ChE 306 Group Heat Exchanger Project
Fall 2010
11-03 (WEDNESDAY): Select team of 1 or 2 or 3
11-05 (FRIDAY): Teams will be e-mailed process fluid information by 5:00 pm
11-08 (MONDAY): We will discuss this hand-out in class
11-15 & 11-19 (Mon & Fri): Project Q&A during class
11-22 (MONDAY): Reports due in class (or electronic submission is OK)
(score is 10 % of course grade)

For each TEAM:
(1) Design 4 heat exchangers for the Bama Chemical Company using the Heat Exchanger software distributed in class, with your team's given fluids (software and fluid info will be sent by e-mail), &
(2) Retrofit these 4 heat exchangers to minimize the use of utility fluids for heating and cooling in the plant. {This will entail using the hot and cold process streams to exchange heat with each other, and using minimal utility fluids}.

SOFTWARE: HEAT EXCHANGER is a very simple package for estimating heat transfer and fluid outlet temperatures based on heat exchanger design, fluid properties and flow rates. An older version is available on computers in Houser. I will send copies of the latest version via e-mail. The software is compatible with recent versions of Windows (I am uncertain if it runs on Macs). You'll need to unzip the file, then click set-up to install the software (it's a fairly small file). A sample print-out from the software package is included in this handout.

For heating and cooling purposes, you have unlimited supplies of the following utility fluids:

Sea Water at 200 ^oF
Mobiltherm 600 at 302 ^oF
Freon 12 at - 40 ^oF
Sea Water at 40 ^oF

Use appropriate fouling factors for the seawater or refrigerating liquids (Freon), or assume clean pipes for the oil. (Table 11.1, p. 674)

Constraints:
UTILITY FLUID COSTS (OPERATING COSTS):
Heating Fluids: Mobiltherm 600 heat transfer fluid at 302 ^oF is \$0.52/2000-lb and hot water at 200 ^oF is \$0.30/2000-lb.
Cooling Fluids: Seawater at 40 ^oF costs \$0.23/2000-lb and Freon-12 at -40 ^oF costs \$0.65/2000-lb.

EQUIPMENT COSTS (CAPITAL COSTS)
Shell & Tube Heat Exchangers: \$6500 per 100 square feet of effective surface area
Concentric Tube (Double Pipe) Heat Exchangers: \$2200 per 100 square feet effective surface area

PRESSURE DROP & TYPES OF HEAT EXCHANGERS: All fluids are at 100 psi entering.
Max. allowable pressure drop across any shell and tube heat exchanger (shell or tube side) is 25 psi.
At least one heat exchanger must be concentric tube (max. allowable pressure drop = 75 psi).

Fluid properties:
Fluid properties are for every fluid that may be assigned as part of this assignment are included in this handout (at the back). Please note that some properties are in SI units and others are English. You can also use any data table of physical properties (e.g. Appendices A5-A6 in the 306 textbook).

Part (1): **Design**
The objective is to maximize heat transfer while trying to minimize the total cost to Bama Chemical. Here, you may play with any of the variables in constructing the 4 heat exchangers that will (hopefully) minimize the operating costs (use of utility fluids). One of the exchangers must be a concentric tube heat exchanger.

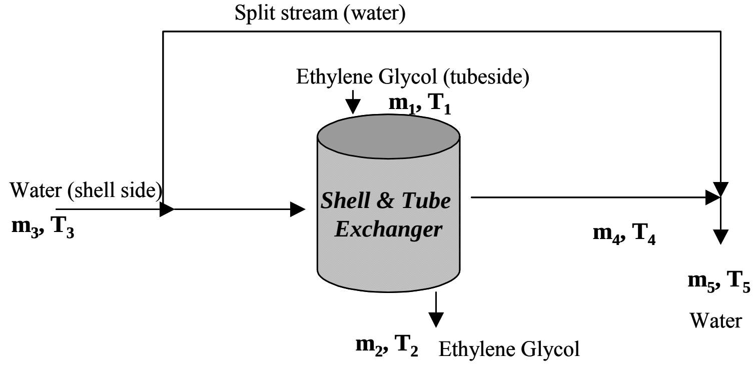
Include a print-out of the software results for the 4 heat exchangers (or submit the electronic file), and find the total usage rate for each utility fluid, and total cost for capital and utility costs for 10 years. Report your cost as 10-year cost, which will be the total of the heat exchanger purchase price plus the cost of utility fluids for running the exchanger 24 hours a day for 10 years.

Part (2): Retrofit, use the **<u>same 4 heat exchangers</u>** that you designed in part (1), but use the process fluids themselves as the heating and cooling sources. You can split streams as needed to get the mass flow rates needed in the heat exchangers, and calculate a new temperature for the streams after they are re-mixed (see HW 7, problem 8 for an example). (using $m_1\, c_{p1}\, (T_3\text{-}T_1) = m_2\, c_{p2}\, (T_2\text{-}T_3)$ to get $m_3 = m_1 + m_2$ exiting at temperature T_3). You may be able to reduce the total number of exchangers to as little as 2, but you will probably still need the other heat exchangers, as well as SOME heating and cooling using the sea water/oil/Freon to reach the desired outlet temperatures.

<u>If necessary, you can design one additional heat exchanger</u> to get all 4 fluids to their final desired temperatures. You may still use the utility hot and cold fluids for heating and cooling, but the objective is to *minimize* costs due to external heating and cooling sources.

Sketch the flow pattern (process flow diagram- you can use Powerpoint for a basic diagram) used in the retrofit process. What is the reduction in use of each utility fluid? Compare the 10-year costs of utility fluids for the original design vs. the retrofit. How much money could be saved? Was there any difference in selecting fluids for shell or tube side?

