CHAPTER 6

COMPUTER PROGRAM FOR THE DESIGN OF PLATE HEAT EXCHANGERS

A simple computer program, which is coded in TURBO BASIC, is presented in appendix A6. The program uses the Effectiveness-NTU, or E-NTU, approach as design procedure and uses the published E-NTU relationships for the countercurrent flow configuration of two channels per loop as presented in Fig. 2.5.4. The configuration is similar to the flow arrangement of the plate heat exchanger in the present experiments. In case of turbulent-flow liquid/liquid heat exchanger the experimental correlation obtained in the present study is applicable. Therefore,

$$Nu = 0.02\ Re^{0.87}\ Pr^{0.78} \qquad (6-1)$$

The computer program requires the design engineer to make simplifying assumptions that would guide line in the selection of a small set of flow patterns, which should provide a design close to the optimum in most cases. The following simplifying assumption are implicit in the design method [1,16].

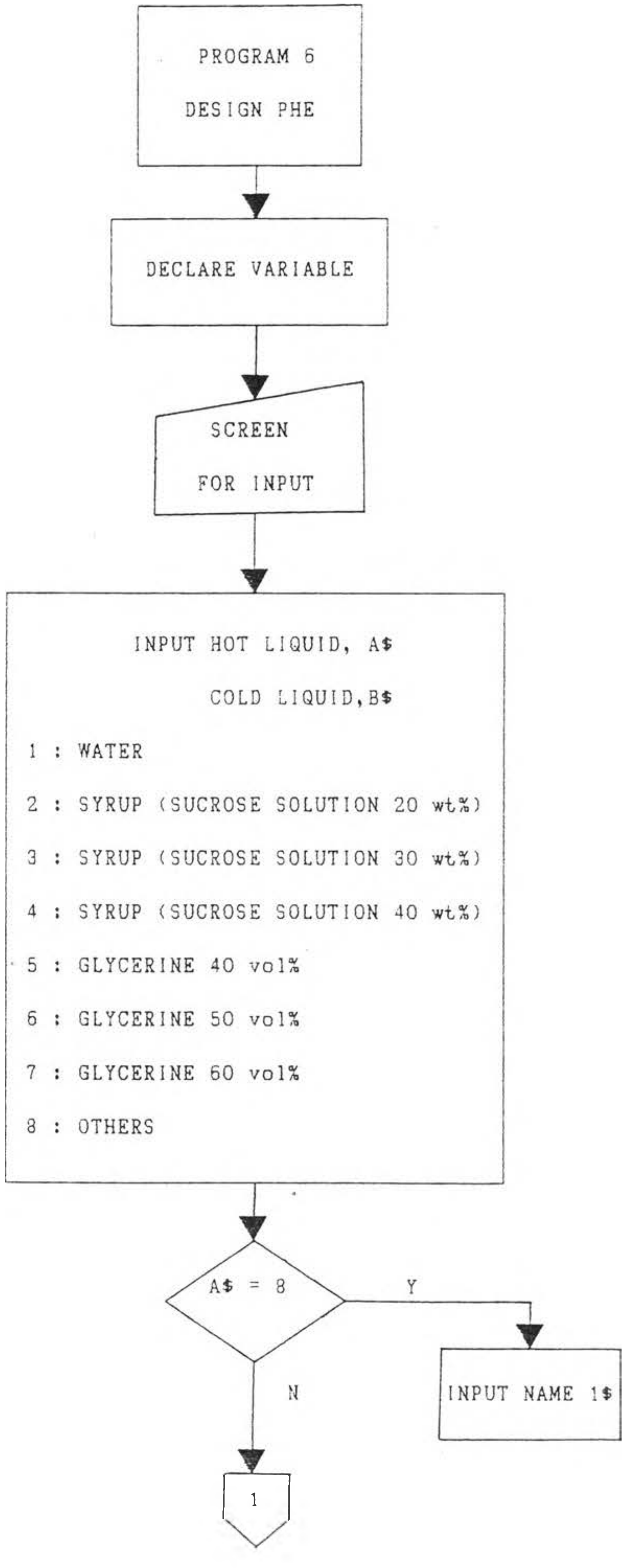
1. Heat losses are negligible.
2. There are no air pockets in the exchangers
3. The average overall heat transfer coefficient is constant throughout the exchanger.
4. Channel temperature varies only in the flow direction.
5. The stream splits equally between channels in the case

