Table 6.32 Materials for rudder bearings

Material	Comment
PTFE, polyethylenes polypropylenes, nylon	Low friction and good wear resistance at low bearing pressures
Glass-reinforced PTFE, filled polyethylenes and polypropylenes	Excellent wear and corrosion resistance in sea water. A viable alternative to bronze if bearing pressures are not too large
Silicon carbide SiC, alumina Al_2O_3, tungsten carbide WC	Good wear and corrosion resistance but poor impact properties and very low damping

Postscript. Recently, at least one manufacturer of marine bearings has started to supply cast Nylon-6 bearings for large ship rudders. The makers claim just the advantages we would expect from this case study:

(a) wear and abrasion resistance with water lubrication is improved;
(b) deliberate lubrication is unnecessary;
(c) corrosion resistance is excellent;
(d) the elastic and damping properties of Nylon-6 protect the rudder from shocks (see the damping/modulus chart);
(e) there is no fretting;
(f) the material is easy to handle and install, and is inexpensive to machine.

Figure 6.32 suggests that a filled polymer or composite might be even better. Carbon–fiber filled nylon has better wear resistance than unfilled nylon, but it is less tough and flexible, and it does not damp vibration as effectively. As in all such problems, the best material is the one that comes closest to meeting *all* the demands made on it, not just the primary design criterion (in this case, wear resistance). The suggestion of the chart is a useful one, worth a try. It would take sea-tests to tell whether it should be adopted.

6.18 Materials for heat exchangers

This and the next case study illustrate the output of the CES software described in Sections 5.5.

Heat exchangers take heat from one fluid and pass it to a second (Figure 6.33). The fire-tube array of a steam engine is a heat exchanger, taking heat from the hot combustion gases of the firebox and transmitting it to the water in the boiler. The network of finned tubes in an air conditioner is a heat exchanger, taking heat from the air of the room and dumping it into the working fluid of the conditioner. A key element in all heat exchangers is the tube wall or membrane that separates the two fluids. It is required to transmit heat, and there is frequently a pressure difference across it, which can be large.

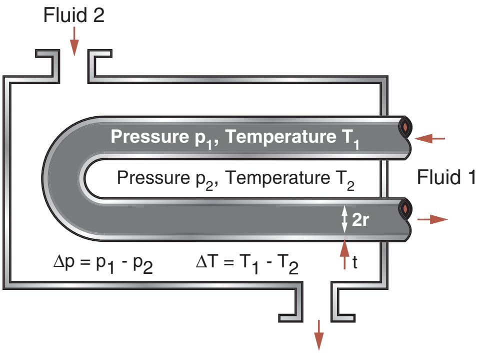

Figure 6.33 A heat exchanger. There is a pressure difference Δp and a temperature difference ΔT across the tube wall that also must resist attack by chloride ions.

Table 6.33 Design requirements for a heat exchanger

Function	Heat exchanger
Constraints	• Support pressure difference, Δp • Withstand chloride ions • Operating temperature up to 150°C • Modest cost
Objective	• Maximize heat flow per unit area (minimum volume exchanger) or • Maximize heat flow per unit mass (minimum mass exchanger)
Free variables	• Tube-wall thickness, t • Choice of material

What are the best materials for making heat exchangers? Or, to be specific, what are the best materials for a conduction-limited exchanger with substantial pressure difference between the two fluids, one of them containing chloride ions (sea water). Table 6.33 summarizes these requirements.

The model. First, a little background on heat flow. Heat transfer from one fluid, through a membrane to a second fluid, involves *convective* transfer from fluid 1 into the tube wall, *conduction* through the wall, and *convection* again to transfer it into fluid 2. The heat flux into the tube wall by convection (W/m^2) is described by the heat transfer equation:

$$q = h_1 \Delta T_1 \tag{6.66}$$

in which h_1 is the heat transfer coefficient and ΔT_1 is the temperature drop across the surface from fluid 1 into the wall. Conduction is described by the conduction (or Fourier) equation, which, for one-dimensional heat-flow takes the form:

$$q = \lambda \frac{\Delta T}{t} \tag{6.67}$$

where λ is the thermal conductivity of the wall (thickness t) and ΔT is the temperature difference across it. It is helpful to think of the *thermal resistance* at surface 1 as $1/h_1$; that of surface 2 is $1/h_2$; and that of the wall itself is t/λ. Then continuity of heat flux requires that the total resistance $1/U$ is

$$\frac{1}{U} = \frac{1}{h_1} + \frac{t}{\lambda} + \frac{1}{h_2} \tag{6.68}$$

where U is called the "total heat transfer coefficient". The heat flux from fluid 1 to fluid 2 is then given by

$$q = U(T_1 - T_2) \tag{6.69}$$

where $(T_1 - T_2)$ is the difference in temperature between the two working fluids.

When one of the fluids is a gas—as in an air conditioner—convective heat transfer at the tube surfaces contributes most of the resistance; then fins are used to increase the surface area across which heat can be transferred. But when both working fluids are liquid, convective heat transfer is rapid and conduction through the wall dominates the thermal resistance; $1/h_1$ and $1/h_2$ are negligible compared with t/λ. In this case, simple tube or plate elements are used, making their wall as thin as possible to minimize t/λ. We will consider the second case: conduction-limited heat transfer, where the heat flow is adequately described by equation (6.63).

