

Reactor Boiler and Auxiliaries - Course 133

HEAT TRANSPORT FLUID REQUIREMENTS

Thermal energy is produced in a reactor as a result of the fissioning of a fissile material. The heat transport fluid is used to transport this heat either to a boiler, where it is used to produce steam, or it is used as a thermodynamic heat engine fluid which passes directly to the turbine. There are two objectives of reactor design which are significant when the heat transport fluid is being considered. These objectives are: -

- (a) That the heat be transported out of the reactor in a useful form and, therefore, at as high a temperature as possible.
- (b) That the maximum amount of energy is obtained from the fuel (i.e. as high a fuel burn-up as possible).

The higher the heat transport temperature the higher the thermal cycle efficiency. In the boiler of a coal or oil fired station the source of heat (i.e. the combustion gases) is at the highest temperature of the system. The structural material is at a lower temperature, which is essentially the steam temperature. In a nuclear station, the fuel elements are the heat sources and they must operate at 300°F to 500°F higher than the steam temperatures, in order to obtain reasonable heat transfer. The materials in the reactor must also withstand these higher temperatures. However, if materials were used, which could withstand these higher temperatures the capital cost of the station would be increased. Such materials might also capture more neutrons and, thus, lower the fuel burnup. Because of these conflicting factors a lower thermal efficiency is usually acceptable but this is offset by other compensating factors.

There is no theoretical upper limit to the power that can be produced by a reactor through fission. The maximum power is frequently determined only by the rate at which the heat can be transported from the reactor. The transfer of heat from the fuel elements can be improved either by further subdivision of the fuel, so as to increase the contact area, or by increasing the volume of fluid in the fuel channel. Both result in a decrease of the neutron multiplication factor, k , which means an increase in reactor critical size.

The discussion above shows that the heat transfer and nuclear requirements may conflict. It also illustrates that the heat transfer and heat transport characteristics of a particular fluid may substantially affect both reactor core and fuel element design. This lesson will consider both nuclear and non-nuclear requirements of heat transport fluids.

Nuclear Considerations

(a) Neutron Absorption Cross-Section

The heat transport fluid passes through the reactor core. One important requirement, therefore, is that this fluid have a small neutron absorption (or capture) cross-section. The neutron economy of a reactor system has an important influence on the size and on the over-all cost of a reactor. There is a substantial volume of heat transport fluid in the reactor and so it is imperative that the absorption cross-section per atom or molecule be small. Table 1 lists the thermal neutron absorption cross-section, σ_a , for some possible heat transfer fluids.

TABLE 1

Material	σ_a (barns)	Material	σ_a (barns)
Lithium - 7	0.033	Light Water	0.66
Bismuth	0.032	Heavy Water	0.0003
Sodium	0.5	Polyphenyls	0.33
56% Sodium-44% Potassium	1.1		
Mercury	380		

The cross-sections for gases are not listed since the absorption cross-section per atom is not the important factor. The low density of a gas, (i.e. the small number of atoms or molecules per unit volume), is of greater significance when neutron absorption is being considered.

The cross-sections listed are those for thermal neutrons and are pertinent only for thermal reactors. The absorption cross-sections for fast neutrons are substantially smaller and other factors are more important when deciding on a heat transport fluid for fast reactors.

It may be seen, from Table 1, that the most attractive fluid, from the point of view of neutron economy, are heavy water, lithium, bismuth and the gases. These can be used in thermal reactors using natural uranium fuel. The cross-section for the polyphenyls is also low enough to allow it to be used as a heat transport fluid in a natural uranium fuelled, heavy water moderated reactor. The use of any other heat transport fluid would necessitate enrichment of the fuel. However, if the light water is allowed to boil, with boiling occurring, say, half way along the fuel channels, then it can be used without fuel enrichment in a heavy water moderated reactor.