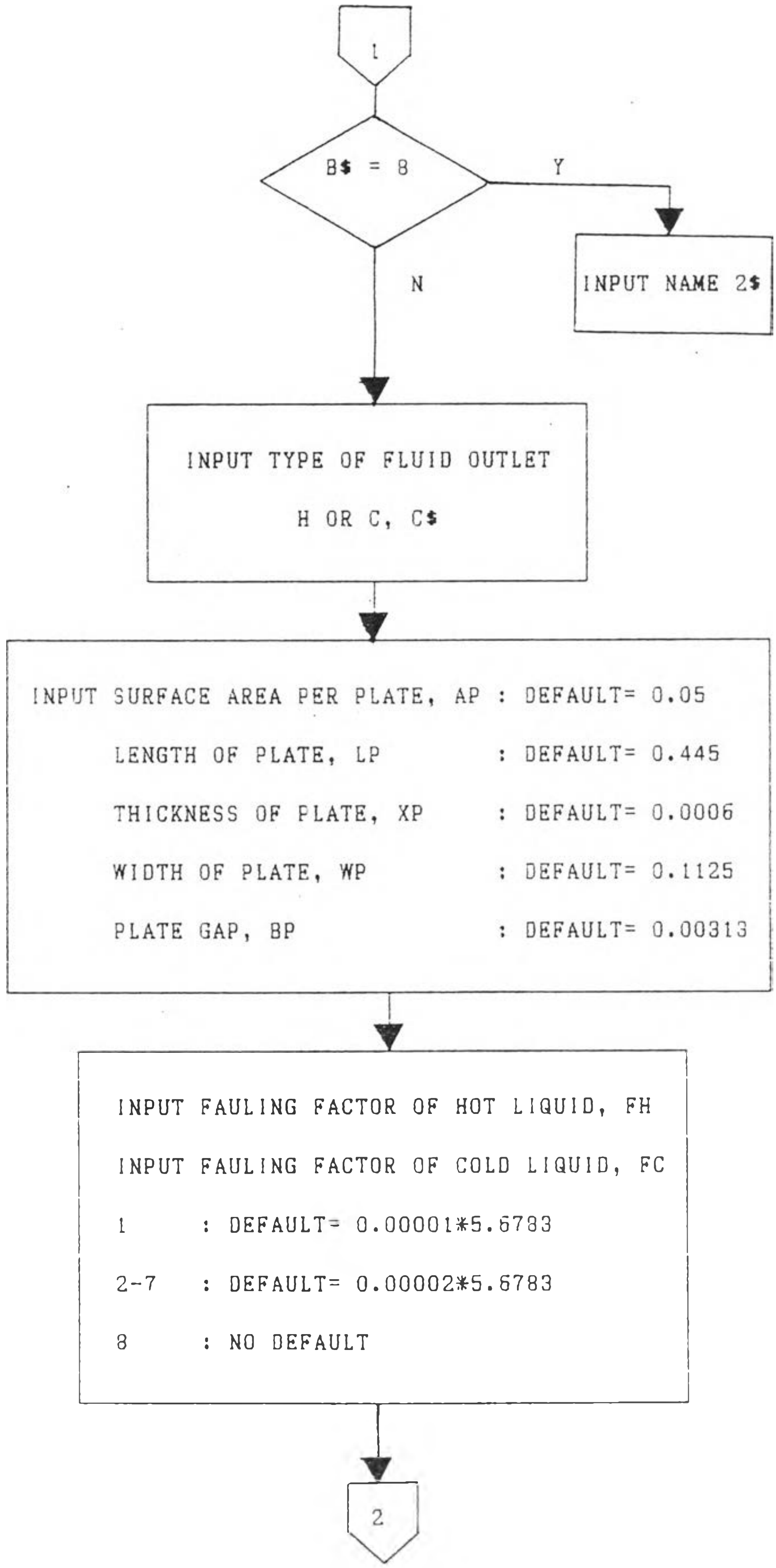
of parallel flow.

