GBH Enterprises, Ltd.

Process Engineering Guide:
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Graphite Heat Exchangers

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DOCUMENTS REFERRED TO IN THIS PROCESS ENGINEERING GUIDE
0 INTRODUCTION/PURPOSE

This guide is one of a series of Heat Transfer Process Engineering Guides produced for GBH Enterprises.

1 SCOPE

This guide discusses the material used for exchanger fabrication, describes the types of unit available and gives guidance on how to rate thermal performance of such units.

2 FIELD OF APPLICATION

This Guide applies to process engineers in GBH Enterprises worldwide, who may be involved in the specification, design, rating or operation of heat transfer equipment.

3 DEFINITIONS

For the purposes of this Guide, the following definitions apply:

Heat Transfer and Fluid Flow Service (HTFS)  A cooperative research organization, with headquarters in the UK, involved in research into the fundamentals of heat transfer and two phase flow and the production of design guides and computer programs for the design of industrial heat exchange equipment.

4 TYPES OF GRAPHITE

Graphite, having a high resistance to corrosion and good thermal conductivity, is a suitable material of construction for heat exchangers, particularly for highly corrosive duties. The artificial graphite used for heat exchangers is manufactured from a mixture of coke and pitch, which is first cured at 1000°C and subsequently recrystallized at 3000°C.
Since the volatile binders have been removed during the high temperature treatments, the graphite produced is permeable. To overcome this, a variety of impregnations are used. The choice of impregnation should be decided upon after consultation with a Materials Scientist, but for initial guidance the types are given below. Note: not all manufacturers offer all of these types.

4.1 **Phenolic Resin Impregnation**

The manufacturers claim this is suitable for up to 165-185°C, depending on the residual permeability of the starting graphite. The resin will in general have a lower chemical resistance than the graphite. This may lead to a progressive leaching out of the resin, eventually resulting in the material becoming permeable.

4.2 **Furane Resin Impregnation**

This has a similar operational range to phenolic resin. It is not usually specified by GBH Enterprises, the phenolic impregnation being regarded as standard.

4.3 **PTFE Impregnation**

This offers both higher corrosion resistance than the resins, and a higher operating temperature (up to 230°C), but at a higher price, typically twice that of resin impregnated graphite. Note, however, that the PTFE used for impregnation is a relatively low molecular weight polymer and can be prone to leaching in some conditions. PTFE impregnated graphite also has a lower mechanical strength than the resin impregnated material.

4.4 **Carbon Impregnation**

This is the ultimate in corrosion resistance and operating temperature (up to 400°C in oxidizing environments, and 1000°C in reducing conditions) but costs about three times the price of a resin impregnated exchanger.
5 TYPES OF EXCHANGER

There are three basic types of heat exchanger using graphite as a material of construction.

5.1 Shell and Tube

These units are similar in general form to conventional shell and tube exchangers, with tubes and tubesheets fabricated from graphite. The mechanical properties of graphite require careful design of the tube-tubesheet joints and influence the dimensions, but the manufacturers have evolved designs which, treated with reasonable care, can give good service. It is possible to re-tube the units.

Graphite tubular exchangers have been built with surface areas over 1000 m² and tube lengths of 6.7 m (22 feet), although one manufacturer states that the maximum length of their tubes without a joint is 4 m. Standard designs have shell diameters between 200 to 1880 mm (8" to 74"). Tube diameters typically range from 25 x 16 mm (1" x 5/8") up to 51 x 38 mm (2" x 1").

The design pressure of the exchangers is limited to 6 bar on both sides. This form of construction is usually the most expensive per m² of heat transfer area (see Clause 7).

5.2 Cubic Block Exchangers

These exchangers consist of single cuboid blocks of graphite, (in the case of some manufacturers, built up from thinner layers cemented together), compressed between cast iron clamping plates, see Figure 1. There is a series of parallel holes or slots between opposing faces of the block for the passage of process and service fluids, the rows of holes alternating through the block. Headers are bolted to four faces of the block for the inlet and outlet of the fluids. The headers can be lined with graphite or PTFE. A variety of multi-pass arrangements can be accommodated by incorporating partitions on the inside of the headers.
The exchangers come in standard size ranges. Two European manufacturers produce two ranges which are essentially identical between the manufacturers. In one of these, usually designated type 'A', both sets of holes are cylindrical, with a diameter of 9.5 mm (3/8"). The surface areas on both sides are equal, the largest units having 14 m\(^2\) of heat transfer surface. In type 'B' blocks, the service side is similar to the type A units, but the process side consists of a series of slots 9.5 mm by 3.2 mm (3/8" by 1/8"). This results in a surface area for that side almost twice that of the other side, with a maximum heat transfer surface of 28 m\(^2\). The choice of which type to use will be governed by the heat transfer and pressure drop requirements of the particular duty.

