COMPUTERIZED HEAT EXCHANGER DESIGN PROCEDURE

MAGDI ASSAAD

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ABSTRACT

COMPUTERIZED HEAT EXCHANGER DESIGN PROCEDURE

By: Magdi Assaad, Eng.

The heat exchanger is the most widely used device in HVAC applications. Although it is only a part of the overall system, a heat exchanger is required in every heating and cooling design problem that the designer solves.

In many cases the flow paths in the heat exchanger are quite complex and in some cases the temperature and heat transfer equations are so complicated that charts and graphs were developed to replace the equations. In order to simplify the design procedure, minimize human error in calculation and save valuable engineering time; the author has developed a program which computerizes the design technique for a simple liquid-to-liquid, counterflow double-pipe heat exchanger. The program is restricted in use for the four standard hairpin sizes available and eleven oils as working fluids, with considerations given for future incorporation of more liquids or oils when more data would be available.

Having successfully completed this research work, the author believes that with further research, similar programs can be written for the more complex, but widely used heat exchangers, such as the shell and tube type.

ACKNOWLEDGEMENT

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SYMBOLS AND NOTATIONS

A	Heat-transfer surface, ft^2
a	Flow area, ft^2
a_p	flow area of pipe, ft^2
a_a	flow area of annulus, ft^2
a''	External surface per linear foot of pipe, ft.
C_h	Specific heat of hot fluid in derivations, Btu/(lb)(°F)
C_c	Specific heat of cold fluid in derivations or either fluid in calculations Btu/(lb)(°F)
D	Inside diameter, ft.
D_1, D_2	For annuli D_1 is the outside diameter of inner pipe, D_2 is the inside diameter of the outer pipe, ft.
D_e, D'_e	Equivalent diameter for heat-transfer and pressure drop, ft.
D_o	Outside diameter, ft.
F_c	Caloric fraction, dimensionless
f	Friction factor, dimensionless
G_h	Mass velocity of the hot fluid, lb/(hr)(ft^2)
G_c	Mass velocity of the cold fluid, lb/(hr)(ft^2)
g	Acceleration of gravity 32.2 ft/sec^2
h, h_i, h_o	Heat-transfer coefficient in general, for inside fluid, and for outside fluid, respectively, Btu/(hr)(ft^2)(°F)
h_{io}	Value of h_i when referred to the pipe outside diameter, Btu/(hr)(ft^2)(°F)
J_h	Heat-transfer factor of the hot fluid, dimensionless
K_c	Caloric factor, dimensionless
k_h	Thermal conductivity of the hot fluid, Btu/(hr)(ft^2)(°F/ft)

k_c	Thermal conductivity of the cold fluid, Btu/(hr)(ft²)(°F/ft)
L	Pipe length or length of path, ft
LMTD	Logarithmic mean temperature difference, °F
$(dP)_h$	Pressure drop for the hot fluid, psi
$(dP)_c$	Pressure drop for the cold fluid, psi
Q	Heat flow, Btu/hr
$(Re)_h$	Reynold's number of the hot fluid for heat transfer, dimensionless.
$(Re)_c$	Reynold's number of the cold fluid for heat transfer, dimensionless
Rea'	Reynolds number pressure drop, dimensionless
S_h	Specific gravity of the hot fluid, dimensionless
S_c	Specific gravity of the cold fluid, dimensionless
T, T_1, T_2	Hot-fluid temperature in general, inlet and outlet of hot fluid, °F
T_c	Caloric temperature of hot fluid, °F
t, t_1, t_2	Cold-fluid temperature in general, inlet and outlet of cold fluid, °F
t_c	Caloric temperature of cold fluid, °F.
t_w	Tube (pipe) wall temperature, °F
ΔT	True or effective temperature difference of the hot fluid, °F
Δt	True or effective temperature difference of the cold fluid, °F
Δt_1, Δt_2	Cold-and hot-terminal temperature difference, °F

U, U_c, U_D	Overall coefficient of heat transfer, clean coefficient, design coefficient, Btu/(hr)(ft²)(°F)
W_h	Weight flow of hot fluid, lb/hr
w_c	Weight flow of cold fluid, lb/hr
μ_h	Viscosity at the caloric temperature of the hot fluid, centipoises x 2.42 = lb/(ft)(hr)
μ_c	Viscosity at the caloric temperature of the cold fluid, centipoises x 2.42 = lb/(ft)(hr)
μ_{wh}	Viscosity at the wall temperature of the hot fluid, centipoises x 2.42 = lb/ft.hr
μ_{wc}	Viscosity at the wall temperature of the cold fluid, centipoises x 2.42 = lb/ft.hr
ϕ_h	$(\mu_h/\mu_{wh})^{0.14}$, dimensionless
ϕ_c	$(\mu_c/\mu_{wc})^{0.14}$, dimensionless

COMPUTERIZED HEAT EXCHANGER DESIGN PROCEDURE

1. Introduction

The term heat exchanger is usually applied to a device in which two process streams separated by a solid surface exchange heat energy. These devices may take many forms. However ordinary metal tubes are the main components of many types. A heat exchanger is a useful and perhaps an essential device in Heating, Ventilating, and Air Conditioning applications. Few examples of these applications are:

1. Refrigerant-to-water in the case of chillers.
2. Water-cooled condensers where shell and tube configurations are commonly used.
3. Water-to-air and refrigerant-to-air where finned tubes are usually used.
4. Air-to-air in the case of heat recovery systems where plate-fin type may be used.

The double pipe heat exchanger is the simplest industrial type available today. It is extremely useful because it can be assembled in any pipe fitting shop from standard parts and provides inexpensive heat-transfer surface.

The flow paths in the heat exchanger are quite complex and the calculation of "U_D", the overall design heat transfer coefficient is so difficult and subject to large errors in some cases. In the case of a double pipe heat exchanger, U_D is given by:

$$1/U_D = 1/h_o + 1/h_{io} + R$$

where

h_o = film heat transfer coefficient of the liquid on the outside surface of the pipe BTU/(hr)(ft²)(°F)

h_{io} = film heat transfer coefficient of the liquid on the inside surface of the pipe BTU/(hr)(ft²)(°F)

R = reasonable assumed dirt or fouling factor (hr)(ft²)(°F)/BTU

U_D = overall design heat-transfer coefficient for the heat exchanger BTU/(hr)(ft²)(°F)

The heat transfer surface required is then established from Fourier's equation as follows:-

A = $Q/(U_D \times LMTD)$ where:

A = heat transfer surface required ft²

Q = heat flow BTU/hr

U_D = The overall design heat transfer coefficient for the heat exchanger BTU/(hr)(ft²)(°F)

LMTD = Logarithmic mean temperature difference (°F)

The above equation has been developed using the following assumptions:-

1. The overall design heat transfer coefficient U_D, the weight rates of flow W_h and w_c and the specific heats C_h and C_c are all constants where the subscripts c and h refer to the cold and hot streams.
2. There is no heat loss or gain external to the heat exchanger and there is no axial conduction in the heat exchanger.
3. A single bulk temperature applies to each stream at a given cross section.

Usually the designer is given the following process conditions:-

+ Inlet and outlet temperatures of the hot liquid
+ Inlet and outlet temperatures of the cold liquid
+ The mass rate of flow for the hot or cold liquid
+ A set of standard arrangements of double pipes or hairpins available which he can choose from.
+ Design performance criteria, such as the maximum pressure drop on both sides of the tube, the maximum Reynold's number allowable etc..

The solution is usually arrived at by the "trial and error" meth[od] as outlined below:-

1. An arrangement of flow is assumed.
2. A standard hairpin is selected in size and length.
3. Using the temperature equations, the caloric temperatures of the hot and cold liquids are determined.
4. At these temperatures, the physical and thermodynamical properties of both liquids are found from tables, charts and graphs.
5. Using fluid flow and heat transfer equations, the remaining process conditions are established and compared to the pre-set design performance criteria.
6. If the design performance criteria are not met, the designer repeats steps 1 to 5 for a different flow arrangement and hairpin size, until a satisfactory solution is found.

This paper deals primarily with the design technique of the double-pipe heat exchanger using a computer program. The program is restricted to eleven selected oils (10° API, 15° API → 60° API) to be used as working fluids in the four standard sizes of the commercially available hairpins.

The program is self explanatory and all the instructions for the designer have been clearly given throughout the program. A sample problem will be studied and analyzed in order to illustrate the applicability and the accuracy of the program.

2. Description of the Double-Pipe Heat Exchanger:

The double-pipe heat exchanger is a simple unit to recover heat between two process streams. The principal parts of the exchanger are two sets of concentric pipes, two connecting Tees, a return head and a return bend. The inner pipe is supported within the outer pipe by packing glands and the fluid enters the inner pipe through a threaded connection located outside the exchanger section proper. The Tees have nozzles or screwed connections attached to them to permit the entry and exit of the annulus fluid which crosses from one leg to the other through the return head. See figure (1). The two lengths of the inner pipe are connected by a return head which is usually exposed and does not provide effective heat-transfer surface. When arranged in two legs as in fig. (1), the unit is a hairpin. The standard sizes of Tees and return heads are given in Table 1. Double-pipe heat exchangers are usually assembled in 12, 15, 20 and 40 ft. effective lengths, the effective length being the distance in each leg over which heat transfer occurs and excludes inner pipe protruding beyond the exchanger section.

3. Computerized Heat Exchanger Design Procedure:

A general program which includes all the known liquids and oils used as heat exchanger working fluids was impossible to develop due to the limited time of this research project. Data on the physical and thermodynamical properties and their variations with temperature and pressure were not readily available for all the oils.

In addition, storing the data into the computer was a complicated and time consuming process and was irrelevant to this present research. Since the main objective of the program was to show how the design process is computerized rather than how to store data on liquids/oils in the computer, it was decided to generate the program to be used for eleven oils, with consideration given for future incorporation of more liquids/oils into the program when more data would be available. The eleven oils are:-

10° API, 15° API, 20° API, 25° API, 30° API, 35° API, 40° API, 45° API, 50° API, 55° API, 60° API.

The physical and thermodynamical properties of these oils were found in References (1), (2), (3), (4) and (5) in forms of graphs and tables. Using linearization techniques, it was possible to replace these graphs and tables with equations which were subsequently programmed as subroutines to be used in the main program when needed. See figures (1) to (11) in the appendix for detailed information on the linearization coefficients and equations.

4. The Computer Program:

A computer program has been developed based on the design procedure outlined in chapters (3), (5) and (6) in Reference (1) for a double-pipe liquid-to-liquid heat exchanger. The program has the following limitations on its use:

1. Restricted to eleven hydrocarbon liquid oils. The program

generates values of °API in increments of 5, starting from 10° API up to 60° API.

2. Would select one of the four standard commercially available hairpin sizes, these are:

   2" x 1¼" IPS

   2½" x 1¼" IPS

   3" x 2" IPS

   4" x 3" IPS

3. The maximum temperature allowable for the working fluids is 600°F, without phase change.

4. The temperature range or difference for each stream is not to exceed 500°F.

The computerization process is illustrated by the flow charts presented on the following pages.

DEFINITIONS AND EXPLANATIONS

Arrays used in Main Program.

IAPI	=	Array of API values
ATCON	=	Array of TH. COND constants used in formula.
ASPHT	=	Array of constants for Specific Heat
ASPGRV	=	Array of constants for Specific Gravity
T	=	Array in which input temps. are stored
T1	=	1st element of T: inlet temp. of hot fluid
T2	=	2nd element of T: outlet temp. of hot fluid
T3	=	3rd element of T: inlet temp. of cold fluid
T4	=	4th element of T: outlet temp. of cold fluid
AVIS	=	Array of viscosity values
AKC	=	Array of constants for KC
IAPIV	=	Array in which input API values are stored
T11	=	Table 1 from report [Table 11 - Ref (1)]
T6.2	=	Table 2 from report [Table 6-2 - Ref (1)]
AJH	=	Array of constants for JH formulas
SHP	=	Array in which hairpin size is stored
IAPIA	=	Special array of API values for viscosity subroutine
ATEM	=	Array of temp. values used for viscosity subroutine
DARA	=	Array in which calculated data is stored to facilitate printing
IBIG, NUM, DEC, SET, FRA	=	Arrays used in "Fracto": - the subroutine which converts a decimal number into a fraction

S = Array in which input hairpin size is stored

NAME = Array in which names of parameters printed are stored

Arrays used in Subprograms:

Viscos:	IAPIVF	=	input API = IAPIV (main)
	TCOF	=	input temp.
	IAPIAV	=	IAPIA (main, prog)
	AT	=	ATEM (main, prog)
	AV	=	AVIS (main, prog)
SPGRAV:	IAPIF	=	IAPIV (main)
	TSGF	=	input temp. (TC2 or TC1)
	IAPISG	=	IAPI (main)
	ASG	=	ASPGRV (main)
FC:	FK	=	KC
	RF	=	R (ratio)
FKC:	IAPIFK	=	IAPIV (main)
	DTF	=	DT
	IAPIAK	=	IAPI (main)
	AK	=	AKC (main)
FJH:	RE	=	(Reynold's number)
	DUL	=	L/D
	AJ	=	AJH (main)
T COND:	IAPIT	=	IAPIV (main)
	TTCF	=	TC2 or TC1
	IAPITA	=	IAPI (main)
	ATC	=	ATCONC (")

<u>Specific Heat</u>:	IAPISH	=	IAPIV (main)
	TSHF	=	TC2 <u>or</u> TC1
	IAPISA	=	IAPI (main)
	ASH	=	ASPHI (main)
<u>FRIC</u>:	REF	=	RE

FLOWCHART

for

DOUBLE-PIPE HEAT EXCHANGER DESIGN PROGRAM

(Start)

Read Arrays

Generate values of API.

Read data for design problem.

Print headings, input data.