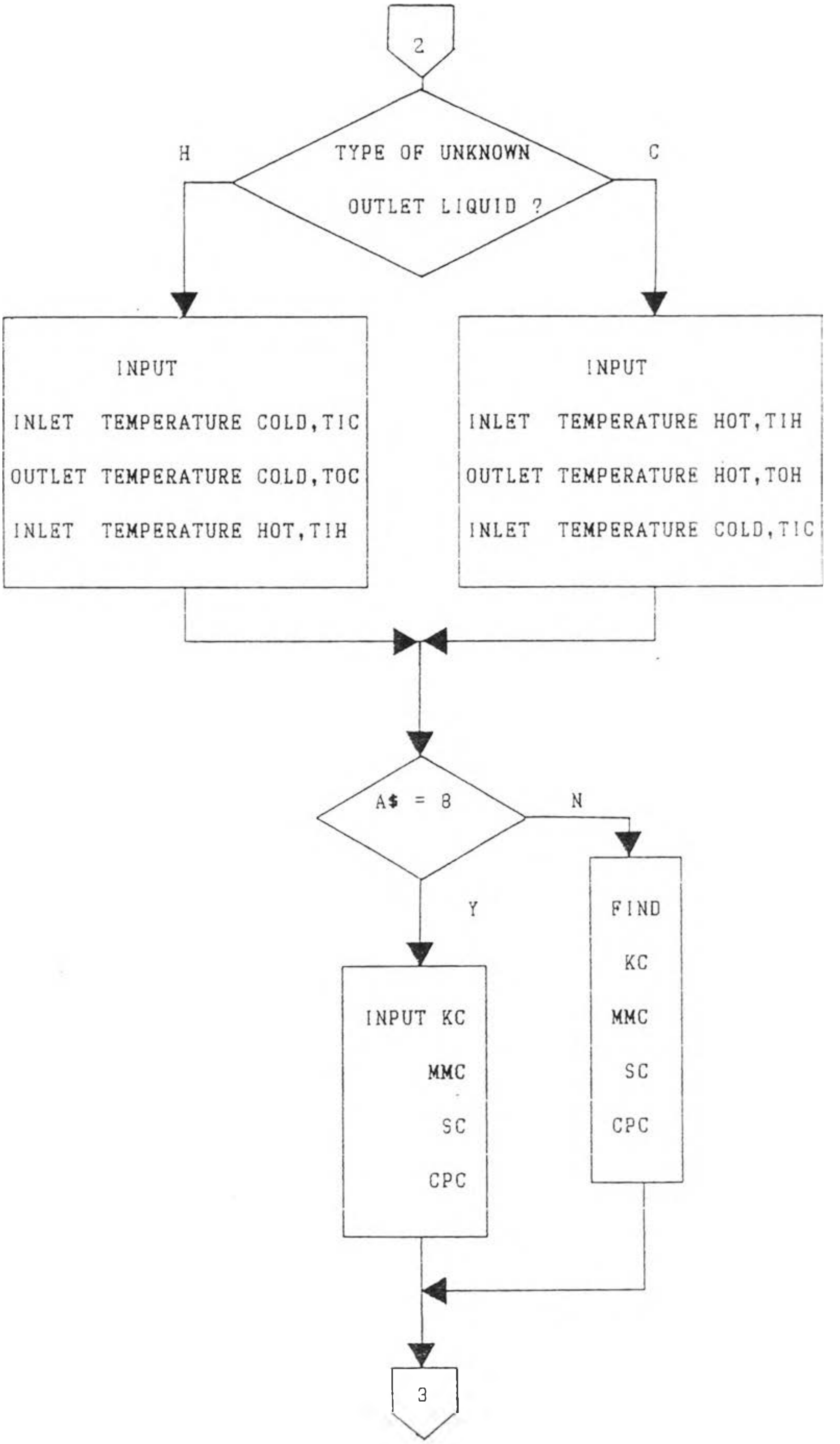
The program contains default values of the characteristics of the plate exchanger as given in section 4.1.1, the fouling factor as given in section 2.4, and the physical properties of the liquids used in the present study. Of course other liquids may be selected, but their physical properties must be input into the program for use in the calculation of the Reynolds number, pressure drop, heat transfer rate, the overall heat transfer coefficient, the total surface area, and the number of thermal plates.

