1952

PROBLEM

The peacetime use of atomic energy requires the development of an atomic power system. Such a system must convert the kinetic energy released by the nuclear fission into useful electrical or mechanical power. At the present time no direct method is known that will accomplish this conversion.

The process now envisaged involves a nuclear reactor transferring heat to a fluid heat transfer medium. This medium is circulated through a steam generator to produce steam which is utilized in a turbine. The turbine can then be used to drive an electric generator or as the motivating power for a mobile unit, such as a ship. Once the heat has been transferred to a suitable heat transfer medium, the engineering becomes conventional; however, the design of a nuclear reactor involves many new and difficult problems.

The fissionable material is the source of heat and is distributed throughout the reactor. There are three principal types of fissionable materials which may be used: U-233, U-235, and Pu-239. These materials vary in their nuclear properties, but the energy released per fission is of the same general magnitude and character. The total quantities of fissionable material, or fuel, must be maintained within definite or critical limits. If the quantity is too small, the chain reaction will not be maintained. If the quantity is too large, the reaction will be difficult to control. The amount of the fuel is also dependent on the specific absorption of neutrons by materials within the reactor. Since the fissionable materials in general do not possess strength and may be subject to erosion, it is necessary to reinforce or to can the fissionable material with a material of good structural properties. Structural and heat transfer materials used in the reactor should have low neutron absorption. In addition, the heat transfer medium should not change phase (density) in a nuclear reactor, as this change would make the nuclear control problem more difficult.

Possible heat transfer fluids include gases or liquids. Because of its heat transfer and nuclear properties, helium appears to be a promising gas. Unfortunately, a gas requires a large heat transfer area, which means large surface areas within the reactor. Also, the quantities of gas which must be pumped through the reactor would be extremely large, and so the pumping power required might become prohibitive.

Liquid metals, such as sodium, potassium, sodium-potassium alloys, tin, mercury, lead, and lead alloys, may be considered for use as coolants. The high thermal conductivity of a liquid metal is a very favorable property, as it minimizes the possibility of hot spots occurring in the structural material and fuel cans.

INTRODUCTION

This problem considers the removal of heat from a nuclear reactor by means of a heat-exchange medium flowing in a closed circuit. The heat is transferred from the fluid flowing in the reactor to the working fluid of a conventional heat engine. A reactor is merely a new type of heat source in which nuclear energy is developed in the form of heat. Owing to the high heat rate and nuclear considerations, the removal of heat from the reactor presents some new and unique problems. Since the nuclear calculations are beyond the scope of this problem, only the method of heat removal will be evaluated.

PROBLEM

1. Make a general survey of possible heat transfer fluids. Choose the most suitable coolant and give the reasons for your choice. The following items should be considered when the choice is made.
    a. Pumping power.
    b. The operating temperature of the reactor.
    c. Physical properties of the coolant including thermal stability, heat transfer characteristics, and corrosiveness.

2. Design the coolant passages through the reactor and draw a sketch of your solution.

3. On the basis of your choice of a coolant and the reactor flow passages, you are asked to estimate the performance of the power plant that you propose. This should include a complete flow sheet from the reactor through the generator indicating coolant flows, pressure, temperature, pump power, pipe size, plant efficiency and other data that you think important in this design.

In this analysis, questions may arise for which you do not have adequate data to come to a solution. Make reasonable assumptions and state what they are.

DESIGN-DATA SPECIFICATIONS

1. Reactor heat output is 80,000 kw.
2. The dimensions of the reactor are 2 by 2 by 2 ft., which include fuel, structural material, and coolant.
3. Coolant passages are 25% by volume.

4. Assume that the fissionable material is separated from the coolant by a structural material of your choice. The structural material can be assumed 30 mils (0.030 in.) thick.

5. Assume the fissionable material to be uniformly dispersed in the volume not occupied by structural material or coolant.

6. Assume uniform heat generation in the fissionable material.

7. The maximum temperature of the fissionable material cannot exceed 2,500°F. Assume its thermal conductivity to be 3.0 B.t.u./(hr.)(ft./°F.)

8. The temperature rise across the reactor should not exceed 400°F. This limit is set to avoid excessive thermal stress during transient operation.

LITERATURE CITED

1. Goodman, Clark, "The Science to Engineering of Nuclear Power," Vols. I and II, Addison Wesley Press, Inc. (1949).
2. Davidson, Ward, Elec. Eng., 67, No. 10 (October, 1948).

APPENDIX

The following pages were reproduced from the "Liquid Metals Handbook," Atomic Energy Commission, Department of the Navy, Washington, D.C. (June 1, 1950), which is out of print. This appendix contains information of assistance in the solution of the problem.