A process flow diagram such as the one below can be done in powerpoint (or MS word), or you can neatly sketch the PFD by hand.



PUTTING TOGETHER YOUR REPORT

The report should have the following sections. Please staple your report when turning it in.

I. Cover page with an executive summary. (1 paragraph summary of the report, including your findings on design vs. retrofit cost, include team members on cover)

II. General Heat Exchanger Design (~ 1 page)

Discuss the effect of design parameters on heat transfer- how would you optimize heat transfer for a given situation?

Discuss how the following variables impact heat transfer: (Do any problems arise that constrict the range of numbers you can choose)

- shell & tube vs. concentric tube?
- baffle spacing/pitch?
- material of construction?
- which fluids are tube-side and shell-side?
- the flow rates of utility fluids?
- tube pitch?
- tube diameter?
- # of tubes?
- shell inner diameter (the software calculates this as how much bigger is the shell than the tube bundle, so a shell diameter of 0 inches may be possible)?

Discuss which utility fluids to would be best to use? What if you could use saturated steam instead of hot engine oil or water as the heating fluid, would you expect to require higher or lower mass flow rates of utility fluid?

III. Project Goals/Heat Load Calculations (~ 1 paragraph)

Summarize the requirements your team has for heating/cooling 4 fluids. Include a table listing fluid, flow rate, inlet & outlet temperature and rate of change of internal energy (English units)

IV. Design of your 4 Heat Exchangers (~1-2 pages, plus 4-8 pgs for diagrams/software printouts)

Discuss your team's decisions on how to design the 4 heat exchangers for the 4 fluids.
How did you decide which fluid should be in the concentric tube exchanger?
What parameters did you try to optimize in the "Results" section from the software?
Include a diagram showing each heat exchanger and listing the flowrates of the two fluids entering each exchanger and the inlet/outlet temperatures. Indicate which fluid is shell-side (annulus) or tube-side. Include software printouts from the 4 exchangers you designed.

V. Retrofit Layout (~1 page, plus 5-6 pages for diagrams/software printouts).

Discuss how you matched process streams from the design portion to reduce your use of utility fluids. Did you have to design a new heat exchanger? If so, why?
Include a process flow diagram to show the flow of all process and utility fluids, which heat exchanger is which (i.e., Design#1), flow rates, temperatures, and shell/tube side fluids.

VI. Cost Comparison (<1 page)

Calculate the capital costs of the equipment bought for the 4 designed heat exchangers. Tabulate the operating costs (utility fluids) for all 4 heat exchangers in the design portion over a 10 year period. Calculate the total 10-year operating costs for the utility fluids in the retrofit portion. What are the 10-year savings that can be realized by the retrofit layout?

GRADING SHEET FOR 306 GROUP PROJECTS

1. DESIGN PORTION

A. Diagram of Exchangers (10 pts)

☐ Include a schematic of the process- doesn't have to be a formal process flow diagram, but draw out each exchanger to show which fluids are used as utility fluids, and which fluids are shell-side and tube-side (or inner and annular flow for the concentric tube exchanger). Show mass flow rates and temperatures at the inlet and outlets.

☐ B. Heat Load Calculations (5 pts)

Determine the requirements for heating/cooling for each stream and present in a table. (ΔU)

C. Answers to Questions & Discussion of Your Design (25 pts)

☐ Discuss each of the questions on page 2 (qualitative answers are fine). Discuss the designs chosen for your 4 heat exchangers.

☐ D. Exchanger Specification (10 pts)

Include print-outs of the software calculations for each exchanger.

2. RETROFIT PORTION

☐ A. Redesign of Process Layout (15 pts)

How are the streams redistributed to minimize the use of heating and cooling utility fluids? Draw the new schematic/flow diagram, indicating inlet and outlet temperatures, tube-side/shell-side fluids, and flowrates.

B. Discussion (10 pts)

☐ Discuss your methodology in redesigning flow pattern in the heat exchangers. Answer the questions on page 2 of this handout.

☐ C. Exchanger Specification (5 pts)

Include print-outs of the software calculations for each exchanger.

3. COST ANALYSIS (20 pts)

☐ Determine the cost of purchasing the 4 heat exchangers (capital cost) and the cost of using utility fluids (operating cost) for 10 years. Tabulate the utility fluids with their required flow rates and operating cost for both the design & retrofit. Compare your total operating costs and determine the money saved over 10 years using the retrofit layout.

4. CLARITY OF REPORT (5 pts)

☐ Make it easy to read & clear (typewritten- you can hand-draw the flow diagrams, if done neatly).

Answers to some questions RE: Heat Exchanger Project:

Q1. How should the SEA WATER be treated as a utility fluid?

Assume that most of the salt has been filtered out by the time it reaches the heat exchanger, so that the properties of regular water will be adequate. (A really good thing about using water is that the properties are built in to the software, so you can just choose water from the drop-down menu.) The only important aspect of SEA WATER is that you should use a fouling factor appropriate for sea water.

Q2. The software prints out with a bad format sometimes.

This shouldn't be a problem with the software I e-mailed out, but the software on the campus computers is an older version. As long as most of the sheet is readable, I have no problem with turning in the print-outs that may be a little off. If you have serious problems printing, then you can submit the software heat exchanger designs electronically, by SAVING the designs you choose, and attaching them to an e-mail to me when you turn in the rest of the report. (It's also OK to submit the entire report electronically). A sample report (1 page) is shown following these FAQs.