Consider, then, a heat exchanger with n tubes of length L, each of radius r and wall thickness t. Our aim is to select a material to maximize the total heat flow:

$$Q = qA = \frac{A\lambda}{t}\Delta T \tag{6.70}$$

where $A = 2\pi rLn$ is the total surface are of tubing.

This is the objective function. The constraint is that the wall thickness must be sufficient to support the pressure Δp between the inside and outside, as in Figure 6.33. This requires that the stress in the wall remain below the elastic limit, σ_y, of the material of which the tube is made (multiplied by a safety factor—which we can leave out):

$$\sigma = \frac{\Delta p r}{t} < \sigma_y \tag{6.71}$$

This constrains the minimum value of t. Eliminating t between equations (6.70) and (6.71) gives

$$Q = \frac{A\Delta T}{r\Delta p}(\lambda\sigma_y) \tag{6.72}$$

The heat flow per unit area of tube wall, Q/A, is maximized by maximizing

$$M_1 = \lambda\sigma_y \tag{6.73}$$

Four further considerations enter the selection. It is essential to choose a material that can withstand corrosion in the working fluids, which we take to be water containing chloride ions (sea water). Cost, too, will be of concern. The maximum operating temperature must be adequate and the materials must have sufficient ductility to be drawn to tube or rolled to sheet. Cost, too, will be of concern.

The selection. A preliminary search (not shown) for materials with large values of M_1, using the CES Level 1/2 database , suggests *copper alloys* as one possibility. We therefore turn to the Level 3 database for more help. The first selection stage applies limits of 150°C on maximum service temperature, 30 percent on elongation, a material cost of less than $4/kg and requires a rating of "very good" resistance to sea water. The second stage (Figure 6.34) is a chart of σ_y versus λ enabling $M_1 = \sigma_y \lambda$ to be maximized. The materials with large M_1 are listed in Table 6.34.

Postscript. Conduction may limit heat flow in theory, but unspeakable things go on inside heat exchangers. Sea water — often one of the working fluids — seethes with bio-fouling organisms that attach themselves to tube walls and thrive there, like barnacles on a boat, creating a layer of high thermal resistance

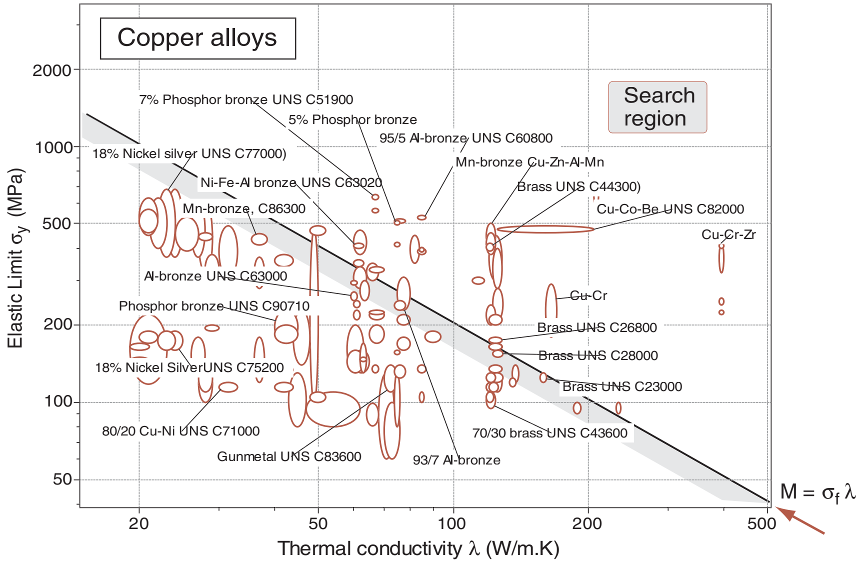

Figure 6.34 A chart of yield strength (elastic limit) σ_y against thermal conductivity, λ, showing the index M_l, using the Level 3 CES database.

Table 6.34 Materials for heat exchangers

Material	Comment
Brasses	Liable to dezincification
Phosphor bronzes	Cheap, but not as corrosion resistant as aluminum-bronzes
Aluminum-bronzes, wrought	An economical and practical choice
Nickel-iron-aluminum-bronzes	More corrosion resistant, but more expensive

impeding fluid flow. A search for supporting information reveals that some materials are more resistant to biofouling than others; copper-nickel alloys are particularly good, probably because the organisms dislike copper salts, even in very low concentrations. Otherwise the problem must be tackled by adding chemical inhibitors to the fluids, or by scraping—the traditional winter pastime of boat owners.

It is sometimes important to minimize the weight of heat exchangers. Repeating the calculation to seek materials the maximum value of Q/m (where m is the mass of the tubes) gives, instead of M_1, the index

$$M_2 = \frac{\lambda {\sigma_y}^2}{\rho} \tag{6.74}$$

where ρ is the density of the material of which the tubes are made. (The strength σ_y is now raised to the power of 2 because the weight depends on wall thickness as well as density, and wall thickness varies as $1/\sigma_y$ (equation 6.71).) Similarly, the cheapest heat exchangers are those made of the material with the greatest value of

$$M_3 = \frac{\lambda {\sigma_y}^2}{C_m \rho} \tag{6.75}$$

where C_m is the cost per kg of the material. In both cases aluminum alloys score highly because they are both light and cheap. The selections are not shown but can readily be explored using the CES system.

Further reading

Holman, J.P. (1981) *Heat Transfer*, 5th edition, McGraw-Hill, New York, USA.

Related case studies

6.11	Safe pressure vessels
6.16	Materials to minimize thermal distortion in precision devices