TABLE I

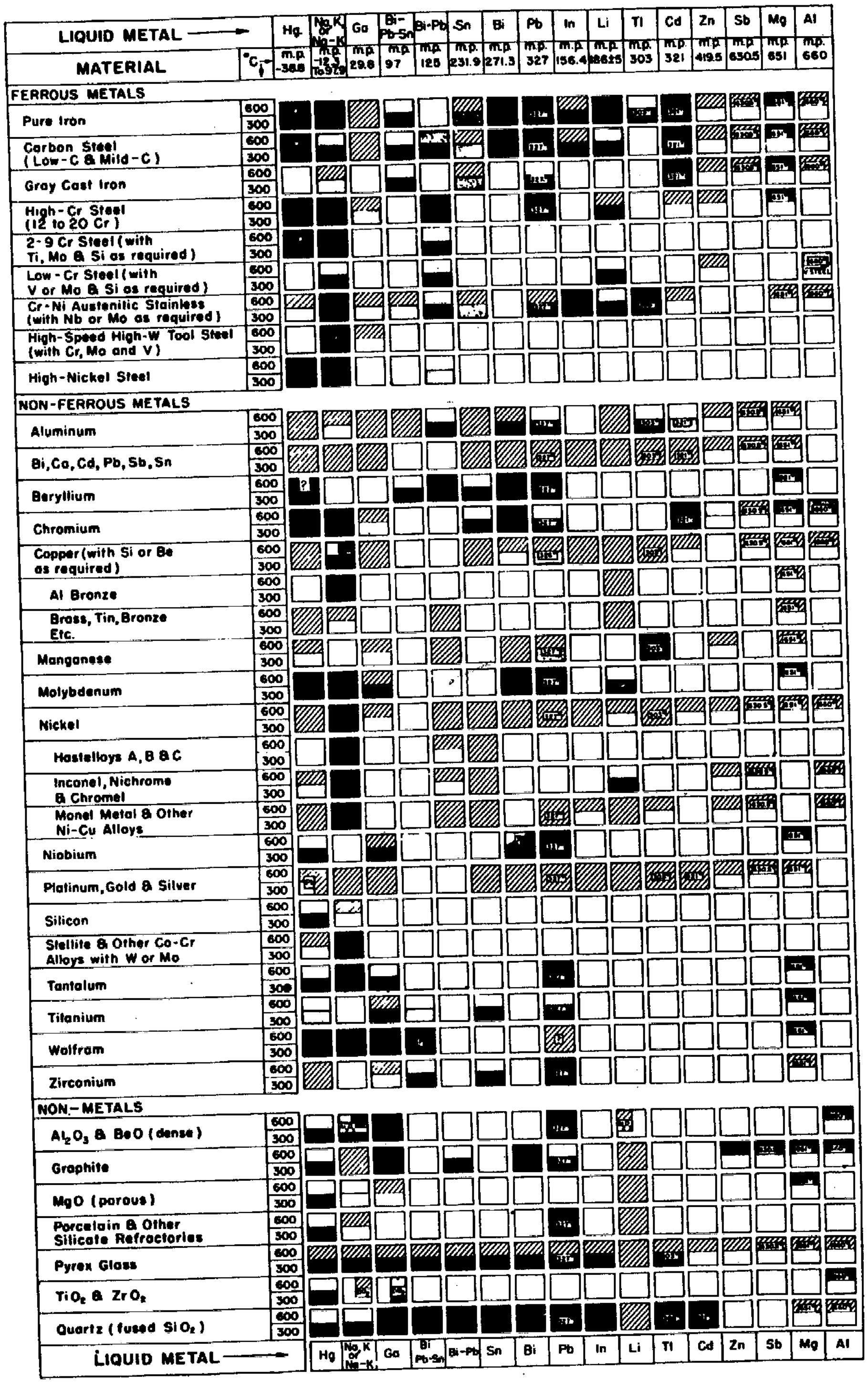
TABLE OF HEAT TRANSFER PROPERTIES

Name	Thermal Conductivity $\frac{BTU/hr}{(ft^2)(°F/ft)}$		Density $\frac{lb}{ft^3}$		Specific Heat $\frac{BTU}{(lb)(°F)}$		Kinematic Viscosity $\frac{ft^2}{hr}$		Thermal Diffusivity ft^2/hr		$\frac{ft \times hr}{lb}$		Pr	
	k	°F	ρ	°F	c	°F	ν	°F	$\frac{k}{c\rho}$	°F	$\frac{c}{k}$	°F	$\frac{c\mu}{k}$	°F
Aluminum	53.2 50.8 49.6	1292 1472 1652	148.2 147.5 144.0 140.7	1220 1292 1652 2012	0.260	1220 to 1832			1.386 (1.340) 1.325	1292 1472 1652	0.00489 0.00512 0.00524	1292 1472 1652		
Antimony	12.6 12.1	1166 1346	405 403 398 393	1130 1292 1472 1778	0.0656	1202 to 1742	0.00780 0.00677 (0.00611) (0.00559)	1296 1474 1652 1836	0.474 0.458	1166 1346	0.00521 0.00542	1166 1346	(0.0185) (0.0164)	1166 1346
Bismuth	9.92 8.95 8.95 8.95 8.95	572 752 1032 1112 1292	626 619 603 587 574	572 752 1112 1476 1764	0.0340 0.0354 0.0376 0.0397 0.0419	520 752 1112 1472 1832	0.00645 (0.00504) 0.00432	579 844 1112	(0.462) (0.459) (0.404) 0.395	572 579 844 1112	(0.00346) 0.00396 0.00420 (0.00432)	572 752 1112 1292	(0.0141) (0.0125) 0.0107	579 844 1112