Calculate:

$DT2 = |T1 - T4|$

$DT1 = |T2 - T3|$

$Ratio = DT1/DT2$

$DT = |T1 - T2|$

$$LMTD = \left| \frac{DT2 - DT1}{\ln[DT2/DT1]} \right|$$

Larger of | KC - Hot | KC - Cold

$TC2 = T2 + FC * |(T1 - T2)|$

$TC1 = T3 + FC * |T4 - T3|$

CH = SPHEAT

CC = SPHEAT

μC = Viscos

μH = Viscos

$Q = WH * CH * DT$

$WC = Q/[CC * |T4 - T3|]$

(1)

1

From tables: 1, 2:-

Find values for AP, AA, D, DE, DO, A", DE"

Calculate:

G - HT	=	WH * 144 / [AP or AA]
G - CLD	=	WC * 144 / [AA or AP]
RE - HT	=	[D or DE] * G - HOT / [μH * 12]
RE - CLD	=	[DE or D] * G - CLD / [μC * 12)
TH. COND. - HT	=	T COND
TH. COND. - CLD	=	T COND
FACT - HT	=	$\text{TH - COND - HT} * [\frac{\text{CH} * \mu\text{H}}{\text{TH - COND - HT}}]^{1/3}$
FACT - CLD	=	$\text{TH - COND - CLD} * [\frac{\text{CH} * \mu\text{C}}{\text{TH - COND - CLD}}]^{1/3}$
L/D - HT	=	PL * 12 * n / [D or DE]
L/D - CLD	=	PL * 12 * n / [DE or D)
HI/ϕ_{HT}	=	$\frac{\text{FJH} * \text{FACT - HT} * 12}{[\text{D or DE}]}$
HO/ϕ_{CLD}	=	$\frac{\text{FJH} * \text{FACT - CLD} * 12}{[\text{DE or D}]}$
HIO/ϕ_p	=	Take for pipe $\left\lvert \begin{matrix} HI/\phi_{HT} \\ \text{- or -} \\ HO/\phi_{CLD} \end{matrix} \right. * \frac{D}{DO}$
TW	=	TCL-(H10/ϕ_p/[HIO/ϕ_p+Take-Ann. $\left\lvert \begin{matrix} HI/\phi_{HT} \\ \text{- or -} \\ HO/\phi_{CLD} \end{matrix} \right.$ * [TC2-TC1]
μWC	=	Viscos
μWH	=	Viscos
ϕ_{HT}	=	$(\mu H/\mu WH)^{0.14}$
ϕ_{CLD}	=	$(\mu C/\mu WC)^{0.14}$
HIO	=	(HIO/ϕ_p) * Take Pipe $\left\lvert \begin{matrix} \phi_{HT} \\ \phi_{CLD} \end{matrix} \right.$

2

(2)

$HO = \text{Take Annulus} \left| \begin{matrix} HI/\phi_{HT} \\ HO/\phi_{CLD} \end{matrix} \right. * \text{Take Annulus} \left| \begin{matrix} \phi_{HT} \\ \phi_{CLD} \end{matrix} \right.$

$UD = [\frac{1}{HIO} + \frac{1}{HO} + DF]^{-1}$

$A = Q/[UD * LMTD]$

$L = A/a''$

$N = L/PL$

$REA'' = DE'' * \text{Take Annulus} \left| \begin{matrix} G - HT \\ G - CLD \end{matrix} \right. / [(\mu C \text{ or } \mu H) * 12]$

SP-GRAV-HT = SPGRAV

SP-GRAV-CLD = SPGRAV

FP = FRIC

FA = FRIC

$DOM - HT = 5.22 * 10^{10} * (D \text{ or } DE) * SP_{HT} * \phi_{HT}$

$DP - HT = (G - HT)^2 * N * 12 * \begin{matrix} \text{Take} \\ \text{Hot} \end{matrix} \left| \begin{matrix} FP \\ FA \end{matrix} \right. * PL \bigg/ DOM - HT$

$DOM - CLD = 5.22 * 10^{10} * (D \text{ or } DE) * SP_{CLD} * \phi_{CLD}$

$DP - CLD = (G - CLD)^2 * N * 12 * \begin{matrix} \text{Take} \\ \text{Cold} \end{matrix} \left| \begin{matrix} FP \\ FA \end{matrix} \right. * PL \bigg/ DOM - CLD$

Print

Trial number and calculated data

Check

if pressure drops are within limits - and print appropriate message

(3)

(3)

If pressure drops are not within limits:

- and -

If RE > 10,000 - and - no more hairpins: Go to 100.

If RE > 10,000 - and - hairpins not depleted then recalculate using larger hairpin.

If RE < 10,000 increase the number of hairpins and recalculate.

If all of above not true ie.: pressure drops within limits go to next problem.

100 If flows already exchanged print

"Unable to Solve"

otherwise switch flows and recalculate starting with smallest hairpin.

Flow of Charts of Subroutines

1. Viscosity Subroutine

SUBROUTINE VISCOS

Read data, Arrays:-

- API given
- Temp. given
- Array of API values
- Array of temp. values
- Array of viscosity values

↓

Using Given values:-

Find values in table (viscosity) which lie on both sides of given values.

↓

Interpolate between these values and calculate viscosity. Return to main program.

2. Specific Gravity Subroutine

SUBROUTINE SPGRAV

Read Arrays:, data:-

- API given
- Temp. given
- Array of API values
- Array of data to be used in SPGRAV formulas.

↓

Find appropriate values to use in formulas.

↓

Find which range temperature lies in.

↓

Calculate using appropriate formula.

Return

3. Caloric Temperature Factor K_C

SUBROUTINE FKC (KC)

Read Arrays, data:-

- API given
- DT
- Array for API values
- Array of constants used in KC formulas.

↓

Find constants to use for API given.

↓

Calculate KC using these constants.

Return

4. Tube-side Heat Transfer Curve

SUBROUTINE FJH (JH)

Read Arrays, data:-

- RE given
- L/D given
- Array of constants to be used in formulas.

↓

Find set of constants to use for L/D given.

Find which formula to use for RE given.

↓

Calculate JH for L/D higher and lower than L/D given and interpolate for result.

Return

5. Thermal Conductivity

SUBROUTINE TCOND (TH. CONDUCTIVITY)

Read Arrays, data:-

- API given
- Temp. given
- Array of API values
- Array of constants used in formula.

↓

Find constants to use for given API.

↓

Calculate using these constants in formula.

Return

6. Specific Heat

SUBROUTINE SPHEAT

Read Arrays, data:-

- API given
- Temp. given
- Array of API values
- Array of constants used in formula.

↓

Find appropriate constants for API given.

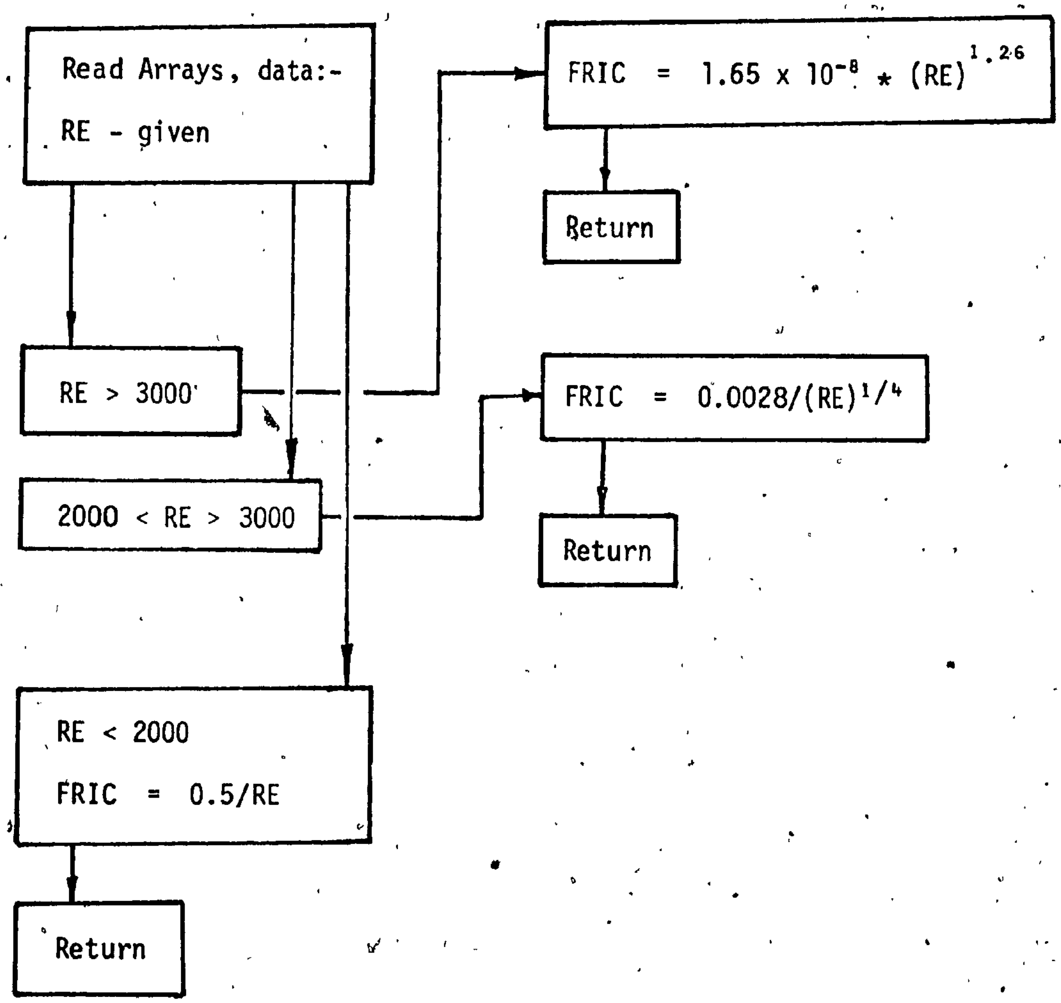
↓

Calculate using these in formula.

Return

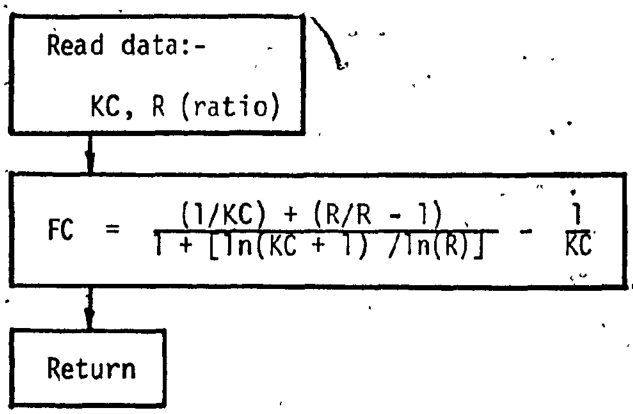
7. Friction Factor

SUBROUTINE FRIC

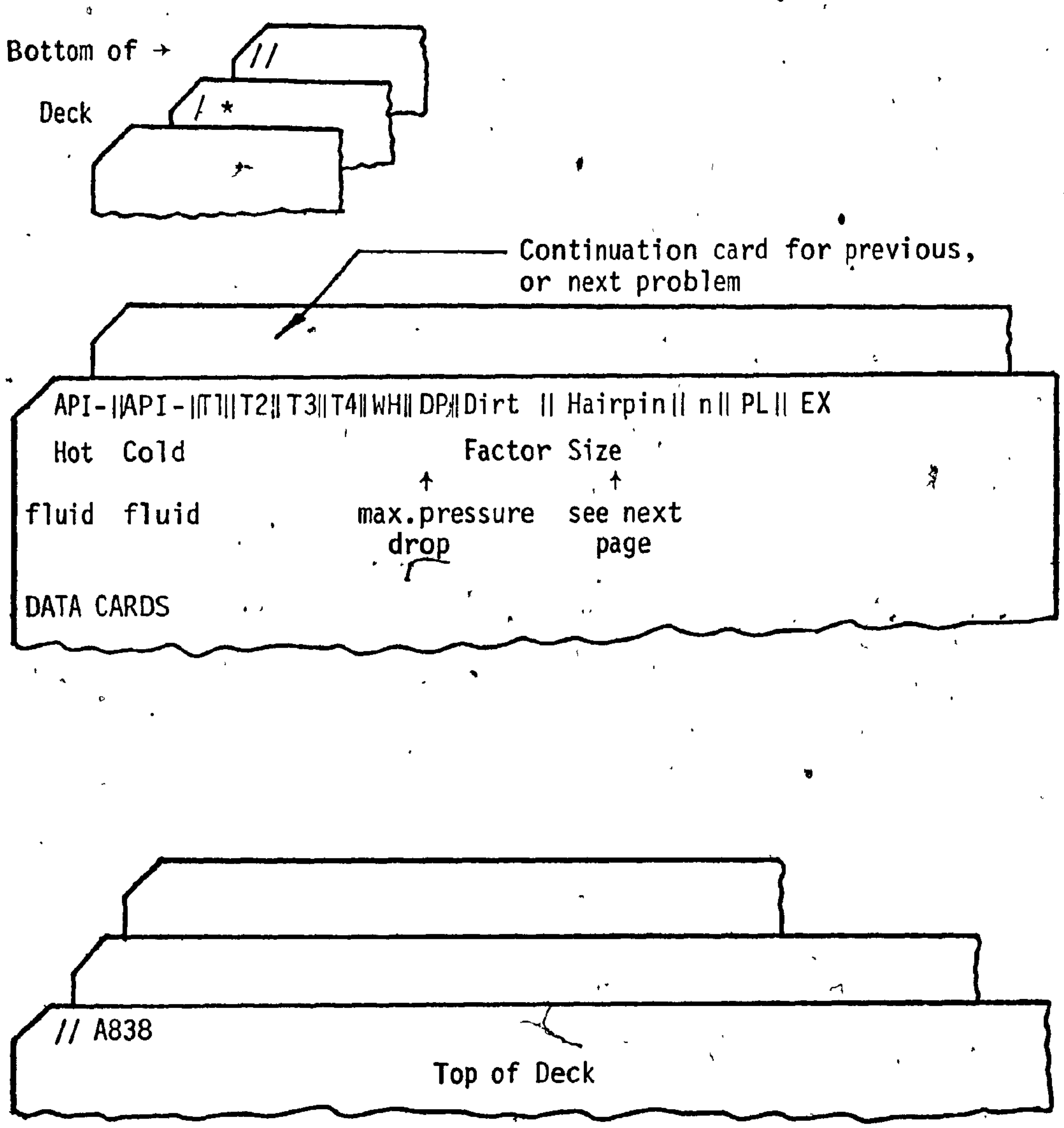


8. Caloric Temperature Factor F_C

SUBROUTINE FC



METHOD OF ENTERING DATA



Definitions: n = initial number of hairpins

PL = length of hairpin

EX = 1, -1 (see next page)

- Data must be entered as shown above.
- Data need not be placed starting at first column though at least one space must be allowed between values.
- If data does not fit on one card, (can use up to col. 80) it may be continued on a following card.
- Though needless to say, a value should not be split between 2 cards.
- If more than one problem is to be solved, the values for this must be placed on a new card in the above manner.
- In its present form, the program can handle about 10 problems in a single run.
- The final value entered per problem is named ex: and must be given a value of either 1 or -1.
- If 1, the hot fluid will be initially placed in the pipe, and the cold fluid in the Annulus.
- A -1, will cause the reverse of the above.
- The method of entering the hairpin size is best demonstrated by an example:
- If hairpin size = $2\frac{1}{2} \times 1\frac{1}{4}$ IPS, this would be punched on the card as:

```
|| 2|| 1|| 2|| 1|| 4
```

- Note however that: for 4 x 3 IPS, this would be entered as:

```
|| 4|| 0|| 1|| 3|| 0|| 1
```

5. Sample design problem:

A double-pipe heat exchanger design problem will be illustrated in order to demonstrate the design procedure and to explain the applicability and the accuracy of the program.

