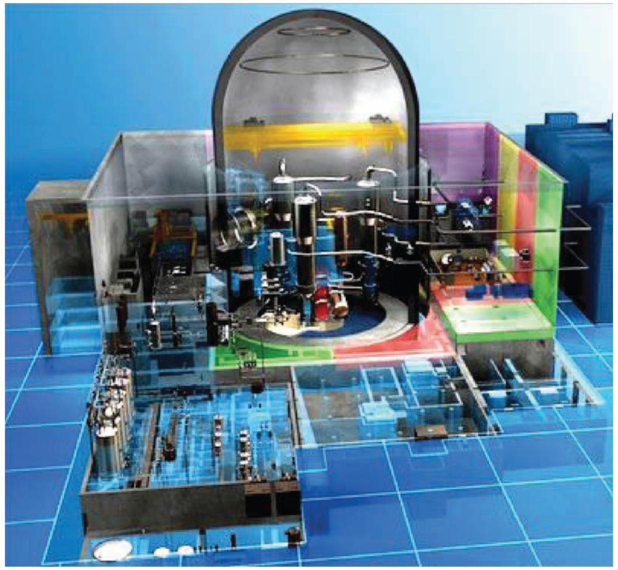
Convective Heat Transfer



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Physical Mechanism of Convection

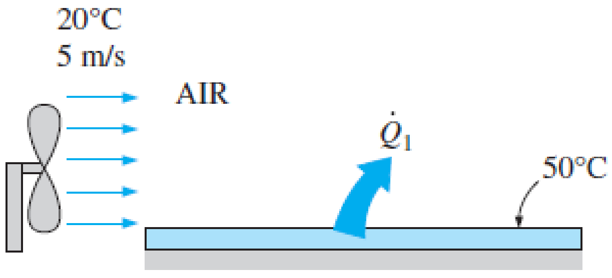
- **Convection is the main mode of heat removal in nuclear reactors**
- **Proper understanding of convection heat transfer is necessary for a successful thermal design and operation of nuclear reactors**
- **Conduction and convection both require the presence of a material medium but convection requires fluid motion.**
- **Convection involves fluid motion as well as heat conduction.**
- **Heat transfer through a solid is always be conduction.**

Physical Mechanism of Convection

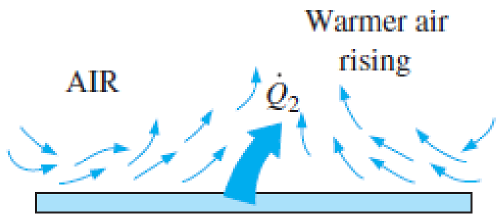
- **Heat transfer through a fluid is by convection in the presence of bulk fluid motion and by conduction in the absence of it.**

- **The fluid motion enhances heat transfer, since it brings warmer and cooler chunks of fluid into contact, initiating higher rates of conduction at a greater number of sites in a fluid.**

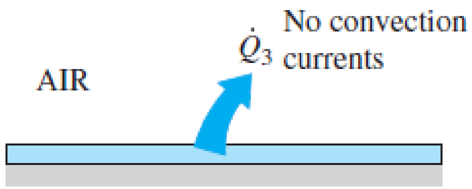
- **The rate of heat transfer through a fluid is much higher be convection than it is by conduction.**



(*a*) Forced convection



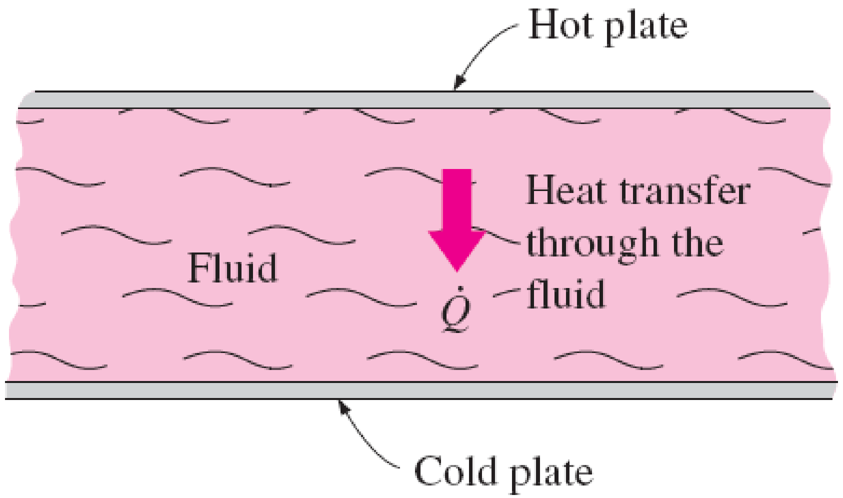
(*b*) Free convection



(*c*) Conduction

Physical Mechanism of Convection

- **In fact, the higher the fluid velocity, the higher the rate of heat transfer.**



Heat transfer through a fluid sandwiched between two parallel plates.

$$q''_{conv} = h(T_s - T_\infty) \qquad [\frac{W}{m^2}]$$

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty) \qquad [W]$$

Convection heat transfer coefficient, h: The rate of heat transfer between a solid surface and a fluid per unit surface area per unit temperature difference.