Cadmium	25.6 25.4 25.4 28.8	671 681 716 815	500 499 495 488 482	626 662 752 932 1112	0.0634	610 to 1292	0.00699 (0.00627) 0.00585 0.00553	660 880 943 1116	0.808 (0.928)	660 815	0.00248 0.00250 0.00250 0.00220	671 681 716 815	0.00865 (0.00695)	660 815
Cesium	12.1 to 15.7	(MP)83			0.060	83					0.0050 to 0.0038	83		
Gallium	16.9 to 21.8	(MP)86	380 369 357 350 340	90 573 1112 1483 2012	0.082	545 to 392	0.0121 0.00676 0.00583 0.00544 0.00452 0.00412	127 573 756 932 1483 2012	0.651 to 0.700	86	0.00404 to 0.00376	86	(0.0196) to (0.0182)	86
Indium	21.8 to 29.0	(MP)314			0.0613	314					0.00281 to 0.00211	314		
Lead	9.43 9.19 8.95 8.71 8.71	626 752 932 1112 1292	667 658 643 636 629	(MP)621 842 1202 1382 1562	0.039 0.037 0.037	(MP)621 752 932	0.00778 0.00759 0.00633 0.00511 0.00456	826 853 1024 1297 1551	0.362 0.375 0.370	621 752 932	0.00414 0.00403 0.00413	621 752 932	(0.023) (0.021) 0.019	752 826 932
Lithium	20.6 to 26.6	(MP)367	31.5 30.9 30.2 29.6 29.0	572 752 932 1112 1292	1.22 to 1.00	356 to 2241					0.0592 0.0376	367 2241		
Magnesium			98.14 96.8 95.9	(MP)1204 1252 1292	0.317 0.321 0.332	1204 1341 1701								