Manufacturer A also offer the designs developed by a leading USA manufacturer. These have process holes of 5/32" and service holes of 3/8" giving process areas of up to 93 m\(^2\) (1000 ft\(^2\)) with service areas of half the process area.

The maximum permissible operating pressure of a cubic block is usually 5 bar g.

Cubic block exchangers are significantly more compact than graphite shell and tube units with the same heat transfer surface. They are the cheapest graphite exchanger per m\(^2\) of heat transfer area, but are limited in maximum area (see Clause 7). They are commonly used in the fine chemicals and pharmaceutical industries, where their resistance to a wide range of chemicals makes them...
attractive on multi-product plants. The Works generally try to standardize on a limited range of sizes to reduce spares holdings and allow modular construction.

5.3 Cylindrical Graphite Block Exchangers

These units are built up in modular fashion from standard cylindrical graphite blocks. The blocks are mounted inside a steel shell. The process fluid normally flows through a series of holes drilled longitudinally down the blocks, successive blocks being arranged so that the holes line up. The 'service' fluid flows through a second set of holes or slots, drilled at right angles to, and passing between, neighboring rows of process holes. PTFE gaskets between the blocks prevent cross contamination. Baffles between the blocks and the shell allow several cross passes for the service fluid. If the 'service' fluid is also corrosive, the shell may be lined with PTFE. More than one process pass is possible. The mechanical design, in which the blocks are held in compression by spring loaded tie rods, requires these units to be mounted vertically. See Figures 2 and 3.

Hole sizes typically range between 8 mm and 35 mm. Blocks are available in diameters up to 1.8 m. The largest units may have up to 1000 m² of surface, making them comparable with shell and tube units. The design pressure for the process side is typically 5-6 bar; for the service side 8 bar is normal.

6 LIMITATIONS ON USE

Graphite is a relatively weak material, which can be damaged by mechanical shock. However, treated with reasonable care, this should not cause problems. The shell and tube types are probably the least sturdy, although several of these units gave many years of satisfactory service on several European plants, their life being limited by gradual leaching of the resin impregnation rather than mechanical failure. On the other hand, a large shell and tube unit on one site location in Europe suffered from failure early in its life. Although there was some suspicion that this may have been damaged during installation, the unit was replaced by a cylindrical block type.
FIGURE 2  TYPICAL BLOCK FROM A CYLINDRICAL GRAPHITE BLOCK HEAT EXCHANGER
Because of the brittle nature of the graphite, care must be taken in plant design to avoid placing high loads onto the branches of the exchangers. It may also be necessary to provide some isolation to prevent vibrations from other equipment being transmitted to the exchanger.
Manufacturer A states that the block types are able to handle differential temperatures of 100-120°C. Shell and tube units are more limited. As a result of its high conductivity, graphite has a good tolerance to thermal shock. However, this information is for guidance only, and the manufacturer should be consulted in particular cases.

7 COSTS OF GRAPHITE EXCHANGERS

It is not possible to provide definitive statements on whether one type of exchanger will be more expensive than another in general terms; each case has to be taken on its merits. A comparison on the basis of pounds per unit area will be misleading unless the achieved heat transfer coefficients are similar. Some duties fit better than others into a particular exchanger type. Moreover, the installed cost will be several times the main plant item cost, and installation factors may differ with different exchanger types.

Figure 4 shows some data produced for the MPI cost of several exchanger types as a function of area. The types covered are graphite tubes in a carbon steel shell, cubic blocks with phenolic resin impregnation and cubic blocks with PTFE impregnation. Also shown for comparison are data for shell and tube exchangers with all carbon steel construction and with stainless steel tubes in a carbon steel shell. It can be seen that graphite is comparable in cost with the stainless steel units.

Note: These costs are for guidance only. Manufacturers should be approached for firm data.
8 RATING OF GRAPHITE EXCHANGERS

The manufacturers of graphite exchangers normally offer a range of standard sizes. Many (but not all) of them have a thermal design capability. However, there is still the need for GBH Enterprises to check their designs, particularly for difficult duties such as multi-component condensation.

Graphite shell and tube units offer no thermal rating problem; the normal shell and tube programs (commercially available) can be used with the tube dimensions supplied by the manufacturers. Manufacturer A quote the thermal conductivity of the graphite in the radial direction (without the resin film) as 35-64 W/m.K.

Block exchangers cannot be modeled so easily with standard computer programs. If the fluids handled are both single phase, hand calculations should present no real problem, as the individual heat transfer coefficients can be estimated using modified versions of the Sieder & Tate equations (see below). For modeling a condenser, however, hand calculations can be particularly difficult. Nonetheless, it is possible to use normal shell and tube programs to model the performance of block exchangers, as outlined below.

8.1 Rating Cylindrical Block Exchangers

In a cylindrical block exchanger, for most duties, the process fluid will be flowing through the longitudinal holes, which can be regarded as the tubes of a conventional exchanger. Shell and tube computer program methods should apply.

