The Fundamentals of Heat Exchangers

FEATURE

by Dean A. Bartlett

To control the temperature of a system or substance, pick one of three types of heat exchangers and use these equations to estimate the size you need

Heat exchangers serve a straightforward purpose: controlling a system's or substance's temperature by adding or removing thermal energy. Although there are many different sizes, levels of sophistication, and types of heat exchangers, they all use a thermally conducting element—usually in the form of a tube or plate—to separate two fluids, such that one can transfer thermal energy to the other. Home heating systems use a heat exchanger to transfer combustion-gas heat to water or air, which is circulated through the house. Power plants use locally available water or ambient air in quite large heat exchangers to condense steam from the turbines. Many industrial applications use small heat exchangers to establish or maintain a required temperature. In industry, heat exchangers perform many tasks, ranging from cooling lasers to establishing a controlled sample temperature prior to chromatography.

Figure 1. Coil heat exchangers are capable of handling high pressures and wide temperature differences.

Anyone who wants to use a heat exchanger faces a fundamental challenge: fully defining the problem to be solved, which requires an understanding of the thermodynamic and transport properties of fluids. Such knowledge can be combined with some simple calculations to define a specific heat-transfer problem and select an appropriate heat exchanger.

Fluid fundamentals

How heat gets transferred from one fluid to another depends largely on the physical characteristics of the fluids involved, especially their density, specific heat, thermal conductivity, and dynamic viscosity.

Density (ρ) is a fluid's mass per unit volume, measured as lb_m/ft^3 (where lb_m represents pounds of mass) or kg/m^3. Density can be used to convert a measurement from a mass-flow rate, such as lb_m/hr, to the more common volumetric units, such as gallons per minute for liquids, or cubic feet per minute for gases. Throughout a heat exchanger, the mass-flow rate remains constant, but changes in temperature and pressure can change the volumetric flow rate, particularly for a gas. So a gas flow should be stated as a mass flow, a volumetric flow at standard conditions, or as a volumetric flow including temperature and pressure. In any case, the operating pressure should always be specified.

Specific heat (c or c_p for a gas, where p represents a constant pressure) is the amount of heat required to raise the temperature of one unit of fluid mass by one degree. Its units are BTU/(lb_m °C) or J/(kg °C). Specific heat relates the quantity of transferred heat to the temperature change of the fluid while passing through the heat exchanger.

Thermal conductivity (k) represents the ability of a fluid to conduct heat. It is measured in BTU/[ft^2 hr (°F/ft)], BTU/(ft hr °F), or W/(m °C).

Dynamic viscosity (μ) indicates a fluid's resistance to flow. A fluid with high dynamic viscosity produces a high pressure loss because of the shear resistance, primarily along the heat exchanger surfaces. Its units are lb_m/(ft hr), (lb_f hr)/ft^2 (where lb_f is pounds of force), kg/(m s), (N s)/m^2, Pa s, and many others. The selection of units usually depends on the industry, but they can be converted to one of the above forms. In most cases, viscosity is given in centipoise [1 centipoise = 1,000 Pa s= 2.42 lb_m/(ft hr)].

Fluid flow

Inside a heat exchanger, the fluid flow is either turbulent or laminar. Turbulent flow produces better heat transfer, because it mixes the fluid. Laminar-flow heat transfer relies entirely on the thermal conductivity of the fluid to transfer heat from inside a stream to a heat-exchanger wall.

An exchanger's fluid flow can be determined from its Reynolds number (N_{Re}):

$$N_{Re} = \frac{\rho \times V \times D}{\mu}$$

where V is flow velocity and D is the diameter of the tube in which the fluid flows. The units cancel each other, making the Reynolds number dimensionless. If the Reynolds number is less than 2,000, the fluid flow will be laminar; if the Reynolds number is greater than 6,000, the fluid flow will be fully turbulent. The transition region between laminar and turbulent flow produces rapidly increasing thermal performance as the Reynolds number increases.