Magnesium			98.14 96.8 95.9	(MP)1204 1252 1292	0.317 0.321 0.332	1204 1341 1701								
Mercury	5.27 5.64 6.00 8.44 9.31	-34.6 -5.3 32 210 300	851.9 845.7 833.4 818.4 804.2	-4 68 212 392 572	0.0342 0.0334 0.0327 0.0321 (0.0332)	-34.6 32 176 320 500	0.00526 0.00480 0.00444 0.00352 0.00299	-4 32 68 212 392	0.180 0.212 0.305 0.350	-39.6 32 200 300	0.00649 0.00557 0.00393 0.00346	-34.6 32 200 300	0.0226 0.118 0.00909	32 200 300
Potassium	36.3 to 48.4	(MP)147	51.14 48.9 46.6 44.4 42.2	212 482 752 1022 1292	0.206 0.204 0.201 0.200 0.200	147 197 261 351 621	0.024	147	3.40 to 4.50	147	0.0057 to 0.0043	147	0.082 to 0.108	147
Rubidium	20.6 26.6	(MP)102	92.1	102	0.0918	102 to 212			2.43 to 3.15	102	0.00446 to 0.00345	102		
Sodium	49.1 46.7 42.3	212 392 662	57.9 55.6 53.3 51.0 48.7	212 482 752 1022 1292	0.3305 0.3199 0.3055 0.3002 0.3040 0.3093	212 392 752 1112 1472 1652	0.0293 0.0194 0.0128	212 392 662	2.57 2.59 2.53	212 392 662	0.00673 0.00685 0.00730	212 392 662	0.0114 0.00749 0.00506	212 392 662
Thallium			704.8 702.6 702,0 702.6	584 620 626 632	0.0348	577 to 932								
Tin	19.4 19.6 19.1 18.9	464 558 783 928	426.6 422.0 420.0 416.5 414.5	768 973 1065 1198 1299	0.0580 0.0758	482 2012	0.0104 0.00960 0.00921 0.00905	482 536 590 626	0.778	482	0.00297	482	0.0134	482
Zinc	33.4 32.9 32.7	932 1112 1292	432 425 410	(MP)787 1112 1472	0.1199 0.1173 0.1076 0.1044 0.1012	787 1112 1472 1652 1832	0.0127	1112	(0.659) 0.659 0.737	787 1112 1472	(0.00351) 0.00357 0.00331	787 1112 1472	0.0193	1112
Sodium Potassium Alloy 56% Na 44% K Wgt. Percent	14.93 15.31 15.68 16.01 16.33	212 392 572 752 932	55.3 (53.8) 53.1 (52.3) 50.8 (49.35) 48.6 46.3	212 (392) 482 (752) 752 (932) 1022 1292	0.274 0.267 0.262 0.260 (0.259)	212 392 572 662 (752)	0.0243 0.0239 0.0184 0.0165 0.0144 0.0130 0.0110 0.00842	(212) 218.7 333.5 392 482 (572) 752 1292	0.983 1.068 1.145 (1.215)	212 392 572 752	0.0184 0.0174 0.0167 (0.0162)	212 392 572 752	0.0247 0.0154 0.0114 (0.00905)	212 392 572 752
Sodium Potassium Alloy-Eutectic 22% Na - 78% K Wgt. Percent	14.10 14.59 15.00 15.20 15.38	212 (392) (572) 662 752	52.9 51.4 50.6 49.6 49.1 48.4 47.2 46.1 43.9	212 (392) 482 (572) (662) 752 (932) 1022 1292	0.231 0.226 0.224 0.223 (0.222)	212 392 572 662 (752)	0.0218 0.0215 0.0168 0.0150 0.0133 0.0121 0.0111 0.0103 0.00806	212 218.7 333.5 (392) 482 (572) (662) 752 1292	1.152 1.255 1.353 1.385 (1.435)	212 392 572 662 752	0.0164 0.0155 0.0149 0.0147 (0.0144)	212 392 572 662 752	0.0189 0.0120 0.00894 0.00801 (0.00718)	212 392 572 662 752
Lead-Bismuth Eutectic Alloy 44.5% Pb-55.5% Bi Wgt. Percent	5.32 5.56 5.81 6.29 6.35 6.53	320 392 464 572 (581) 608	634	581	0.035	291 to 676	(0.0069)	(581)	0.286	(581)	0.00658 0.00602 0.00551	320 464 (581)	(0.024)	(581)

CHART I

CONDENSED SUMMARY OF RESISTANCE OF MATERIALS TO ATTACK BY LIQUID METALS AT 300°C. AND AT 600°C*



DEGREE OF RESISTANCE

■	GOOD	— Consider for long-time use.
▬	LIMITED	— For short-time use only.
▨	POOR	— No structural possibilities.
☐	UNKNOWN	— No data for these temperatures.

*See text for discussion of these data
○ Inhibitor used. See text.

Evidence to the contrary is adduced--for some of these metals--in some of the following pages. Metals for possible use as containers are listed by Brewer in order of decreasing preference, based on "availability" and extent of attack, as follows:

MOLTEN METALS	CONTAINER METALS
Alkali Metals	Fe, Co, Cr, Nb, W, Ta, Mo, Re
Mg	Fe, Nb, Be, W, Ta, Re, Mo, Cr
Zn	Nb, Zr, Ta, W, Cr, Ti, Ir, V
Cd	Nb, Ta, W, Mo, Fe, Cr
Hg	Fe, W, Ta, Re, Mo, Nb, Rh, Ni, Be, Co
Pb	Fe, Co, Ir, Zr, Rh
Sn	W, Mo, Ta, Nb, Cr
Bi	W, Zr, Fe, Ta, Rh, Cr, Ti, V, Co
Ga	W, Ta, Mo, Nb, Os, Ir
Tl, In	Fe, W, Ta, Mo, Nb, Co

THEORY OF LIQUID-METAL HEAT TRANSFER

Two types of heat conductivity exist in ordinary turbulently flowing fluids, molecular conductivity and turbulent conductivity. The molecular conductivity is that due to the transfer of molecular movement within the liquid by collision of one molecule with the next.

Turbulent or eddy conductivity is due to the physical transport of macroscopic portions of the fluid from one part of the fluid to another. In turbulent flow, mixing by eddies accounts for most of the heat transfer in the bulk of the flowing stream, masking almost completely the molecular conductivity except near the walls where the eddying is less pronounced. It should be borne in mind that molecular conductivity exists throughout the stream, but that it is important only where little if any eddying exists, i.e., near the walls.

In metals, heat is also transferred by the migration of electrons. This third mechanism results in an apparent increase in the molecular conductivity, and may, in some cases, increase this apparent conductivity by a factor of more than one hundred.