(b) Moderating Ratio

A good moderating ratio is desirable but not essential for a heat transport fluid in a thermal reactor. If the heat transport fluid has a high moderating ratio the amount of moderator used can be reduced, the fuel channel separation can be smaller and, hence, the reactor size is smaller. Furthermore, if the reactor is not overmoderated, (i.e. the fuel channel separation is only just sufficient to thermalize the average neutron), then loss of heat transport fluid leads to a reduction in reactivity. The resulting decrease in neutron absorption, however, causes an increase in reactivity. If the two effects cancel or the overall void coefficient is zero or slightly negative, then a high moderating ratio is desirable. It is not desirable if the void coefficient is positive (as in an overmoderated reactor such as NPD) or if it has a large negative value. Both conditions would result in power transients or power swings if voids occur due to boiling.

Good slowing down materials (i.e. of low atomic weights) are to be avoided in a fast reactor where the neutron energy must be as high as possible.

(c) Induced Radioactivity

If the neutron absorption cross-section of the heat transport fluid was zero radioactive nuclei would not be produced in the fluid by neutron capture, i.e. there would be no induced radioactivity. However, since this is rarely the case, the heat transport fluid activity becomes a factor requiring the following considerations:-

1. The radioactive nuclei produced should not emit gamma rays or, if they are gamma emitters, the gamma ray energies must be as low as possible. If gamma ray emitters are produced, the system, external to the reactor, is not accessible during reactor operation and requires shielding to avoid exposure of station personnel to the radiation. This precludes maintenance to the equipment during operation at power. The higher the gamma ray energy the thicker the shield required.

An example of such induced activity is the production of N-16 in water by absorption of fast neutrons in oxygen.



The Nitrogen-16 nuclei emit 6 Mev and 7 Mev gamma rays. At NPD this resulted in a 4ft thick concrete shield being placed around the heat transport system.

The induced activity in organic fluids, (containing only hydrogen and carbon), on the other hand, only occurs as a result of neutron absorption in impurities.

2. The half-lives of the radioactive nuclei produced should be as short as possible. This allows the equipment in the heat transport system to be approached by station personnel soon after reactor shutdown. The half-life of the N-16 above is only 7.35 secs. However, the half-life of Sodium-24, produced in sodium, is 14.5 hours. This would delay maintenance on heat transport equipment until the activity decayed to an acceptable level.
3. The neutron activation should not result in the formation of a substance which could be an internal hazard if it leaked out of the system. There are two excellent, but entirely different, examples of the production of such a substance.

Tritium (H^3), a beta emitter, is formed by neutron capture in deuterium ($H^2 + n^1 = H^3 + \gamma$). Being a hydrogen isotope it is absorbed by the body in tritiated water. This together with its long half-life, makes it an internal hazard.

Bismuth-209 captures a neutron to form Bi-210, which is a beta emitter with a 5 day half-life. Bi-210 decays to Polonium-210, a high energy alpha emitter with a half-life of 138 days. Polonium is highly toxic and is one of the most powerful physiological poisons known.

(d) Radiation Stability

Radiation should not cause dissociation or damage to fluids used in the heat transport system. There must be a minimum of cross-linking, tar or coke formation and a minimum change in desirable physical properties resulting from such effects.

Heat Transfer Considerations

The temperature in a conventional fossil fired station is limited to that resulting from the combustion of the fuel. In nuclear fuel heat energy is being continuously produced by fission. If the rate of heat removal was less than the rate of heat generation, the temperature in the reactor would steadily rise until the reactor was destroyed. Therefore, the rates of heat generation and heat removal must be properly balanced. For any reactor the maximum operating power is limited by some temperature in the system. For instance the temperature at the centre of the fuel may be limited to reduce fission product gas diffusion to the sheath so that the fission product gas pressure does not cause sheath failure. Alternatively the fuel temperature may be limited in order to avoid a phase change which would cause distortion. The fuel surface temperature may be limited to avoid the sheath melting or to avoid local boiling and the resulting change in reactivity. The heat transport temperature may be limited to minimize corrosion or to avoid pump cavitation. During the design stage these maximum permissible temperatures must be established, the magnitude and distribution of the heat sources estimated and the temperature differences along the various paths of heat flow determined. The analysis involves considerations of heat conduction through solid components such as the fuel element and sheath and transfer of heat by convection from the solid surface to the heat transport fluid. The heat is then transported, by flow of fluid, along the reactor channel to a heat exchanger or some other heat sink. The heat transport fluid will therefore be chosen on the basis of its conduction, convection, heat transfer and heat transport characteristics.

