condenses to form a highly corrosive film of concentrated sulfuric acid.

The condensation of sulfuric acid onto a heat exchanger surface depends on three variables:

1. the concentration of sulfuric acid vapor in the gas,
2. the amount of water vapor in the gas and
3. the temperature of the surface.

The first two variables combine to determine the acid dew point temperature for the flue gas. This is the temperature at which the two vapors are in equilibrium with a liquid condensate. If the surface temperature is above the dew point temperature, no condensation will occur. As the surface temperature drops below the dew point temperature of the gas, condensation will occur at a rate that depends on the surface temperature.⁴

Figure 1 shows how the dew point temperature depends on the acid vapor concentration for three different amounts of water vapor in the flue gas. (Water vapor content depends on the fuel burned and the amount of excess air.) This graph is based on an empirical formula developed by Verhoff and Banchero³ that gives a reasonable fit to measured dew point temperatures. Typical sulfuric acid concentrations in a flue gas are in the range 10-50 ppm by volume, giving dew points (for 10% water vapor) in the range 137 to 154°C. Conventional metal heat exchangers must be kept above this temperature range in order to avoid acid corrosion.

It is important to realize that the liquid which condenses onto the heat exchanger surfaces has a much higher acid concentration than the flue gas does. This is basically because sulfuric acid is much less volatile than water. When the vapor condenses, the acid condenses first, with relatively little water, producing a very concentrated acid solution. For example, an atmosphere containing 10% water vapor and 50 ppm sulfuric acid vapor will give a condensate at the dew point (154°C) which is ~ 84 wt % sulfuric acid. This highly concentrated acid is the source of heat exchanger corrosion.

2.2.2 Flue-Gas Temperature

It is clear from Table 1 (categories 4 and 5) that flue-gas streams exist over a wide temperature range. It would be quite impractical for a plastic-based heat exchanger to cover this entire range. But this is not necessary, since conventional metal heat exchangers are suitable for cooling the gas to ~ 200°C, which is still above the acid dew point. The plastic heat exchangers
need be considered only for the corrosive temperature range below 200°C. With this arrangement—a conventional heat exchanger cooling the flue gas to ~200°C and a plastic heat exchanger cooling it further—each type of heat exchanger can be optimised for a limited range of operation. The conventional metal heat exchanger is not exposed to the corrosion conditions and the plastic heat exchanger is not operated at high temperatures.

2.2.3 Particulates

Particulates can be a significant component of the flue gas and are a major factor in causing heat exchanger fouling. The source of the particulates can be the residual ash fraction of the fuel or can be carbon (soot) arising from incomplete combustion. In either case, the particulates tend to collect on heat exchange surfaces, particularly if these surfaces are wet with condensation. As the layer of particulate fouling grows, the heat exchanger performance deteriorates.

A second major factor in fouling is the occurrence of surface corrosion. This not only produces a layer of corrosion products, it also aggravates particulate fouling. The flue-gas particulates tend to collect more readily and adhere more strongly when surface corrosion has occurred.
Plastic heat exchangers are expected to resist fouling by

- Eliminating surface corrosion and
- Having very slippery surfaces to which particulates cannot adhere.

3.0 USING PLASTICS

3.1 GENERAL PROPERTIES OF PLASTICS

Modern plastics have attained quite remarkable thermal and physical properties, with some plastics usable to temperatures > 350°C, and some having tensile strength > 200 MPa. But in many respects, all plastics are quite similar. Some of the properties common to most plastics are

- Chemical resistance,
- Low thermal conductivity,
- Smooth surface,
- Low temperature limit (compared to metals), and
- Good fabricability.

These properties are discussed in the following sections.

3.1.1 Chemical Resistance

It is chemical resistance that makes plastics so useful for heat exchanger applications. This inertness is basically a result of the strong covalent bonds that exist in most polymers—bonds that resist attack by the corrosive agent. Of course, there can still be quite a range of behavior as different plastics are exposed to different corrosives. The molecular structure of a particular plastic has a significant effect on its response to corrosive attack. For example, the structures of polyamides and polyesters give them low resistance to acid attack because the amide and ester linkages are susceptible to acid hydrolysis. On the other hand, fluorinated hydrocarbons have only strong carbon-carbon and carbon-fluorine bonds and are resistant to virtually all solvents and corrosives.

3.1.2 Thermal Conductivity

Plastics are quite good thermal insulators, with typical conductivities in the range of 0.1 to 0.3 W/(m·K). Although fillers can increase the conductivity somewhat (to 1.0 W/(m·K) or more), these materials are still far from being good thermal conductors. For example, a metal such as aluminum has a thermal conductivity of about 200 W/(m·K). In a heat transfer application, the low conductivity of plastic is a real problem.