Note: Values between brackets are those obtained from the computer print-out.

a) Problem

12,000 lb/hr of 25° API lube oil is to be cooled from 450°F to 350°F by heating 40° API lube oil from 325°F to 375°F. A pressure drop of 10 PSI is permissible on both streams and a maximum dirt factor of 0.004 should be provided. Find the size, length and the number of hairpins required and the flow arrangement.

b) Solution

Given Data:

T_1	=	450 °F	(450)
T_2	=	350 °F	(350)
t_1	=	325 °F	(325)
t_2	=	375 °F	(375)
W_h	=	12,000 lb/hr	(12,000)

Maximum Dirt Factor = "R" = 0.004 (hr)(ft²)(°F)/BTU (0.004)

Maximum Pressure drop = 10 PSI (10)

1. Arrangement #1 (Design problem #2 - Trial #1)

Assume that hot fluid is placed in the pipe and cold fluid is in the annulus. See figure (2). (Trial #1)

Calculations:

Assume hairpin size is $2\frac{1}{2} \times 1\frac{1}{4}$ IPS	(Trial #1)
$a_p = 1.5$ in^2	(1.5)
$a_a = 2.63$ in^2	(2.63)
$D = 1.38$ in	(1.38)
$D_e = 2.02$ in	(2.02)
$D_o = 1.66$ in	(1.66)
$a'' = 0.435$ ft^2	(0.435)
$D_e' = 0.81$ in	(0.81)
$\Delta t_2 = T_1 - t_2 = 450-375 = 75$ °F	(75)
$\Delta t_1 = T_2 - t_1 = 350-325 = 25$ °F	(25)
Ratio $= \Delta t_1/\Delta t_2 = 25/75 = 0.333$	(0.333)
$\Delta T = T_1 - T_2 = 450-350 = 100$ °F	(100)
$\Delta t = t_2 - t_1 = 375-325 = 50$ °F	(50)
LMTD $= (\Delta t_2 - \Delta t_1)/\ln(\Delta t_2/\Delta t_1)$	
$= (75-25)/\ln(75/25) = 45.5$ °F	(45.512)
$K_c = 0.48$ from fig. (7)	(0.46)
($\Delta T = 100$, 25° API)	
$F_c = 0.38$ from fig. (7)	
(ratio $= 0.333$, $K_c = 0.48$)	
$T_c = T_2 + F_c\,(\Delta T)$	
$= 350 + 0.38\,(100) = 388$ °F	(387.96)
$t_c = t_1 + F_c\,(\Delta t)$	
$= 325 + 0.38\,(50) = 344$ °F	(343.98)

C_h = 0.61 BTU/(lb)(°F)
(25° API, T_c = 388) - figure (4) (0.6103)

C_c = 0.62 BTU/(lb)(°F)
(40° API, t_c = 344) (0.6209)

μ_h = 0.8 C.P. from figure (8)
(25° API, T_c = 388)
i,e = 0.8 x 2.42 ≃ 1.93 lb/(ft)(hr) (2.604)

μ_c = 0.4 C.P. from figure (8)
(40° API, t_c = 344)
i,e = 0.4 x 2.42 ≃ 0.97 lb/(ft)(hr) (1.0795)

k_h = 0.067 BUT/(hr)(ft^2)(°F/ft) (0.0672)
from figure (5) (25° API, T_c = 388)

k_c = 0.0745 BTU/(hr)(ft^2)(°F/ft) (0.0746)
(40° API, t_c = 344)
from figure (5)

$Q = W_h \times C_h \times \Delta T$
= 12,000 x 0.61 x 100 (732,377.7)
= 732,000 BTU/hr

$w_c = Q/(C_c \times \Delta t)$
= 732,000/(0.62 x 50) (23,592.6)
= 23,612.9 lb/hr

$G_h = W_h/a_p$
= 12,000/(1.5/144) (1,152,000)
= 1,152,000 lb/(hr)(ft^2)

$G_c = w_c/a_a$
= 23,612.9/(2.63/144) (1,291,763)
= 1,292,873.6 lb/(hr)(ft^2)

$(Re)_h = (D \times G_h)/\mu_h$

$= (1.38/12) \times (1{,}152{,}000)/(1.93)$ (50,857.3)

$= 68{,}642.5$

$(Re)_c = (D_e \times G_c)/\mu_h$

$= (2.02/12) \times (1{,}292{,}873.6)/(0.97) = 224{,}364.6$ (201,434.9)

Assume 6 hairpins (6)

length of each hairpin = 40 ft (40)

from figure (9)

$(Fact)_h = k_h\,[C_h \times \mu_h/k_h]^{1/3} = 0.175$ BTU/hr(ft)(°F/ft) (0.1929)

(25° API, μ_h = 0.8 C.P.)

$(Fact)_c = k_c\,[C_c \times \mu_c/k_c]^{1/3} = 0.145$ BTU/hr(ft²)(°F/ft)

(40° API, μ_c = 0.4 C.P.) (0.1551)

from figure (10)

$J_h = 185$ ($Re_h = 6.86 \times 10^4$)

$J_c = 500$ ($Re_c = 2.24 \times 10^5$)

$Hi/\phi_h = J_h \times (Fact)_h \times 1/D$

$= 185 \times 0.175 \times 1/(1.38/12)$

$= 281.5$ BTU/(hr)(ft²)(°F) (247.85)

$Ho/\phi_c = J_c \times (Fact)_c \times 1/De$

$= 500 \times 0.145 \times 1/(2.02/12)$

$= 430.7$ BTU/(hr)(ft²)(°F) (422.26)

$H_{io}/\phi_p = (Hi/\phi_h \times D/D_o)$

$= 281.5 \times (1.38/12)/(1.66/12)$

$= 234$ BTU/(hr)(ft²)(°F) (206.04)

$t_w = t_c + (H_{io}/\phi_p)(T_c - t_c)/[H_{io}/\phi_p + H_o/\phi_c]$

$= 344 + (234)(388-344)/[234 + 430.7]$

$= 359.5$ °F (358.4)

From figure (8) find values of viscosities at wall temperature

$\mu_{wh} = 1.00$ C.P. or 2.42 lb/(ft)(hr) (3.356)

$\mu_{wc} = 0.38$ C.P. or 0.9196 lb/(ft)(hr) (0.9573)

$\phi_h = (\mu_h/\mu_{wh})^{0.14} = (0.8/1.00)^{0.14} = 0.969$ (0.965)

$\phi_c = (\mu_c/\mu_{wc})^{0.14} = (0.4/0.38)^{0.14} = 1.0072$ (1.017)

$H_{io} = (H_{io}/\phi_p)(\phi_h) = 234 \times 0.969$

$= 226.746$ BTU/(hr)(ft^2)(°F) (198.86)

$H_o = (H_o/\phi_c)(\phi_c) = 430.7 \times 1.0072$

$= 433.8$ BTU/(hr)(ft^2)(°F) (429.42)

$1/U_D = 1/H_{io} + 1/H_o + R$

$= 1/(226.746) + 1/(433.8) + 0.004$

$\therefore U_D = 1/0.0107 = 93.32$ BTU/(hr)(ft)(°F) (88.05)

$A = Q/(U_D \times LMTD) = (732{,}000)/(93.32 \times 45.5)$

$= 172.39$ ft^2 (182.76)

$L = A/a'' = 172.39/0.435 = 396.3$ ft (420.13)

$n = L/l = 396.3/40 = 9.9 \approx 10$ (11)

$(Rea') = (De)\ (Gc)/\mu_c$

$= (0.81/12)\ (1{,}292{,}873.6)/0.97 = 89{,}968$ (80,773)

from figure (11)

$f_h = 0.000170$ $(Re_h = 6.8 \times 10^4)$ (0.0002)

$f_c = 0.000160$ $(Rea' = 8.99 \times 10^4)$ (0.0002) from figure (6)

$(S.G.)_h$ = 0.78 (T_c = 388, 25° API) (0.7802)

$(S.G.)_c$ = 0.72 (T_c' = 344, 40° API) (0.7113)

$(DP)_h$ = $[f_h \times (G_h)^2 \times (1)\ (n)]/[5.22 \times 10^{10} \times De \times (S.G.)_h \times \phi_h]$

= $[0.00017 \times (1,152,000)^2 \times (40)\ (10)]/[5.22) \times 10^{10} \times$

$(1.38/12) \times 0.78 \times 0.969]$

= 19.889 > 10 PSI <u>NOT OK</u> (24.08)

$(DP)_c$ = $[f_c \times (G_c)^2 \times (1)\ (n)]/[5.22 \times 10^{10} \times De \times (S.G.)_c \times \phi_c]$

= $[0.00016 \times (1,292,873.6)^2 \times (40)\ (10)]/[5.22 \times 10^{10} \times$

$(2.02/12) \times 0.72 \times 1.0072]$

= 16.788 > 10 PSI <u>NOT OK</u> (19.1854)

2. <u>Arrangement #2</u> (Design Problem #1 - Trial #1)

Assume that cold fluid is placed in the pipe and hot fluid is in the annulus. See figure (3).

<u>Calculations</u>

Assume hairpin size is $2\frac{1}{2} \times 1\frac{1}{4}$ IPS (Trial #1)

a_p	=	1.5 in^2	(1.5)
a_a	=	2.63 in^2	(2.63)
D	=	1.38 in	(1.38)
D_e	=	2.02 in	(2.02)
D_o	=	1.66 in	(1.66)
a"	=	0.435 ft^2	(0.435)
D'_e	=	0.81 in	(0.81)
Δt_2	=	$T_1 - t_2$ = 450-375 = 75 °F	(75)
Δt_1	=	$T_2 - t_1$ = 350-325 = 25 °F	(25)

Ratio	=	$\Delta t_1/\Delta t_2$ = 25/75 = 0.333	(0.333)
ΔT	=	T_1-T_2 = 450-350 = 100 °F	(100)
LMTD	=	$(\Delta t_2-\Delta t_1)/\ln(\Delta t_2/\Delta t_1)$	
	=	(75-25)/ln(75/25) = 45.5 °F	(45.51)
K_c	=	0.48 from figure (7)	(0.46)
		(ΔT = 100, 25° API)	
F_c	=	0.38 from figure (7)	
		(ratio = 0.333, K_c = 0.48)	
T_c	=	$T_2 + F_c\ (\Delta T)$	
	=	350 + 0.38 (100) = 388 °F	(387.96)
t_c	=	$t_1 + F_c\ (\Delta T)$	
	=	325 + 0.38 (50) = 344 °F	(343.98)
C_h	=	0.61 BTU/(lb)(°F)	(0.6103)
		from figure (4) (T_c = 388, 25° API)	
C_c	=	0.62 BTU/(lb)(°F)	(0.6209)
		from figure (4) (t_c = 344, 40° API)	
μ_h	=	0.8 C.P. OK	
		from figure (8) (25° API, T_c = 388)	
		or 0.8 x 2.24 = 1.93 lb/(ft)(hr)	(2.604)
μ_c	=	0.4 C.P. from figure (8)	
		(40° API, t_c = 344)	
		or 0.4 x 2.42 = 0.97 lb/(ft)(hr)	(1.0795)
k_h	=	0.067 BTU/(hr)(ft²)(°F/ft)	(0.0672)
		from figure (5) (25° API, T_c = 388)	
k_c	=	0.0745 BTU/(hr)(ft²)(°F/ft)	(0.0746)
		from figure (5) (40° API, t_c = 344)	

$Q = W_h \times C_h \times \Delta T$

$= 12,000 \times 0.61 \times 100 = 732,000$ BTU/hr (732,377.7)

$w_c = Q/(C_c \times \Delta t)$

$= 732,000/(0.62 \times 50) = 23,612.9$ lb/hr (23,592.6)

$G_h = W_h/a_a = 12,000/(2.63/144)$ (657,034.1)

$= 657,034.2$ lb/(hr)(ft^2)

$G_c = w_c/a_p = 23,612.9/(1.5/144)$

$= 2,266,838.4$ lb/(hr)(ft^2) (2,264,892)

$(Re)_h = (D_e \times G_h)/\mu_h = (2.02/12) \times (657,034.2/1.93)$

$= 57,306.1$ (42,458.16)

$(Re)_c = (D \times G_c/\mu_c) = (1.38/12) \times (2,266,838.4)/(0.97)$

$= 268,748.8$ (241,283.2)

Assume 6 hairpins (6)

length of each hairpin = 40 ft (40)

$(Fact.)_h = k_h\,[C_h \times \mu_h/k_h]^{1/3} = 0.175$ BTU/hr(ft^2)(°F/ft)

(0.1929)

from figure (9) (25° API, $\mu_h = 0.8$ C.P.)

$(Fact.)_c = k_c[C_c \times \mu_c/k_c]^{1/3} = 0.145$ BTU/hr(ft^2)(°F/ft) (0.1551)

from figure (9) (40° API, $\mu_c = 0.4$ C.P.)

from figure (10):-

$J_h = 165 \quad (Re_h = 5.73 \times 10^4)$

$J_c = 570 \quad (Re_c = 2.69 \times 10^5)$

$Ho/\phi_h = J_h \times (Fact)_h \times 1/De$

$= 165 \times 0.175 \times 1/(2.02/12)$

$= 171.5$ BTU/(hr)(ft^2)(°F) (146)

Hi/ϕ_c = J_c x $(Fact.)_c$ x 1/D

= 570 x 0.145 x 1/(1.38/12)

= 718.69 BTU/(hr)(ft^2)(°F) (716.95)

H_{io}/ϕ_p = $[Hi/\phi_c \times (D/Do)]$

= [718.69 x (1.38/12)/(1.66/12)]

= 597.46 BTU/(hr)(ft^2)(°F) (596.02)

t_w = $t_c + (H_{io}/\phi_p) \times (T_c - t_c)/[H_{io}/\phi_p + Ho/\phi_h]$

= 344 + (597.46) x (388-344)/(597.46 + 171.5)

= 378.18 °F (379.3)

from figure (8), find values of viscosities at wall temperature

μ_{wh} = 1.00 C.P.

or μ_c = 1.0 x 2.42 = 2.42 lb/(ft)(hr) (2.82)

μ_{wc} = 0.3 C.P.

or μ_c = 0.3 x 2.42 = 0.75 lb/(ft)(hr) (0.78)

ϕ_h = $(\mu_c/\mu_{wc})^{0.14} = (1.93/2.42)^{0.14} = 0.968$ (0.98)

ϕ_c = $(\mu_c/\mu_{wc})^{0.14} = (0.97/0.75)^{0.14} = 1.036$ (1.046)

H_{io} = $(H_{io}/\phi_p) \times (\phi_c)$ = (597.46)(1.036)

= 619.36 BTU/(hr)(ft^2)(°F) (623.7)

Ho = $(Ho/\phi_h) \times (\phi_h)$ = 171.5 x 0.968 = 166.0

= 166.0 BTU/(hr)(ft^2)(°F) (144)

$1/U_D$ = $1/H_{io}$ + 1/Ho + R

= 1/(619.36) + 1/(166) + 0.004 = 0.01163

U_D = 1/0.01163 = 85.92 BTU/(hr)(ft^2)(°F) (79.79)

A = $Q/(U_D \times LMTD)$ = (732,000)/(85.92 x 45.5)

= 187.24 ft^2 (201.66)

$L = A/a'' = 187.24/0.435 = 430.4$ ft (463.59)

$n = L/l = 430.4/40 = 10.76 \simeq 11$ (12)

$(Rea'), \mu_h = (D_e \times G_h)\mu_h = (0.81/12)(657{,}034.2)/1.93$

$= 22{,}979.1$ (17,025.3)

from figure (11):-

$f_h = 0.00023 \quad (Rea' = 2.297 \times 10^2)$ (0.0002)

$f_c = 0.00012 \quad (Re_c = 2.687 \times 10^5)$ (0.0001)

from figure (6)

$(S.G.)_h = 0.78 \quad (T_c = 388,\ 25°\ API)$ (0.7802)

$(S.G.)_c = 0.72 \quad (t_c = 344,\ 40°\ API)$ (0.7113)

$(DP)_h = [f_h \times (G_h)^2 \times (l) \times (n)]/[5.22 \times 10^{10} \times D_e \times (S.G.)_h \times \phi_h]$

$= [(0.00023)(657{,}034.2)^2 \times 40 \times 11]/[5.22 \times 10^{10} \times (2.02/12) \times 0.78 \times 0.968]$

$= 6.58 < 10$ PSI <u>OK</u> (7.49)

$(DP)_c = [f_c \times (G_c)^2 \times (l) \times (n)]/[5.22 \times 10^{10} \times D \times (S.G.)_c \times \phi_c]$

$= [0.00012 \times (2{,}266{,}838.4)^2 \times (40)(11)]/[5.22 \times 10^{10} \times (1.38/12) \times 0.72 \times 1.036]$

$= 60.589 > 10$ PSI <u>NOT OK</u> (69.61)

6. Conclusion:

This project clearly demonstrates that double pipe heat exchanger design can be computerized successfully. The program was restricted to eleven selected oils (10° API → 60° API). Data not presently incorporated on other liquids and oils should be gathered in order to widen the relevance and scope of the design.

Through such research, a useful and widely applicable computerized procedure for the design of the complex, but widely used heat exchangers such as the shell and tube type could become readily available, thus saving valuable engineering design time.