For a heat path of length L , and constant cross-sectional area A , (e.g. slab), shown in Figure 1, the flow of heat by conduction, q , is given by: -

$$q = kA \frac{\Delta t}{L} = \frac{\Delta t}{L/kA} \text{ - - - - - (1)}$$

where k is the thermal conductivity in Btu/hr-ft-°F and Δt is the temperature decrease along the heat path. Because of the analogy to Ohm's Law, the quantity L/kA is often called the thermal resistance of the heat path.

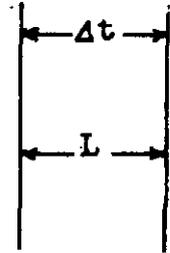


Fig. 1

Convective heat transfer between a solid and a fluid is governed by Newton's Law of cooling: -

$$q = hA \Delta t = \frac{\Delta t}{1/hA} \text{ - - - - - (2)}$$

where q is the rate of heat transfer from a surface of area A which is at a temperature Δt above its surroundings, h is the heat-transfer coefficient in Btu/hr-ft²-°F. The quantity $1/hA$ is the thermal resistance to the heat transfer. These thermal resistances are additive.

Suppose, for instance, that heat is transferred, by convection, to face A of the slab, in Fig. 2. The heat is then conducted through the slab and transferred, by convection, from face B. Let the temperatures on each side of the slab be t_a and t_b , as shown, and the heat transfer coefficients are h_a and h_b .

The thermal resistance, R_1 , at interface A is $1/h_a A$, that in the slab, R_2 , is L/kA and that at interface B, R_3 , is $1/h_b A$. These three can be considered as three resistances in series, as shown in Fig. 3. The total thermal resistance, R , is then given by: -

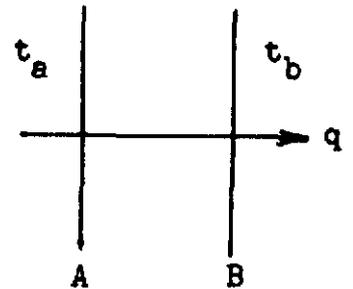


Fig. 2

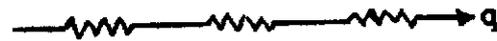
$$R = \frac{1}{h_a A} + \frac{L}{kA} + \frac{1}{h_b A} = \frac{1}{UA} \text{ - - (3)}$$

$$q = \frac{t_a - t_b}{R} = UA(t_a - t_b) \text{ - - - - - (4)}$$

U is known as the overall coefficient of heat transfer.

The values of such quantities as h and U determine the suitability of a fluid as a heat transport medium. The value of h depends not only on the physical properties of the fluid but also on the shape and dimensions of the interface and the nature, direction and velocity of the fluid flow.

The value of h is larger, for instance, with turbulent flow than with laminar flow and in most cases, where forced convection is used for heat removal, the flow is turbulent. The wire wraps on the NPD fuel elements encourage turbulence. Heat transfer coefficients for turbulent flow of ordinary fluids can be expressed in terms of the Nusselt number (Nu) and the Prandtl number (Pr) for the fluid.



$$R_1 = \frac{1}{h_a A} \quad R_2 = \frac{L}{kA} \quad R_3 = \frac{1}{h_b A}$$

Fig. 3

$$Nu = \frac{hD}{k} \quad \text{and} \quad Pr = \frac{c_p \mu}{k}$$

where D is the pipe diameter c_p the specific heat at constant pressure and μ is the coefficient of viscosity.