In some cases, when little mechanical strength is required, the plastic can be used alone to form thin-wall channels. But when rigidity or bursting strength is needed, plastics alone are not strong enough unless impractically thick walls are used. Therefore we have emphasized the use of metal for strength and good thermal conductivity, while the plastic is used only for corrosion protection. In this way, the plastic can be kept very thin, so that its low thermal conductivity is not important.
Consider the case of a thin plastic coating applied to a metal heat exchanger tube. The effect of various thicknesses of plastic are shown in Figure 2, assuming the uncoated tube to have a heat transfer coefficient of 100 W/(m²·K). The coefficient for the coated tube is normalized by dividing by 100, the value for the uncoated tube. The particular plastic used for the calculation was a fluorocarbon (Teflon), but other plastics would be very similar. (The value of \( U_0 = 100 \) is based on flue gas flowing around tubes of diameter 0.025 m. The maximum Reynolds number is ~18,000.) Figure 2 shows that the plastic coating degrades heat transfer by only ~8-20% if the thickness is kept in the range 0.2-0.6 mm. It will be shown later that this thickness range provides the needed corrosion protection.

\[ U_0 = 100 \text{ W/(m}^2\cdot\text{K)} \]

**Fig. 2.** Effect of plastic coating on heat transfer coefficient.

Why do these coatings have so little effect on heat transfer performance? The basic reason is that the primary resistance to heat transfer is in the gas, not in the plastic. The plastic is not the major barrier to heat flow, as long as it is kept thin. The layer of plastic is comparable to a thin fouling layer in its effect on performance. Such a layer is routinely accommodated in heat exchanger calculations, and does not greatly affect performance.
3.1.3 Surface Properties

Fluorocarbon plastics (e.g., Teflons) are a familiar example of the slippery, nonstick surface of many plastics. This characteristic is related to the chemical nature of the plastic as well as to its physical properties. Although some plastics are not particularly slippery, most of those considered for this project are quite good in this respect. The polyphenylene sulfide, in particular, has a very smooth, nonstick surface that is essentially as good as the fluorocarbons. Therefore, most of our candidate plastics can be expected to resist fouling and be easy to clean.

3.1.4 Temperature Limit

Most common plastics, such as vinyl, polyethylene and polystyrene, have an upper temperature limit ~ 120°C or below, making them unsuitable for application to flue-gas heat exchangers. This application requires a plastic that can survive at 200°C, preferably higher. For this temperature range it is necessary to consider the class of engineering plastics, which generally have higher temperature limits, greater strengths, and higher prices.

When using a plastic in a hot environment, there are three ways to assure that the plastic will survive and perform its required task:

- Select a plastic that has a high temperature limit, preferably above that of the environment,
- Keep the plastic sufficiently cool, and
- Minimize the strength needed in the plastic.

The first two points are obvious, but the third one relates to the high temperature behavior of plastics. Plastics usually lose their strength gradually as they are heated, so the useful temperature limit depends on how much strength is required. If very little strength is required, a particular material may be usable at temperatures well above its normal temperature limit (defined by standardized tests).

The Argonne approach uses all three of the ideas listed above. In addition to selecting plastics with high temperature limits (ranging from 150 to 260°C), we incorporate water cooling and metal reinforcement in the conceptual design of the heat exchanger. In this way, the plastics can survive exposure to flue gases at temperatures well above their usual design limits. For example, cooling water at 65°C is able to keep a thin plastic coating below the nominal design limit of 200°C with flue gas at temperatures up to 500°C.

3.1.5 Fabricability

One of the reasons that plastics have become so common today is that they can be easily fabricated in a variety of ways. This is a major advantage in our present application because it offers a wide choice of methods for applying the thin plastic films. Among the techniques that can be considered are
Molding (compression or rotational),
Spraying (slurry, solution or electrostatic),
Hot flocking (powder spraying onto heated part),
Extrusion,
Shrink coating,
Electrophoresis, and
Fluidized bed coating.

The choice among these methods is based on the type of plastic to be used, the coating thickness, and the geometry of the part.

Most of the coatings we tested were applied by spraying. This method is versatile in that it can give different thicknesses and can be used on complex shapes. Electrostatic spraying, in particular, is good for coating complex metal parts. For simple shapes, such as plain unfinned tubes, shrink coating is a convenient method. The technique involves placing a pre-expanded sleeve of plastic over the tube to be protected and then heating it to the "shrink temperature", causing the sleeve to shrink tightly around the tube. This method is easy, but it is not suitable for protecting finned tubes.