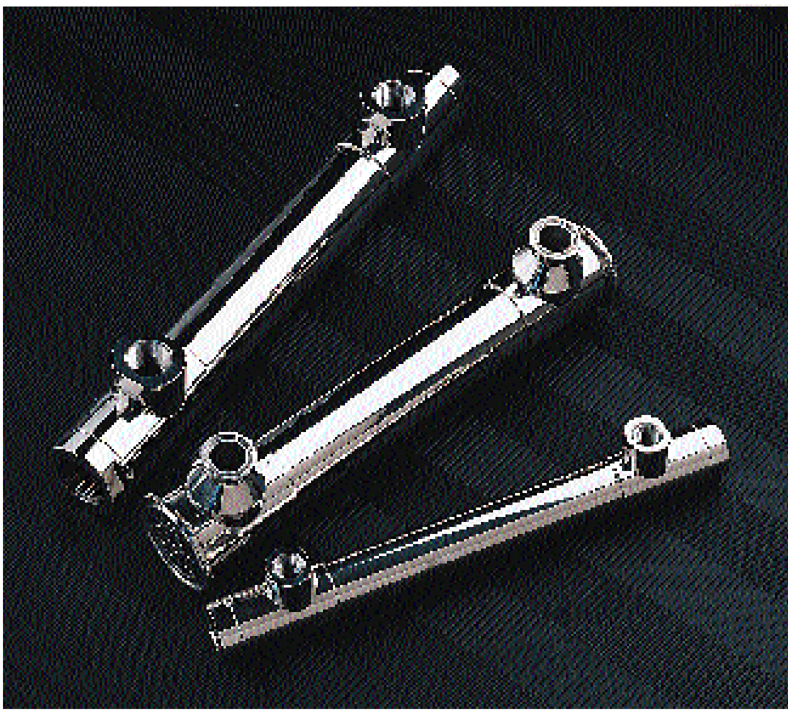
The type of flow determines how much pressure a fluid loses as it moves through a heat exchanger. This is important because higher pressure drops require more pumping power. Although a manufacturer will normally determine the pressure drop, it is useful to predict the pressure drops that can occur with changing rates of flow. Laminar flow produces the smallest loss, which increases linearly with flow velocity. For example, doubling the flow velocity doubles the pressure loss. For Reynolds numbers beyond the laminar region, the pressure loss is a function of flow velocity raised to a power in the range 1.6–2.0. In other words, doubling the flow could increase the pressure loss by a factor of four.

Balance and effectiveness

The characteristics of fluids contribute to a fundamental property of heat exchangers—the heat-transfer rate ($\dot{Q}$). The heat transferred to the colder fluid must equal that transferred from the hotter fluid, according to the following equation:

$$\begin{aligned}\dot{Q} &= [\dot{m} \times c_p \times (T_{out} - T_{in})]_{cold} \\ &= -[\dot{m} \times c_p \times (T_{out} - T_{in})]_{hot}\end{aligned}$$

where $\dot{m}$ represents the mass flow per unit time. So the heat transferred per unit time equals the product of mass flow per unit time, specific heat, and the temperature change. This quick calculation should be done before specifying any heat exchanger. Although heat exchangers are commonly specified only with desired temperatures,



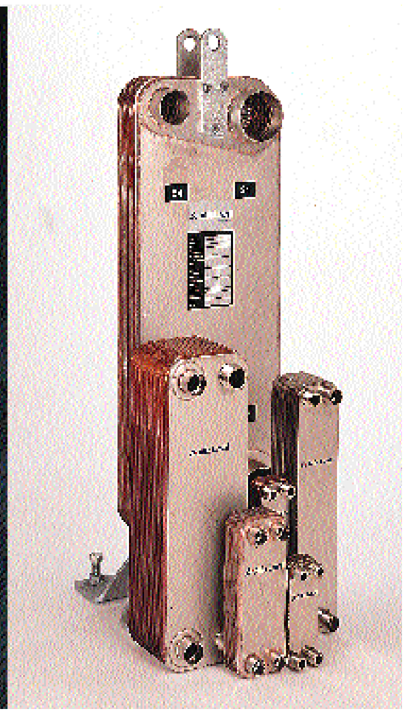


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Figure 2 (left). Thermal performance of shell-and-tube exchangers is high. Figure 3 (right). Plate heat exchangers have high heat-transfer coefficients and area.

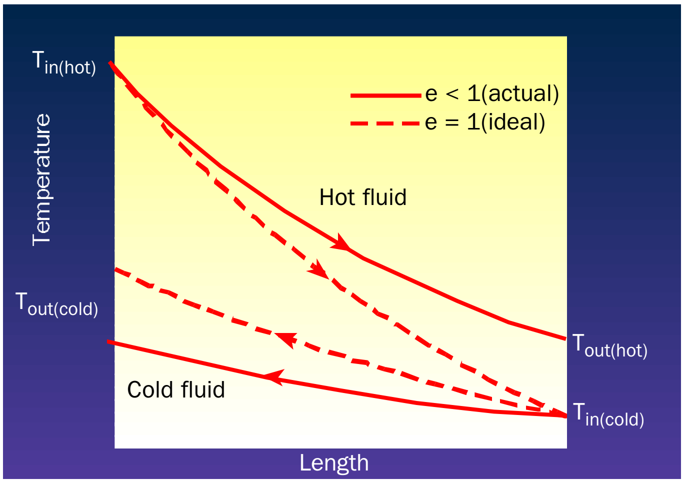

Figure 4. Stream temperatures through a heat exchanger in counter-current flow.

the heat-transfer rate is the prime criterion.