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APPENDIX

TABLE 6.2. FLOW AREAS AND EQUIVALENT DIAMETERS IN DOUBLE PIPE EXCHANGERS

Exchanger, IPS	Flow area, in.^{2}		Annulus, in.	
	Annulus	Pipe	d_e	d_e'
2 × 1¼	1.19	1.50	0.915	0.40
2½ × 1¼	2.63	1.50	2.02	0.81
3 × 2	2.93	3.35	1.57	0.69
4 × 3	3.14	7.38	1.14	0.53

Table 1: Flow Areas and Equivalent Diameters of Standard Double-Pipe Heat Exchangers

TABLE 11. DIMENSIONS OF STEEL PIPE (IPS)

Nominal pipe size, IPS, in.	OD, in.	Schedule No.	ID, in.	Flow area per pipe, in.²	Surface per lin ft, ft.²/ft. Outside	Surface per lin ft, ft.²/ft. Inside	Weight per lin ft, lb steel
1/8	0.405	40*	0.269	0.058	0.106	0.070	0.25
		80†	0.215	0.036		0.056	0.32
1/4	0.540	40*	0.364	0.104	0.141	0.095	0.43
		80†	0.302	0.072		0.079	0.54
3/8	0.675	40*	0.493	0.192	0.177	0.129	0.57
		80†	0.423	0.141		0.111	0.74
1/2	0.840	40*	0.622	0.304	0.220	0.163	0.85
		80†	0.546	0.235		0.143	1.09
3/4	1.05	40*	0.824	0.534	0.275	0.216	1.13
		80†	0.742	0.432		0.194	1.48
1	1.32	40*	1.049	0.864	0.344	0.274	1.68
		80†	0.957	0.718		0.250	2.17
1 1/4	1.66	40*	1.380	1.50	0.435	0.362	2.28
		80†	1.278	1.28		0.335	3.00
1 1/2	1.90	40*	1.610	2.04	0.498	0.422	2.72
		80†	1.500	1.76		0.393	3.64
2	2.38	40*	2.067	3.35	0.622	0.542	3.66
		80†	1.939	2.95		0.508	5.03
2 1/2	2.88	40*	2.469	4.79	0.753	0.647	5.80
		80†	2.323	4.23		0.609	7.67
3	3.50	40*	3.068	7.38	0.917	0.804	7.58
		80†	2.900	6.61		0.760	10.3
4	4.50	40*	4.026	12.7	1.178	1.055	10.8
		80†	3.826	11.5		1.002	15.0
6	6.625	40*	6.065	28.9	1.734	1.590	19.0
		80†	5.761	26.1		1.510	28.6
8	8.625	40*	7.981	50.0	2.258	2.090	28.6
		80†	7.625	45.7		2.000	43.4
10	10.75	40*	10.02	78.8	2.814	2.62	40.5
		60	9.75	74.6		2.55	54.8
12	12.75	30	12.09	115	3.338	3.17	43.8
14	14.0	30	13.25	138	3.665	3.47	54.6
16	16.0	30	15.25	183	4.189	4.00	62.6
18	18.0	20‡	17.25	234	4.712	4.52	72.7
20	20.0	20	19.25	291	5.236	5.05	78.6
22	22.0	20‡	21.25	355	5.747	5.56	84.0
24	24.0	20	23.25	425	6.283	6.09	94.7

* Commonly known as standard.
† Commonly known as extra heavy.
‡ Approximately.

Table 2: Dimensions of Steel Pipe (IPS)

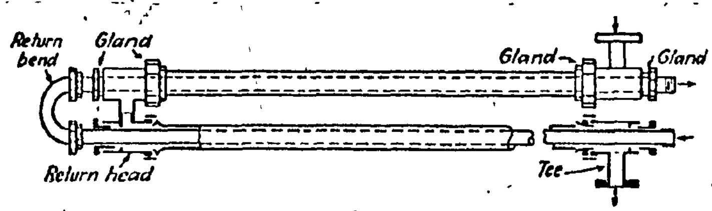

Figure (1) The double pipe Heat Exchanger

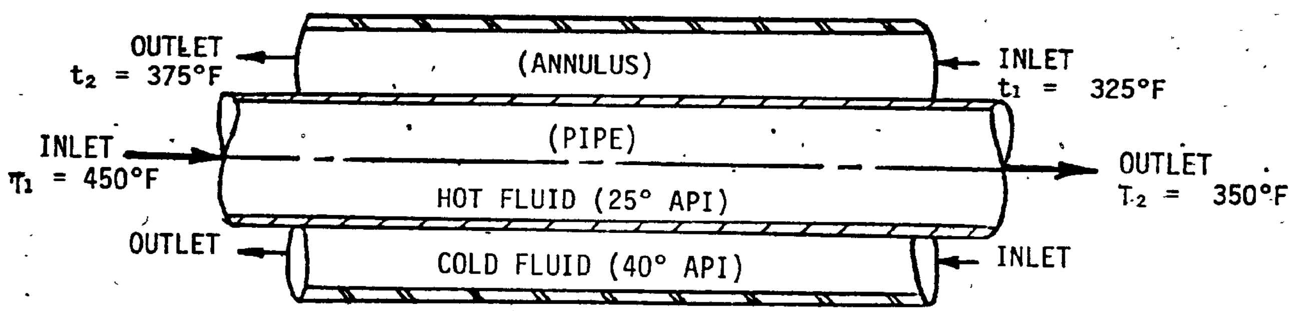

Figure (2): Double-pipe heat exchanger with hot fluid in pipe and cold fluid in annulus

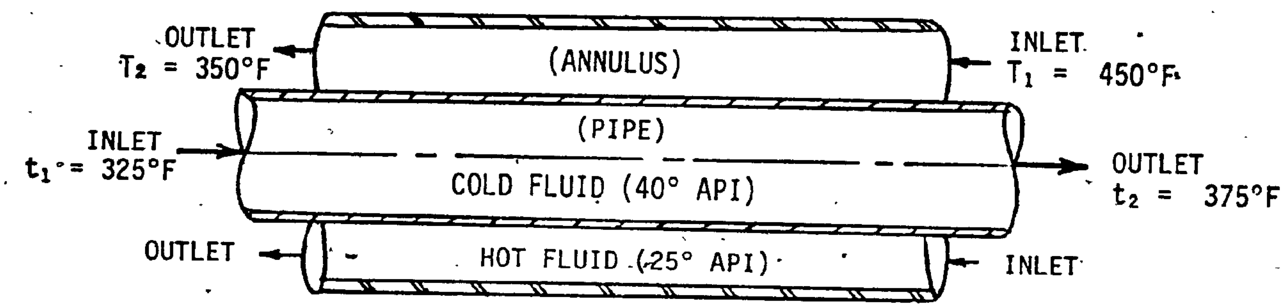

Figure (3): Double-pipe heat exchanger with cold fluid in pipe and hot fluid in annulus

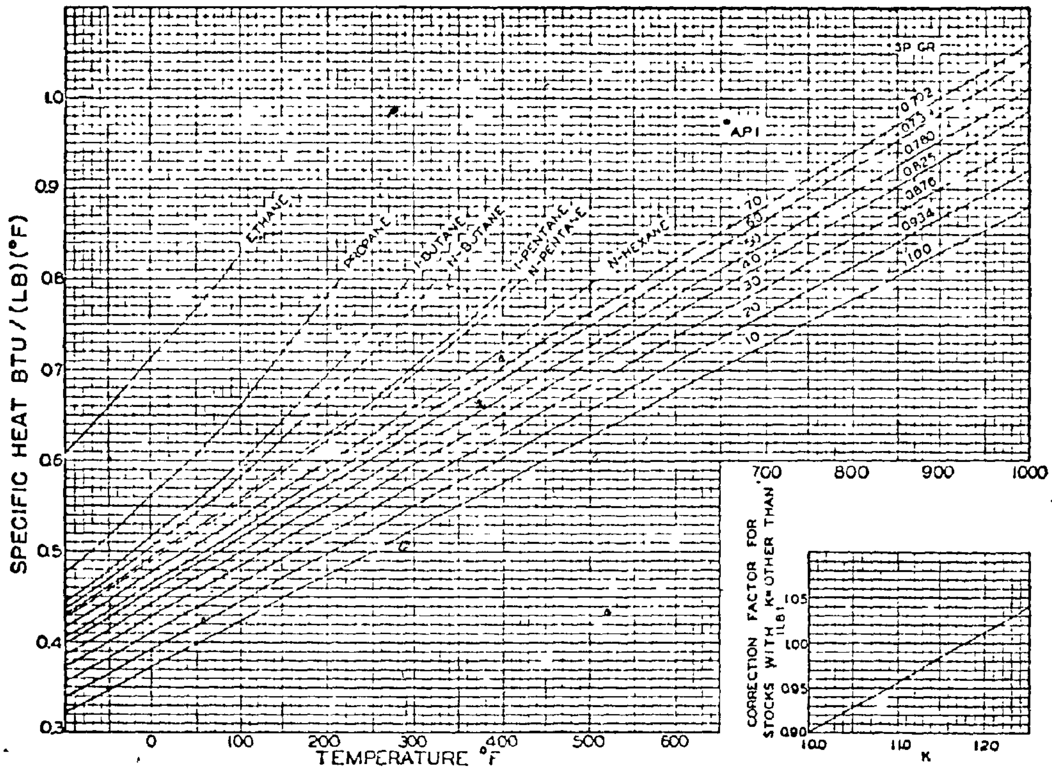

FIG. 4. Specific heats of hydrocarbon liquids. [*Holcomb and Brown, Ind. Eng. Chem.*, **34**, 595 (1942).]
† K — characterization factor.

Fig. (4): Specific Heats of Hydrocarbon Liquids

$$C = C_1 (t + 100) + C_2$$

Liquid 0:1	C_1	C_2
10° API	0.000510	0.3230
15° API	0.000518	0.3315
20° API	0.000527	0.3400
25° API	0.000535	0.3495
30° API	0.000542	0.3590
35° API	0.000549	0.3665
40° API	0.000556	0.3740
45° API	0.000562	0.3810
50° API	0.000567	0.3880
55° API	0.000576	0.3940
60° API	0.000584	0.4000

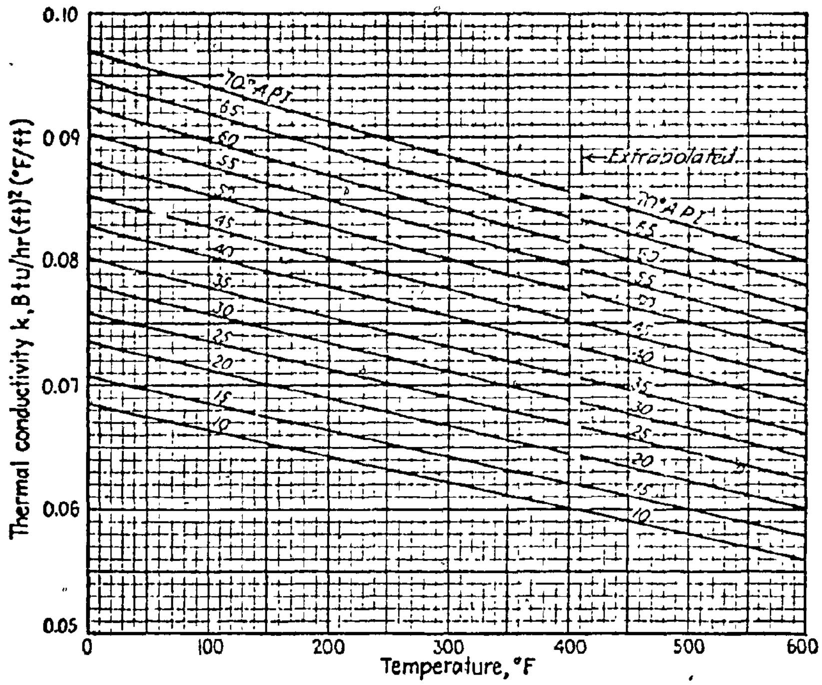

FIG. 1. Thermal conductivities of hydrocarbon liquids. (*Adapted from Natl. Bur. Standards Misc. Pub.* 97.)

Fig. (5): Thermal Conductivities of Hydrocarbon Liquids

$$K = C_1 - C_2 (t)$$

Liquid Oil	C_1	C_2
10° API	0.0685	0.0000208
15° API	0.0708	0.0000213
20° API	0.0735	0.0000225
25° API	0.0759	0.0000225
30° API	0.0780	0.0000230
35° API	0.0801	0.0000250
40° API	0.0830	0.0000243
45° API	0.0852	0.0000248
50° API	0.0880	0.0000258
55° API	0.0902	0.0000267
60° API	0,0925	0.0000275

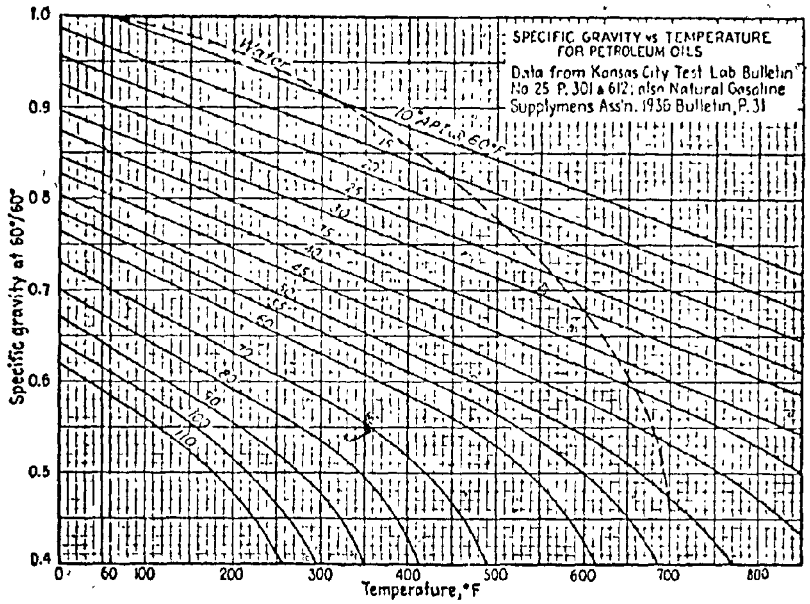

Fig. 6. Specific gravities of hydrocarbons.