3.2 COMPARISON WITH METALS

Metals are the usual choice for heat exchanger material because they combine good strength, high thermal conductivity, and high temperature limit. Plastics are relatively poor in all three of these properties, having a major advantage only in the area of chemical resistance. Therefore, plastics alone are seldom used to construct heat exchangers. But in cases where plastic has an important advantage, it has been used alone with considerable success. For example, heaters for acid pickling baths have been made of bundles of plastic tubes with steam carried on the inside. The corrosion resistance of the plastic outweighs the low strength and thermal conductivity. Other characteristics which can give plastic an advantage over metal are

Fouling resistance,
Flexibility and toughness,
Ease of fabrication,
Low cost, and
Light weight.

Much more versatility can be achieved by using plastics together with metals. The heat exchanger can use the best features of each material while overcoming the disadvantages of each. One of the simplest ways to do this is to apply a thin layer of plastic over a metal heat exchanger. Another method is to use a woven metal matrix that is filled and covered with plastic. In both cases, the metal component provides strength while the plastic provides corrosion resistance. The Argonne test program has concentrated on heat exchanger elements constructed on this principle.
3.3 CANDIDATE PLASTICS

3.3.1 Criteria for Candidates

Plastics for use in flue gas heat recovery must meet certain performance criteria. These criteria are based on the need for resistance to sulfuric-acid attack, survival in hot gas streams, and economy of fabrication. The majority of plastics fail to meet one or more of these criteria and need not be considered further. Only those plastics that meet the criteria (or at least don't obviously fail) need to be examined more closely.

The specific criteria used for initial screening of plastics are

- Resistance to sulfuric acid attack,
- Maximum service temperature > 230°C, and
- Cost < $65/kg.

These criteria are not definitive, since data on acid resistance and service temperature can be incomplete or ambiguous for some plastics. Therefore, these criteria were used primarily to eliminate plastics that did not come close to the required performance level.

3.3.2 Selection of Candidates

Preliminary screening eliminated most plastics, leaving only a few high-performance plastics. These plastics were then examined in detail using technical literature and vendor contacts. The field of candidate plastics was narrowed by eliminating those listed in Table 2. The remaining plastics, listed in Table 3, are those which seemed most promising for use in flue-gas heat exchangers. In many cases, the data on acid resistance were meager and not applicable to thin films. So, we could not be sure that any particular plastic would be suitable. Also, some of the plastics listed have rather low service temperatures, but were included in the test program for evaluation of their acid resistance.

Three of the candidate plastics are types of Teflon fluorocarbon polymer. The three types have different mechanical and thermal properties, but all three can be expected to have excellent acid resistance. A fourth plastic, Kynar PVDF, is also a fluorocarbon polymer, but has only half as many fluorine bonds as the Teflons. This gives it poorer thermal and chemical properties. The last two plastics, Ryton PPS and Victrex PES, are polymers consisting of linked benzene rings. In Ryton the links are sulfur atoms and in Victrex the links are oxygen atoms and sulfone groups. Both plastics have good thermal, mechanical, and chemical properties, making them good candidates for this application.

3.3.3 Test Pieces

Plastics can be combined with metal to make a heat exchanger in a number of ways. The metal must form a continuous matrix in order to provide the needed strength, so using the metal in the form of powder, flakes, or fibers is not suitable. But other shapes are suitable and can be categorized as follows:
Table 2. Unsuitable Plastics

<table>
<thead>
<tr>
<th>Plastic</th>
<th>Trade Name</th>
<th>Reason for Elimination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diallyl isophthalate</td>
<td>Dapon (FMC)</td>
<td>Not available in coating form</td>
</tr>
<tr>
<td>Polyphenylene oxide</td>
<td>Noryl (GE)</td>
<td>Low service temperature</td>
</tr>
<tr>
<td>Polyamide-imide</td>
<td>Torlon (Amoco)</td>
<td>Degrades in hot acid</td>
</tr>
<tr>
<td>Polyarylate</td>
<td>Ardel (Union Carbide)</td>
<td>Attacked by acid</td>
</tr>
<tr>
<td>Polyetherimide</td>
<td>Ultem (GE)</td>
<td>Not available in coating form</td>
</tr>
<tr>
<td>Polyimide</td>
<td>Kapton (DuPont)</td>
<td>Attacked by acid</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>Udel (Union Carbide)</td>
<td>Attacked by acid</td>
</tr>
<tr>
<td>Polyyphenyl sulfone</td>
<td>Radel (Union Carbide)</td>
<td>Too expensive</td>
</tr>
<tr>
<td>Polyetheretherketone</td>
<td>PEEK (ICI)</td>
<td>Dissolves in strong acid</td>
</tr>
</tbody>
</table>

- Flat plates,
- Plain cylindrical tubes,
- Finned or corrugated tubes, and
- Flat or cylindrical woven mesh.

The flat plates or flat woven mesh can be stacked to form a plate-type heat exchanger, while the cylindrical shapes can be used to form a shell-and-tube heat exchanger. In each case, the metal would be protected from corrosion by a thin layer of plastic.