The limitation of the program is that specifed the flow loop pattern must be as specified, the corrugation on the plate should be chevron (θ = 50 degress) as presented in Fig(4.2), the temperature should be between 273 and 410 K the range of operation for the nitrile rubber gaskets, and the flow must be in the turbulent regime (fully turbulent flow begins at Re = 1,000, and the transition regime is between Re 10 - 150), in which the heat transfer correlation obtained is applicable.

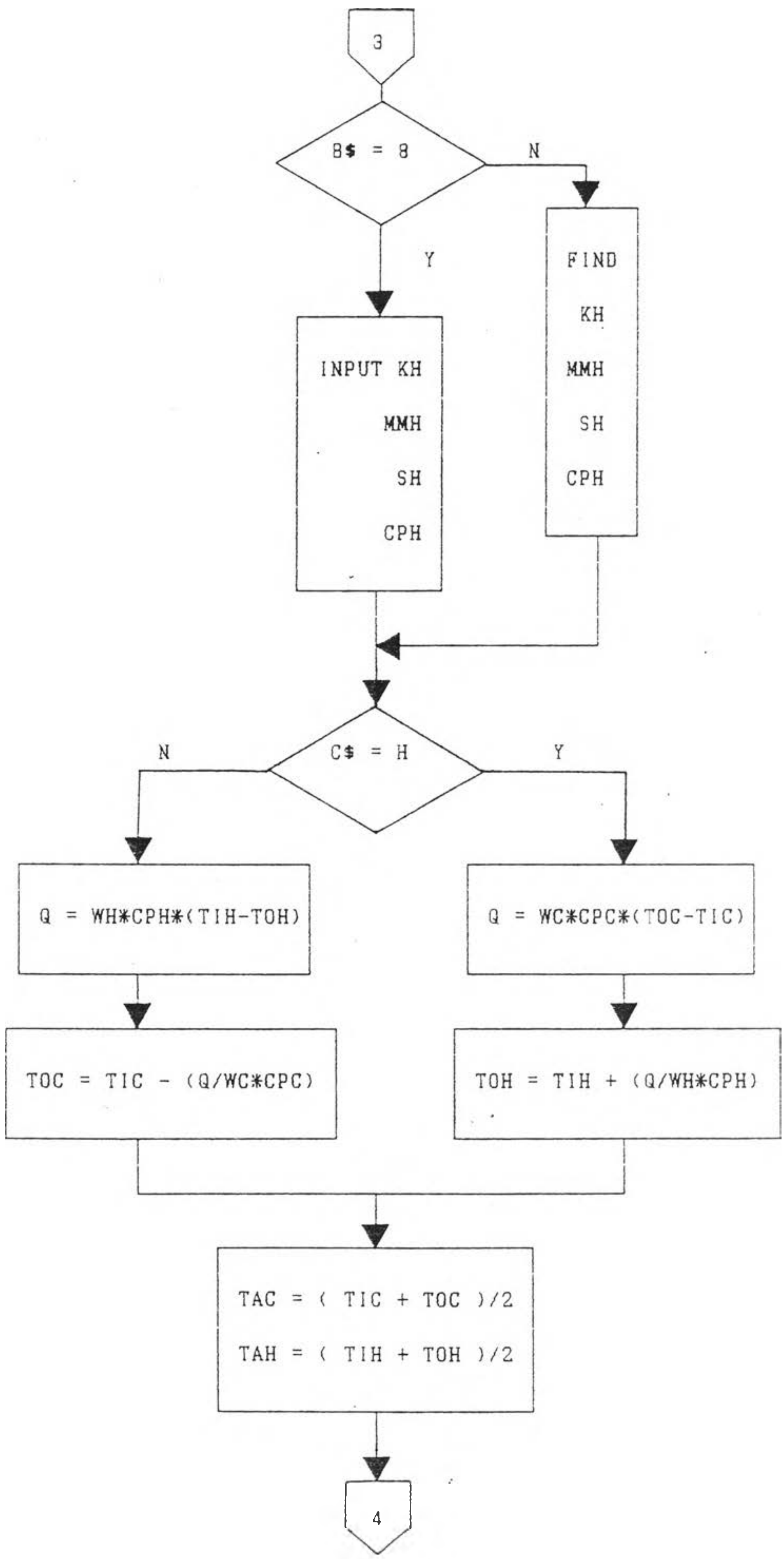
The simplified flow chart is presented as follow:

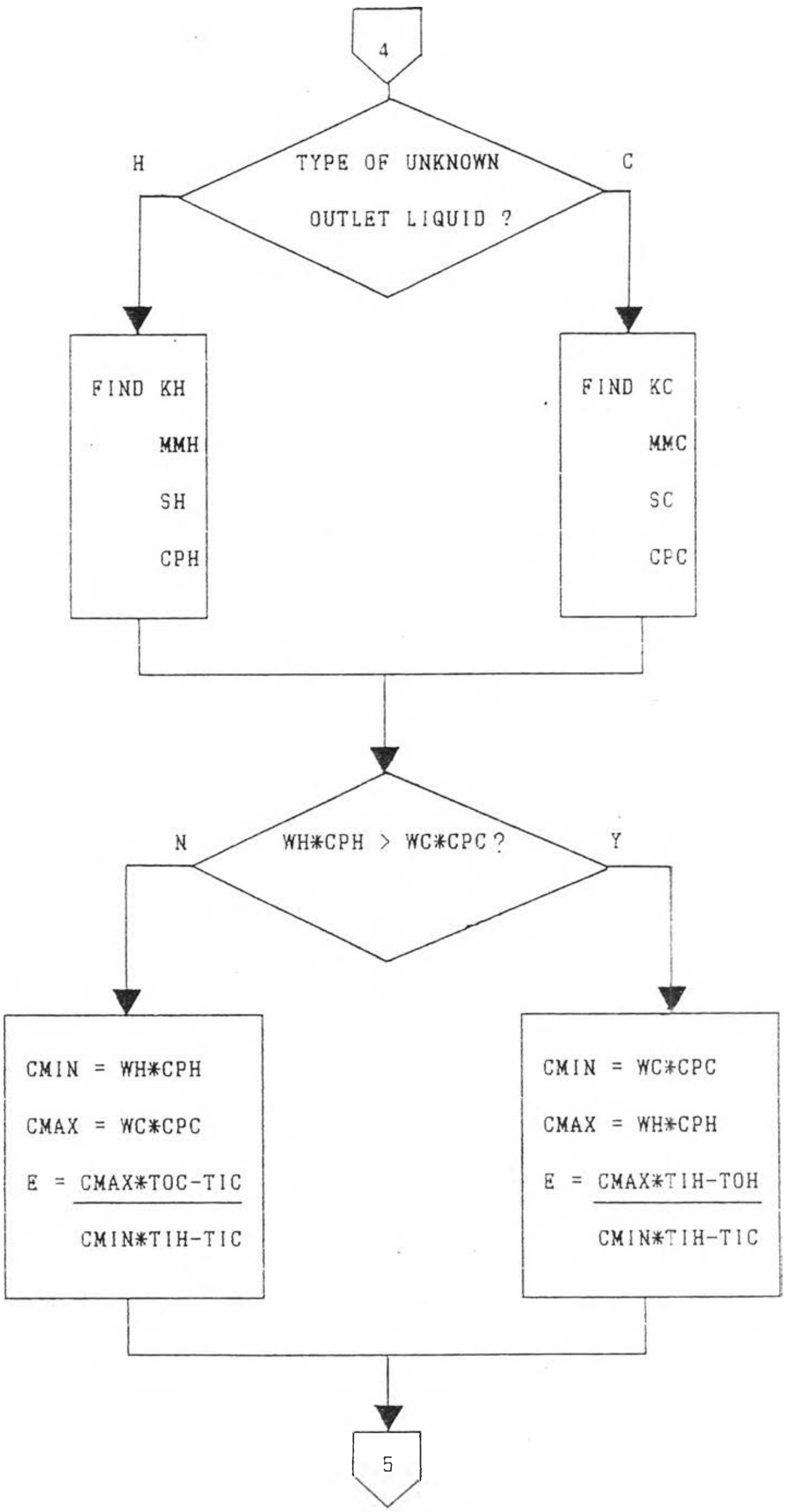

PROGRAM 6
DESIGN PHE
DECLARE VARIABLE
SCREEN
FOR INPUT
INPUT HOT LIQUID, A$
COLD LIQUID,B$
1 : WATER
2 : SYRUP (SUCROSE SOLUTION 20 wt%)
3 : SYRUP (SUCROSE SOLUTION 30 wt%)
4 : SYRUP (SUCROSE SOLUTION 40 wt%)
5 : GLYCERINE 40 vol%
6 : GLYCERINE 50 vol%
7 : GLYCERINE 60 vol%
8 : OTHERS
A$ = 8
Y
INPUT NAME 1$
N
1


1
B$ = 8
Y
N
INPUT NAME 2$
INPUT TYPE OF FLUID OUTLET
H OR C, C$
INPUT SURFACE AREA PER PLATE, AP : DEFAULT= 0.05
LENGTH OF PLATE, LP : DEFAULT= 0.445
THICKNESS OF PLATE, XP : DEFAULT= 0.0006
WIDTH OF PLATE, WP : DEFAULT= 0.1125
PLATE GAP, BP : DEFAULT= 0.00313
INPUT FAULING FACTOR OF HOT LIQUID, FH
INPUT FAULING FACTOR OF COLD LIQUID, FC
1 : DEFAULT= 0.00001*5.6783
2-7 : DEFAULT= 0.00002*5.6783
8 : NO DEFAULT
2



2
TYPE OF UNKNOWN OUTLET LIQUID ?
H
C
INPUT
INLET TEMPERATURE COLD,TIC
OUTLET TEMPERATURE COLD,TOC
INLET TEMPERATURE HOT,TIH
INPUT
INLET TEMPERATURE HOT,TIH
OUTLET TEMPERATURE HOT,TOH
INLET TEMPERATURE COLD,TIC
A$ = 8
N
Y
INPUT KC
MMC
SC
CPC
FIND
KC
MMC
SC
CPC
3


3
B$ = 8
N
Y
FIND
KH
MMH
SH
CPH
INPUT KH
MMH
SH
CPH
C$ = H
N
Y
Q = WH*CPH*(TIH-TOH)
Q = WC*CPC*(TOC-TIC)
TOC = TIC - (Q/WC*CPC)
TOH = TIH + (Q/WH*CPH)
TAC = (TIC + TOC)/2
TAH = (TIH + TOH)/2
4

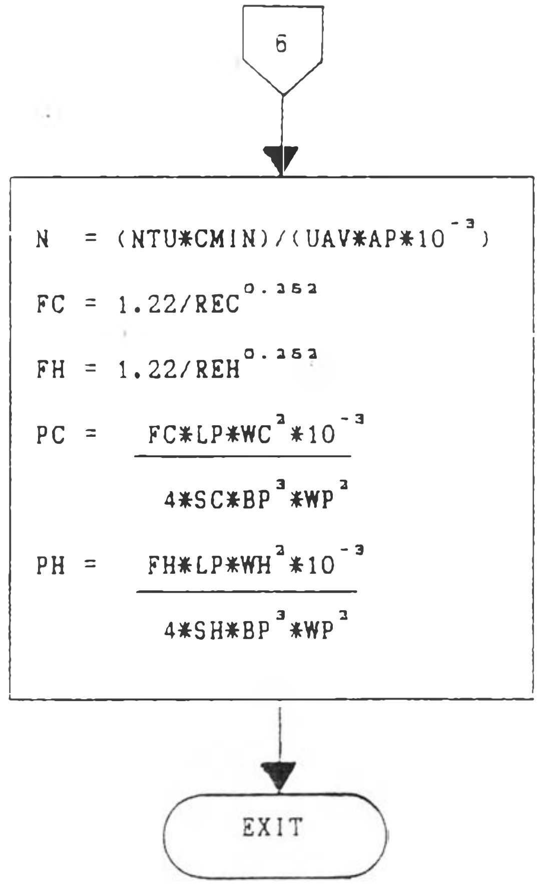

4
TYPE OF UNKNOWN
OUTLET LIQUID ?
H
C
FIND KH
MMH
SH
CPH
FIND KC
MMC
SC
CPC
WH*CPH > WC*CPC ?
N
Y
CMIN = WH*CPH
CMAX = WC*CPC
E = CMAX*TOC-TIC
CMIN*TIH-TIC
CMIN = WC*CPC
CMAX = WH*CPH
E = CMAX*TIH-TOH
CMIN*TIH-TIC
5