Heat Removal and Pumping Power

- **Coolants remove heat from fuel elements in the core and blanket (if any) and from thermal shields, pressure vessels, etc., and may transfer this heat to an intermediate or secondary coolant or to the working fluid in a heat exchange.**

- **The heat transferred, $q\ (Btu/hr)$**

$$q = hA_s(T_s - T_f)$$

- **In power reactor the coolant is force-circulated (by a liquid pump or a gas blower) and forced-convection heat transfer coefficients is apply.**

- **Turbulent-flow conditions also predominate in such cases.**

Heat Removal and Pumping Power

Convection heat transfer strongly depends on:

- **Fluid properties – dynamic viscosity, thermal conductivity, density, and specific heat.**
- **Flow conditions – fluid velocity, laminar, turbulence.**
- **Surface geometry – geometry, surface roughness of the solid surface.**

- **In fact, the question of convection heat transfer comes down to determining the heat transfer coefficient, h**
- **This mainly depends on the velocity and thermal boundary layers.**
- **Consequently, a wide range of values for h is to expected.**

Heat Removal and Pumping Power

- **Because of size limitations as well as the large thermal output of power reactors.**

- **The pumping work, $W\ (\mathrm{ft-lb_f/hr})$, required by the circulating coolant to overcome pressure losses through a complete loop.**

$$W = \Delta P A_c v$$

where

ΔP - Pressure drop through loop, $\mathrm{lb_f/ft^2}$
A_c - Cross-sectional area of coolant passage, $\mathrm{ft^2}$
v - coolant speed, $\mathrm{ft/hr}$

Heat Removal and Pumping Power

ΔP in turbulent flow expressed by the Darcy formula:

$$\Delta P = f \frac{L}{D_e} \frac{\rho v^2}{2 g_c}$$

where

ΔP - Pressure drop through loop, $\mathrm{lb_f/ft^2}$
f - friction factor, dimensionless
L - Channel length, ft
D_e - Equivalent diameter of channel = $\frac{4A_c}{P}$, where P is wetted perimeter
ρ - density of coolant, $\mathrm{lb_m/ft^3}$
g_c - conversion factor = $4.17 \times 10^8\ \mathrm{lb_m \cdot ft/lb_f \cdot hr^2}$

For highly turbulent flow in a circular channel with smooth surfaces, f may be given by

Heat Removal and Pumping Power

For highly turbulent flow in a circular channel with smooth surfaces, f may be given by

$$f = \frac{0.184}{Re^{0.2}}$$

where

Re - Reynolds number, dimensionless

$$Re = \frac{D_e v \rho}{\mu}$$

μ - absolute viscosity of coolant, $\mathrm{lb/hr \cdot ft}$

Heat Removal and Pumping Power

$$W = \Delta P A_c v$$

$$\Delta P = f\frac{L}{D_e}\frac{\rho v^2}{2g_c}$$

$$W = (f\frac{L}{D_e}\frac{\rho v^2}{2g_c})A_c v$$

$$f = \frac{0.184}{(\frac{D_e v\rho}{\mu})^{0.2}}$$

$$W = (\frac{0.184}{(\frac{D_e v\rho}{\mu})^{0.2}}\frac{L}{D_e}\frac{\rho v^2}{2(4.17 \times 10^8)})A_c v$$

$$\boxed{W = 2.2 \times 10^{-10}\frac{A_c L}{D_e^{1.2}}(v^{2.8})(\rho^{0.8})(\mu^{0.2})}$$

Heat Removal and Pumping Power

- **The heat removed by the coolant**

$$q = \rho\, A_c\, v\, c_p\, \Delta T_f$$

where

c_p - coolant specific heat at constant pressure, $\mathrm{Btu/lb_m \cdot {}^\circ F}$
ΔT_f - coolant temperature rise in length L, °F

- **The dimensionless ratio**

$$\frac{W'}{q} = \frac{W}{Jq}$$

J - Energy conversion factor ($778.16\ \mathrm{lb_f \cdot ft/Btu}$)

$$\frac{W'}{q} = \frac{2.2\times10^{-10}\,\frac{A_c L}{D_e^{1.2}}(v^{2.8})(\rho^{0.8})(\mu^{0.2})}{(778.16\ \mathrm{lb_f\cdot ft/Btu})(\rho\, A_c\, v\, c_p\, \Delta T_f)} = 2.83\times10^{-13}\,\frac{L}{D_e^{1.2}}\left(\frac{v^{1.8}}{\Delta T_f}\right)\left(\frac{\mu^{0.2}}{\rho^{0.2} c_p}\right)$$

Heat Removal and Pumping Power

- **A second correlation involving fuel temperatures (limited by fuel material) and coolant temperature (affecting plant thermal efficiency) can be obtained by writing q in the form**

$$\boldsymbol{q = h\,A\,\Delta T_m}$$

where

$\boldsymbol{A}$ - area heat is transferred between fuel and coolant in fuel channel or circumferential area of coolant channel $= PL = 4A_c/D_e$, ft^2

$\Delta \boldsymbol{T_m}$ - mean temperature difference between channel wall and coolant, °F

$$\frac{W'}{q} = \frac{2.2\times10^{-10}\,\dfrac{A_c L}{D_e^{1.2}}(v^{2.8})(\rho^{0.8})(\mu^{0.2})}{(778.16\ lb_f\cdot ft/Btu)(h\,(\dfrac{4A_c}{D_e})\Delta T_m)} = \boldsymbol{7.07\times10^{-14}\,\frac{1}{D_e^{0.2}}(\frac{v^{2.8}}{h\Delta T_m})(\rho^{0.2}\mu^{0.2})}$$