Our evaluation of heat exchanger geometries has rejected the plate-type heat exchanger as unsuitable for this application. Not only is the plate-type geometry inefficient for gas-to-liquid heat exchange, the plastic coating would be very vulnerable. Plate clamping forces would tend to displace the coating and plate vibration would quickly lead to destruction of the coating at points of plate-to-plate contact.
Table 3. Candidate Plastics

<table>
<thead>
<tr>
<th>Plastic</th>
<th>Trade Name</th>
<th>Service Temp. °C</th>
<th>Tensile Yield MPa</th>
<th>Thermal Cond. W/(m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polytetrafluoroethylene (TFE)</td>
<td>Teflon</td>
<td>260</td>
<td>9</td>
<td>0.24</td>
</tr>
<tr>
<td>Fluorinated ethylene propylene (FEP)</td>
<td>Teflon</td>
<td>200</td>
<td>12</td>
<td>0.24</td>
</tr>
<tr>
<td>Perfluoroalkoxy (PFA)</td>
<td>Teflon</td>
<td>260</td>
<td>15</td>
<td>0.24</td>
</tr>
<tr>
<td>Polyvinylidene fluoride (PVDF)</td>
<td>Kynar</td>
<td>150</td>
<td>51</td>
<td>0.13</td>
</tr>
<tr>
<td>Polyphenylene sulfide (PPS)</td>
<td>Ryton</td>
<td>170</td>
<td>66</td>
<td>0.29</td>
</tr>
<tr>
<td>Polyethersulfone (PES)</td>
<td>Victrex</td>
<td>203</td>
<td>83</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Some of the possible cylindrical geometries are shown in the photograph, Figure 3. These are, from the left,

- Plain steel tube coated with Victrex PES,
- Copper mesh tube, impregnated with Teflon FEP,
- Corrugated aluminum tube coated with Ryton PPS, and
- Finned steel tube coated with Teflon TFE.

Each of these types of heat exchanger element, which combine metal and plastic in a rigid cylindrical tube, have been included in our evaluation program.

4.0 TESTING

In order to evaluate plastic coatings for use in heat exchangers, we have established a laboratory testing program. This allows us to test the various plastics and coating methods under conditions that are representative of the actual application. The standard data available for the plastics are helpful but not really adequate for a proper evaluation. In particular, the effectiveness of thin layers of plastic in giving corrosion resistance is seldom discussed in the usual technical literature. Our testing provides a very direct evaluation of the samples by exposing them to conditions similar to those found in an actual flue gas. This has been done in two separate tests: exposure to sulfuric acid vapor at moderate temperatures (with acid condensation on the samples), and exposure to high temperatures in dry air. These tests represent two of the most destructive aspects of the flue-gas environment.
Fig. 3. Plastic-coated heat exchanger tubes: (from left) Victrex PES on plain steel tube; Teflon FEP on copper mesh tube; Ryton PPS on corrugated aluminum tube; Teflon TFE on finned steel tube.

4.1 CORROSION TEST

The most useful test of corrosion resistance is exposure of the test pieces to sulfuric acid condensation. Neither vapor nor liquid exposure alone can adequately simulate actual flue-gas conditions. The three factors that must be carefully simulated are:

- Nature of the corrosive (H₂SO₄ in this case),
- Vapor condensation onto heat exchanger surfaces, and
- Temperature of heat exchanger surfaces.

These factors are quite restrictive and make the results specific to these conditions. A different application with a different corrosive agent or a different temperature range would need modified test conditions.
The test apparatus which was built for the flue-gas application is shown schematically in Figure 4. A glass test chamber holds the tubular test pieces by Teflon seals at each end of the chamber. End plates of Incoloy 825 can hold as many as four test pieces. A flask of boiling sulfuric acid is connected to the test chamber and provides the corrosive vapor for the test. Water-cooled condensers are connected to the chamber outlet and prevent the escape of acid vapor, with all condensate returned by gravity to the acid flask. Condensation on the test pieces is controlled by keeping their temperature below the acid dew point temperature. This is done by circulating oil at the desired temperature through the inside of the test pieces. (The oil circulation system is not shown.)

The operating conditions of this apparatus are determined primarily by the concentration of acid in the flask and by the temperature of the test pieces. The total pressure in the chamber is near one atmosphere, but there is relatively little air. This means that the sulfuric acid vapor is quite concentrated around the test pieces and the dew point temperature is essentially the same as the boiling temperature in the flask. Titration of samples of the condensate collecting on the test pieces shows that this liquid is quite concentrated, as expected. Typical operating conditions for the apparatus are summarized in Table 4. Because the acid concentration in the vapor is much higher than in any flue gas, this testing represents a more severe environment and will accelerate any degradation of the plastics that might occur in service. However, the test conditions are realistic enough to give confidence in the results. This cannot be said of other test methods, such as immersion of the test pieces in hot acid.