5

```
R     = CMIN/CMAX
REC  =  WH/(WP*MMH)
REH  =  WC/(WP*MMC)
W(1)=  0.02*REH^0.87
W(2)=  (CPH*MMH/KH*10^-3)
W(3)=  KH/(2*BP)
HH   =  W(1)*W(2)*W(3)
W(1)=  0.02*REC^0.87
W(2)=  (CPC*MMC/KC*10^-3)
W(3)=  KC/(2*BP)
HC   =  W(1)*W(2)*W(3)
W(1)=  1/HH
W(2)=  1/HC
W(3) =  XP/16.26858
UAV  = 1/(W(1)+W(2)+W(3)+FH(1)+FC(1))
```

FIND NTU

6


6
N = (NTU*CMIN)/(UAV*AP*10^-3)
FC = 1.22/REC^0.252
FH = 1.22/REH^0.252
PC = FC*LP*WC^2*10^-3 / 4*SC*BP^3*WP^2
PH = FH*LP*WH^2*10^-3 / 4*SH*BP^3*WP^2
EXIT

5.1 Design Examples

The following examples illustrate the working of the developed computer code. Examples 1 to 3 rely on experimental data, and the last example is taken from a reference [4]. The purpose of calculations is to find the outlet temperature of either the hot or cold fluid and the required number of thermal plates using the available defualt values of the characteristics of the plate heat exchanger.

Example 1

Given: Both the hot, and cold water flow rates are 0.1167 kg/s, and the inlet and outlet temperatures of the cold stream are 358, 351 K, respectively. The inlet temperature of the hot stream is 363 K.

Design Procedure:

Step 1. "SELECT THE CODE NUMBER OF THE HOT LIQUID ..(1-8).."; 1

1. WATER
2. SYRUP (SUCROSE SOLUTION 20 wt%)
3. SYRUP (SUCROSE SOLUTION 30 wt%)
4. SYRUP (SUCROSE SOLUTION 40 wt%)
5. GLYCERINE 40 vol%
6. GLYCERINE 50 vol%
7. GLYCERINE 60 vol%
8. OTHERS

Step 2. "SELECT THE CODE NUMBER OF THE COLD LIQUID ..(1-8).."; 1

Step 3. "THE UNKNOWN OUTLET TEMPERATURE SIDE IS H=HOT OR C=COLD "; H

Step 4. "SURFACE AREA PER PLATE,AP(M^2)="; 0.05 OR ENTER

Step 5. "LENGTH OF PLATE,LP(M)="; 0.445 OR ENTER

Step 6. "THICKNESS OF PLATE, XP(M)= "; 0.0006 OR ENTER

Step 7. "WIDTH OF PLATE, WP(M)="; 0.1125 OR ENTER

Step 8. "PLATE GAP,BP(M)="; 0.00313 OR ENTER

Step 9. "FOULING FACTOR OF THE HOT STREAM,FH(M^2K/W)="; 0.00005678 OR ENTER

Step 10. "FOULING FACTOR OF THE COLD STREAM,FC(M^2K/W)=";0.00005678 OR ENTER

Step 11. "HOT STREAM FLOW RATE,WH(KG/S)="; 0.1167

Step 12. "COLD STREAM FLOW RATE,WC(KG/S)="; 0.1167

Step 13. "INLET TEMPERATURE OF THE COLD STREAM(K)"; 351

Step 14. "OUTLET TEMPERATURE OF THE COLD STREAM(K)"; 358

Step 15. "INLET TEMPERATURE OF THE HOT STREAM(K)"; 363

Next the screen the of personal computer shows the output data (shown below) and the following choices to select from:

(1) "NEW CALCULATION" means "go back to the program for new design calculation".

(2) "PRINT" means "the output results are to be printed". In this case the printer must be ready before selecting this choice.

(3) "DOS" means "quit the program and go back to the DOS system".

The output results of example 1 are presented below:

INPUT DATA		HOT LIQUID	COLD LIQUID
Type		WATER	WATER
Mass Flow Rate	, KG/S	0.1167	0.1167
Inlet Temperature	, K	363.0	351.0
Outlet Temperature	, K	356.0	358.0
Fouling Factor	, M^2K/W	$6*10^{-5}$	$6*10^{-5}$

PLATE CHARACTERISTICS

Surface Area per Plate	, M^2	0.05000
Thickness	, M	0.00060
Length	, M	0.44500
Width	, M	0.11250
Plate Gap	, M	0.00313

OUTPUT RESULTS

Reynolds Number		3,147.68	2,964.56
Pressure Drop	, KN/M^2	0.63	0.64
Heat Transfer Rate	, KW	3.43	
Overall Heat Transfer Coefficient	, W/M^2K	1,584.53	
Total Surface Area Required	, M^2	0.51	
Number of Thermal Plates		10.27	

Example 1 above uses experimental data obtained for equal water /water flow rates at 7 LPM, and uses the inlet and outlet temperatures of the heating section. The output result from the program shows the outlet temperature of the hot water stream is 356 K and the required number of thermal plates is 10 plates, which agree well with equal the experimental data.