Q3. What temperature should utility fluid streams be looked up at? Tmean?

While you are adjusting parameters to determine a design for the heat exchangers, choose a temperature somewhat above or below the inlet temperature (accounting for the fluid heating or cooling inside the exchanger), and stick with that (the properties of most fluids won't change too much over the temperature ranges in the project). When you get to a final design, you'll have a better idea of what T mean is for the utility fluids and can re-calculate the fluid properties. Of course, if you use water, and select it in the drop-down menu, the software will calculate properties for you.

Q4. What pressure should be used for the inlet streams for the process & utility fluids?

Use 100 psia. This is high enough to see if there will be a > 25 psi or > 75 psi pressure drop inside the exchanger. Since all of the fluids are LIQUIDS, the pressure will have essentially no impact on fluid properties. If you are getting a large pressure drop, recall what you've learned in ChE 304. Try pipes with larger diameters, more tubes, shorter lengths, wider baffle or tube pitches, etc. Of course you are always trying to balance a reasonable pressure drop with a high Reynolds number, so there is some tension between ChE 306 (high velocities, high Re, high h) and ChE 304 (high velocities, big pressure drop).

Q5. What should be used for tube gauge?

This is part of "playing" with the software. Tube gauge refers to the thickness metal wall of the tubes, and is one of the important resistance variables in the equation for UA. Does this choice affect heat transfer much? That's for the write-up.

Q6. What about the selection of number of tubes, length of tubes, etc.?

This is also part of "playing" with the software, but these variables affect fluid flow (think Reynold's number), as well as pressure drop, as well as what the total surface area for heat transfer are. So- while there's not a "correct" answer, you can work with the program to determine what might be a better design than others.

Q7. What value should be optimum for effectiveness?

Not 1! If a heat exchanger is 100% effective, then it is delivering q_{max}. While this may sound good, this means that a heat exchanger is over-designed, and has far too much area (and likely requires a large number of NTUs). This will come into play when you determine the cost of the exchangers (which is based on the total surface area).

Q8. What should the value of U be?

Obviously, the higher the better. Think about what you've learned in class that can affect the variables that make up UA. How do you increase k, h_i, h_o, etc.? There is no set number, but typical ranges of U are listed in our book (water-to-water, 850-1700 W/m^2-K)

Q9. Some fluids don't work as a tube-side fluid (likely glycerin or ethylene glycol). What should we do?

While in reality, these can go on the tube-side, the software package that we are using is fairly simple, and relies on some of the correlations that we've seen in our book to determine h values. This means that for some fluids, the correlations have a minimum or maximum viscosity or other fluid property that may give problems for some fluids. In these cases, use the process fluid (glycerin, etc.) as the shell-side fluid.

Q10. The shell diameter seems to have little impact on the answers or shell-side pressure drop.

This is one variable that I am not sure how it is incorporated into the software. It seems to me that the software's shell diameter must refer to how much bigger the shell is than the tube bundle. (The software works fine for the double pipe exchangers). So you can choose a shell diameter of 1 inch, and still get a good result.

Q11. I'm uncertain what you mean about the retrofit part of the project.

This will be worked similar to problem 8 on Homework set #7, in that the fluids may be split to bypass the heat exchanger, then re-combined. The objective is to get rid of as much of the utility fluids as possible. I'll discuss & answer more questions in class.

Q12. Freon-12 didn't work as a concentric tube fluid.

Similar to #9, some fluids fall out of the range of the correlations that are programmed into the software. Try it in a different exchanger, or in the annulus of the concentric tube exchanger, if it gives errors.

Q13. What is 25% Cut Shellside Pressure Loss?

The 25% cut refers to how the baffles are cut. A 100 % cut would mean that there were no baffles (think of a disc-shaped sheet- a 50% cut would be a perfect semicircle). So 25% cut means that the top 25 % of the baffle is open for fluid flow. This number is not a variable in the software package, but 25% is a common value. The smaller the cut, the less room there is for the shell-side fluid to pass through.

Q14. An error "Prandtl Number not in range" keeps popping up.

Check your fluid properties. Glycerin might be the only fluid where this might be a problem. Please note the units on the handout (the English units)- they are not all the same as what must be entered into the software.

Q15. For which fluids do we need to use a fouling factor?
You can assume all of the process fluids are "clean" and F = 0. The only fluids where you need to use a fouling factor for this project is the hot or cold sea water (utility fluid).

Q16. The software asks for new fluid properties to be entered at a new temperature for some of the fluids when calculating results.
This happens because the software is estimating what the outlet temperature of the fluid will be and is giving you a chance to enter a more accurate value for viscosity, etc. Since all of your process fluids have a known mean temperature in the design (you are given T in & T out)... you don't need to change the properties- just find them at Tmean for each of your fluids. If you are using water, the software has those properties built-in, so it will update the properties as needed. For the other utility fluids (oil and freon) or when you are doing a retrofit, it may make a small difference if you enter new numbers based on a new mean temperature, but it will likely be small (most groups have fluids where dT is less than 100 ^{o}F in most cases).