For fluid flowing in a long straight channel

$$Nu = 0.023 \quad Re^{0.8} \quad Pr^{0.33} \quad \text{--- (5)}$$

where $Re = \frac{Dv\rho}{\mu}$ is Reynolds number, v is the average velocity of the fluid and ρ is its density.

$$\text{Therefore:-} \quad \frac{hD}{k} = 0.023 \left(\frac{Dv\rho}{\mu} \right)^{0.8} \left(\frac{c_p \mu}{k} \right)^{0.33} \quad \text{--- (6)}$$

If the physical properties of the fluid, such as density, viscosity specific heat and thermal conductivity, are known the value of the heat transfer coefficient, for turbulent flow, can be calculated. Equation (6), however, does not hold for liquid metals. The values of the physical quantities in equation(6), particularly the viscosity, vary with temperature.

With liquid metals the most important heat transport mechanism is molecular conduction rather than by fluid movement as in gases and non-metallic liquids. For liquid metals an equation of the type: -

$$\frac{hD}{k} = 7 + 0.025 \left\{ \frac{D v \rho c_p}{k} \right\}^{0.8} \text{ --- (7)}$$

is used. Equation (7) gives values of h which are too high and, so, some modification of (7) is used in practice.

The following table gives the values of ρ , μ , k and c_p at 400°F for (a) carbon dioxide at 10 atm. pressure and a velocity of 100 ft/sec, (b) water at 20 ft/sec and (c) liquid sodium at 20 ft/sec, flowing through a long straight tube of 0.1 ft diameter.

TABLE 2

	CO ₂	Water	Liquid Na
ρ (lb/ft ³)	0.656	53.7	53.2
μ (lb/hr-ft)	0.0504	0.148	
k (Btu/hr-ft-°F)	0.0184	0.380	47.1
c_p (Btu/lb-°F)	0.265	1.0	0.320

Using these values in equation (6), for CO₂ and water, and in equation (7) for liquid sodium: -

$$h \text{ (for CO}_2\text{)} = 124 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

$$h \text{ (for water)} = 8150 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

$$h \text{ (for Na)} = 9650 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

The value of μ for water in the above table appears to be too low. However, the calculated values of h still serve to compare the heat transfer coefficients of the three fluids.

Table 3, below, lists the values of ρ , μ , k and c_p at the temperatures indicated. The values for the gases are all^p at atmospheric pressure.

TABLE 3

Fluid	Temp. (°F)	Density (lb/ft ³)	Specific Heat (BTU/lb) (°F)	Thermal Conduc- tivity	Viscosity (lb/(hr)(ft))
Water (H ₂ O) m.p. 32°F b.p. 212°F	212	60	1.006	0.395	0.70
	482	50	1.21	0.35	0.45
Water (D ₂ O) m.p. 39°F b.p. 215°F	215	66	0.993	0.372	0.79
	504	54	1.18	0.305	0.28
Terphenyl m.p. 250°F b.p. 750°F	600	53	0.60	0.066	0.77
Sodium m.p. 208°F b.p. 1621°F	752	53	0.306	41.1	0.65
	1022	51	0.301	37.4	0.54
Sodium-Potassium (56 Na-44K) m.p. 66°F b.p. 1518°F	752	51	0.252	16.0	0.56
	1022	49	0.248	16.4	0.47
Molten Salts (50NaF- 46ZrF ₄ -4UF ₄) m.p. 970°F	1300	240	0.47	2.6	20.5
Air (dry)	1160	0.0246	0.268	0.0359	0.0946
	1700	0.0184	0.280	0.0434	0.1123
Carbon Dioxide	440	0.0670	0.241	0.0194	0.0463
	1160	0.0372	0.287	0.0359	0.0875
Helium	1160	0.00339	1.248	0.1570	0.1003
Hydrogen	1160	0.00171	3.54	0.2560	0.0451
Nitrogen	1160	0.0237	0.274	0.0350	0.0925
	1700	0.0178	0.288	0.0415	0.1115
Steam	440	0.027	0.48	0.018	0.044
	1160	0.017	0.52	0.038	0.072

Pumping Power Consideration

The power utilized in pumping the heat transport fluid through a reactor is given by: -

$$\begin{aligned} \text{Pumping power} &= \text{Pressure drop} \times \text{Volume flow rate} \\ &= (\Delta p) (A_f v) \quad \text{--- (8)} \end{aligned}$$

where Δp is the total pressure drop due to all causes, A_f is the total cross-section, or flow, area of all fuel channels and v is the flow velocity. For turbulent flow, the pressure drop due to fluid friction is given by: -

$$\Delta p_f = 4 f \frac{L}{D} \frac{\rho v^2}{2g} \quad \text{--- (9)}$$

where f is the friction factor, which depends on the Reynold's number, L is the length and D the diameter of the pipe.