4.2 HIGH-TEMPERATURE TEST

In addition to the corrosion testing, high-temperature testing has been performed on the plastic samples. This is intended to define the upper temperature limits of the different plastics and composites. Since acid condensation is not a problem at these higher temperatures, it is not necessary to do the testing in the presence of acid vapor; we have done this testing in dry air in a tube furnace. The samples are heated to stepwise increasing temperatures, with each temperature held for several hours. After each step, any change of the samples is noted. Such testing provides a good indication of the useful operating range of the material, as well as showing how it would withstand a brief temperature excursion. The range of test temperatures was 150 to 360°C.

5.0 RESULTS

The sections which follow give a summary of the results of our laboratory testing and fabrication experience, grouped by type of test piece. These results were reported in preliminary form in two earlier papers. 8,10

5.1 BARE TUBES

Plain, uncoated tubes of stainless steel (Type 321) and aluminum (Type 6061) were exposed in the corrosion test apparatus. Both metals were badly corroded in a few hours. This confirms the corrosivity of the test atmosphere and shows how unsuitable bare metal is in this application.
Fig. 4. Schematic drawing of corrosion test apparatus.
Table 4. Typical Test Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid Concentration in Flask</td>
<td>85% H$_2$SO$_4$ by wt.</td>
</tr>
<tr>
<td>Boiling Point of Acid</td>
<td>225°C</td>
</tr>
<tr>
<td>Chamber Pressure</td>
<td>0.95 atm</td>
</tr>
<tr>
<td>Acid Concentration in Vapor</td>
<td>0.6% H$_2$SO$_4$ by vol.</td>
</tr>
<tr>
<td>Dew Point Temperature of Vapor</td>
<td>220°C</td>
</tr>
<tr>
<td>Test Piece Temperature</td>
<td>120°C</td>
</tr>
<tr>
<td>Acid Concentration in Condensate</td>
<td>50-60% H$_2$SO$_4$ by wt.</td>
</tr>
</tbody>
</table>

5.2 COATED FIN-TUBES

Several plastics and several coating methods were used to coat various finned and corrugated tubes. No method was found that could apply a uniform coating of moderate thickness (0.1 to 0.4 mm) to such complex shapes. Non-uniform coatings are unacceptable because they give inadequate corrosion protection in the thin areas (fin edges) and excessive thermal resistance in the thick areas (fin roots). Several fin-tubes were coated with a thin coating (0.04 mm thick) of Teflon TFE that appeared to be quite uniform. When these pieces were exposed to the sulfuric acid vapor, severe corrosion was observed in less than 100 hours. The damage to one such piece is shown in Figure 5. It is clear that such a thin coating does not give adequate protection. The failure cannot be attributed only to the problem of coating the fin edges; similar damage, with lifting of large pieces of the coating, was observed on the relatively smooth corrugated tube.

5.3 MESH/PLASTIC COMPOSITE

An interesting type of heat exchanger material has been developed recently by the United Wire Group of Edinburgh. This material combines a woven metal mesh with a plastic which coats the metal and fills the holes in the mesh. This mesh/plastic composite (MPC) forms a relatively strong and light material that combines corrosion resistance with good thermal conductivity. Two different pieces of tubular MPC were tested in the corrosion apparatus. Both pieces used copper mesh; one piece was coated with Teflon FEP, the other with a thermoset polyester.

Both MPC pieces performed poorly in the corrosion test. The first piece, with Teflon FEP plastic, had been formed with many tiny air bubbles included in the plastic. This allowed the acid to reach the metal mesh and produce serious corrosive attack on the metal. The result of testing on this piece is shown in Figure 6, after 42 hours of exposure. In some spots the metal has been completely dissolved. The second piece, using polyester plastic, showed
Fig. 5. Photograph of coated high-fin tube after 115 hours exposure in corrosion test apparatus.

Fig. 6. Photograph of copper mesh/plastic composite after 42 hours exposure in corrosion test apparatus.
a gradual degradation of the plastic itself. After 900 hours of exposure, this piece had formed a softened layer of plastic at the surface. Such degradation is not too surprising, since polyester is not very resistant to acid attack.

5.4 COATED PLAIN TUBES

The test results for the coated plain tubes are summarized in Tables 5 and 6. The corrosion tests include a range of coating thickness for most of the different plastics. The high temperature tests were conducted on a more limited range of coatings.

Most of the coatings listed in Table 5 performed quite well, with only two types of coatings giving poor corrosion protection. One type is the PVDF coatings, which degraded under acid attack and allowed corrosion of the metal tube in a relatively short time. The other type of coating is the class of very thin coatings (~ 0.02 mm or less), which performed very poorly, regardless of the plastic used. The remaining coatings held up well for thousands of hours, showing only occasional discoloration or blistering. A thick coating of PPS developed a crack after extended testing, probably caused by thermal expansion. The thinner (more flexible) coatings did not have this problem. Figures 7-9 show some of the test pieces after exposure.