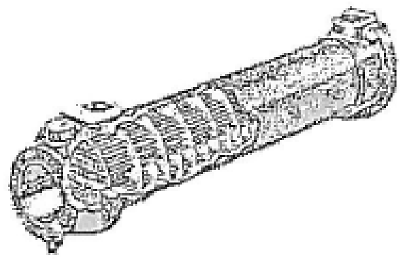
SAMPLE PRINT-OUT FROM HEAT EXCHANGER SOFTWARE

Top portion: INPUT DATA

Bottom portion: RESULTS

Thermal Analysis Systems Company

Shell &Tube Heat Exchanger



Shell & Multi Tube Heat Exchanger

Project: Retro-1

System: EG-W

Date/Time: April 17, 2001/02:36

Input

Tubeside Fluid Properties		Shellside Fluid Properties	
Fluid:	Ethylene Glycol	Fluid:	Water
Specific Heat, Btu/lb-F:	0.5850	Specific Heat, Btu/lb-F:	1.0160
Density, lb/cuft:	69.070	Density, lb/cuft:	60.878
Viscosity, lbm/hr-ft	24.9040	Viscosity, lbm/hr-ft	0.9081
Conductivity, Btu/hr-ft-F:	0.1460	Conductivity, Btu/hr-ft-F:	0.3854
Flow, lb/hr:	5,952.42	Flow, lb/hr:	4,250.0
Inlet Temp, F:	95.0	Inlet Temp, F:	167.0
Pressure, psia:	14.7	Pressure, psia:	N/A

Construction

Tube Outer Diameter, in:	0.2	Shell Inner Diameter, in:	18.0
Tube Passes per Shell:	2	Shellside Passes, each Shell:	1
Tube Count, each Tube Pass:	300	Baffle Pitch, in:	0.5
Tube Length per Pass, in:	120.0	Tube Pitch, in:	0.5
Number of Shells:	1	Tube Pitch:	Triangular

Flow Arrangement: One Shell, Even Number of Passes

Material: 70-30 CU-Ni Gauge (Thickness, in): 18 (0.049)

Fouling Factors, hr-sf-R/Btu Tubeside: 0.0009 Shellside: 0.0001

Results

Coefficients

Tubeside Velocity, fps:	1.4062	Shellside Velocity, fps:	0.5171
Tubeside Reynolds Number:	119.34	Shellside Reynolds Number:	12154.65
Tubeside Prandtl Number:	99.7866	Shellside Prandtl Number:	2.3938
Tubeside Nusselt Number:	4.2296	Shellside Nusselt Number:	84.9473
Tubeside Film Coeff, Btu/hr/sf/F:	72.649	Shellside Film Coeff, Btu/hr/sf/F:	336.19

Final Temperatures & Heat Transferred

Exit Tubeside Temperature, F:	140.8	Clean Overall U, Btu/hr/sf/F:	35.6823
Exit Shellside Temperature, F:	130	Design Overall U, Btu/hr/sf/F:	34.3393
Heat Transferred, mmBtu/hr:	0.1597	No. of Transfer Units, (ua/wcmin):	3.0981
Tubeside Pressure Loss, psi:	1.7895	Cap Ratio, (wcmin/wcmax):	0.80695
25% Cut Shellside Press Loss, psi:	1.9311	Effectiveness:	0.6368
		Effective Surface, sqft:	314.16

FLUID PROPERTIES

Heat Transfer Fluids

TABLE 23 Mobiltherm 600

Temperature, T			Density, ρ (kg/m^3)	Coefficient of Thermal Expansion, $\beta \times 10^3$ (1/K)	Specific Heat, c_p (J/kg K)	Thermal Conductivity, k (W/m K)	Thermal Diffusivity, $\alpha \times 10^{10}$ (m^2/s)	Absolute Viscosity, $\mu \times 10^3$ (N s/m^2)	Kinematic Viscosity, $\nu \times 10^6$ (m^2/s)	Prandtl Number, Pr	$\frac{g\beta}{\nu^2} \times 10^{-6}$ (1/K m^3)
°F	K	°C	$\times 6.243 \times 10^{-2}$ = (lb$_m$/ft^3)	$\times 0.5556$ = (1/R)	$\times 2.388 \times 10^{-4}$ = (Btu/lb$_m$ °F)	$\times 0.5777$ = (Btu/h ft °F)	$\times 3.874 \times 10^4$ = (ft^2/h)	$\times 0.6720$ = (lb$_m$/ft s)	$\times 3.874 \times 10^4$ = (ft^2/h)		$\times 1.573 \times 1($ = (1/R ft^3)
50	283	10	953	0.621	1549	0.123	833				
122	323	50	929	0.637	1680	0.120	769	30.28	32.60	424	5.9
212	373	100	899	0.658	1859	0.116	694	5.48	6.10	87.9	173
302	423	150	870	0.680	2031	0.113	640	2.04	2.34	36.6	1218
392	473	200	839	0.705	2209	0.110	594	1.05	1.25	21.0	4425
482	523	250	810	0.730	2386	0.106	545	0.64	0.790	14.5	11,470

Source: P. L. Geiringer, *Handbook of Heat Transfer Media*, Krieger, New York, 1977.