The entrance and exit effects and the effects of fittings must be added to Δp_f to give Δp . However if these are ignored or assumed to be proportional to $\rho v^2/2g$ (which they are for abrupt contractions or expansions), equation (8) now becomes.

$$\text{Pumping power} = k A_f \frac{\rho v^3}{2g}$$

where k is a constant which depend on pipe length and diameter. The mass flow rate $M = \rho A_f v$

$$\text{Hence pumping power} = \frac{k M^3}{2g \rho^2 A_f^2}$$

It may, therefore, be seen that the pumping power required is, roughly, proportional to the cube of the mass flow rate and inversely proportional to the square of the fluid density.

For a given fluid of constant mean density, the mass flow rate required depends on the volumetric heat capacity ρc_p . The higher the volumetric heat capacity the lower the mass flow rate required to remove a specific quantity of heat. Thus, the higher the density and specific heat, the lower the pumping power required. Specific heats do not differ by more than a factor of

around 15, eg, c_p for Sodium-potassium = 0.25, c_p for hydrogen = 3.54. However, densities of gases are generally about 100 times or more lower than those of liquids, and therefore gases require much larger pumping powers. Water has one of the most favourable pumping power characteristics, as may be seen from Table 3, followed by terphenyl and then by the liquid metals.

Other Non-nuclear Considerations

In general, a heat transfer fluid should possess the following additional characteristics: -

- (a) Low Melting Point - It is desirable that the fluid have a melting point below room temperature to avoid the necessity of traceheating or preheating the system and to avoid freezing of the fluid during shutdown. Where the heat transport fluid passes through a heat exchanger cooled by lake or river water, as it would before passing through ion-exchange columns, it is desirable that its melting point be below 32°F.
- (b) High Boiling Point - The most efficient conversion of thermal into electrical energy occurs with high heat transport temperatures. The high boiling point of a liquid permits operation of the heat transport system with little or no pressurization. This means that a strong pressurized system is not necessary which is an advantage from the operational safety point of view and also helps to reduce the capital cost of the station.
- (c) Thermal Stability - The heat transport fluid must be stable at high temperatures.
- (d) Non-corrosive Properties - It is necessary that the fluid should not attack materials, inside or outside the reactor with which it comes into contact, even at elevated temperatures. Corrosion causes damage to components which may mean that they have to be replaced. Their replacement after prolonged reactor operation may be difficult and expensive and is likely to lead to operating losses due to a lengthy unit down time. Corrosion products may also cause flow reductions in fuel channels and cause system contamination when they become radioactive.

Because of the fluid flow in the heat transport system mass transfer due to temperature gradients can be significant. For example, carbon from steel will dissolve in hot molten

sodium and the carbon is then deposited at a cooler spot in the system.

- (e) Non-toxic - Since there may be some leakage out of the heat transport system, it is essential that the heat transport fluid not be toxic nor result in a toxic substance when exposed to radiation.
- (f) Low Cost - The volume of the heat transport system is second only to that of the moderator system. High cost of the heat transport fluid would, therefore, substantially increase the capital cost of the unit. Operational cost, due to fluid losses, would also be higher.

ASSIGNMENT

1. (a) Why are neutron capture cross-sections of heat transport fluids important in thermal but not in fast reactors?
(b) When is a good moderating ratio desirable and when is it not desirable, for a heat transport fluid?
2. What induced radioactivity considerations are important when choosing a heat transport fluid?
3. (a) What physical properties of a fluid determine its heat transfer coefficient?
(b) Briefly compare the heat transfer coefficients of carbon dioxide, water and liquid sodium indicating the primary reasons for the different values.
4. (a) What factors determine the pumping power required to circulate a fluid?
(b) Why are the pumping powers required for gases so much greater than for liquids?

A. Williams