Table 5. Corrosion Test Results

<table>
<thead>
<tr>
<th>Plastic*</th>
<th>Thick. mm</th>
<th>Coating Method</th>
<th>Test Time hours</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFE</td>
<td>0.13</td>
<td>shrink</td>
<td>2357</td>
<td>Slight discoloration of metal tube</td>
</tr>
<tr>
<td>FEP</td>
<td>0.76</td>
<td>shrink</td>
<td>598</td>
<td>Slight discoloration of metal tube</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>shrink</td>
<td>2992</td>
<td>Slight discoloration of metal tube</td>
</tr>
<tr>
<td></td>
<td>0.51</td>
<td>spray</td>
<td>3811</td>
<td>Coating is blistered</td>
</tr>
<tr>
<td>PFA</td>
<td>0.10</td>
<td>spray</td>
<td>5067</td>
<td>Coating is blistered (see Fig. 7)</td>
</tr>
<tr>
<td></td>
<td>0.23</td>
<td>spray</td>
<td>1897</td>
<td>Coating is blistered</td>
</tr>
<tr>
<td>PVDF</td>
<td>0.25</td>
<td>shrink</td>
<td>1087</td>
<td>Slight corrosion of metal tube</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>spray</td>
<td>906</td>
<td>Coating is blistered and discolored</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>spray</td>
<td>906</td>
<td>Coating is blistered and discolored</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>spray</td>
<td>163</td>
<td>Metal is corroded under coating</td>
</tr>
<tr>
<td>PPS</td>
<td>0.76</td>
<td>spray</td>
<td>3614</td>
<td>Crack in coating, metal is corroded</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>spray</td>
<td>5067</td>
<td>Coating is slightly discolored (see Fig. 8)</td>
</tr>
<tr>
<td></td>
<td>0.28</td>
<td>spray</td>
<td>3757</td>
<td>Coating is slightly discolored</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>spray</td>
<td>163</td>
<td>Metal is corroded, coating is destroyed</td>
</tr>
<tr>
<td>PES</td>
<td>0.02</td>
<td>spray</td>
<td>163</td>
<td>Metal is corroded, coating is destroyed (see Fig. 9)</td>
</tr>
</tbody>
</table>

* See Table 3 for names of plastics.
Fig. 7. Photograph of PFA-coated tube after 5067 hours exposure in corrosion test apparatus.

Fig. 8. Photograph of PPS-coated tube after 5067 hours exposure in corrosion test apparatus.
Fig. 9. Photograph of PES-coated tube after 163 hours exposure in corrosion test apparatus.

Table 6. High-Temperature Test Results

<table>
<thead>
<tr>
<th>Plastic</th>
<th>Thick. mm</th>
<th>Coating Method</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFE</td>
<td>0.66</td>
<td>shrink</td>
<td>Softens slightly at 320°C. Turns clear at 340°C.</td>
</tr>
<tr>
<td>FEP</td>
<td>0.51</td>
<td>shrink</td>
<td>Softens at 270°C. Flows at 290°C.</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>spray</td>
<td>Softens at 270°C. Flows at 290°C.</td>
</tr>
<tr>
<td>PFA</td>
<td>0.23</td>
<td>spray</td>
<td>Softens at 300°C. Flows at 340°C.</td>
</tr>
<tr>
<td>PVDF</td>
<td>0.28</td>
<td>shrink</td>
<td>Softens at 170°C. Darkens at 200°C.</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>spray</td>
<td>Softens at 170°C. Darkens at 200°C.</td>
</tr>
<tr>
<td>PPS</td>
<td>0.28</td>
<td>spray</td>
<td>Softens slightly at 280°C. Rubbery up to 360°C.</td>
</tr>
</tbody>
</table>
The high-temperature test (see Table 6) largely confirmed the expected temperature behavior of the various plastics. Only one of the plastics, PVDF, showed thermal degradation at temperatures up to 360°C; it darkened and became brittle as its temperature was raised above 200°C and did not recover its original properties after cooling. The other plastics, however, showed no permanent change after several cycles of heating to 360°C and cooling. Another significant observation is that all of the plastics remained intact at temperatures well above their melting points. Except for the PVDF, they softened progressively but were generally rubbery rather than sticky and showed little tendency to flow at temperatures as high as 340°C.