<u>Fig. (6):</u> <u>Specific Gravities of Hydrocarbon Liquids</u>

$$SP.GR. = C_1 - C_2 \ (t)$$

Liquid Oil	C_1	C_2	
10° API	1.025	0.000360	
15° API	0.955	0.000359	
20° API	0.955	0.000365	
25° API	0.923	0.000368	
30° API	0.895	0.000365	
35° API	0.873	0.000388	
40° API	0.842	0.000380	$0 < t < 700$
	0.985	0.000570	$t > 700$
45° API	0.828	0.000410	$0 < t < 700$
	1.000	0.000660	$t > 700$
50° API	0.805	0.000440	$0 < t < 600$
	1.1	0.000895	$t > 600$
55° API	0.785	0.000446	$0 < t < 550$
	1.185	0.00210	$t > 550$
60° API	0.763	0.000446	$0 < t < 500$
	1.900	0.00242	$t > 500$

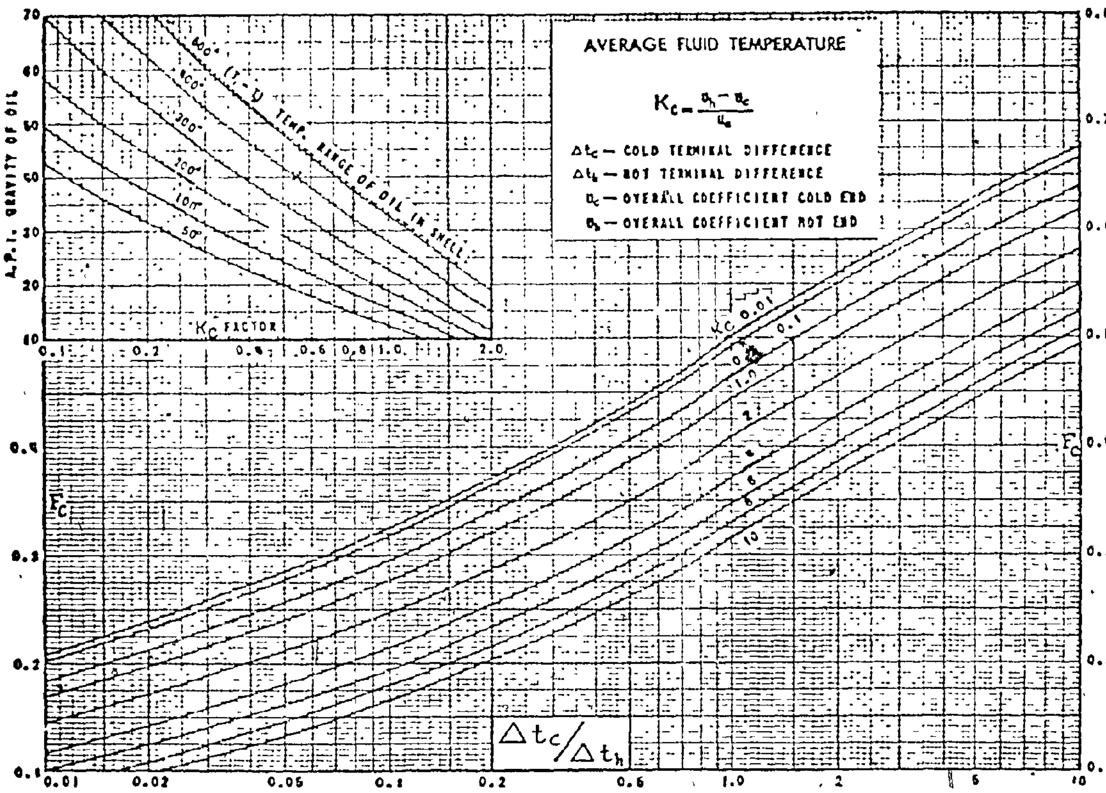

FIG. 17. The caloric temperature factor F_c. *(Standards of Tubular Exchanger Manufacturers Association, 2d ed., New York, 1949.)*

Fig. (7): The Caloric Temperature Factor K_c, F_c for Hydrocarbon Liquids

$$K_c = C_1 (\Delta T) + C_2$$

Liquid Oil	C_1	C_2
10° API	0.003820	1.12
15° API	0.003100	0.75
20° API	0.002380	0.38
25° API	0.002200	0.24
30° API	0.002000	0.10
35° API	0.001670	0.06
40° API	0.001340	0.02
45° API	0.001127	0.01
50° API	0.000914	0.00
55° API	0.000796	0.00
60° API	0.000678	0.00

$$F_c = \frac{\frac{1}{K_c} + \frac{R}{R-1}}{1 + \frac{\ln(K_c + 1)}{\ln(R)}} - \frac{1}{K_c}$$

where $R = \Delta t_1/\Delta t_2$

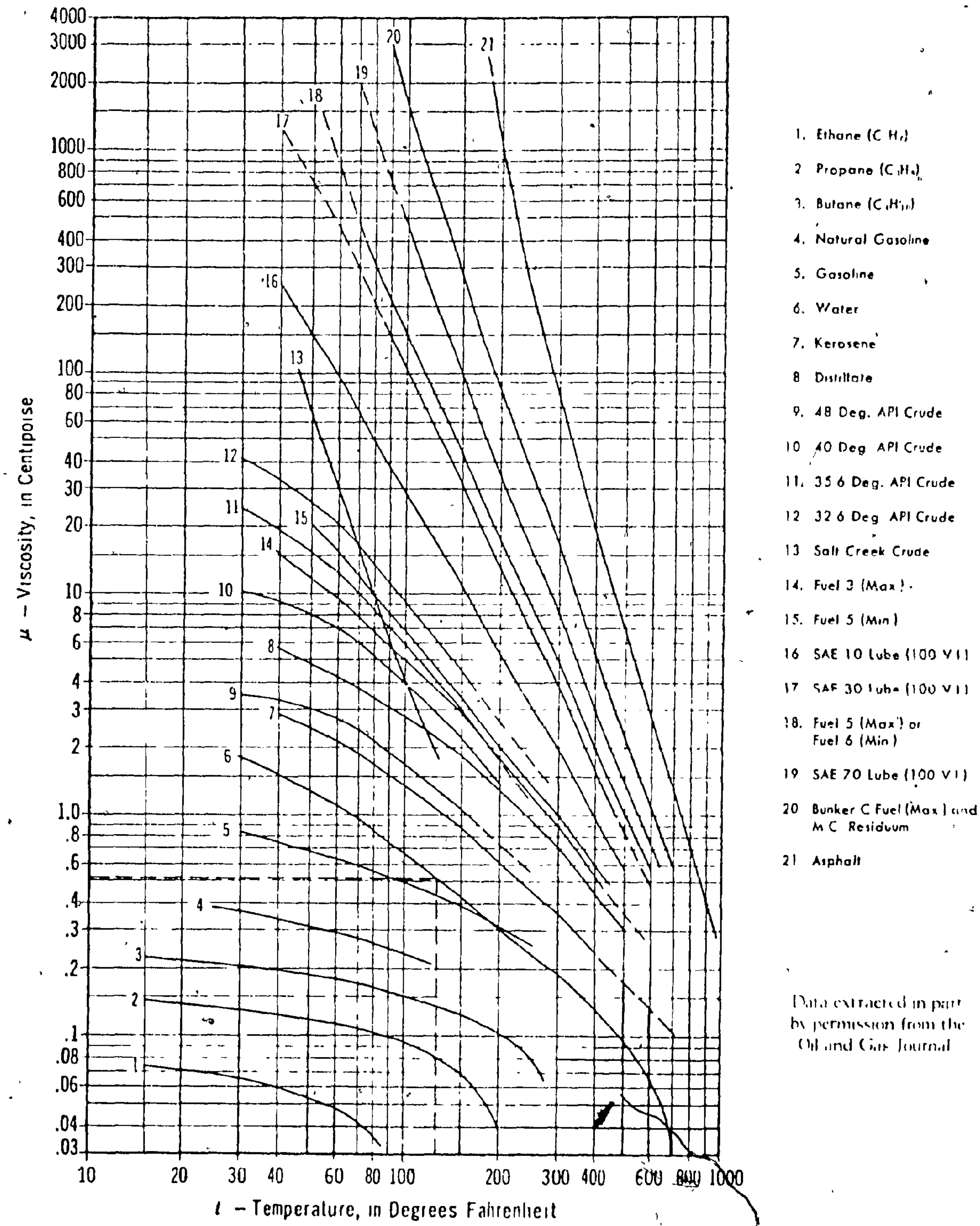

Fig. (8): Viscosity of Water and Petroleum Products

(See table on next page)

10 API	t(°F)	50	100	150	200	300	400	600
	μ(C.P.)	1500	150	45	17	5	2	0.6
20 API	t(°F)	50	100	150	200	300	400	600
	μ(C.P.)	150	28	12	5	2	0.95	0.4
30 API	t (F)	50	100	150	200	300	400	600
	μ(C.P.)	26	9	4.5	2.7	1.3	0.7	0.35
35 API	t(°F)	50	100	150	200	300	400	600
	μ(C.P.)	15	5.9	3	1.7	0.75	0.4	0.15
40 API	t(°F)	50	100	150	200	300	400	600
	μ(C.P.)	8	4	2.3	1.4	0.6	0.25	0.09
45 API	t(°F)	50	100	150	200	300	400	600
	μ(C.P.)	4.8	2.8	1.8	1.3	0.7	0.43	0.26
50 API	t(°F)	50	100	150	200	300	400	600
	μ(C.P.)	3	1.7	1.1	0.7	0.4	0.25	0.125
60 API	t(°F)	50	100	150	200	300	400	600
	μ(C.P.)	0.9	0.65	0.55	0.45	0.30	0.20	0.1

Viscosity Variation with Temperature for Hydrocarbon Liquids

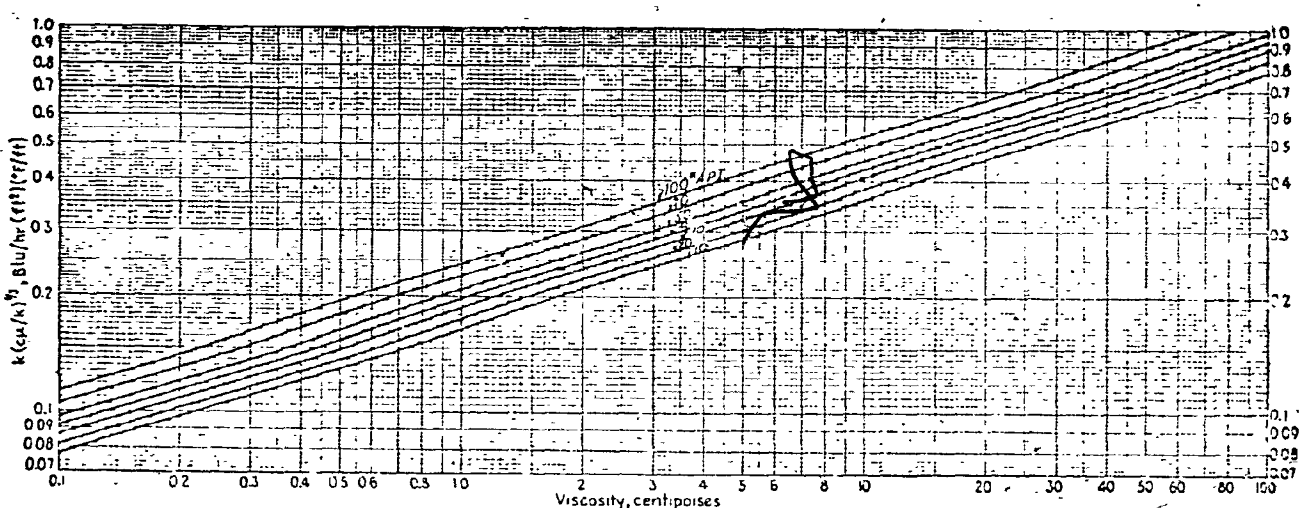

Fig. 16. Values of $k(c\mu/k)^{1/3}$ for hydrocarbons.

Fig. (9): Values of $K\left(\frac{C\mu}{K}\right)^{1/3}$ for Hydrocarbon Liquids

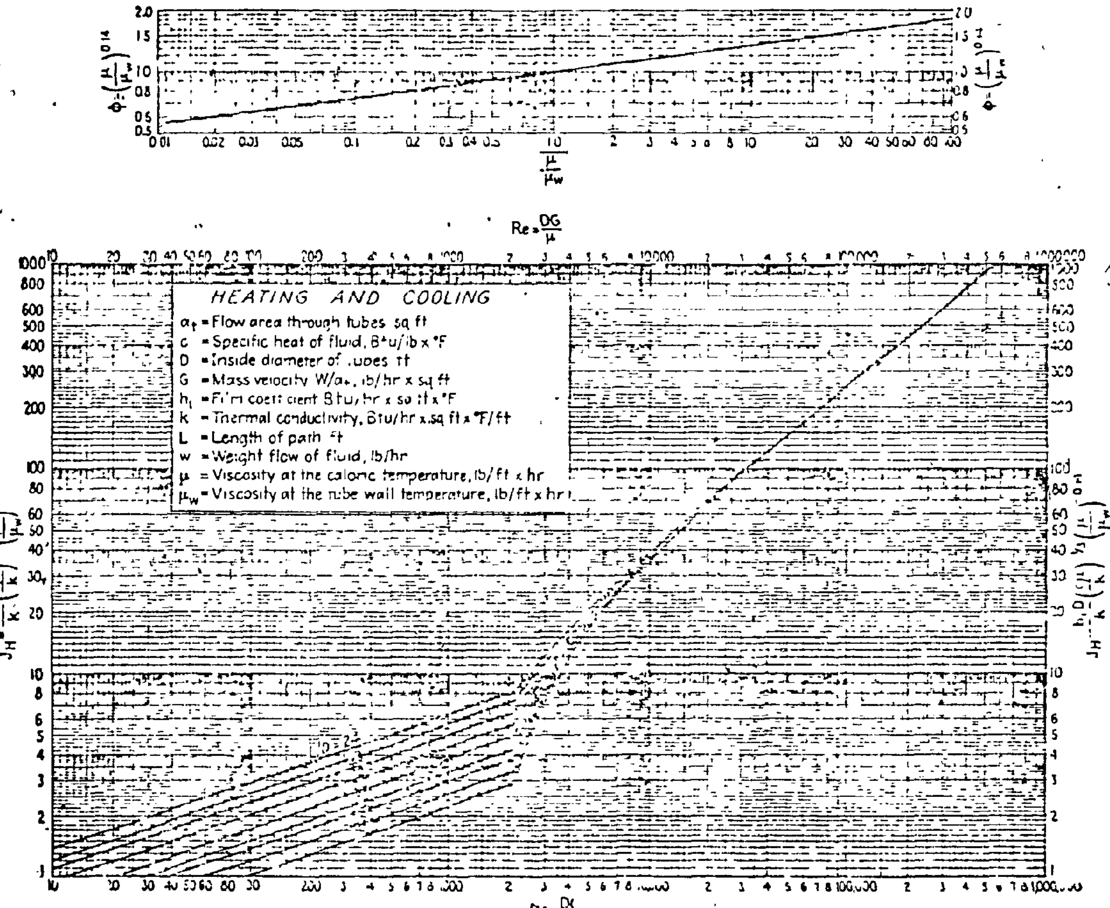

Fig. 24. Tube-side heat-transfer curve. *(Adapted from Sieder and Tate.)*

<u>**Fig. (10):**</u> <u>Tube Side Heat Transfer Curve</u>

FIG. (10) <u>Tube-Side Heat Transfer Coefficient</u>

L/D	$0 < Re. N^{\Omega} \le 2150$	$2150 \le Re < 3000$	$3000 \le Re < 5000$	$5000 \le Re \le 10{,}000$	$Re\ N^{\Omega} > 10{,}000$
24	$J_H = 0.64\ (Re)^{0.333}$	$J_H = 8.2 \times (\frac{Re}{2150})^{1.2655}$	$J_H = 12.5\ (\frac{Re}{3000})^{1.0156}$	$J_H = 21.0\ (\frac{Re}{5000})^{0.9115}$	
35	$J_H = 0.57\ (Re)^{0.333}$	$J_H = 7.5\ (\frac{Re}{2150})^{1.2568}$	$J_H = 11.4\ (\frac{Re}{3000})^{1.0508}$	$J_H = 19.5\ (\frac{Re}{5000})^{1.0074}$	
50	$J_H = 0.50\ (Re)^{0.333}$	$J_H = 6.5\ (\frac{Re}{2150})^{1.4108}$	$J_H = 10.4\ (\frac{Re}{3000})^{1.1797}$	$J_H = 19.0\ (\frac{Re}{5000})^{1.0189}$	
75	$J_H = 0.44\ (Re)^{0.333}$	$J_H = 5.8\ (\frac{Re}{2150})^{1.5437}$	$J_H = 9.7\ (\frac{Re}{3000})^{1.3161}$	$J_H = 19.0\ (\frac{Re}{5000})^{1.0189}$	
120	$J_H = 0.38\ (Re)^{0.333}$	$J_H = 5.0\ (\frac{Re}{2150})^{1.8303}$	$J_H = 9.2\ (\frac{Re}{3000})^{1.3139}$	$J_H = 18.0\ (\frac{Re}{5000})^{1.0395}$	$J_H = 0.02\ (Re)^{0.822}$
180	$J_H = 0.33\ (Re)^{0.333}$	$J_H = 4.1\ (\frac{Re}{2150})^{1.9110}$	$J_H = 9.0\ (\frac{Re}{3000})^{1.3569}$	$J_H = 18.0\ (\frac{Re}{5000})^{1.0395}$	
240	$J_H = 0.295\ (Re)^{0.333}$	$J_H = 3.75\ (\frac{Re}{2150})^{2.2743}$	$J_H = 8.0\ (\frac{Re}{3000})^{1.6198}$	$J_H = 18.0\ (\frac{Re}{5000})^{1.0395}$	
360	$J_H = 0.260\ (Re)^{0.333}$	$J_H = 3.25\ (\frac{Re}{2150})^{2.5102}$	$J_H = 7.5\ (\frac{Re}{3000})^{1.7138}$	$J_H = 18.0\ (\frac{Re}{5000})^{1.0395}$	
600	$J_H = 0.225\ (Re)^{0.333}$	$J_H = 2.9\ (\frac{Re}{2150})^{2.6451}$	$J_H = 7.0\ (\frac{Re}{3000})^{1.7370}$	$J_H = 17.0\ (\frac{Re}{5000})^{1.0825}$	