For simplicity in this handbook the term "thermal conductivity" is used to mean the sum of the molecular conductivity of heat and the electron conductivity of heat.

Diffusivity is a general term describing the rate at which an extensive property is transferred from one place to another within a material by a given concentration gradient. If one thinks of an extensive property, N, as being transferred at a flux rate of n per (unit area)(time) between two points, a given distance apart and with a difference in concentration of n per unit volume, the units for the diffusivity will be seen to be:

$$\frac{n}{(\text{area})(\text{time})} \Big/ \frac{n}{(\text{vol})(\text{length})} = (\text{length})^2/\text{time}$$

The term n does not appear in the reduced units for the diffusivity and it will be observed that the diffusivity of one property can be compared with the diffusivity of another.

In the following discussion, the diffusivity of heat will be compared with the diffusivity of momentum. The diffusivity of heat in a fluid may be found by dividing the thermal conductivity by the volume heat capacity, $c\rho$.

$$D_H = \frac{k}{c\rho}$$

Diffusivity of momentum is the kinematic viscosity:

$$D_M = \frac{\mu}{\rho} = \nu$$

The dimensionless ratio of diffusivity of momentum to diffusivity of heat is usually called the Prandtl number,

$$\frac{D_M}{D_H} = \frac{c\mu}{k} = Pr$$

Most ordinary fluids have values of Pr (which is a physical property) between about .7 and 200. The usual heat-transfer equations have been developed empirically to cover this range. Liquid metals, on the other hand, range in Prandtl number from about 0.1 to about 0.005.

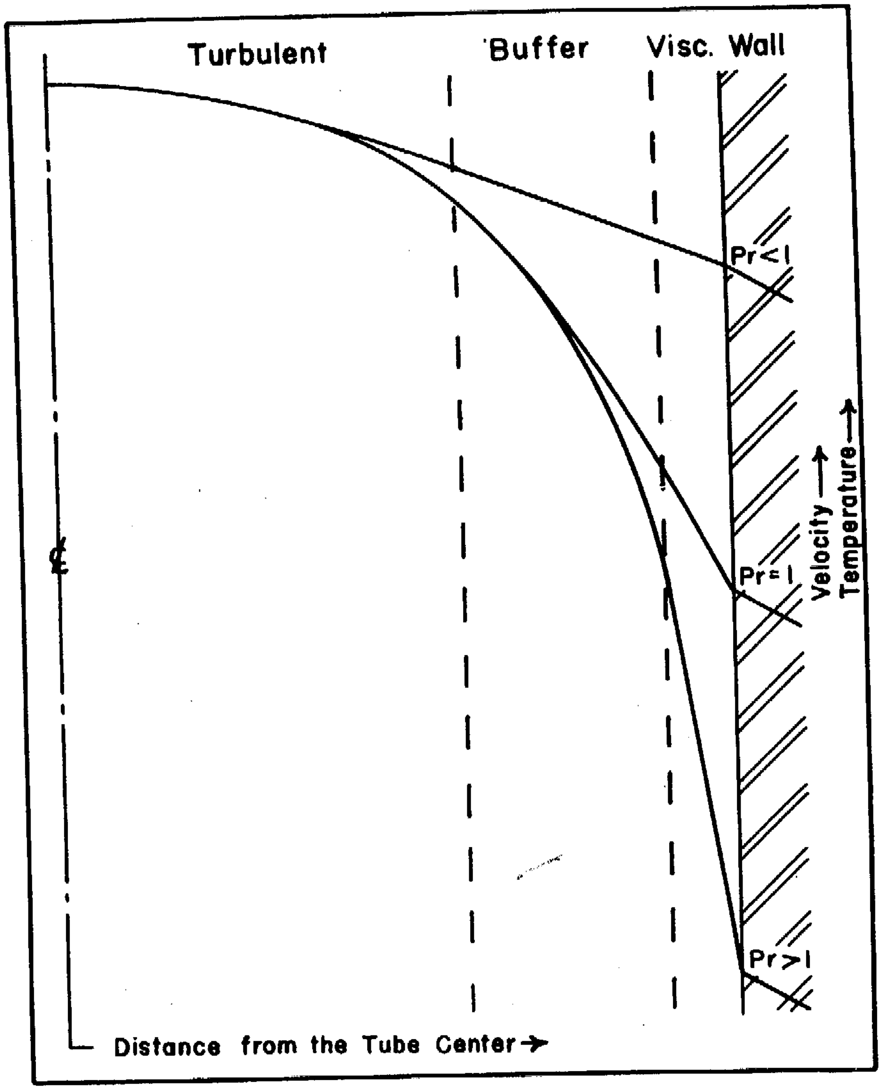


Figure 3 - Qualitative Diagram of Temperature Distribution in Fluids of Various Prandtl Moduli

The current concept of turbulent flow in a tube is shown qualitatively in Figure 3. A thin laminar or viscous region in which no turbulence or eddying takes place occurs adjacent to wall. All conduction of heat and momentum is by molecular motion (and by electron motion in the case of liquid metals).