Heat Removal and Pumping Power

Coolant Performance in Power Reactors

Coolant	h, Btu /hr ft^2 °F	W'/q (relative)
Light and heavy water	5000-8000	1.0
Organic liquids (polyphenyls, etc.)	2000-3000	4-10
Liquid metals (sodium, sodium-potassium alloys, etc.) ..	4000-10,000	3-7
Gases (He, CO_2, N_2, air, etc.)	10-100	~ 100

- **It can be seen that, the heat removal and pumping power, both kinds of water are superior to all other coolants, followed by liquid metals and the organics.**

- **Gases have high values of $\frac{W'}{q}$ and differ widely among themselves.**

Example 1

PWR has fuel rod dimensions of R = 0.15 in and H = 30 in. The reactor operates at the thermal power of 2000 MW. The rods are cooled by pressurized water (P = 2000 psi) , which is flowing at a speed of 55×10^3 ft/hr. The coolant water entering at the bottom of the core with temperature at 600°F and leaving the core with average temperature of 640 °F. Calculate:

a) **the pumping work required for this coolant flow.**
b) **The relative ratio of pumping power to the heat removed by the coolant, $\frac{W'}{q}$**

From Table, at 600°F and 2000 psi, $\rho = 42.9\,\frac{\mathrm{lb}}{\mathrm{ft}^3}$, $\mu = 0.212\ \mathrm{lb/hr \cdot ft}$, $C_p = 1.45\ \mathrm{Btu/lb \cdot {}^\circ F}$, $k = 0.296\ \mathrm{Btu/hr \cdot ft \cdot {}^\circ F}$

Heat Transfer Coefficients General

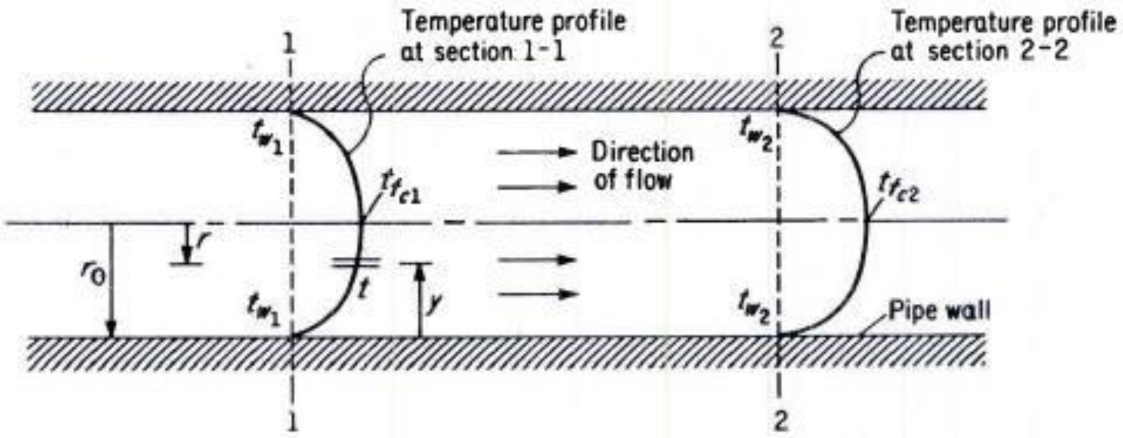
- The heat transfer coefficient, h is defined by Newton's law of cooling.

$$q'' = \frac{q}{A} = h(T_w - T_f)$$

T_w - Temperature of the wall

T_f - Temperature of the coolant fluid

- The fluid temperature is not constant over the cross section, however, and T_f is defined as that temperature which, when multiplied by the coolant mass-flow rate $\dot{m}$ and specific heat c_p,



Heat Transfer Coefficients General

- Thus, between cross-sections 1 and 2 of Fig. the heat transfer is

$$q = \dot{m} c_p (T_{f_2} - T_{f_1})$$

- T_f is given various names, the bulk, the mixed mean, and mixing-cup temperature.

- In highly turbulent flow, the temperature profile is fairly flat over much of the cross section, and the bulk temperature is taken as equal to the temperature at the center of the channel T_{fc} .

- If bulk temperature varies along the axis flow channel, as heat exchange, an average value of h halfway between the cross sections considered.

Heat Transfer Coefficients General

- **The value of h is governed by many factors:**

1. **Operating factors:**
   a) **The geometrical shape of the channel**
   b) **The flow rate of the coolant**
   c) **The heat flux**
   d) **The system temperature**

2. **Physical properties of the coolant**

In most reactor work, the flow of the fluid is forced and turbulent operating conditions.