The service side geometry is different from a shell and tube unit, so the program methods for calculating shell side coefficient do not apply. Most shell and tube rating programs, however, allow the user to specify the heat transfer coefficient for either side. Provided that this coefficient remains reasonably constant, this should allow the program to predict correctly the
FIGURE 4 APPROXIMATE COSTS FOR GRAPHITE HEAT EXCHANGERS

overall performance. In many cases the service fluid will be a single phase liquid, e.g. cooling water, so this is a reasonable supposition. If the service fluid is condensing steam, although the coefficient will not be constant, it is likely not to be controlling, so the actual value is not critical.
The basic approach to the rating is as follows: (This method is based on that given in Reference 1, modified to accommodate the use of standard shell and tube programs.)

(a) Equate the tube count to the number of process holes in the block, and the tube inside diameter to the hole diameter.

(b) Choose some nominal value for the tube wall thickness; 2 mm is reasonable. This gives the equivalent tube outside diameter, which will be used by the shell and tube program. Ideally, one should calculate an equivalent ligament thickness, but as the thermal resistance of the graphite ligament is low, (Reference 1 quotes a coefficient of 8700 W/m².K), any errors introduced will be small.

(c) Estimate the service side coefficient. For a single phase fluid, the modified Sieder-Tate equation given by Reference 1 should be used. Note that this gives the transition Reynolds number for the service side of the block between laminar and transition flow as only 300, compared with 2100 for normal tubes, and between transition and turbulent as 3000, compared with 10000.

(1) Turbulent Flow \( (Re > 3000) \)

\[
Nu = 0.027 \times Re^{0.8} \times Pr^{\frac{1}{3}} \times \left( \frac{\mu}{\mu_w} \right)^{0.14} \times s
\]

(2) Transition Flow \( (3000 > Re > 300) \)

\[
Nu = 12.45 \times Pr^{\frac{1}{3}} \times \left( \frac{\mu}{\mu_w} \right)^{0.14} \times \left\{ \left( \frac{D}{L} \right)^{\frac{1}{3}} + 1.312 \times \frac{D}{2700} \times \left( \frac{Re}{300} \right) \right\} \times s
\]
For condensing steam, the service resistance is unlikely to be critical. 10000 W/m².K is a reasonable value.

If the service side channels are slots rather than holes, see the paragraph on 'B' type cubic blocks below.

(d) Correct this coefficient by the ratio of the actual service side heat transfer area to the area based on the equivalent tube od. given above. Use this corrected coefficient in the shell and tube program.

(e) The service pressure drop given by the shell and tube program will not be relevant. For an exchanger from Manufacturer A, the service pressure drop can be estimated using the method given in Reference 1.

The above approach assumes that you have details of the geometry of the blocks. If a manufacturer has been approached for a design, they should be asked to supply the necessary data. If you are doing a preliminary rating based on manufacturer's literature, not all data may be available. It may be necessary to estimate some items from others.
8.1.1 Commercially Available Programs

The method outlined above for calculating service side coefficients and pressure drops is typically incorporated into commercially available computer programs, including manufacturers published data, on their standard blocks.

8.2 Rating Cubic Block Exchangers

For the type 'A' blocks, where both process and service sides have cylindrical holes, a similar approach to the cylindrical block method described above can be used. However, the effects of the pass arrangements in the block have to be considered.

A unit with only one pass on each side is operating in cross flow, whereas most of the shell and tube programs assume co- or counter current flow. Commercially available programs can be used to model X shells.

For a multi-pass arrangement on both sides, it is probably best to consider the unit as a single pass with the tube length equal to the path length. This ignores the effects of the turn-round regions.

For a type 'B' unit, the problem is slightly more complex because of the non-circular nature of the slots. An equivalent (hydraulic mean) diameter approach is necessary.

If the perimeter of a slot is $P$, its surface $A$ and cross sectional area $X$, then the equivalent diameter is:

$$de = \frac{4X}{P}$$

A pipe of this diameter has a cross section $Xe$ and surface area $Ae$ given by:

$$Xe = \frac{4\pi X^2}{P^2}$$

$$Ae = \frac{4\pi XL}{P}$$
Hence:

\[
\frac{X_e}{X} = \frac{A_e}{A} = \frac{4\pi X}{P^2}
\]

If we use this hydraulic mean diameter with the number of tubes equated to the number of slots, both the surface area and the mass flux will be incorrect. However, if the ratio of the number of tubes in the shell and tube model to the number of slots is changed such that:

\[
\frac{ne}{n} = \frac{P^2}{4\pi X}
\]

then the shell and tube model will have the correct surface area and correct mass flux.

For the standard slot geometry of the type 'B' cubic block,

\[X = 2.85225 \times 10^{-5} \text{ m}^2/\text{slot} \text{ and } P = 2.28531 \text{ m/slot.}\]

Hence: \[ne/n = 1.4571.\]

The service side coefficient will need to be adjusted for the area ratio in a similar manner to that for the cylindrical block.