Between this layer and the turbulent core is a buffer region in which the velocity distribution is determined by the combined action of molecular and eddy diffusion of momentum toward the wall. In the turbulent core the velocity distribution, by definition, is controlled by the eddy diffusion of momentum.

Although the belief has never been adequately established, it may be assumed here that the ratio of eddy diffusivities of heat and momentum is one.

In Figure 3, the curve marked "Pr = 1" may be thought of as picturing qualitatively the temperature distribution in a cooling tube under given conditions where the fluid has a Prandtl modulus of unity. Such a situation is approximated by a gas and by high-temperature water. It also represents the shape of the velocity distribution.

The lower curve represents the temperature distribution for most liquids where the Prandtl modulus is greater than one--poor molecular diffusivity of heat compared with momentum. Here the temperature distribution curve deviates from the velocity distribution curve in the buffer region, because of the low influence of molecular diffusivity of heat.

The temperature distribution curve for liquid metals or other fluids with a high molecular diffusivity of heat and hence Prandtl modulus less than unity is represented by the upper curve. In this case the effect of high molecular diffusivity (and electron diffusivity) of heat will be pronounced even in the turbulent core. For very low Prandtl modulus at moderate Reynolds modulus, the eddying may not completely control heat flow even near the center of the tube.

Since the velocity distribution in turbulently flowing fluids has been accurately measured, it is possible to predict the heat transfer for liquid metals in tubes. Such theoretical investigations have been performed with notable success. As a result the plot in Figure 4 can be drawn to show the heat transfer coefficient in tubes with a constant heat flux through the wall for all fluids in either turbulent or viscous flow. A number of assumptions have been made in the calculations for this plot which limit its accuracy, but it is useful in visualizing the remarkable difference between liquid metals and ordinary fluids.

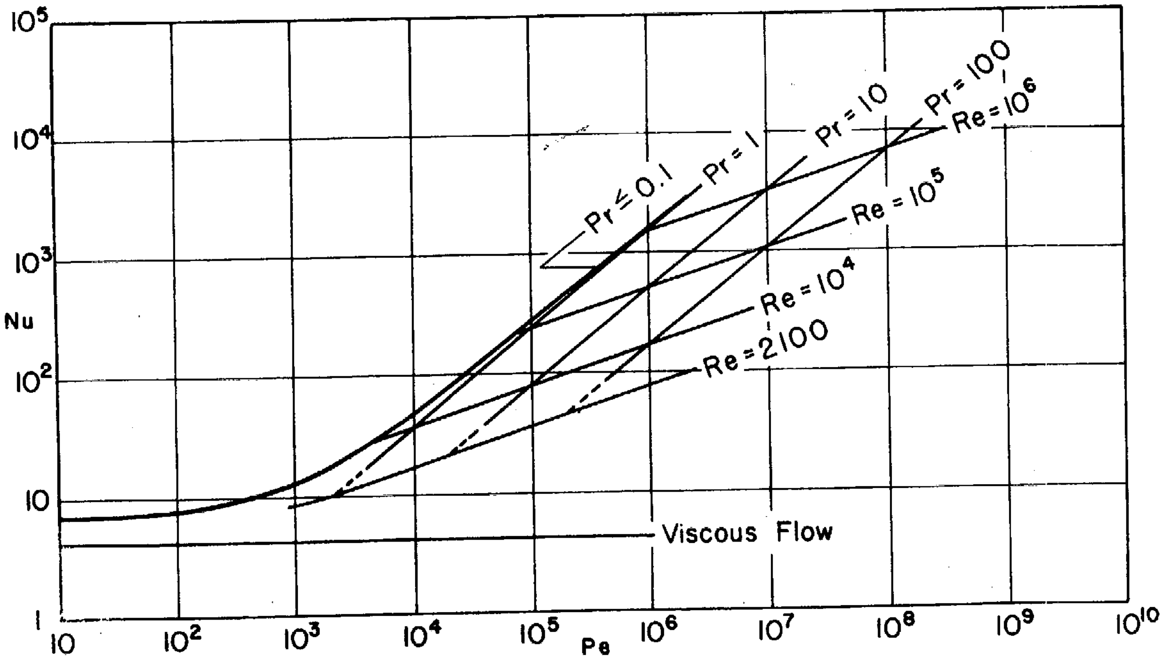


Figure 4 - Nu for Turbulent and Viscous Flow Versus Pe, Pr and Re

Complete analyses of this analogy are given in the following references which are listed at the end of this chapter (1)(3)(8)(9)(10)(11)(15)(16)(17)(18)(19)(20)(23). A qualitative discussion of end effects will be found in the section of this chapter dealing with design considerations.