TABLE 17 Unused engine oil

Temperature, T			Density, ρ (kg/m^3)	Coefficient of Thermal Expansion, $\beta \times 10^3$ (1/K)	Specific Heat, c_p (J/kg K)	Thermal Conductivity, k (W/m K)	Thermal Diffusivity, $\alpha \times 10^{10}$ (m^2/s)	Absolute Viscosity, $\mu \times 10^3$ (N s/m^2)	Kinematic Viscosity, $\nu \times 10^6$ (m^2/s)	Prandtl Number, Pr	$\frac{g\beta}{\nu^2}$ (1/K m^3)
°F	K	°C	$\times 6.243 \times 10^{-2}$ = (lb$_m$/ft^3)	$\times 0.5556$ = (1/R)	$\times 2.388 \times 10^{-4}$ = (Btu/lb$_m$ °F)	$\times 0.5777$ = (Btu/h ft °F)	$\times 3.874 \times 10^4$ = (ft^2/h)	$\times 0.6720$ = (lb$_m$/ft s)	$\times 3.874 \times 10^4$ = (ft^2/h)		$\times 1.573 \times 10^{-2}$ = (1/R ft^3)
32	273	0	899.1		1796	0.147	911	3848	4280	471	
68	293	20	888.2	0.648	1880	0.145	872	799	900	104	7.85×10^3
104	313	40	876.1	0.691	1964	0.144	834	210	240	28.7	1.18×10^5
140	333	60	864.0	0.697	2047	0.140	800	72.5	83.9	10.5	9.72×10^5
176	353	80	852.0	0.704	2131	0.138	769	32.0	37.5	4.90	4.91×10^6
212	373	100	840.0	0.684	2219	0.137	738	17.1	20.3	2.76	1.63×10^7
248	393	120	829.0	0.697	2307	0.135	710	10.3	12.4	1.75	4.44×10^7
284	413	140	816.9	0.706	2395	0.133	686	6.54	8.0	1.16	1.08×10^8
320	433	160	805.9		2483	0.132	663	4.51	5.6	0.84	—

Source: E. R. G. Eckert and R. M. Drake, *Analysis of Heat and Mass Transfer*, McGraw-Hill, New York, 1972.

TABLE A.5 Thermophysical Properties of Saturated Fluids[a]

Saturated Liquids

T (K)	ρ (kg/m³)	c_p (kJ/kg · K)	$\mu \cdot 10^2$ (N · s/m²)	$\nu \cdot 10^6$ (m²/s)	$k \cdot 10^3$ (W/m · K)	$\alpha \cdot 10^7$ (m²/s)	Pr	$\beta \cdot 10^3$ (K⁻¹)
Engine Oil (Unused)								
273	899.1	1.796	385	4280	147	0.910	47,000	0.70
280	895.3	1.827	217	2430	144	0.880	27,500	0.70
290	890.0	1.868	99.9	1120	145	0.872	12,900	0.70
300	884.1	1.909	48.6	550	145	0.859	6400	0.70
310	877.9	1.951	25.3	288	145	0.847	3400	0.70
320	871.8	1.993	14.1	161	143	0.823	1965	0.70
330	865.8	2.035	8.36	96.6	141	0.800	1205	0.70
340	859.9	2.076	5.31	61.7	139	0.779	793	0.70
350	853.9	2.118	3.56	41.7	138	0.763	546	0.70
360	847.8	2.161	2.52	29.7	138	0.753	395	0.70
370	841.8	2.206	1.86	22.0	137	0.738	300	0.70
380	836.0	2.250	1.41	16.9	136	0.723	233	0.70
390	830.6	2.294	1.10	13.3	135	0.709	187	0.70
400	825.1	2.337	0.874	10.6	134	0.695	152	0.70
410	818.9	2.381	0.698	8.52	133	0.682	125	0.70
420	812.1	2.427	0.564	6.94	133	0.675	103	0.70
430	806.5	2.471	0.470	5.83	132	0.662	88	0.70
Ethylene Glycol [$C_2H_4(OH)_2$]								
273	1130.8	2.294	6.51	57.6	242	0.933	617	0.65
280	1125.8	2.323	4.20	37.3	244	0.933	400	0.65
290	1118.8	2.368	2.47	22.1	248	0.936	236	0.65
300	1114.4	2.415	1.57	14.1	252	0.939	151	0.65
310	1103.7	2.460	1.07	9.65	255	0.939	103	0.65
320	1096.2	2.505	0.757	6.91	258	0.940	73.5	0.65
330	1089.5	2.549	0.561	5.15	260	0.936	55.0	0.65
340	1083.8	2.592	0.431	3.98	261	0.929	42.8	0.65
350	1079.0	2.637	0.342	3.17	261	0.917	34.6	0.65
360	1074.0	2.682	0.278	2.59	261	0.906	28.6	0.65
370	1066.7	2.728	0.228	2.14	262	0.900	23.7	0.65
373	1058.5	2.742	0.215	2.03	263	0.906	22.4	0.65
Glycerin [$C_3H_5(OH)_3$]								
273	1276.0	2.261	1060	8310	282	0.977	85,000	0.47
280	1271.9	2.298	534	4200	284	0.972	43,200	0.47
290	1265.8	2.367	185	1460	286	0.955	15,300	0.48
300	1259.9	2.427	79.9	634	286	0.935	6780	0.48
310	1253.9	2.490	35.2	281	286	0.916	3060	0.49
320	1247.2	2.564	21.0	168	287	0.897	1870	0.50

Liquids

T (°F)	ρ (lb_m/ft^3)	c_p (Btu/lb_m °F)	$\mu \times 10^3$ (lb_m/ft sec)	$\nu \times 10^5$ (ft^2/sec)	k (Btu/hr ft °F)	$\alpha \times 10^3$ (ft^2/hr)	Pr	$\beta \times 10^4$ (1/°F)	$g\beta\rho^2/\mu^2 \times 10^{-6}$ (1/°F · ft^3)
Water									
32	62.4	1.01	1.20	1.93	0.319	5.06	13.7	−0.350	
60	62.3	1.00	0.760	1.22	0.340	5.45	8.07	0.800	17.2
80	62.2	0.999	0.578	0.929	0.353	5.67	5.89	1.30	48.3
100	62.1	0.999	0.458	0.736	0.364	5.87	4.51	1.80	107
150	61.3	1.00	0.290	0.474	0.383	6.26	2.72	2.80	403
200	60.1	1.01	0.206	0.342	0.392	6.46	1.91	3.70	1010
250	58.9	1.02	0.160	0.272	0.395	6.60	1.49	4.70	2045
300	57.3	1.03	0.130	0.227	0.395	6.70	1.22	5.60	3510
400	53.6	1.08	0.0930	0.174	0.382	6.58	0.950	7.80	8350
500	49.0	1.19	0.0700	0.143	0.349	5.98	0.859	11.0	17 350
600	42.4	1.51	0.0579	0.137	0.293	4.58	1.07	17.5	30 300