6.0 HEAT EXCHANGER ECONOMICS

Our work has emphasized the technical feasibility of the plastic heat exchangers, but the economic feasibility is also important. Without it, the technology will never be widely used. Since the ultimate goal is the acceptance of this technology by industrial users, costs and other economic factors are very important. For evaluating economic factors, it seems most reasonable to assume that profit maximization will be the primary objective of most industrial companies. Other factors, such as pollution reduction or reduced dependence on foreign oil, will be very minor considerations. Therefore, the decision to purchase a particular piece of equipment, such as a plastic heat exchanger, will be based on a comparison of the dollar value of the resulting costs and benefits.

A recent study of waste heat recovery\textsuperscript{12} describes six different methods of evaluation that can be used to compare investment alternatives. The simpler methods, payback period and return on investment, may not adequately reflect the timing of cash flows but are widely used in the business community. More comprehensive methods, such as net present value, have the advantage of properly discounting future costs and benefits and including the opportunity cost of capital.

Table 7 lists some of the possible types of costs and benefits that would be included in the analysis of an investment in heat recovery equipment. Not all of these costs and benefits will apply in every case, but they are typical.

\begin{table}[h]
\centering
\begin{tabular}{|l|l|}
\hline
Costs & Benefits \\
\hline
\textbullet~Purchase of equipment & \textbullet~Fuel cost savings \\
\textbullet~Planning and installation & \textbullet~Reduced maintenance (on existing equipment) \\
\textbullet~End-of-life replacement & \textbullet~Revenue from recovered energy \\
\textbullet~Maintenance & \textbullet~Depreciation allowance \\
\textbullet~Taxes on capital improvement & \textbullet~Tax credits \\
\textbullet~Taxes on increased revenue & \\
\hline
\end{tabular}
\caption{Types of Costs and Benefits}
\end{table}
One important aspect of investing in new technology is the associated risk. For the plastic heat exchangers this is the uncertainty of the actual lifetime of the heat exchanger. If there is a high probability that replacement will be needed after two years of operation, then the probable cost of the investment becomes quite high. But if replacement is unlikely before ten years of operation, the cost is much lower. Even if the probable cost is low, some companies will prefer to avoid risky investments. For this reason, we have emphasized heat exchanger designs that are expected to be the most reliable—namely, those that can be coated reliably and have minimum coating stresses.

6.1 PLASTIC HEAT EXCHANGERS

The economic evaluation discussed in the preceding section requires knowledge of the relevant costs and benefits. The better this knowledge, the more accurate the evaluation. Unfortunately, plastic heat exchanger technology is too new for reliable cost estimates to be made. The two biggest cost components, initial cost and lifetime, are still quite uncertain. But we have developed estimates that may help to put costs in perspective. A more complete evaluation will be done when the coatings and application techniques are more certain.

Approximate prices have been obtained for three of the materials used in our test program. These prices are for plastic-coated tubes 2.5 cm in diameter in large lots (up to 10,000 meters):

- FEP (0.50 mm thick) $23.00/meter
- PPS (0.50 mm thick) $10.00/meter
- MPC (mesh/plastic composite) $13.00/meter

Each of these prices can be expected to drop significantly if a real market develops for the material. The prices represent mostly labor costs since the amount of plastic in these materials is quite small. It is likely that large scale production can produce these materials at a substantially lower cost.

Using these tube costs, the cost for 200 m² (2150 ft²) of heat transfer area is:

- FEP $59K
- PPS $25K
- MPC $33K

This area is sufficient for a heat recovery rate of about 1.0 MW (3.41 x 10⁶ Btu/hr), assuming that the flue gas is cooled from 230°C to 65°C by water in the tubes and the tubes are arranged for low pressure drop [about 275 Pa (0.04 psi)] across the tube bank.

The primary benefit attributed to this heat recovery is the cost savings on an equivalent amount of fuel. Assuming fuel costs of $30/bbl or $17.4/MM·hr, the recovered energy is worth approximately $35K/year (operating 2000 hr/year). Ignoring all heat exchanger costs except the tubing itself, this would give a payback period of:
22

<table>
<thead>
<tr>
<th>Material</th>
<th>Payback Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEP</td>
<td>1.5 years</td>
</tr>
<tr>
<td>PPS</td>
<td>0.7 years</td>
</tr>
<tr>
<td>MPC</td>
<td>0.9 years</td>
</tr>
</tbody>
</table>

This analysis, though crude, gives an indication of how quickly an investment in plastic heat exchangers could pay for itself.

6.2 COST COMPARISONS

The decision to invest in plastic heat exchangers would not be made without considering alternatives. Even though the economics might be very favorable, those of another technology could be better. For this reason, we have looked at several alternative technologies which would probably satisfy the technical requirements for flue-gas heat recovery. These technologies are described in the following sections.