RECOMMENDED EQUATIONS AND DESIGN CONSIDERATIONS

Contact Resistance with Nonwetting

Only a very rough estimate of the contact resistance can be made at the present time. The only empirical approximation published to date is Harrison's equation(6) for the nonwetting contact heat-transfer coefficient, h_x, based on experimental results by Musser and Page(14) with mercury and applicable with accuracy only to their results.

1. $h_x = 1/10 \text{ Re}$ Btu/(hr)(ft^2)(°F)

When the liquid wets the wall, it may be assumed that the contact resistance is negligible. Wetting may be improved in mercury and lead-bismuth alloys by the addition of about 0.1 - 0.2 wt.% sodium or magnesium(26). (See also the discussion of mercury in Chapter 4).

Circular Tubes

A simplified approximation of the theoretical results first obtained by Martinelli(11) can be written(10)

2. $\text{Nu} = 7 + .025 \text{ Pe}^{.8}$

This may also be written:

3. $h = k/d \; [7 + .030 \; (W/D)^{.8} \; (c/k)^{.8}]$

This equation is an approximation based on theoretical calculations. It has been corroborated experimentally by Werner, King and Tidball(27) and by Lyon(10) using NaK.

Parallel Plates With Heat Through One Side Only

Harrison and Menke(8) have developed theoretical relationships for this situation which may be roughly generalized by the equation:

4. $\text{Nu} = 4.9 + 0.0175 \text{ Pe}^{.8}$

or

5. $h = \frac{k}{2d} \; [4.9 + 0.031 \; (W_w)^{.8} \; (c/k)^{.8}]$

where d is the distance between the plates, and W_w is the weight rate of flow per foot of channel width parallel to the walls.

Equation 4 and 5 give values of Nu and h which are 0.7 of the values obtained by using the circular tube equations with a value of D equal to 2d and a value of W equal to that obtained in such a tube with the same average velocity as between the plates. Seban(18) has recently developed the generalization:

6. $\text{Nu} = 5.8 + 0.02 \text{ Pe}^{.8}$

which may be written

7. $h = \frac{k}{2d} \; [5.8 + 0.035 \; (W_w)^{.8} \; (c/k)^{.8}]$

In view of errors recently found by Harrison and Menke(7) in their calculations, the latter equations are probably more accurate, though less conservative.

Equations 6 and 7 give values of Nu and h which are approximately 0.8 of those obtained with circular tubes.

Parallel Plates With Heat Through Both Walls

Seban(18) proposes that the effects due to heat flow through each of the two walls may be superimposed on each other to give the actual temperature and heat-transfer coefficient at each wall. The coefficient assuming heat flow only through one wall, h′, may be calculated from the preceding equation:

7. $h' = \frac{k}{2d} \left[5.8 + 0.035 (W_W)^{.8} (c/k)^{.8}\right]$

A term, X, is defined as $\frac{t_o - t'_m}{t_o - t'_D}$, where the prime indicates the situation which would exist if heat flowed only through the wall of subscript "o" and no heat flowed through the opposite wall designated by subscript "D".

In Figure 5, the values which Seban(18) has calculated for X are plotted as solid lines. A rough generalization for these values for X is plotted as broken lines, and may be written as

8. $X = 0.87 \, Pr^{0.046}$

with the limitation that above Pr = 10, X may be assumed to be approximately unity.