Heat Transfer Coefficients General

- **The value of h in forced convection is governed by the thermal conductivity of the fluid as well as by those factors representing turbulence and operating conditions.**

- **In the correlations for h, it is given as part of the Nusselt number, a dimensionless group which includes the thermal conductivity of the fluid and the equivalent diameter of the channel.**

- **The Nusselt number is a function of the Reynolds and Prandtl numbers, a fact that can be proved by theoretical analysis, dimensional analysis, or by experiment. Thus**

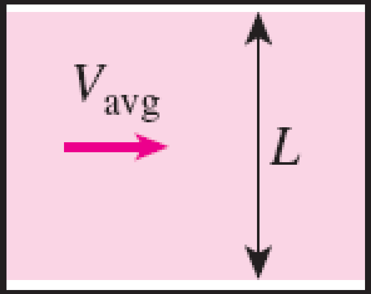
$$\boldsymbol{Nu = f\ (Re, Pr)}$$

Reynolds Number

- **The transition from laminar to turbulent flow depends on the *geometry*, *surface roughness*, *flow velocity*, *surface temperature*, and *type of fluid*.**

- **The flow regime depends mainly on the ratio of *internal forces* to *viscous forces* (Reynolds number)**

$$Re = \frac{\text{Inertial forces}}{\text{Viscous forces}}$$



$$\mathrm{Re} = \frac{\text{Inertia forces}}{\text{Viscous forces}} = \frac{\rho V_{avg}^2 L^2}{\mu V_{avg} L} = \frac{\rho V_{avg} L}{\mu} = \frac{V_{avg} L}{\nu}$$

Reynolds Number

At large Reynolds Number,

- **The internal forces, which are proportional to the fluid density and the square of the fluid velocity,**
- **The viscous forces cannot prevent the random and rapid fluctuations of the fluid (turbulent)**

At small or moderate Reynolds numbers,

- **The viscous forces are large enough to suppress these fluctuations and to keep the fluid "in line" (laminar)**

- **Critical Reynolds number, $Re_{x,c}$: The Reynolds number at which the flow becomes turbulent.**

- **The value of the critical Reynolds number is different for different geometries and flow conditions**

Nusselt Number

- **Nusselt number: Dimensionless convection heat transfer coefficient.**

- **Nusselt number represents the enhancement of heat transfer through a fluid layer as a result of convection relative to conduction across the same fluid layer.**

$$\dot{q}_{conv} = h\Delta T \qquad \dot{q}_{cond} = k\frac{\Delta T}{L} \qquad \frac{\dot{q}_{conv}}{\dot{q}_{cond}} = \frac{h\Delta T}{k\frac{\Delta T}{L}} = \frac{hL}{k} = Nu$$

$$\boxed{Nu = \frac{hL_c}{k}}$$

L_c - characteristics length

- **The larger the Nusselt number, the more effective the convection.**

- **A Nusselt number of Nu = 1 for a fluid layer represents heat transfer across the layer by pure conduction.**

Prandtl Number

- **The relative thickness of the velocity and the thermal boundary layer is best described by the dimensionless parameter *Prandtl number***

$$Pr = \frac{\text{Molecular diffusivity of momentum}}{\text{Molecular diffusivity of heat}} = \frac{\nu}{\alpha} = \frac{\mu c_p}{k}$$

Typical ranges of Prandtl numbers for common fluids

Fluid	Pr
Liquid metals	0.004–0.030
Gases	0.19–1.0
Water	1.19–13.7
Light organic fluids	5–50
Oils	50–100,000
Glycerin	2000–100,000

Prandtl Number

- **The Prandtl numbers of gases are about 1, which indicates that both momentum and heat dissipate through the fluid at about the same rate.**

- **Heat diffuses very quickly in liquid metals (Pr << 1) and very slowly in oils (Pr >> 1) relative to momentum.**

- **Consequently, the thermal boundary layer is much thicker for liquid metals and much thinner for oils relative to the velocity boundary layer.**

The Heat Transfer Coefficient-Nonmetallic Coolants

- Boiling reactors can use many types of liquid coolants, such as
  - light and heavy water,
  - liquid metals, and
  - organic coolants,

- It is mostly used light water because of its availability and the advanced state of knowledge concerning it.

Some Properties of Air, Water, and Selected Liquid Metals

Coolant	Temperature, °F	k, Btu/hr ft °F	Boiling point, °F	Melting point, °F
Air	600	0.027		
Water	600	0.356	212	32
Liquid sodium	600	43.3	1621	208
NaK (50% Na by mass)	600	15.69	1518	66
Liquid bismuth	600	9.77	2691	520
Mercury	300	9.31	675	-40

The Heat Transfer Coefficient-Nonmetallic Coolants

- **If every portion of the fluid moves parallel to the walls of the channel,**
- **then the heat travels radially into the fluid largely by conduction.**
- **The flow, in this case, is said to be laminar.**
- **If there are significant radial components of velocity fluctuations within the fluid,**
- **the heat is picked up at the wall by portions of the fluid and carried directly into the interior of the channel.**
- **This is the description of turbulent flow.**