<u>Example 2</u>

Given: The flow rate of a syrup (sucrose 20 wt%) stream is 0.1128 kg/s, and its inlet and outlet temperatures are 352, 358.5 K, respectively. The syrup stream is heated by hot water at flow rate of 0.1 kg/s. The inlet temperature of the hot stream is 364.5 K.

Design Procedure:

Step 1. "SELECT THE CODE NUMBER OF THE HOT LIQUID ..(1-8).."; <u>1</u>

1. WATER
2. SYRUP (SUCROSE SOLUTION 20 wt%)
3. SYRUP (SUCROSE SOLUTION 30 wt%)
4. SYRUP (SUCROSE SOLUTION 40 wt%)
5. GLYCERINE 40 vol%
6. GLYCERINE 50 vol%
7. GLYCERINE 60 vol%
8. OTHERS

Step 2. "SELECT THE CODE NUMBER OF THE COLD LIQUID ..(1-8).."; 3

Step 3. "THE UNKNOWN OUTLET TEMPERATURE SIDE IS H=HOT OR C=COLD "; H

Step 4. "SURFACE AREA PER PLATE,AP(M^2)="; 0.05 OR ENTER

Step 5. "LENGTH OF PLATE,LP(M)="; 0.445 OR ENTER

Step 6. "THICKNESS OF PLATE, XP(M)= "; 0.0006 OR ENTER

Step 7. "WIDTH OF PLATE,WP(M)="; 0.1125 OR ENTER

Step 8. "PLATE GAP,BP(M)="; 0.00313 OR ENTER

Step 9. "FOULING FACTOR OF THE HOT STREAM,FH(M^2K/W)="; 0.000056783 OR ENTER

Step 10. "FOULING FACTOR OF THE COLD STREAM,FC(M^2K/W)=";0.00011356 OR ENTER

Step 11. "HOT STREAM FLOW RATE,WH(KG/S)="; 0.1

Step 12. "COLD STREAM FLOW RATE,WC(KG/S)="; 0.1128

Step 13. "INLET TEMPERATURE OF THE COLD STREAM(K)"; 352

Step 14. "OUTLET TEMPERATURE OF THE COLD STREAM(K)"; 358.5

Step 15. "INLET TEMPERATURE OF THE HOT STREAM(K)"; 364.5

The output results are presented below:

INPUT DATA		HOT LIQUID	COLD LIQUID
Type		WATER	SYRUP 20 wt%
Mass Flow Rate	, KG/S	0.1000	0.1128
Inlet Temperature	, K	364.5	352.0
Outlet Temperature	, K	358.1	358.5
Fouling Factor	, M^2K/W	$6*10^{-5}$	$11*10^{-5}$

PLATE CHARACTERISTICS		
Surface Area per Plate	, M^2	0.05000
Thickness	, M	0.00060
Width	, M	0.11250
Length	, M	0.44500
Plate Gap	, M	0.00313

OUTPUT RESULTS			
Reynolds Number		2,754.16	1,847.57
Pressure Drop	, KN/M^2	0.48	0.59
Heat Transfer Rate	, KW	2.69	
Overall Heat Transfer Coefficient	, W/M^2K	1,290.18	
Total Surface Area Required	, M^2	0.40	
Number of Thermal Plates		7.93	

This example uses the experimental data obtained for equal water/syrup (sucrose 20 wt%) flow rates at 6 LPM. The output results from this program show that the outlet temperature of the hot water stream is 358.1 K, whereas the observed value is 356.5 K. The actual number of plates is 10 compared to the 8 plates calculated, which agree reasonably well with the experimental data.

Example 3

Given: The flow rate of glycerine (50 vol% conc.) is 0.098 kg/s, and its inlet and outlet temperatures are 351 and 353 K, respectively. The glycerine stream is heated by hot water at flow rate of 0.083 kg/s and temperature of 366 K.

Design Procedure:

Step 1. "SELECT THE CODE NUMBER OF THE HOT LIQUID ..(1-8)..": 1

1. WATER
2. SYRUP (SUCROSE SOLUTION 20 wt%)
3. SYRUP (SUCROSE SOLUTION 30 wt%)
4. SYRUP (SUCROSE SOLUTION 40 wt%)
5. GLYCERINE 40 vol%
6. GLYCERINE 50 vol%
7. GLYCERINE 60 vol%
8. OTHERS