An exchanger's effectiveness (ε) is the ratio of the actual heat transferred to the heat that could be transferred by an exchanger of infinite size. Effectiveness is the best way to compare different types of heat exchangers.

For example, Figure 4 shows a hot-fluid stream being cooled by a cold-fluid stream in a counterflow heat exchanger. When the hot stream exits the exchanger, it must be warmer than the inlet temperature of the cold stream. In an ideal heat exchanger, with ε = 1, the outgoing hot stream's temperature equals the incoming cold stream's temperature. In addition, this heat exchanger's cold stream exits at a temperature lower than the inlet temperature of the hot stream.

The heat-balance equation can be applied to this problem as:

$$\varepsilon = \frac{(\dot{m}\, c_p)_{hot}(T_{in} - T_{out})_{hot}}{(\dot{m}\, c_p)_{min}(T_{in\ hot} - T_{in\ cold})}$$
$$= \frac{(\dot{m}\, c_p)_{cold}(T_{out} - T_{in})_{cold}}{(\dot{m}\, c_p)_{min}(T_{in\ hot} - T_{in\ cold})}$$

where the denominator, or maximum possible rate of heat transfer, is based on the stream with the smallest (mass-flow rate)(specific heat) product, also known as the minimum thermal-capacity rate and indicated by the subscript "min". Given that the temperature drop on the hot stream is greater than the temperature gain in the cold stream in this example, the product of the mass-flow rate and the specific heat of the hot stream must be less than that of the cold stream, because of the required heat-transfer rate balance.

Exchanger equation

The heat-transfer rate ($\dot{Q}$) of a given exchanger depends on its design and the properties of the two fluid streams. This characteristic can be defined as:

$$\dot{Q} = UA\Delta T_{log\ mean}$$

where U is the overall heat-transfer coefficient, or the ability to transfer heat between the fluid streams, A is the heat-transfer area of the heat exchanger, or in other words the total area of the wall that separates the two fluids, and $\Delta T_{log\ mean}$ is the average effective temperature difference between the two fluid streams over the length of the heat exchanger.

A heat exchanger's performance is predicted by calculating the overall heat transfer coefficient U and the area A. The inlet temperatures of the two streams can be measured, which leaves three unknowns—the two exit temperatures and the heat-transfer rate. These unknowns can be determined from three equations (the one above using an arithmetic average for $\Delta T_{log\ mean}$ plus the heat-balance equation for each stream):

$$\dot{Q} = U\,A\,\frac{(T_{in\ hot} - T_{out\ cold}) + (T_{out\ hot} - T_{in\ cold})}{2}$$
$$= [\dot{m} \times \dot{Q}\, c_p \times (T_{out} - T_{in})]_{cold}$$
$$= -\,[\dot{m} \times c_p \times (T_{out} - T_{in})]_{hot}$$

Solving these equations simultaneously usually requires iteration. In any case, a heat exchanger's manufacturer usually completes them.

Types of exchangers

Heat exchangers come in a wide variety of types and sizes. Here are a few of the most common ones.

Coil heat exchangers (Figure 1) have a long, small-diameter tube placed concentrically within a larger tube, the combined tubes being wound or bent in a helix. One fluid passes through the inner tube, and the other fluid passes through the outer tube. This type of heat exchanger is robust—capable of handling high pressures and wide temperature differences. Although these exchangers tend to be inexpensive, they provide rather poor thermal performance because of a small heat-transfer area. Nevertheless, a coil heat exchanger may be the best choice for low-flow situations, because the single-tube passage creates higher flow velocity and a higher Reynolds number. These exchangers are commonly used to establish a fixed temperature for a process-stream sample prior to taking measurements. These exchangers can also be used to condense high-temperature stream samples.