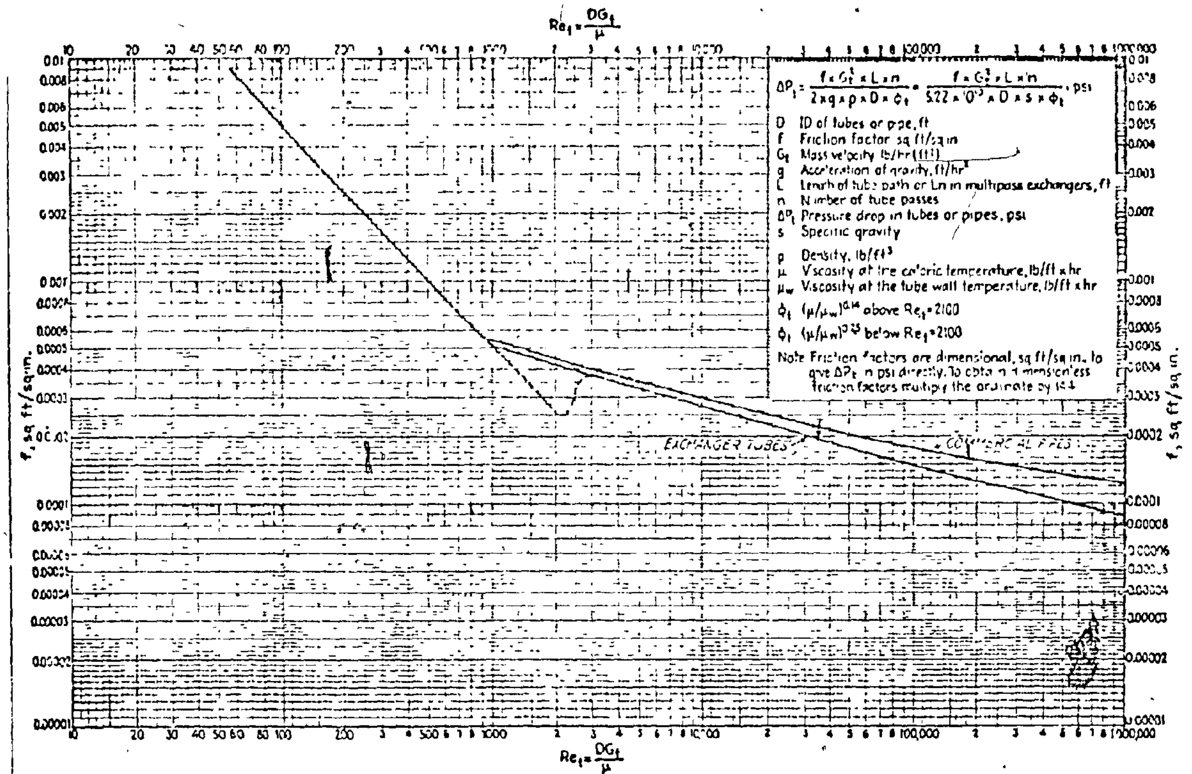

FIG. 20. Tube-side friction factors. (*Standards of Tubular Exchanger Manufacturers Association, 2d ed., New York, 1949.*)

<u>Fig. (11): Tube-Side Friction Factor</u>

$$f = C_1 (Re. N^{o})^{C_2}$$

C_1	=	0.5	&	C_2	=	1.00	Re N^o < 2000
C_1	=	1.65×10^{-8}	&	C_2	=	1.26	2000 < Re. N^o < 3000
C_1	=	0.0028	&	C_2	=	-0.25	Re. N^o > 3000

A

COPY

OF

THE COMPUTER PRINT-OUT

```
         C
         C         *** HEAT EXCHANGER DESIGN PROGRAM ***
         C
         C
   1           REAL KC,KC1,KC2
   2           DIMENSION IAPI(11),ATCON(11,2),ASPHT(11,2),ASPGRV(11,4),T(4),
              +AVISC(11,2),AKC(11,2),IAPIV(2), T11(15,7), T62(4,6),AJH(9,9)
              +,SHP(2),IAPIA(8),ATEM(13),AVIS(13,8),DARA(52),IBIG(2),NUM(2),
              +DEC(2),FRA(2),DARB(50,6)
   3           INTEGER S(6),SET(2),DARI(50,10)
   4           CHARACTER*10 NAME(56)
         C
         C      THIS READS IN DATA FOR :TH.CONDUCTIVITY,SP. HEAT,SP,GRAV,
         C      VISCOSITY,AND KC.
         C
   5         5 READ,((ATCON(I,J),J=1,2),I=1,11),((ASPHT(K,L),L=1,2),K=1,11),
              +((ASPGRV(I1,J1),J1=1,4),I1=1,11),((AVISC(I2,J2),J2=1,2),I2=1,11),
              +((AKC(I3,J3),J3=1,2),I3=1,11)
         C
         C      THIS GENARATES VALUES OF API IN INCREMENTS OF 5.
         C
   6           IS=0;DO3II=10,60,5;IS=IS+1
   9         3 IAPI(IS)=II
         C
         C      THIS READS TABLE-11,TABLE-6.2,AND DATA   FOR JH.
         C
  10           READ,(( T11(I,J),J=1,7),I=1,15),(( T62(K,L),L=1,6),K=1,4),
              +((AJH(M,NN),NN=1,9),M=1,9)
  11           READ,(IAPIA(I),I=1,8),(ATEM(J),J=1,13),((AVIS(KZ,LZ),LZ=1,8),KZ=1,
              +13)
  12           DO 1070 J=1,49,8;K=J+7
  14      1070 READ(5,158) (NAME(I),I=J,K)
  15       158 FORMAT(8A10)
  16           PRINT7
  17         7 FORMAT('1',37X,'*** H E A T   E X C H A N G E R   D E S I G N ***'/
              +/6X,60('*',1X)////)
         C      THIS IS A COUNTER FOR DESIGN PROBLEMS
  18           KOUNT=0
         C      THIS IS A COUNTER FOR THE TRIAL.
  19        10 ITRY=1
         C
         C      THIS READS DATA FOR DESIGN PROBLEM.
         C
  20           READ,(IAPIV(I),I=1,2),(T(J),J=1,4),WH,DP,DF,(S  (I),I=1,6),N,PL,EX
```

```
      IF(IAPIV(1).EQ.0) STOP
      SHP(1)=FLOAT(S(1))+FLOAT(S(2))/FLOAT(S(3))
      SHP(2)=FLOAT(S(4))+FLOAT(S(5))/FLOAT(S(6))
      KOUNT=KOUNT+1;PRINT107,KOUNT ;PRINT13,(S(I),I=1,6),PL,DF,DP;SW=-EX
  107 FORMAT( 5X,'** DESIGN PROBLEM # ',I2,' **'///5X,'** INPUT DATA **'
     +////5X,'** DESIGN CONSIDERATIONS **'//)
   13 FORMAT(5X,I1  ,1X,I1  ,'/',I1  ,' X ',I1  ,1X,I1  ,'/',I1  ,
     +' IPS',5X,F5.2,' FT. LONG',3X,'DIRT FACTOR (MAX.) = ',F6.4,5X,'MAX
     + PRESSURE DROP = ',F4.1,' PSI'///)
 2070 PRINT8
    8 FORMAT(19X,'API=PIPE FLUID',4X,'TEMP.-IN  ',3X,'TEMP.-OUT',4X,'API
     +=ANNULUS FLUID',7X,'TEMP.-IN ',6X,'TEMP.-OUT ',4X,'WH'/9X,115('*')
     +/)
      PRINT9,IAPIV((3+SW)/2),T(2+SW),T(3+SW),IAPIV((3-SW)/2),T(2-SW)
     +,T(3-SW),WH
    9 FORMAT(25X,I2,11X,F6.2,8X,F6.2,14X,I2,2X,2(11X,F6.2),2X,
     +F7.1)
C
C       CALCULATIONS THAT DO NOT INVOLVE N (#OF HAIRPINS).
C
      TA2=(T(1)+T(2))/2
      TA1=(T(3)+T(4))/2
      DT2=ABS(T(1)-T(4));DARA(8)=DT2
      DT1=ABS(T(2)-T(3));DARA(9)=DT1
      R=DT1/DT2;DARA(10)=R
      DT=ABS(T(1)-T(2));DARA(11)=DT
      ELMTD=ABS((DT2-DT1)/ALOG(DT2/DT1));DARA(12)=ELMTD
      KC1=FKC(IAPIV(1),DT,IAPI,AKC);KC2=FKC(IAPIV(2),DT,IAPI,AKC)
      IF(ABS(KC2).GT.ABS(KC1)) GOTO4010;KC=KC1; GOTO4020
 4010 KC=KC2
 4020 IF(KC.EQ.-1) GOTO10 ;DARA(13)=KC
      TC2=T(2)+FC(KC,R)*ABS(T(1)-T(2)) ;DARA(14)=TC2
      TC1=T(3)+FC(KC,R)*ABS(T(4)-T(3));DARA(15)=TC1
      CH=SPHEAT(IAPIV(1),TC2,IAPI,ASPHT);DARA(16)=CH
      CC=SPHEAT(IAPIV(2),TC1,IAPI,ASPHT);DARA(17)=CC
      UC=VISCOS(IAPIV(2),TC1,IAPIA,ATEM,AVIS);DARA(18)=UC
      UH=VISCOS(IAPIV(1),TC2,IAPIA,ATEM,AVIS);DARA(19)=UH
      Q=WH*CH*DT         ;DARA(20)=Q
      WC=Q/(CC*ABS(T(4)-T(3)));DARA(21)=WC
      PRINT163
  163  FORMAT(/////13X,'** RESULTS **')
C
C       THIS FINDS APPROPRIATE VALUES FROM TABLE  11,AND TABLE 6,2
      DO 55 IF=1,4
      IF((T62(IF,1).EQ.SHP(1)).AND.(T62(IF,2).EQ.SHP(2))) GOTO82
```

```
   55 CONTINUE
      PRINT42,(S(I),I=1,6)
   42 FORMAT(//30X,'*** NO DATA FOR ',I1,1X,I1,'/',I1,' X ',I1,1X,I1,
     +'/',I1,' IPS',10X,' - SMALLEST IPS TAKEN AS INITIAL SIZE ***'////)
      IF=1
 1090 SHP(1)=T62(IF,1);SHP(2)=T62(IF,2)
   82 DO 65 JF=1,15
      IF(T11(JF,1).EQ.SHP(2)) GOTO32
   65 CONTINUE
   32 AP=T62(IF,4);DARA(1)=AP
      AA=T62(IF,3);DARA(2)=AA
      D=T11(JF,3);DARA(3)=D
      DE=T62(IF,5);DARA(4)=DE
      DO=T11(JF,2);DARA(5)=DO
      AIN=T11(JF,5);DARA(6)=AIN
      DE1=T62(IF,6);DARA(7)=DE1
      WON=(1-SW)/2; ZERO=(1+SW)/2
      DIV1=AP*WON+AA*ZERO;DIV2=AP*ZERO+AA*WON
      GP=WH*144/DIV1;DARA(22)=GP
      GA=WC*144/DIV2;DARA(23)=GA
      REP=(DE*ZERO+D*WON)*GP/(UH*12);DARA(25)=REP;DARB(ITRY,1)=REP
      REA=(DE*WON+D*ZERO)*GA/(UC*12);DARA(24)=REA;DARB(ITRY,2)=REA
      TKP=TCOND(IAPIV(1),TC2,IAPI,ATCON);DARA(26)=TKP
      TKA=TCOND(IAPIV(2),TC1,IAPI,ATCON);DARA(27)=TKA
      CHECK1=CH*UH/TKP;CHECK2=CC*UC/TKA;IF ((CHECK1.LE.0).OR.(
     +CHECK2.LE.0)) GOTO3050;GOTO3070
 3050 PRINT3060 ;GOTO10
 3060 FORMAT(///20X,'*** WRONG DATA - EITHER SP.HEAT,OR VISCOSITY OR TH.
     + CONDUCTIVITY IS NEGATIVE ***',60(/))
 3070 FACTP=TKP*(CH*UH/TKP)**0.33333333;DARA(28)=FACTP
      FACTA=TKA*(CC*UC/TKA)**0.33333333;DARA(29)=FACTA
  130 DLP=PL*12*FLOAT(N)/(D*WON+DE*ZERO);DARA(30)=DLP
      DLA=PL*12*FLOAT(N)/(WON*DE+ZERO*D);DARA(31)=DLA
      HIFIP=FJH(REP,DLP,AJH)*FACTP*12/(D*WON+DE*ZERO);DARA(32)=HIFIP
      IF(HIFIP.LT.0) GOTO10
      HOFIA=FJH(REA,DLA,AJH)*FACTA*12/(DE*WON+D*ZERO);DARA(33)=HOFIA
      HIFI1=HIFIP*WON+HOFIA*ZERO;HIFI2=HIFIP*ZERO+HOFIA*WON
      HIOFIP=HIFI1*D/DO;DARA(34)=HIOFIP
      TW=TC1+(HIOFIP/(HIOFIP+HIFI2))*(TC2-TC1);DARA(35)=TW
      UWC=VISCOS(IAPIV(2),TW,IAPIA,ATEM,AVIS);DARA(36)=UWC
      UWH=VISCOS(IAPIV(1),TW,IAPIA,ATEM,AVIS);DARA(37)=UWH
      FIP=(UH/UWH)**0.14;DARA(38)=FIP
      FIA=(UC/UWC)**0.14;DARA(39)=FIA
      HIO=HIOFIP*(FIP*WON+FIA*ZERO);DARA(40)=HIO
      HO=HIFI2*(FIP*ZERO+FIA*WON);DARA(41)=HO
```

```
      UD=1/(1/HIO+1/HO+DF);DARA(42)=UD;DARB(ITRY,4)=UD
      A=Q/(UD*ELMTD);DARA(43)=A
      EL=A/AIN ;DARA(44)=EL
      EN=EL/PL;KK=INT(EN);DIFF=(EN-FLOAT(KK))*10
      IF(DIFF.EQ.0) GOTO91;NBIG=KK+1;GOTO53
   91 NBIG=KK
   53 REA1=DE1*(GA*WON+GP*ZERO)/((UC*WON+UH*ZERO)*12);DARA(46)=REA1
      DARA(45)=FLOAT(NBIG);DARB(ITRY,3)=REA1
      SP=SPGRAV(IAPIV(1),TC2,IAPI,ASPGRV) ;DARA(47)=SP
      SA=SPGRAV(IAPIV(2),TC1,IAPI,ASPGRV);DARA(48)=SA
      REPP=REP*WON+REA*ZERO
      FP=FRIC(REPP);DARA(49)=FP
      FA=FRIC(REA1) ;DARA(50)=FA
C
C      THIS CALCULATES THE PRESSURE DROPS ,DECIDES WHETHER TO RECALCU
C      -LATE OR NOT, AND PRINTS THE APPROPRIATE MESSAGE AND DATA.
C
      DPP1=GP**2;DPP2=FLOAT(NBIG)*12;DPP3=(FP*WON+FA*ZERO)*PL
      DPP4=5.22E10
      DPP5=(D*WON+DE*ZERO)*SP*FIP
      DPP=DPP1*DPP2*DPP3/(DPP4*DPP5);DARA(51)=DPP;DARB(ITRY,5)=DPP
      DPA1=GA**2;DPA3=(FA*WON+FP*ZERO)*PL;DPA4=(DE*WON+D*ZERO)*SA*FIA
      DPA=DPA1*DPP2*DPA3/(DPP4*DPA4);DARA(52)=DPA;PRINT110,ITRY,N
      CALL FRACTO(T62,IF,IBIG,DEC,FRA,NUM,SET);DARI(ITRY,1)=IBIG(1)
      DARI(ITRY,2)=NUM(1);DARI(ITRY,3)=SET(1);DARI(ITRY,4)=IBIG(2);DARI(
     +ITRY,5)=NUM(2);DARI(ITRY,6)=SET(2);DARI(ITRY,7)=N;DARI(ITRY,8)=IAP
     +IV(1)*WON+IAPIV(2)*ZERO;DARI(ITRY,9)=IAPIV(1)*ZERO+IAPIV(2)*WON
  110 FORMAT(//////5X,'* TRIAL # ',I2,5X,I3,' HAIRPINS *'/)
      DARI(ITRY,10)=NBIG;DARB(ITRY,6)=DPA;DO159 IK=1,52
  159 PRINT161,IK,NAME(IK),DARA(IK)
  161 FORMAT(6X,I2,':-',A10,'= ',F12.4)
      IF((DPP.GE.DP).OR.(DPA.GE.DP)) GOTO190;PRINT185;GOTO5000
  185 FORMAT(///47X,'*** PRESSURE DROPS ARE WITHIN LIMITS ***')
  190 PRINT195
  195 FORMAT(/49X,'*** PRESSURE DROPS ARE TOO HIGH ***')
      IF((REP.GT.10000).OR.(REA.GT.10000)) GOTO1000
      N=N+2;ITRY=ITRY+1;GOTO130
 1000 IF=IF+1 ;IF (IF.GT.4) GOTO1020
      CALL FRACTO(T62,IF,IBIG,DEC,FRA,NUM,SET)
      ITRY=ITRY+1;PRINT1010,IBIG(1),NUM(1),SET(1),IBIG(2),NUM(2),SET(2)
 1010 FORMAT(///30X,'*** RE > 10,000 ....=  NEW HAIRPIN SIZE: ',
     +I1,1X,I1,'/',I1,' X ',I1,1X,I1,'/',I1,' IPS ***'///)
      GOTO1090
 1020 IF(SW.EQ.EX)GOTO2090;PRINT1030
 1030 FORMAT(///45X,'*** NO DATA FOR REQUIRED LARGER HAIRPIN ***'///
```

```
     +50X,'** F L O W S   E X C H A N G E D **'///)
                SHP(1)=2;SHP(2)=1.25 ;ITRY=ITRY+1 ;SW=-SW
      CALL FRACTO(T62,1,IBIG,DEC,FRA,NUM,SET)
      PRINT4050,IBIG(1),NUM(1),SET(1),IBIG(2),NUM(2),SET(2)
 4050 FORMAT(45X,' NEW HAIRPIN SIZE:',2X,I1,1X,I1,'/',I1,' X ',I1,1X,
     +I1,'/',I1,'  IPS ***'///)
      GOTO2070
 2090 PRINT3000
 3000 FORMAT(///50X,'***  UNABLE TO SOLVE PROBLEM  ***'/////)
 5000 PRINT5010,KOUNT,Q,WH,WC
      DO5020 I=1,ITRY
      PRINT5030,I ,(DARI(I,K
     +),K=1,9),(DARB(I,L),L=1,4),DARI(I,10),(DARB(I,M),M=5,6)
 5020 CONTINUE;PRINT5050;GOTO10
 5010 FORMAT('1'/46X,'*** S U M M A R Y   O F   R E S U L T S ***'/////
     +6X,' ** DESIGN PROBLEM # ',I2,' **'//35X,'Q=',F12.4/34X,'WH=',
     +F12.4/34X,'WC=',F12.4/////4X,'TRIAL # ',5X,
     +'H.P. SIZE',5X,'H.P. #',3X,'API-PIPE',3X,'API-ANNULUS',4X,'RE-HOT'
     +,4X,'RE-CLD',6X,'REA*',9X,'UD',5X,'N',5X,'DP-HOT',5X,'DP-CLD'
     +/2X,130('*')///)
 5030 FORMAT(6X,I2,7X,I1,1X,I1,'/',I1,' X ',I1,1X,I1,'/',I1,3X,I2,9X,
     +I2,11X,I2,5X,4(F10.2,1X),1X,I2,2(F10.2,2X)/)
 5050 FORMAT('1')
      END

      FUNCTION VISCOS(IAPIVF,TCOF,IAPIAV,AT,AV)
      DIMENSION IAPIAV(8),AT(13),AV(13,8)
      DO 205 IV=2,13
      IF(TCOF.LE.AT(IV)) GOTO206
  205 CONTINUE
  206 DO 930 JV=2,6
      IF(IAPIVF.LE.IAPIAV(JV)) GOTO932
  930 CONTINUE
  932 FRAC1=(TCOF-AT(IV-1))/(AT(IV)-AT(IV-1))
      VIS1=(1-FRAC1)*(AV(IV-1,JV-1)-AV(IV,JV-1))+AV(IV,JV-1)
      VIS2=(1-FRAC1)*(AV(IV-1,JV)-AV(IV,JV))+AV(IV,JV)
      FRAC2=(IAPIVF-IAPIAV(JV-1))/(IAPIAV(JV)-IAPIAV(JV-1))
      VISCOS=((1-FRAC2)*(VIS1-VIS2)+VIS2)*2.42
      RETURN
      END

      FUNCTION SPGRAV(IAPIF,TSGF,IAPISG,ASG)
      DIMENSION ASG(11,4),IAPISG(11)
      DO 23 IFSG=1,11
      IF(IAPISG(IFSG).EQ.IAPIF) GOTO47
```

```
   23 CONTINUE
   47 KT=((IAPIF-40)/5)+1
      IF(KT.GE.1) GOTO(50,50,70,90,100),KT
   27 SPGRAV=ASG(IFSG,1)-ASG(IFSG,2)*TSGF
      GOTO15
   50 IF((TSGF.LT.700).AND.(TSGF.GT.0))GOTO27
      GOTO30
   70 IF((TSGF.LT.600).AND.(TSGF.GT.0)) GOTO27
      GOTO30
   90 IF((TSGF.LT.550).AND.(TSGF.GT.0)) GOTO27
      GOTO30
  100 IF((TSGF.LT.500).AND.(TSGF.GT.0)) GOTO27
   30 SPGRAV=ASG(IFSG,3)-ASG(IFSG,4)*TSGF
   15 RETURN
      END

      FUNCTION FC(FK,RF)
      FC=((1/FK)+(RF/(RF-1)))/(1+(ALOG(FK+1)/ALOG(RF)))-1/FK
      RETURN
      END

      FUNCTION FKC(IAPIFK,DTF,IAPIAK,AK)
      DIMENSION IAPIAK(11),AK(11,2)
      DO 210 IK=1,11
      IF(IAPIAK(IK).EQ.IAPIFK) GOTO211
  210 CONTINUE
      PRINT207,IAPIFK
  207 FORMAT(50X,'*** NO DATA FOR API #',I2,'***',60(/))
      FKC=-1
      RETURN
  211 FKC=AK(IK,1)*DTF+AK(IK,2)
      RETURN
      END

      FUNCTION FJH(RE,DUL,AJ)
      DIMENSION AJ(9,9)
      IF(RE.GT.10000) GOTO400
      DO 230 JH=1,8
      IF(DUL.LE.AJ(JH+1,1))GOTO231
  230 CONTINUE
      PRINT215,RE,DUL
  215 FORMAT(///,50X,'*** NO DATA FOR RE= ',F6.1,' AND L/D = ',F6.1,
     +' ***'///)
      FJH=-1
      RETURN
```

```
231 IF(RE.LT.2150) GOTO300
    IF(RE.LT.3000) GOTO240
    IF(RE.LT.5000) GOTO245
    F=RE/5000;KJ=8;GOTO250
240 F=RE/2150;KJ=4;GOTO250
300 F=RE;KJ=2;GOTO250
245 F=RE/3000;KJ=6
250 FJH1=AJ(JH,KJ)*F**AJ(JH,KJ+1)
    FJH2=AJ(JH+1,KJ)*F**AJ(JH+1,KJ+1)
    FJH=((DUL-AJ(JH,1))/(AJ(JH+1,1)-AJ(JH,1)))*(FJH2-FJH1)+FJH1
    RETURN
400 FJH=0.02*RE**0.322
    RETURN
    END

    FUNCTION TCOND(IAPIT,TTCF,IAPITA,ATC)
    DIMENSION IAPITA(11),ATC(11,2)
    DO 200 IFT=1,11
    IF(IAPITA(IFT).EQ.IAPIT) GOTO201
200 CONTINUE
201 TCOND=ATC(IFT,1)-ATC(IFT,2)*TTCF
    RETURN
    END

    FUNCTION SPHEAT(IAPISH,TSHF,IAPISA,ASH)
    DIMENSION IAPISA(11),ASH(11,2)
    DO 203 ISH=1,11
    IF(IAPISA(ISH).EQ.IAPISH) GOTO204
203 CONTINUE
204 SPHEAT=ASH(ISH,1)*(TSHF+100)+ASH(ISH,2)
    RETURN
    END

    FUNCTION FRIC(REF)
    IF(REF.GT.3000) GOTO500
    IF(REF.GT.2000) GOTO490
    FRIC=0.5/REF
    RETURN
490 FRIC=1.65E-8*(REF**1.26)
    RETURN
500 FRIC=0.0028/REF**0.25
    RETURN
    END

    SUBROUTINE FRACTO(T62F,IFF,IBIGF,DECF,FRAF,NUMF,SETF)
```

```
      DIMENSION T62F(4,6),IBIGF(2),DECF(2),FRAF(2),NUMF(2)
      INTEGER SETF(2)
      DO2020 IFK=1,2;DO2000 IFRAC=1,1000;IBIGF(IFK)=INT(T62F(IFF,IFK))
      DECF(IFK)=T62F(IFF,IFK)-FLOAT(IBIGF(IFK))
      FRAF(IFK)=DECF(IFK)*FLOAT(IFRAC);NUMF(IFK)=FRAF(IFK)
      IF(FRAF(IFK).EQ.INT(FRAF(IFK)))GOTO2020
 2000 CONTINUE
 2020 SETF(IFK)=IFRAC
      RETURN
      END
*DATA
```

```
*** H E A T   E X C H A N G E R   D E S I G N ***
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

** DESIGN PROBLEM #  1 **

** INPUT DATA **

** DESIGN CONSIDERATIONS **

2 1/2 X 1 1/4 IPS     40.00 FT. LONG   DIRT FACTOR (MAX.) = 0.0040     MAX PRESSURE DROP = 10.0 PSI

          API-PIPE FLUID   TEMP.-IN    TEMP.-OUT   API-ANNULUS FLUID    TEMP.-IN     TEMP.-OUT    WH
    ****************************************************************************************************
                40          325.00      375.00            25            450.00          350.00   12000.0

        ** RESULTS **

* TRIAL #  1    6 HAIRPINS *

  1:-AP     =     1.5000
  2:-AA     =     2.6300
  3:-D      =     1.3800
  4:-DE     =     2.0200
  5:-DO     =     1.6600
```