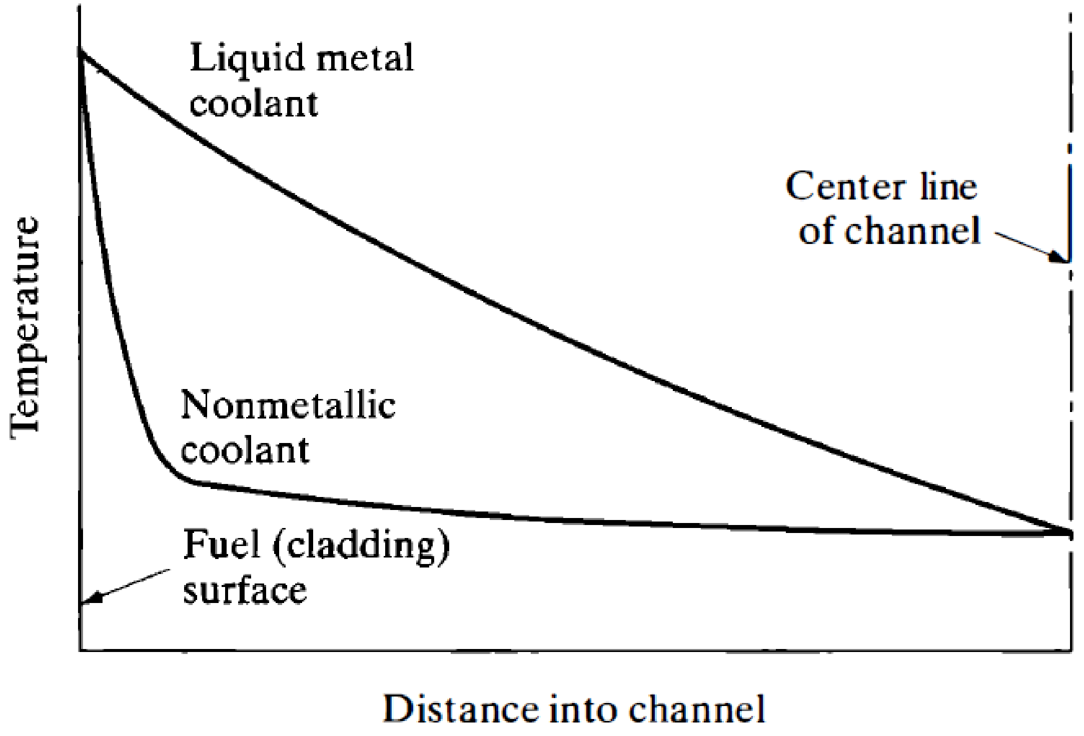
The Heat Transfer Coefficient-Nonmetallic Coolants

- **In reactors, the coolant is pumped through the system (as opposed to reactors cooled by natural convection), the coolant flows under turbulent conditions.**

- **Consequences of the internal motions of the coolant undergoing turbulent flow is that the temperature distribution tends to be more or less uniform over much of the interior region of a coolant channel.**

The Heat Transfer Coefficient-Nonmetallic Coolants

- **Figure shows the temperature drops rapidly with distance in the vicinity of the fuel and quickly reaches the bulk temperature of the fluid.**
- **Even under turbulent conditions, however, some heat is transferred to the interior of a coolant by conduction, but for the non-metallic coolants this contribution is negligibly small.**



The Heat Transfer Coefficient-Nonmetallic Coolants

- **It is possible to characterize the flow of a fluid in terms of a dimensionless parameter known as the Reynolds number, which is defined as**

$$\boldsymbol{Re = \frac{D_e v \rho}{\mu}}$$

$\boldsymbol{D_e}$ - the equivalent diameter of the coolant channel.
$\boldsymbol{v}$ - the average velocity of the fluid.
$\boldsymbol{\rho}$ - the density.
$\boldsymbol{\mu}$ - the fluid viscosity

$$\boldsymbol{D_e = 4 \times \frac{\text{cross−sectional area of coolant channel}}{\text{wetted perimeter of coolant channel}}}$$

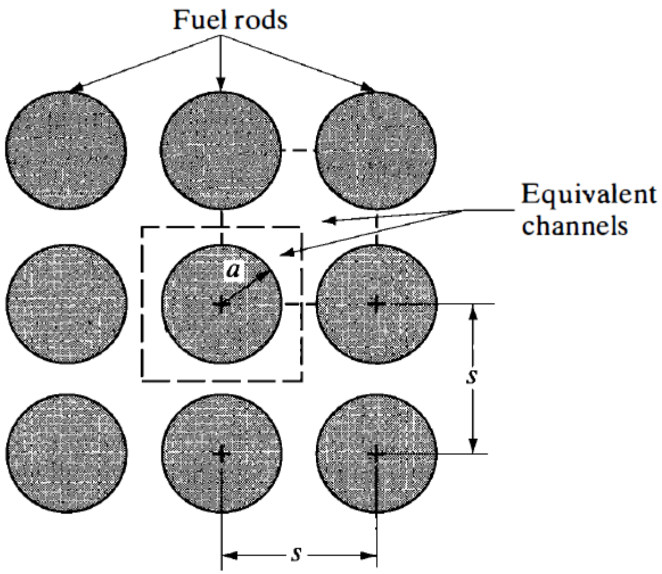
The Heat Transfer Coefficient-Nonmetallic Coolants

- **For a hollow pipe carrying a coolant, the wetted perimeter is simply the interior perimeter of a section of the pipe perpendicular to its axis.**

$$D_e = 4 \times \frac{\pi a^2}{2\pi a} = 2a$$

- **For a bundle of rods of radius, a in a square array of pitch, s**

$$D_e = 2 \times \frac{s^2 - \pi a^2}{\pi a}$$



The Heat Transfer Coefficient-Nonmetallic Coolants

- **It has been found experimentally that the flow of the fluids**

  - ➢ R_e **up to 2,000 the flow is laminar.**
  - ➢ R_e **between 2,000 and 10,000 the flow is partly laminar and partly turbulent (transitional flow).**
  - ➢ R_e **above 10,000 the flow is in fully developed turbulent flow.**