T (K)	ρ (kg/m^3)	c_p (J/kg · K)	$\mu \times 10^6$ (Pa · s)	$\nu \times 10^6$ (m^2/s)	k (W/m · K)	$\alpha \times 10^6$ (m^2/s)	Pr	$g\beta\rho^2/\mu^2 \times 10^{-9}$ (1/K · m^3)
Water								
273	999.3	4226	1794	1.795	0.558	0.132	13.6	
293	998.2	4182	993	0.995	0.597	0.143	6.96	2.035
313	992.2	4175	658	0.663	0.633	0.153	4.33	8.833
333	983.2	4181	472	0.480	0.658	0.160	3.00	22.75
353	971.8	4194	352	0.362	0.673	0.165	2.57	46.68
373	958.4	4211	278	0.290	0.682	0.169	1.72	85.09
473	862.8	4501	139	0.161	0.665	0.171	0.94	517.2
573	712.5	5694	92.2	0.129	0.564	0.139	0.93	1766.0

T (°F)	ρ (lb_m/ft^3)	c_p (Btu/lb_m °F)	$\mu \times 10^3$ (lb_m/ft sec)	$\nu \times 10^5$ (ft^2/sec)	k (Btu/hr ft °F)	$\alpha \times 10^3$ (ft^2/hr)	Pr	$\beta \times 10^3$ (1/°F)	$g\beta\rho^2/\mu^2 \times 10^{-6}$ (1/°F · ft^3)
Aniline									
60	64.0	0.480	305	4.77	0.101	3.29	52.3		
80	63.5	0.485	240	3.78	0.100	3.25	41.8		
100	63.0	0.490	180	2.86	0.100	3.24	31.8	0.45	17.7
150	61.6	0.503	100	1.62	0.0980	3.16	18.4		
200	60.2	0.515	62	1.03	0.0962	3.10	12.0		
250	58.9	0.527	42	0.714	0.0947	3.05	8.44		
300	57.5	0.540	30	0.522	0.0931	2.99	6.28		

T (°F)	ρ (lb_m/ft^3)	c_p (Btu/lb_m °F)	$\mu \times 10^5$ (lb_m/ft sec)	$\nu \times 10^5$ (ft^2/sec)	k (Btu/hr ft °F)	$\alpha \times 10^3$ (ft^2/hr)	Pr	$\beta \times 10^3$ (1/°F)	$g\beta\rho^2/\mu^2 \times 10^{-7}$ (1/°F · ft^3)
					Ammonia				
−60	43.9	1.07	20.6	0.471	0.316	6.74	2.52	0.94	132
−30	42.7	1.07	18.2	0.426	0.317	6.93	2.22	1.02	265
0	41.3	1.08	16.9	0.409	0.315	7.06	2.08	1.1	467
30	40.0	1.11	16.2	0.402	0.312	7.05	2.05	1.19	757
60	38.5	1.14	15.0	0.391	0.304	6.92	2.03	1.3	1130
80	37.5	1.16	14.2	0.379	0.296	6.79	2.01	1.4	1650
100	36.4	1.19	13.5	0.368	0.287	6.62	2.00	1.5	2200
120	35.3	1.22	12.6	0.356	0.275	6.43	2.00	1.68	3180

T (°F)	ρ (lb_m/ft^3)	c_p (Btu/lb_m °F)	$\mu \times 10^5$ (lb_m/ft sec)	$\nu \times 10^5$ (ft^2/sec)	k (Btu/hr ft °F)	$\alpha \times 10^3$ (ft^2/hr)	Pr	$\beta \times 10^4$ (1/°F)	$g\beta\rho^2/\mu^2 \times 10^{-6}$ (1/°F · ft^3)
					Freon-12				
−40	94.5	0.202	125	1.32	0.0650	3.40	14.0	9.10	168
−30	93.5	0.204	123	1.32	0.0640	3.35	14.1	9.60	179
0	90.9	0.212	116	1.28	0.0578	3.00	15.4	11.4	225
30	87.4	0.221	108	1.24	0.0564	2.92	15.3	13.1	277
60	84.0	0.230	99.6	1.19	0.0528	2.74	15.6	14.9	341
80	81.3	0.238	94.0	1.16	0.0504	2.60	16.0	16.0	384
100	78.7	0.246	88.4	1.12	0.0480	2.48	16.3	17.2	439
150	71.0	0.271	74.8	1.05	0.0420	2.18	17.4	19.5	625

T (°F)	ρ (lb_m/ft^3)	c_p (Btu/lb_m °F)	$\mu \times 10^5$ (lb_m/ft sec)	$\nu \times 10^5$ (ft^2/sec)	k (Btu/hr ft °F)	$\alpha \times 10^3$ (ft^2/hr)	Pr	$\beta \times 10^3$ (1/°F)	$g\beta\rho^2/\mu^2 \times 10^{-6}$ (1/°F · ft^3)
					n-Butyl Alcohol				
60	50.5	0.55	335	4.46	0.100	3.59	44.6		
80	50.0	0.58	180	3.60	0.099	3.41	38.0	0.25	6.23
100	49.6	0.61	130	2.62	0.098	3.25	29.1	0.43	2.02
150	48.5	0.68	68	1.41	0.098	2.97	17.1		