6.2.1 Metal Alloys

A recent study\(^\text{13}\) of metal corrosion in oil-fired systems has shown that very few metals withstand the attack of acid condensate. The most corrosion-resistant alloys, including Ferralium, Inconel 671, and Hastelloy G, contain large amounts of chromium and molybdenum. These alloys are quite expensive and difficult to justify for most applications. To compare the cost of metal and plastic heat exchangers, we can first estimate the amount of metal tubing required to give the same 1.0 MW heat recovery rate. For this purpose, we chose a 1.90 cm O.D. low-fin tubing of Hastelloy G. With the same operating conditions as before, the required heat transfer area is ~180 m\(^2\) (1940 ft\(^2\)) and the total amount of finned tubing is 1,000 m. The cost of the tubing alone is ~ $27K; this is comparable to the tubing cost for PPS coated tubes or for MPC. Thus, the plastic technology is about equal to high-alloy tubes with respect to current costs.

6.2.2 Graphite

Graphite heat exchangers are a potential candidate for flue-gas heat recovery because they combine good chemical resistance with good thermal conductivity. Although their temperature is limited to ~175°C by the resin binder used in manufacture, this would not be a serious problem. Water cooling would keep the graphite temperature well below this limit, even if the flue gas temperature were 250°C or more. One drawback of these heat exchangers is the poor tensile strength of graphite. This problem requires designs that can be quite different from those using metal. For example, block-type heat exchangers are well suited to fabrication with graphite. In this design, a block of impervious graphite is drilled longitudinally and laterally to form the heat transfer passages. The high thermal conductivity of the graphite provides good thermal contact between the fluids in the two sets of passages.

For the gas-to-liquid heat exchanger we are considering, the most suitable design appears to be shell-and-tube. In this case, the gas would be on the tube side to take advantage of the chemical resistance of the graphite. With the same 1.0 MW heat transfer rate as before, the heat transfer area required is ~ 230 m\(^2\) (2500 ft\(^2\)) and the complete unit would cost
$150K. This is clearly much more expensive than plastic-coated tubes or high-alloy metals. But the graphite heat exchangers are a proven technology; both the costs and the risks are known when evaluating the investment.

7.0 CONCLUSIONS

7.1 PLASTICS

The laboratory testing program has enabled us to draw the following conclusions:

- Metal fin-tubing cannot be adequately coated with plastic. Present methods do not give coatings that are sufficiently uniform and reliable.

- Very thin coatings (< 0.05 mm) are unsuitable. Such coatings are not effective barriers to the corrosive acid, presumably because of porosity or defects in the coating.

- The mesh/plastic composite (MPC) material is a promising concept in spite of problems with prototype samples. Improved production methods and more appropriate choice of plastic could lead to a very useful material.

- Coatings of plastic with thickness in the range 0.1 to 0.5 mm have generally performed quite well and should not seriously degrade thermal performance.

- Of the plastics tested, only PVDF (see Tables 3, 5 and 6) was completely unsatisfactory. It degraded under acid attack and high temperatures and it allowed corrosion of the underlying metal tube.

- Of the remaining plastics, PPS has performed the best as a corrosion barrier. In 5000 hours of testing, there was no significant metallic corrosion or degradation of the plastic.

- The thermal stability of most of the tested plastics has been very good. With the exception of PVDF, the plastics survived exposure to temperatures as high as 360°C.

- With water cooling of the heat exchanger tubes, the plastic coating (e.g., PPS) could survive exposure to flue gas at a bulk temperature up to 500°C.

7.2 COSTS

The actual costs for producing plastic heat exchanger elements are still uncertain. But current estimates, which can be expected to drop substantially as the technology matures, seem to indicate a favorable cost-to-benefit ratio. Comparison with potential competing technologies shows that high-alloy metal units would be about the same cost, while graphite units would be much more expensive. Therefore, the plastic heat exchanger will have a significant cost advantage if costs can be reduced as expected.
Life-cycle cost, another important factor in the economic evaluation of this equipment, depends primarily on the lifetime that can be expected from the equipment. For now, this can only be guessed at for the plastic heat exchangers. This uncertainty is a serious barrier to the widespread use of the technology.

7.3 FUTURE NEEDS

In order to achieve commercialization of the plastic heat exchanger technology, several intermediate goals must be reached. The most important of these are risk reduction, cost reduction, and industrial involvement. We feel that the following steps are appropriate for achieving these goals:

- Develop coating technology specifically for this application. Plastics suppliers and fabricators will assist in this task.
- Develop heat exchanger designs appropriate for plastic technology.
- Conduct testing under realistic industrial conditions.
- Identify and evaluate in detail a wide range of potential applications.
- Promote active participation of plastics vendors, fabricators, and potential users in all phases of development.

The successful performance of these steps will bring the technology near to commercialization. Once a prototype design has shown both technical and economic feasibility and has demonstrated acceptable lifetime, the major problems will be overcome. The remaining step will be to make potential users aware of the technology and the benefits it can provide.

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