The Heat Transfer Coefficient-Nonmetallic Coolants

Reynolds number Implies

i. **a large amount of turbulence,**

ii. **a high value of the heat transfer coefficient, and**

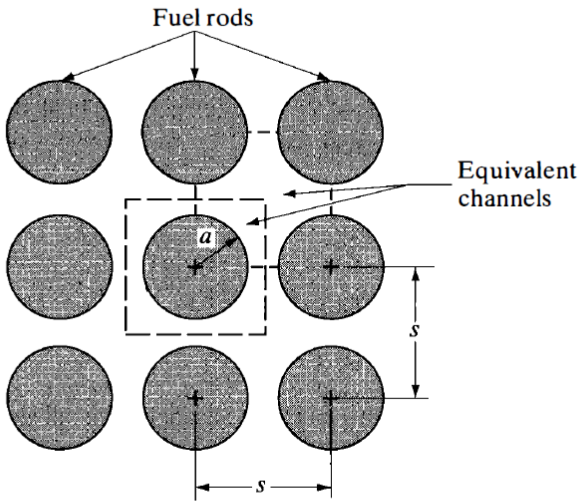
iii. **a high rate of heat flow into the coolant for a given difference in temperature between the cladding and the coolant.**

Example 2

PWR has extrapolated dimensions of R= 67 in and H = 144 in. The reactor operates at the thermal power of 1893 MW. It contains 193 fuel assemblies, each consisting of 204 UO_2 a fueled portion 0.42 in. in diameter that is clad with Zircaloy-4, 0.024 in thick. Each rod is 12 ft long. The fuel rods are placed in a square array with a pitch of 0.600 in. The rods are cooled by pressurized water (P = 2,000 psi), which is flowing at a speed of 15.6 ft/sec. Calculate the Reynolds number for this coolant flow assuming the water temperature is 600°F.

Example 2: solution

The radius of the fuel rods (a)= 0.210 + 0.024=0.234 in



$$D_e = 2 \times \frac{s^2 - \pi a^2}{\pi a}$$

$$D_e = 2 \times \frac{(0.6)^2 - \pi(0.234)^2}{\pi \times 0.234} = 0.512\ in = 0.0427\ ft$$

The flow velocity $= 15.6\,\frac{\text{ft}}{\text{sec}} \times 3600\,\frac{\text{sec}}{\text{hr}} = 56200\,\frac{\text{ft}}{\text{hr}}$

From Table, at 600°F and 2000 psi, $\rho = 42.9\,\frac{\text{lb}}{\text{ft}^3}$, $\mu = 0.212\ \text{lb/hr}\cdot\text{ft}$, $C_p = 1.45\ \text{Btu/lb}\cdot{}^\circ\text{F}$, $k = 0.296\ \text{Btu/hr}\cdot\text{ft}\cdot{}^\circ\text{F}$

$$Re = \frac{D_e v \rho}{\mu} = \frac{(0.0427\ \text{ft})(56200\,\frac{\text{ft}}{\text{hr}})(42.9\,\frac{\text{lb}}{\text{ft}^3})}{0.212\ \text{lb/hr}\cdot\text{ft}} = 486,000$$

The water is clearly flowing under turbulent conditions

The Heat Transfer Coefficient-Nonmetallic Coolants

- **Nusselt number; Nu, defined as**

$$Nu = \frac{hD_e}{k}$$

- **Prandtl number; Pr, defined as**

$$Pr = \frac{\mu c_p}{k}$$

D_e - the equivalent diameter of the coolant channel.
k - thermal conductivity.
c_p - the specific heat.
μ - the fluid viscosity

The Heat Transfer Coefficient-Nonmetallic Coolants

- **The convective heat transfer data can be correlated in terms of three dimensionless numbers-Re, Nu, and Pr.**

$$Nu = C\, R_e^m\, Pr^n$$

Dittus-Boelter equation

Where C, m, and n are constants. The value of h can be obtained

$$h = C\left(\frac{k}{D_e}\right) R_e^m\, Pr^n$$

- **We need to determine the reference temperature of the fluid T_b.**

- **These equations are not valid for liquid metals, which must be considered separately.**

The Heat Transfer Coefficient-Nonmetallic Coolants

- **With ordinary water, heavy water, organic liquids and gases flowing through long, straight and circular tubes, the following values have been recommended for the constants**

$$C = 0.023, m = 0.8, n = 0.4$$

- **In the important case of ordinary water flowing through a lattice of rods, parallel to the axis of the rods, recommended constants are**

$$C = 0.042\frac{P}{D} = 0.024, m = 0.8, n = \frac{1}{3}$$

P and D are lattice pitch and rod diamter

For triangular lattices, $1.1 \leq \frac{P}{D} \leq 1.5$ **For square lattices,** $1.1 \leq \frac{P}{D} \leq 1.3$

The Heat Transfer Coefficient-Nonmetallic Coolants

- **Where large differences between the temperatures of the solid and of the fluid, variations in the physical properties of coolant influence heat transfer.**