T (°F)	ρ (lb_m/ft^3)	c_p (Btu/lb_m °F)	$\mu \times 10^5$ (lb_m/ft sec)	$\nu \times 10^5$ (ft^2/sec)	k (Btu/hr ft °F)	$\alpha \times 10^3$ (ft^2/hr)	Pr $\times 10^{-2}$	$\beta \times 10^4$ (1/°F)	$g\beta\rho^2/\mu^2 \times 10^{-6}$ (1/°F · ft^3)
					Benzene				
60	55.2	0.395	44.5	0.806	0.0856	3.93	7.39		
80	54.6	0.410	38	0.695	0.0836	3.73	6.70	7.5	498
100	53.6	0.420	33	0.615	0.0814	3.61	6.13	7.2	609
150	51.8	0.450	24.5	0.473	0.0762	3.27	5.21	6.8	980
200	49.9	0.480	19.4	0.390	0.0711	2.97	4.73		

T (°F)	ρ (lb_m/ft^3)	c_p (Btu/lb_m °F)	$\mu \times 10^5$ (lb_m/ft sec)	$\nu \times 10^5$ (ft^2/sec)	k (Btu/hr ft °F)	$\alpha \times 10^3$ (ft^2/hr)	Pr	$\beta \times 10^3$ (1/°F)	$g\beta\rho^2/\mu^2 \times 10^{-4}$ (1/°F · ft^3)
				Hydraulic fluid (MIL-M-5606)					
0	55.0	0.400	5550	101	0.0780	3.54	1030	0.76	2.39
30	54.0	0.420	2220	41.1	0.0755	3.32	446	0.68	13.0
60	53.0	0.439	1110	20.9	0.0732	3.14	239	0.60	44.1
80	52.5	0.453	695	13.3	0.0710	3.07	155	0.52	95.7
100	52.0	0.467	556	10.7	0.0690	2.84	136	0.47	132
150	51.0	0.499	278	5.45	0.0645	2.44	80.5	0.32	346
200	50.0	0.530	250	5.00	0.0600	2.27	79.4	0.20	258

T (°F)	ρ (lb_m/ft^3)	c_p (Btu/lb_m °F)	μ (lb_m/ft sec)	$\nu \times 10^2$ (ft^2/sec)	k (Btu/hr ft °F)	$\alpha \times 10^3$ (ft^2/hr)	Pr $\times 10^{-2}$	$\beta \times 10^3$ (1/°F)	$g\beta\rho^2/\mu^2$ (1/°F · ft^3)
				Glycerin					
30	79.7	0.540	7.2	9.03	0.168	3.91	832		
60	79.1	0.563	1.4	1.77	0.167	3.75	170		
80	78.7	0.580	0.6	0.762	0.166	3.64	75.3		
100	78.2	0.598	0.1	0.128	0.165	3.53	13.1	0.30	166

T (°F)	ρ (lb_m/ft^3)	c_p (Btu/lb_m °F)	$\mu \times 10^5$ (lb_m/ft sec)	$\nu \times 10^5$ (ft^2/sec)	k (Btu/hr ft °F)	$\alpha \times 10^3$ (ft^2/hr)	Pr	$\beta \times 10^3$ (1/°F)	$g\beta\rho^2/\mu^2 \times 10^{-4}$ (1/°F · ft^3)
				Kerosene					
30	48.8	0.456	800	16.4	0.0809	3.63	163		
60	48.1	0.474	600	12.5	0.0805	3.53	127	0.58	120
80	47.6	0.491	490	10.3	0.0800	3.42	108	0.48	146
100	47.2	0.505	420	8.90	0.0797	3.35	95.7	0.47	192
150	46.1	0.540	320	6.83	0.0788	3.16	77.9		

T (°F)	ρ (lb_m/ft^3)	c_p (Btu/lb_m °F)	$\mu \times 10^5$ (lb_m/ft sec)	$\nu \times 10^5$ (ft^2/sec)	k (Btu/hr ft °F)	$\alpha \times 10^3$ (ft^2/hr)	Pr	$\beta \times 10^3$ (1/°F)	$g\beta\rho^2/\mu^2 \times 10^{-9}$ (1/°F · ft^3)
				Liquid hydrogen					
−435	4.84	1.69	1.63	0.337	0.0595	7.28	1.67		
−433	4.77	1.78	1.52	0.319	0.0610	7.20	1.59		
−431	4.71	1.87	1.40	0.297	0.0625	7.09	1.51	7.1	2.59
−429	4.64	1.96	1.28	0.276	0.0640	7.03	1.41		
−427	4.58	2.05	1.17	0.256	0.0655	6.97	1.32		
−425	4.51	2.15	1.05	0.233	0.0670	6.90	1.21		