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6:=A*	=	0.4350
7:=DE*	=	0.8100
8:=DT2	=	75.0000
9:=DT1	=	25.0000
10:=RATIO	=	0.3333
11:=DT	=	100.0000
12:=LMTD	=	45.5120
13:=KC	=	0.4600
14:=TC2	=	387.9600
15:=TC1	=	343.9800
16:=CH	=	0.6103
17:=CC	=	0.6209
18:=MUC	=	1.0795
19:=MUH	=	2.6049
20:=Q	=	732377.3000
21:=WC	=	23592.6200
22:=G-HT	=	657034.1000
23:=G-CLD	=	2264892.0000
24:=RE-CLD	=	241283.2000
25:=RE-HT	=	42458.1600
26:=T-COND-HT	=	0.0672
27:=T-COND-CLD	=	0.0746
28:=FACT-HT	=	0.1929
29:=FACT-CLD	=	0.1551
30:=L/D-HT	=	1425.7420
31:=L/D-CLD	=	2086.9560
32:=HIFI-HT	=	145.9760
33:=HOFI-CLD	=	716.9534
34:=HIOFIP	=	596.0212
35:=TW	=	379.3074
36:=MUWC	=	0.7803
37:=MUWH	=	2.8248
38:=FI-HT	=	0.9887
39:=FI-CLD	=	1.0465
40:=HIO	=	623.7317
41:=HO	=	144.3294
42:=UD	=	79.7967
43:=A	=	201.6621
44:=L	=	463.5908
45:=N	=	12.0000
46:=REA*	=	17025.3000
47:=SP.GV.-HT	=	0.7802
48:=SP.GV.-CLD	=	0.7113
49:=FRIC-P	=	0.0001
50:=FRIC-A	=	0.0002

```
51:=DP=HT      =        7,4931
52:=DP=CLD     =       69,6166

                    *** PRESSURE DROPS ARE TOO HIGH ***

     *** RE > 10,000 ... =  NEW HAIRPIN SIZE: 3 0/1 X 2 0/1 IPS ***

* TRIAL #  2          6 HAIRPINS *

  1:=AP        =        3,3500
  2:=AA        =        2,9300
  3:=D         =        2,0670
  4:=DE        =        1,5700
  5:=DO        =        2,3800
  6:=A"        =        0,6220
  7:=DE"       =        0,6900
  8:=DT2       =       75,0000
  9:=DT1       =       25,0000
 10:=RATIO     =        0,3333
 11:=DT        =      100,0000
 12:=LMTD      =       45,5120
 13:=KC        =        0,4600
 14:=TC2       =      387,9600
 15:=TC1       =      343,9800
 16:=CH        =        0,6103
 17:=CC        =        0,6209
 18:=MUC       =        1,0795
 19:=MUH       =        2,6049
 20:=Q         =   732377,3000
 21:=WC        =    23592,6200
 22:=G=HT      =   589761,0000
 23:=G=CLD     =  1014130,0000
 24:=RE=CLD    =   161821,0000
 25:=RE=HT     =    29620,8400
```

```
26:=T=COND=HT  =      0,0672
27:=T=COND=CLD=       0,0746
28:=FACT=HT    =      0,1929
29:=FACT=CLD   =      0,1551
30:=L/D=HT     =   1834,3950
31:=L/D=CLD    =   1393,3230
32:=HIFI=HT    =    139,7018
33:=HOFI=CLD   =    344,6821
34:=HIOFIP     =    299,3521
35:=TW         =    373,9658
36:=MUWC       =      0,8255
37:=MUWH       =      2,9605
38:=FI=HT      =      0,9822
39:=FI=CLD     =      1,0383
40:=HIO        =    310,8074
41:=HO         =    137,2214
42:=UD         =     68,9421
43:=A          =    233,4127
44:=L          =    375,2615
45:=N          =     10,0000
46:=REA"       =  13018,0800
47:=SP,GV,=HT  =      0,7802
48:=SP,GV,=CLD=       0,7113
49:=FRIC=P     =      0,0001
50:=FRIC=A     =      0,0003
51:=DP=HT      =      6,9679
52:=DP=CLD     =      8,6490

                  *** PRESSURE DROPS ARE WITHIN LIMITS ***
```