- **Such variation is most significant for the viscosity**

$$Nu = C\, R_e^m\, Pr^n \left(\frac{\mu}{\mu_W}\right)^{0.14}$$

$$C = 0.042\frac{P}{D} = 0.024,\ m = 0.8,\ n = \frac{1}{3}$$

μ - the fluid viscosity μ_w - the wall viscosity

The Heat Transfer Coefficient-Nonmetallic Coolants

- **For many gases, including helium, carbon dioxide, and air, Pr is approximately 0.70, and so equation.**

$$\boldsymbol{Nu = 0.70 \times C\, R_e^m}$$

$$\boldsymbol{C = 0.042\frac{P}{D} = 0.024, m = 0.8,}$$

Example 3

PWR has extrapolated dimensions of R = 67 in and H = 144 in. The reactor operates at the thermal power of 1893 MW. It contains 193 fuel assemblies, each consisting of 204 UO2 a fueled portion 0.42 in. in diameter that is clad with Zircaloy-4, 0.024 in thick. Each rod is 12 ft long. The fuel rods are placed in a square array with a pitch of 0.600 in. The rods are cooled by pressurized water (P = 2, 000 psi), which is flowing at a speed of 15.6 ft/sec. Calculate the heat transfer coefficient for the water flowing through the lattice for this coolant flow assuming the water temperature is 600°F.

Example 3: Solution

P= 0.6 in, a= 0.234 in

From Table , at 600 °F and 2,000 psi, ρ= 42.9 lb/ft^3 and

μ= 0.212 lb/hr-ft, C_p = 1.45 Btu/lb-°F, k=0.296 Btu/hr-ft°F.

$$C = 0.042\frac{P}{D} - 0.024$$

$$C = 0.042\frac{0.6}{0.468} - 0.024 = 0.0299$$

$$Pr = \frac{C_p \mu}{k}$$

$$Pr = \frac{1.45 \times 0.212}{0.296} = 1.039$$

Example 3: Solution

$$Re = 486{,}000 \text{ and } D_e = 0.0427 \, ft$$

$$h = C\left(\frac{k}{D_e}\right) Re^m \, Pr^n$$

$$h = 0.024\left(\frac{0.296}{0.0427}\right)(486{,}000)^{0.8}(1.039)^{1/3}$$

$$h = 7436 \; Btu/hr\text{-}ft^2 \; {}^0F.$$

The Heat Transfer Coefficient-Liquid Metals

- **Heat transfer to liquid metal coolants is strikingly different from the transfer of heat to ordinary fluids largely.**

- **Thermal conductivities of liquid metals are so much higher than those of other types of coolants.**

- **At 400 °F, the thermal conductivity of liquid sodium is 46.4 Btu/hr-ft- °F, whereas it is only 0.381 Btu/hr-ft °F for ordinary water and 0.115 Btu/hr-ft-°F for helium at 1 atm.**

- **Even they are flowing under turbulent conditions, these coolants absorb heat mostly by conduction.**

The Heat Transfer Coefficient-Liquid Metals

- **The temperature distribution within a coolant channel containing a liquid metal resembles the temperature distribution in a solid conductor whose axis and circumference are held at different temperatures.**

- **Temperature varies more slowly across the channel with a liquid metal than with a nonmetallic coolant.**

- **For a liquid metal flowing under turbulent conditions through a hexagonal lattice of rods, parallel to the rods, Dwyer has given the following correlation**

The Heat Transfer Coefficient-Liquid Metals

$$Nu = 6.66 + 3.126\left(\frac{s}{d}\right) + 1.184\left(\frac{s}{d}\right)^2 + 0.0155(\bar{\psi}Pe)^{0.86}$$

$\frac{s}{d}$ - the ratio of lattice pitch to rod diameter
Pe – Peelet number
$\bar{\psi}$ - a function given graphically by Dwyer

$$\bar{\psi} = 1 - \frac{0.942\left(\frac{s}{d}\right)^{1.4}}{Pr\left(\frac{Re}{10^3}\right)^{1.281}}$$

$$Pe = Re \times Pr = \frac{D_e\, v\, \rho\, c_p}{k}$$

Equation is valid only for lattices with $\frac{s}{d} > 1.35$

The Heat Transfer Coefficient-Liquid Metals

- **Equations may be used for square lattices by replacing the ratio s/d in these expressions by 1.075 $(s/d)_s$.**