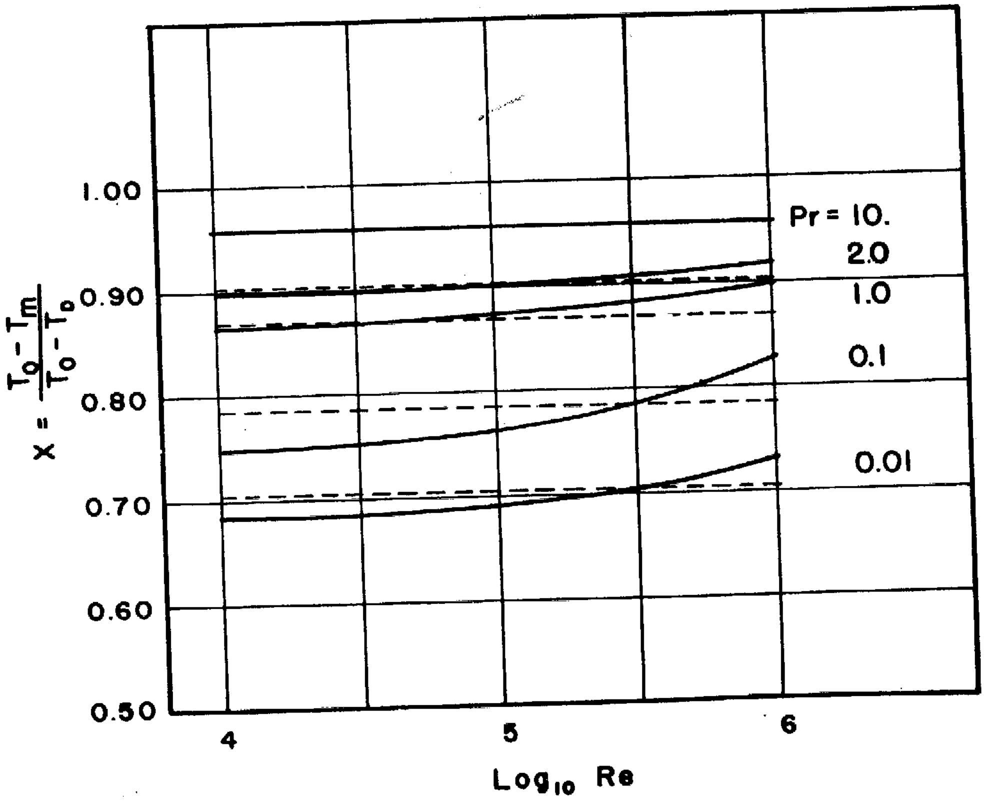


Figure 5 - Sebans Values

In most cases it will be unnecessary to calculate the actual coefficients for the two sides. Usually it will be desired to calculate two of the following quantities: Q_o, Q_D, t_o, t_D, t_m from the remaining three and the values of h′ and X for the system. Once this is done values of h_o and h_D can be obtained, if required, from the equations

9a. $h_o = \frac{Q_o}{(t_o - t_m)}$

9b. $h_D = \frac{Q_D}{(t_m - t_D)}$

Any two of the five temperature and heat flux variables listed above are found from the remaining three plus h′ and X by use of the following relationships which are a simple extension of Seban's paper.

10. $X h' (t_o - t_D) = Q_o + Q_D$

11a. $h' (t_o - t_m) = Q_o + (\frac{1}{X} - 1) Q_D$

11b. $h' (t_m - t_D) = Q_D + (\frac{1}{X} - 1) Q_o$

12a. $Q_o = \frac{X(t_o - t_D) - (t_m - t_D)}{2 - \frac{1}{X}} h'$

12b. $Q_D = \frac{X(t_o - t_D) - (t_o - t_m)}{2 - \frac{1}{X}} h'$

Annuli

Thin annuli with r_o/r_i close to unity may be treated as though they were parallel plates, and the Equations 4 through 12 applied with assurance. This has been very roughly checked with NaK by Lyon(10).

Annuli of r_o/r_i greater than about 1.4, however, will have higher heat transfer rates than indicated by this means, and more complex equations must be applied.

Bailey(1) has developed the following theoretical expressions which have been checked experimentally with NaK in thick annuli by Werner, King and Tidball(27), as well as fitting Lyon's data(10) for thinner annuli

13. $Nu = Nu_s + .0106 R_o^{.37} Pe^{.86}$

where

13a. $1/Nu_s = \frac{1}{8B(R_o + 1)^2} \quad -3-12B-14B^2 - 4B^3 +4(B+1)^4 \ln R$

13b. $B = \frac{r_i}{r_o - r_i}$

13c. $R_o = \frac{r_o}{r_i} = \frac{1}{B} + 1$

An empirical approach by Werner, King, and Tidball(27) also checks their experimental results and those of Lyon(10). It consists of the application of a correction factor of .7 $(r_o/r_i)^{0.53}$ to the circular tube equation (Equation 2). This was suggested by the correction of .87 $(r_o/r_i)^{0.53}$ to the Dittus and Boelter(4) tube equation which Monrad and Pelton(12) recommend with water in an annulus.

The coefficient of .7 was chosen since this factor makes the tube equation (Equation 2) fit approximately the Harrison and Menke(8) parallel plate equation would be approximately: $0.82\ (r_o/r_i)^{0.53}$.

Bailey's(1) equations may be represented in the same form by the approximate equation:

14. $Nu_{Ann} = 0.75\ Nu_{Tube}\ (r_o/r_i)^{0.30}$

Use of this equation at high values of R leads to substantially lower values than those using Werner's correction, although they both fit present experimental data which are for relatively low R. For the sake of conservatism, and because of the theoretical basis of Equation 14, it is recommended for annuli until data have been obtained at higher R.