*** S U M M A R Y   O F   R E S U L T S ***

** DESIGN PROBLEM # 1 **

Q= 732377.3000
WH= 12000.0000
WC= 23592.6200

TRIAL #.	H.P. SIZE	H.P. #	API-PIPE	API-ANNULUS	RE-HOT	RE-CLD	REA"	UD	N	DP-HOT	DP-CLD
1	2 1/2 X 1 1/4	6	40	25	42458.16	241283.20	17025.30	79.80	12	7.49	69.62
2	3 0/1 X 2 0/1	6	40	25	29620.85	161821.00	13018.08	68.94	10	6.97	8.65

** DESIGN PROBLEM # 2 **

** INPUT DATA **

** DESIGN CONSIDERATIONS **

2 1/2 X 1 1/4 IPS   40.00 FT. LONG   DIRT FACTOR (MAX.) = 0.0040   MAX PRESSURE DROP = 10.0 PSI

API-PIPE FLUID	TEMP.-IN	TEMP.-OUT	API-ANNULUS FLUID	TEMP.-IN	TEMP.-OUT	WH
25	450.00	350.00	40	325.00	375.00	12000.0

** RESULTS **

* TRIAL # 1   6 HAIRPINS *

1:-AP	=	1.5000
2:-AA	=	2.6300
3:-D	=	1.3800
4:-DE	=	2.0200
5:-DO	=	1.6600
6:-A"	=	0.4350
7:-DE"	=	0.8100
8:-DT2	=	75.0000
9:-DT1	=	25.0000
10:-RATIO	=	0.3333
11:-DT	=	100.0000

```
12:=LMTD        =     45.5120
13:=KC          =      0.4600
14:=TC2         =    387.9600
15:=TC1         =    343.9800
16:=CH          =      0.6103
17:=CC          =      0.6209
18:=MUC         =      1.0795
19:=MUH         =      2.6049
20:=Q           =  732377.3000
21:=WC          =   23592.6200
22:=G=HT        = 1152000.0000
23:=G=CLD       = 1291763.0000
24:=RE=CLD      =  201434.9000
25:=RE=HT       =   50857.3200
26:=T=COND=HT   =      0.0672
27:=T=COND=CLD  =      0.0746
28:=FACT=HT     =      0.1929
29:=FACT=CLD    =      0.1551
30:=L/D=HT      =   2086.9560
31:=L/D=CLD     =   1425.7420
32:=HIFI=HT     =    247.8519
33:=HOFI=CLD    =    422.2598
34:=H[illegible]OFIP       =    206.0454
35:=TW          =    358.4026
36:=MUWC        =      0.9573
37:=MUWH        =      3.3560
38:=FI=HT       =      0.9652
39:=FI=CLD      =      1.0170
40:=HIO         =    198.8656
41:=HO          =    429.4192
42:=UD          =     88.0495
43:=A           =    182.7605
44:=L           =    420.13[illegible]
45:=N           =     11.0000
46:=REA"        =   80773.3700
47:=SP.GV.=HT   =      0.7802
48:=SP.GV.=CLD  =      0.7113
49:=FRIC=P      =      0.0002
50:=FRIC=A      =      0.0002
51:=DP=HT       =     24.0846
52:=DP=CLD      =     19.1854
```

*** PRESSURE DROPS ARE TOO HIGH ***

*** RE > 10,000 ... = NEW HAIRPIN SIZE: 3 0/1 X 2 0/1 IPS ***

* TRIAL # 2 6 HAIRPINS *

1:=AP	=	3.3500
2:=AA	=	2,9300
3:=D	=	2,0670
4:=DE	=	1,5700
5:=DO	=	2,3800
6:=A"	=	0,6220
7:=DE"	=	0,6900
8:=DT2	=	75,0000
9:=DT1	=	25,0000
10:=RATIO	=	0,3333
11:=DT	=	100,0000
12:=LMTD	=	45,5120
13:=KC	=	0,4600
14:=TC2	=	387,9600
15:=TC1	=	343,9800
16:=CH	=	0,6103
17:=CC	=	0,6209
18:=MUC	=	1,0795
19:=MUH	=	2,6049
20:=Q	=	732377,3000
21:=WC	=	23592,6200
22:=G=HT	=	515820,8000
23:=G=CLD	=	1159500,0000
24:=RE=CLD	=	140530,5000
25:=RE=HT	=	3410[illegible],3700
26:=T=COND=HT	=	0,0672
27:=T=COND=CLD	=	0,0746
28:=FACT=HT	=	0,1929
29:=FACT=CLD	=	0,1551
30:=L/D=HT	=	1393,3230
31:=L/D=CLD	=	1834,3950

```
32:=HIFI-HT      =     119,1571
33:=HOFI-CLD     =     404,1106
34:=HIOFIP       =     103,4864
35:=TW           =     352,9463
36:=MUNC         =       1,0035
37:=MUWH         =       3,4946
38:=FI-HT        =       0,9597
39:=FI-CLD       =       1,0103
40:=HIO          =      99,3159
41:=HO           =     408,2585
42:=UD           =      60,5389
43:=A            =     265,8120
44:=L            =     427,3503
45:=N            =      11,0000
46:=REA*         =   61761,8600
47:=SP,GV,=HT    =       0,7802
48:=SP,GV,=CLD   =       0,7113
49:=FRIC-P       =       0,0002
50:=FRIC-A       =       0,0002
51:=DP-HT        =       3,5827
52:=DP-CLD       =      21,4093

                *** PRESSURE DROPS ARE TOO HIGH ***

      *** RE > 10,000 ... = NEW HAIRPIN SIZE: 4 0/1 X 3 0/1 IPS ***

* TRIAL #  3       6 HAIRPINS *

  1:=AP          =       7,3800
  2:=AA          =       3,1400
  3:=D           =       3,0680
  4:=DE          =       1,1400
  5:=DO          =       3,5000
  6:=A*          =       0,9170
```

```
 7:-DE"          =       0,5300
 8:-DT2          =      75,0000
 9:-DT1          =      25,0000
10:-RATIO        =       0,3333
11:-DT           =     100,0000
12:-LMTD         =      45,5120
13:-KC           =       0,4600
14:-TC2          =     387,9600
15:-TC1          =     343,9800
16:-CH           =       0,6103
17:-CC           =       0,6209
18:-MUC          =       1,0795
19:-MUH          =       2,6049
20:-Q            =  732377,3000
21:-WC           =   23592,6200
22:-G-HT         =  234146,3000
23:-G-CLD        = 1081954,0000
24:-RE-CLD       =   95216,8700
25:-RE-HT        =   22980,7600
26:-T-COND-HT    =       0,0672
27:-T-COND-CLD=          0,0746
28:-FACT-HT      =       0,1929
29:-FACT-CLD     =       0,1551
30:-L/D-HT       =     938,7222
31:-L/D-CLD      =    2526,3140
32:-HIFI-HT      =      58,0277
33:-HOFI-CLD     =     404,1387
34:-HIOFIP       =      50,8654
35:-TW           =     348,8965
36:-MUWC         =       1,0378
37:-MUWH         =       3,5975
38:-FI-HT        =       0,9558
39:-FI-CLD       =       1,0055
40:-HIO          =      48,6176
41:-HO           =     406,3701
42:-UD           =      36,9966
43:-A            =     434,9580
44:-L            =     474,3271
45:-N            =      12,0000
46:-REA"         =   44267,5200
47:-SP,GV,-HT    =       0,7802
48:-SP,GV,-CLD=          0,7113
49:-FRIC-P       =       0,0002
50:-FRIC-A       =       0,0002
51:-DP-HT        =       0,6613
```

```
52:=DP=CLD   =      30.5819

                *** PRESSURE DROPS ARE TOO HIGH ***

              *** NO DATA FOR REQUIRED LARGER HAIRPIN ***

                  ** F L O W S   E X C H A N G E D **

              NEW HAIRPIN SIZE:  2 0/1 X 1 1/4  IPS ***

     API=PIPE FLUID   TEMP.=IN   TEMP.=OUT   API=ANNULUS FLUID   TEMP.=IN   TEMP.=OUT   WH
*******************************************************************************************
            40        325.00     375.00            25            450.00     350.00   12000.0

  ** RESULTS **

* TRIAL #  4      6 HAIRPINS *

   1:=AP     =      1.5000
   2:=AA     =      1.1900
   3:=D      =      1.3800
   4:=DE     =      0.9150
   5:=DO     =      1.6600
   6:=A"     =      0.4350
   7:=DE"    =      0.4000
   8:=DT2    =     75.0000
   9:=DT1    =     25.0000
```

```
10:=RATIO        =        0,3333
11:=DT           =      100,0000
12:=LMTD         =       45,5120
13:=KC           =        0,4600
14:=TC2          =      387,9600
15:=TC1          =      343,9800
16:=CH           =        0,6103
17:=CC           =        0,6209
18:=MUC          =        1,0795
19:=MUH          =        2,6049
20:=Q            =   732377,3000
21:=WC           =    23592,6200
22:=G=HT         =  1452101,0000
23:=G=CLD        =  2264892,0000
24:=RE=CLD       =   241283,2000
25:=RE=HT        =    42504,9600
26:=T=COND=HT    =        0,0672
27:=T=COND=CLD   =        0,0746
28:=FACT=HT      =        0,1929
29:=FACT=CLD     =        0,1551
30:=L/D=HT       =     3147,5400
31:=L/D=CLD      =     2086,9560
32:=HIFI=HT      =      322,5554
33:=HOFI=CLD     =      716,9534
34:=HIOFIP       =      596,0212
35:=TW           =      372,5164
36:=MUWC         =        0,8378
37:=MUWH         =        2,9974
38:=FI=HT        =        0,9805
39:=FI=CLD       =        1,0361
40:=HIO          =      617,5520
41:=HO           =      316,2805
42:=UD           =      113,8817
43:=A            =      141,3044
44:=L            =      324,8376
45:=N            =        9,0000
46:=REA"         =    18581,4000
47:=SP,GV,=HT    =        0,7802
48:=SP,GV,=CLD   =        0,7113
49:=FRIC=P       =        0,0001
50:=FRIC=A       =        0,0002
51:=DP=HT        =       59,7837
52:=DP=CLD       =       52,7349

                  *** PRESSURE DROPS ARE TOO HIGH ***
```

***. RE > 10,000 ... = NEW HAIRPIN SIZE: 2 1/2 X 1 1/4 IPS ***

* TRIAL # 5 6 HAIRPINS *

1:=AP	=	1,5000
2:=AA	=	2,6300
3:=D	=	1,3800
4:=DE	=	2,0200
5:=DO	=	1,6600
6:=A"	=	0,4350
7:=DE"	=	0,8100
8:=DT2	=	75,0000
9:=DT1	=	25,0000
10:=RATIO	=	0,3333
11:=DT	=	100,0000
12:=LMTD	=	45,5120
13:=KC	=	0,4600
14:=TC2	=	387,9600
15:=TC1	=	343,9800
16:=CH	=	0,6103
17:=CC	=	0,6209
18:=MUC	=	1,0795
19:=MUH	=	2,6049
20:=Q	=	732377,3000
21:=WC	=	23592,6200
22:=G=HT	=	657034,1000
23:=G=CLD	=	2264892,0000
24:=RE=CLD	=	241283,2000
25:=RE=HT	=	42458,1600
26:=T=COND=HT	=	0,0672
27:=T=COND=CLD	=	0,0746
28:=FACT=HT	=	0,1929
29:=FACT=CLD	=	0,1551

```
30:=L/D=HT       =    1425,7420
31:=L/D=CLD      =    2086,9560
32:=HIFI=HT      =     145,9760
33:=HOFI=CLD     =     716,9534
34:=HIOFIT       =     596,0212
35:=TW           =     379,3074
36:=MUWC         =       0,7803
37:=MUWH         =       2,8248
38:=FI=HT        =       0,9887
39:=FI=CLD       =       1,0465
40:=HIO          =     623,7317
41:=HO           =     144,3294
42:=UD           =      79,7967
43:=A            =     201,6621
44:=L            =     463,5908
45:=N            =      12,0000
46:=REA"         =   17025,3000
47:=SP,GV,=HT    =       0,7802
48:=SP,GV,=CLD   =       0,7113
49:=FRIC=P       =       0,0001
50:=FRIC=A       =       0,0002
51:=DP=HT        =       7,4931
52:=DP=CLD       =      69,6166

                    *** PRESSURE DROPS ARE TOO HIGH ***

       *** RE > 10,000 ... =  NEW HAIRPIN SIZE: 3 0/1 X 2 0/1 IPS ***

 * TRIAL #  6        6 HAIRPINS *

 1:=AP           =       3,3500
 2:=AA           =       2,9300
 3:=D            =       2,0670
 4:=DE           =       1,5700
```

5:=DO	=	2,3800
6:=A*	=	0,6220
7:=DE*	=	0,6900
8:=DT2	=	75,0000
9:=DT1	=	25,0000
10:=RATIO	=	0,3333
11:=DT*	=	100,0000
12:=LMTD	=	45,5120
13:=KC	=	0,4600
14:=TC2	=	387,9600
15:=TC1	=	343,9800
16:=CH	=	0,6103
17:=CC	=	0,6209
18:=[illegible]	=	1,0795
19:=M[illegible]	=	2,6049
20:=Q	=	732377,3000
21:=WC	=	23592,6200
22:=G-HT	=	589761,0000
23:=G-CLD	=	1014130,0000
24:=RE-CLD	=	161821,0000
25:=RE-HT	=	29620,8400
26:=T-COND-HT	=	0,0672
27:=T-COND-CLD	=	0,0746
28:=FACT-HT	=	0,1929
29:=FACT-CLD	=	0,1551
30:=L/D-HT	=	1834,3950
31:=L/D-CLD	=	1393,3230
32:=HIFI-HT	=	139,7018
33:=HOFI-CLD	=	344,6821
34:=HIOFIP	=	299,3521
35:=TW	=	373,9658
36:=MUWC	=	0,8255
37:=MUWH	=	2,9605
38:=FI-HT	=	0,9822
39:=FI-CLD	=	1,0383
40:=HIO	=	310,8074
41:=HO	=	137,2214
42:=UD	=	68,9421
43:=A	=	233,4127
44:=L	=	375,2615
45:=N	=	10,0000
46:=REA*	=	13018,0800
47:=BP,GV,-HT	=	0,7802
48:=BP,GV,-CLD	=	0,7113
49:=FRIC-P	=	0,0001

```
50:=FRIC=A     =      0.0003
51:=DP=HT      =      6.9679
52:=DP=CLD     =      8.6490
```

*** PRESSURE DROPS ARE WITHIN LIMITS ***

*** SUMMARY OF RESULTS ***

** DESIGN PROBLEM # 2 **

Q= 732377.3000
WH= 12000.0000
WC= 23592.6200

TRIAL #	H.P. SIZE	H.P. #	API-PIPE	API-ANNULUS	RE-HOT	RE-CLD	REA*	UD	N	DP-HOT	DP-CLD
1	2 1/2 X 1 1/4	6	25	40	50857.32	201434.90	80773.38	88.05	11	24.08	19.19
2	3 0/1 X 2 0/1	6	25	40	34108.37	140530.50	61761.87	60.54	11	3.58	21.41
3	4 0/1 X 3 0/1	6	25	40	22980.77	95216.88	44267.52	37.00	12	0.60	30.58
4	2 0/1 X 1 1/4	6	40	25	42504.96	241283.20	18581.41	113.88	9	59.78	52.73
5	2 1/2 X 1 1/4	6	40	25	42458.16	241283.20	17025.30	79.80	12	7.49	69.62
6	3 0/1 X 2 0/1	6	40	25	29620.85	161821.00	13018.08	68.94	10	6.97	8.65

```
CORE USAGE      OBJECT CODE=  22064 BYTES,ARRAY AREA=    6036 BYTES,TOTAL AREA AVAILABLE=  495616  BYTES
DIAGNOSTICS       NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=       0
COMPILE TIME=     0.17 SEC,EXECUTION TIME=     0.17 SEC,     17.05.09     MONDAY       23 APR 79     WATFIV - JAN 1976 V1L5

        C*STOP
```