- **For tightly packed square lattices, the following correlation may be used**

$$\boldsymbol{Nu = 0.48 + 0.0133(Pe)^{0.70}}$$

The Heat Transfer Coefficient-Liquid Metals

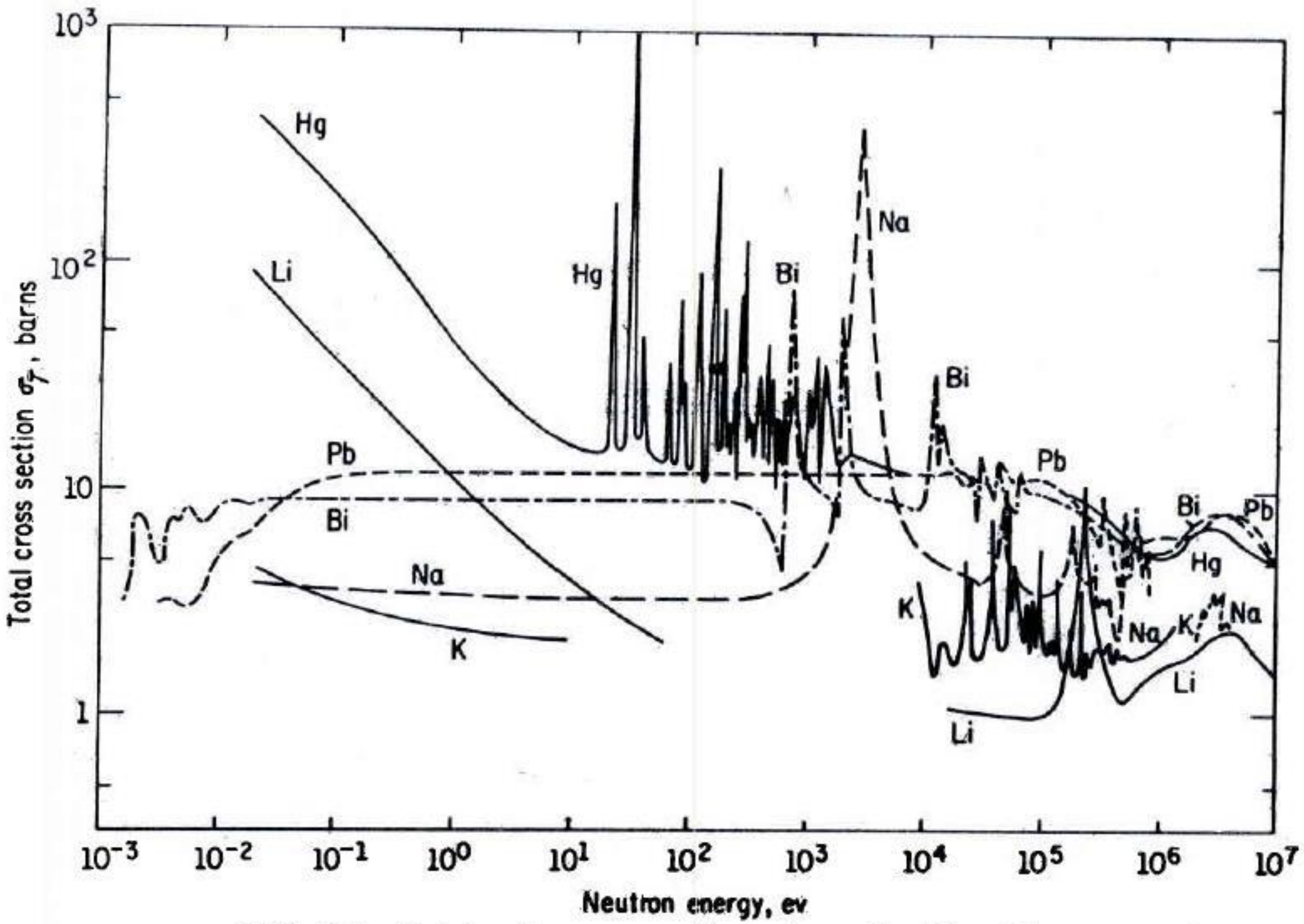


FIG. 10-1. Total neutron cross sections of some liquid metals.

The Heat Transfer Coefficient-Liquid Metals

TABLE IV.5 PROPERTIES OF SODIUM*

Temp., °F	Density, lb/ft³	Specific Heat, Btu/lb-°F	Enthalpy,† Btu/lb	Thermal Conductivity, k, Btu/hr-ft-°F	Viscosity, μ lb/ft-hr	Prandtl Number
212	57.87	0.3305			1.706	
302			239.9		1.309	
392	56.44	0.3200	268.9	47.11	1.089	0.0074
482			301.8		0.949	
572	55.06	0.3116	332.6	43.75	0.835	0.0059
752	53.63	0.3055	381.4	42.15	0.687	0.0051
932	52.07	0.3015	436.0	38.61	0.588	0.0046
1112	50.51	0.2998	490.1	36.24	0.508	0.0042
1292	48.88	0.3003	544.2	34.10	0.450	0.0040
1472	47.26	0.3030	598.5	31.62	0.399	0.0038
1652		0.3079	653.4		0.363	

Example 4

The core of an LMFBR consists of a square lattice of 13,104 fuel rods 0.158 in in diameter, 30.5 in long, on a 0.210 -in pitch. The fuel rods are 26 w/o enriched uranium clad in 0.005-in stainless steel. Liquid sodium enters the core at approximately 300 °C and passes through the core at an average speed of 31.2 ft s-1. The core produces 270 MW of thermal power, with a maximum-to-average power density of 1.79. Where the maximum heat production rate 3.27x10^8 Btu/hr ft^3. Calculate:

[Note: Take the heat transfer coefficient to be 35,000 Btu/hr-ft^2 °F, Density of sodium 55.06 Ib/ ft^3 ,
Cp = 0.3116 Btu/Ib °F , μ(572 F)= 0.835, μ(586 °F)= 0.687), ρ (572 °F)= 55.06 Ib/ ft^3, ρ (586 °F)= 53.63 Ib/ ft^3].

i. total coolant flow area;
ii. sodium flow rate in lb/hr;
iii. average sodium exit temperature;
iv. Reynolds number for the sodium entering and leaving (at the temperature in part [iii) the core;

Thank You

Stay safe!