TABLE A-11

Properties of saturated ammonia

Temp., T, °C	Saturation Pressure, P, kPa	Density, ρ, kg/m³ Liquid	Density, ρ, kg/m³ Vapor	Enthalpy of Vaporization, h_{fg}, kJ/kg	Specific Heat, C_p, J/kg · °C Liquid	Specific Heat, C_p, J/kg · °C Vapor	Thermal Conductivity, k, W/m · °C Liquid	Thermal Conductivity, k, W/m · °C Vapor	Dynamic Viscosity, μ, kg/m · s Liquid	Dynamic Viscosity, μ, kg/m · s Vapor	Prandtl Number, Pr Liquid	Prandtl Number, Pr Vapor	Volume Expansion Coefficient, β, 1/K, Liquid	Surface Tension, N/m
−40	71.66	690.2	0.6435	1389	4414	2242	—	0.01792	2.926×10^{-4}	7.957×10^{-6}	—	0.9955	0.00176	0.03565
−30	119.4	677.8	1.037	1360	4465	2322	—	0.01898	2.630×10^{-4}	8.311×10^{-6}	—	1.017	0.00185	0.03341
−25	151.6	671.5	1.296	1345	4489	2369	0.5968	0.01957	2.492×10^{-4}	8.490×10^{-6}	1.875	1.028	0.00190	0.03229
−20	190.1	665.1	1.603	1329	4514	2420	0.5853	0.02015	2.361×10^{-4}	8.669×10^{-6}	1.821	1.041	0.00194	0.03118
−15	236.2	658.6	1.966	1313	4538	2476	0.5737	0.02075	2.235×10^{-4}	8.851×10^{-6}	1.769	1.056	0.00199	0.03007
−10	290.8	652.1	2.391	1297	4564	2536	0.5621	0.02138	2.117×10^{-4}	9.034×10^{-6}	1.718	1.072	0.00205	0.02896
−5	354.9	645.4	2.886	1280	4589	2601	0.5505	0.02203	2.003×10^{-4}	9.218×10^{-6}	1.670	1.089	0.00210	0.02786
0	429.6	638.6	3.458	1262	4617	2672	0.5390	0.02270	1.896×10^{-4}	9.405×10^{-6}	1.624	1.107	0.00216	0.02676
5	516	631.7	4.116	1244	4645	2749	0.5274	0.02341	1.794×10^{-4}	9.593×10^{-6}	1.580	1.126	0.00223	0.02566
10	615.3	624.6	4.870	1226	4676	2831	0.5158	0.02415	1.697×10^{-4}	9.784×10^{-6}	1.539	1.147	0.00230	0.02457
15	728.8	617.5	5.729	1206	4709	2920	0.5042	0.02492	1.606×10^{-4}	9.978×10^{-6}	1.500	1.169	0.00237	0.02348
20	857.8	610.2	6.705	1186	4745	3016	0.4927	0.02573	1.519×10^{-4}	1.017×10^{-5}	1.463	1.193	0.00245	0.02240
25	1003	602.8	7.809	1166	4784	3120	0.4811	0.02658	1.438×10^{-4}	1.037×10^{-5}	1.430	1.218	0.00254	0.02132
30	1167	595.2	9.055	1144	4828	3232	0.4695	0.02748	1.361×10^{-4}	1.057×10^{-5}	1.399	1.244	0.00264	0.02024
35	1351	587.4	10.46	1122	4877	3354	0.4579	0.02843	1.288×10^{-4}	1.078×10^{-5}	1.372	1.272	0.00275	0.01917
40	1555	579.4	12.03	1099	4932	3486	0.4464	0.02943	1.219×10^{-4}	1.099×10^{-5}	1.347	1.303	0.00287	0.01810
45	1782	571.3	13.8	1075	4993	3631	0.4348	0.03049	1.155×10^{-4}	1.121×10^{-5}	1.327	1.335	0.00301	0.01704
50	2033	562.9	15.78	1051	5063	3790	0.4232	0.03162	1.094×10^{-4}	1.143×10^{-5}	1.310	1.371	0.00316	0.01598
55	2310	554.2	18.00	1025	5143	3967	0.4116	0.03283	1.037×10^{-4}	1.166×10^{-5}	1.297	1.409	0.00334	0.01493
60	2614	545.2	20.48	997.4	5234	4163	0.4001	0.03412	9.846×10^{-5}	1.189×10^{-5}	1.288	1.452	0.00354	0.01389
65	2948	536.0	23.26	968.9	5340	4384	0.3885	0.03550	9.347×10^{-5}	1.213×10^{-5}	1.285	1.499	0.00377	0.01285
70	3312	526.3	26.39	939.0	5463	4634	0.3769	0.03700	8.879×10^{-5}	1.238×10^{-5}	1.287	1.561	0.00404	0.01181
75	3709	516.2	29.90	907.5	5608	4923	0.3653	0.03862	8.440×10^{-5}	1.264×10^{-5}	1.296	1.612	0.00436	0.01079
80	4141	505.7	33.87	874.1	5780	5260	0.3538	0.04038	8.030×10^{-5}	1.292×10^{-5}	1.312	1.683	0.00474	0.00977
85	4609	494.5	38.36	838.6	5988	5659	0.3422	0.04232	7.645×10^{-5}	1.322×10^{-5}	1.338	1.768	0.00521	0.00876
90	5116	482.8	43.48	800.6	6242	6142	0.3306	0.04447	7.284×10^{-5}	1.354×10^{-5}	1.375	1.871	0.00579	0.00776
95	5665	470.2	49.35	759.8	6561	6740	0.3190	0.04687	6.946×10^{-5}	1.389×10^{-5}	1.429	1.999	0.00652	0.00677
100	6257	456.6	56.15	715.5	6972	7503	0.3075	0.04958	6.628×10^{-5}	1.429×10^{-5}	1.503	2.163	0.00749	0.00579

Note: Kinematic viscosity ν and thermal diffusivity α can be calculated from their definitions, $\nu = \mu/\rho$ and $\alpha = k/\rho C_p = \nu/\text{Pr}$. The properties listed here (except the vapor density) can be used at any pressures with negligible error except at temperatures near the critical point value.