Plate heat exchangers (Figure 3) consist of a stack of parallel thin plates that lie between heavy end plates. Each fluid stream passes alternately between adjoining plates in the stack, exchanging heat through the

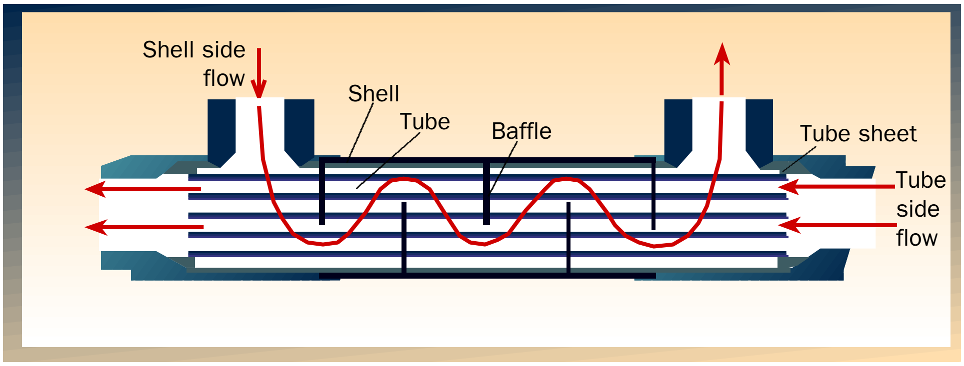

Figure 5. Shell-and-tube heat exchanger with counter-current flow.

plates. The plates are corrugated for strength and to enhance heat transfer by directing the flow and increasing turbulence. These exchangers have high heat-transfer coefficients and area, the pressure drop is also typically low, and they often provide very high effectiveness. However, they have relatively low pressure capability.

Shell-and-tube heat exchangers (Figures 2 & 5) consist of a bundle of parallel tubes that provide the heat-transfer surface separating the two fluid streams. The tube-side fluid passes axially through the inside of the tubes; the shell-side fluid passes over the outside of the tubes. Baffles external and perpendicular to the tubes direct the flow across the tubes and provide tube support. Tubesheets seal the ends of the tubes, ensuring separation of the two streams. The process fluid is usually placed inside the tubes for ease of cleaning or to take advantage of the higher pressure capability inside the tubes. The thermal performance of such an exchanger usually surpasses a coil type but is less than a plate type. Pressure capability of shell-and-tube exchangers is generally higher than a plate type but lower than a coil type.

Technical tips

For any heat-exchanger application, a user will profit from the following pointers:

- Consider heat exchangers early in system design.
- Avoid being overly safe in specifying performance criteria. Asking for more temperature change, higher flow capability, and other just-in-case possibilities can easily double an exchanger's size and cost. Consider the required effectiveness values, but remember that an exchanger's size approaches infinity asymptotically as effectiveness approaches 1. So it takes considerably more heat-exchanger area to raise the effectiveness from 0.8 to 0.9 than it does to go from 0.7 to 0.8. High effectiveness—greater than 0.9—can be very expensive.
- Consider increasing pumping power rather than increasing an exchanger's size. Higher velocity flow can produce or increase turbulence, which leads to an increased pressure drop and the need for more pumping power. Nevertheless, turbulence also increases the heat-transfer coefficient, thereby decreasing the required heat-exchanger size. Accepting the increased pressure drop may be a more viable option than increasing size.
- Remember that the prime criterion is the product of the overall heat-transfer coefficient and the transfer area (*UA*)—not just the transfer area. For laminar-flow tubes, the total tube length, not the transfer area, is usually the important factor; so 10 feet of 1/4-inch tubing works as well as 10 feet of 1-inch tubing.
- Specify the smallest possible tubing for tube-type heat exchangers, because it gives the maximum thermal performance with the minimum volume. However, be aware of the effects of fouling or particulates that may clog small tubes.
- Strive for turbulent flow to enhance heat transfer, even though that can be difficult with viscous fluids and low flow rates.
- Be aware of fluid thermal conductivity when specifying the cooling or heating fluid. Perhaps surprisingly, water usually works the best.
- Match the inlet-port size to the piping sizes expected for the rest of the system.
- Consider an exchanger's lifetime and maintenance requirements. Choose the type and thickness of material that will reduce failure caused by corrosion and erosion. Also consider a system's ease of mechanical or chemical cleaning as well as filtration of the fluid streams.
- Provide the heat-exchanger vendor with as much information on the total system as possible.

These technical tips, basic concepts, and equations should give you the tools for defining a heat-exchange problem and considering the possible heat-exchanger solutions. For information on specific exchangers, look at manufacturers' catalogs, which provide more details about what can be accomplished with different types of heat exchangers.

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