Step 2. "SELECT THE CODE NUMBER OF THE COLD LIQUID ..(1-8)..": 6

Step 3. "THE UNKNOWN OUTLET TEMPERATURE SIDE IS H=HOT OR C=COLD ": H

Step 4. "SURFACE AREA PER PLATE,AP(M^2)="; 0.05 OR ENTER

Step 5. "LENGTH OF PLATE,LP(M)="; 0.445 OR ENTER

Step 6. "THICKNESS OF PLATE, XP(M)= "; 0.0006 OR ENTER

Step 7. "WIDTH OF PLATE,WP(M)="; 0.1125 OR ENTER

Step 8. "PLATE GAP,BP(M)="; 0.00313 OR ENTER

Step 9. "FOULING FACTOR OF THE HOT STREAM,FH(M^2K/W)="; 0.000056783 OR ENTER

Step 10. "FOULING FACTOR OF THE COLD STREAM,FC(M^2K/W)=";0.00011356 OR ENTER

Step 11. "HOT STREAM FLOW RATE,WH(KG/S)="; 0.083

Step 12. "COLD STREAM FLOW RATE,WC(KG/S)="; 0.098

Step 13. "INLET TEMPERATURE OF THE COLD STREAM(K)"; 351

Step 14. "OUTLET TEMPERATURE OF THE COLD STREAM(K)"; <u>359</u>

Step 15. "INLET TEMPERATURE OF THE HOT STREAM(K)"; <u>366</u>

The output results are presented below:

INPUT DATA		HOT LIQUID	COLD LIQUID
Type		WATER	GLYCERINE 50 vol%
Mass Flow Rate	, KG/S	0.0830	0.098
Inlet Temperature	, K	366.0	351.0
Outlet Temperature	, K	358.1	359.0
Fouling Factor	, M^2K/W	$6*10^{-6}$	$11*10^{-6}$

PLATE CHARACTERISTICS		
Surface Area per Plate	, M^2	0.05000
Thickness	, M	0.00060
Length	, M	0.44500
Width	, M	0.11250
Plate Gap	, M	0.00313

OUTPUT RESULTS			
Reynolds Number		2,306.29	782.52
Pressure Drop	, KN/M^2	0.34	0.53
Heat Transfer Rate	, KW	2.74	
Overall Heat Transfer Coefficient	, W/M^2K	1,077.29	
Total Surface Area Required	, M^2	0.42	
Number of Thermal Plates		8.34	

This example takes its data from equal water/glycerine flow rate at 5 LPM, (conc 50 vol%) and the inlet and outlet temperature from the heating section. The output results from this program shows that the outlet temperature of the hot stream is 358.1 K and the required number of thermal plates is 8.3 plates, whereas the measured outlet temperature is 356 K , and the actual plates is 10 plates, which agree resonably well with the experimental data.

Example 4

Given: We want to heat 7.78 kg/s of wash oil from 331 K to 371 K by using regenerative heat from the hot feed of oil at 383 K. (Assume that the fouling factors of both sides = 0.00057883 K/Wm^2, and the allowable pressure loss is less than 130 kN/m^2)

Physical properties of wash oil(assumed constant):

Thermal conductivity = 0.125 W/mK

Density = 880 kg/m^3

Specific heat = 1.926 kJ/kgK

Viscosity = 3*10^{-3} kg/ms

Design Procedure:

Step 1. "SELECT THE CODE NUMBER OF THE HOT LIQUID ..(1-8).."; 8

1. WATER
2. SYRUP (SUCROSE SOLUTION 20 wt%)
3. SYRUP (SUCROSE SOLUTION 30 wt%)
4. SYRUP (SUCROSE SOLUTION 40 wt%)
5. GLYCERINE 40 vol%
6. GLYCERINE 50 vol%
7. GLYCERINE 60 vol%
8. OTHERS

Step 2. "SELECT THE NUMBER OF COLD LIQUID ..(1-8).."; 8

Step 3. "NAME OF HOT LIQUID"; WASH OIL

"NAME OF COLD LIQUID"; WASH OIL

Step 4. "THE UNKNOWN OUTLET TEMPERATURE SIDE IS H=HOT OR C=COLD";H

Step 5. "SURFACE AREA PER PLATE,AP(M^2)="; 0.05 OR ENTER

Step 6. "LENGTH OF PLATE,LP(M)="; 0.445 OR ENTER

Step 7. "THICKNESS OF PLATE, XP(M)= "; 0.0006 OR ENTER

Step 8. "WIDTH OF PLATE,WP(M)="; 0.1125 OR ENTER

Step 9. "PLATE GAP,BP(M)="; 0.00313 OR ENTER

Step 10. "FOULING FACTOR OF THE HOT STREAM,FH(M^2K/W)="; 0.00056783

Step 11. "FOULING FACTOR OF THE COLD STREAM,FC(M^2K/W)=";0.0056783

Step 12. "HOT STREAM FLOW RATE,WH(KG/S)="; 7.78

Step 13. "COLD STREAM FLOW RATE,WC(KG/S)="; 7.78

Step 14. "INLET TEMPERATURE OF THE COLD STREAM(K)"; 331

Step 15. "OUTLET TEMPERATURE OF THE COLD STREAM(K)"; 371

Step 16. "INLET TEMPERATURE OF THE HOT STREAM(K)"; 383

Step 17. "PHYSICAL PROPERTIES OF THE HOT LIQUID"

"THERMAL CONDUCTIVITY (KG/MS) ="; 0.125

"VISCOSITY (KG/MS) = "; 0.003

"DENSITY (KG/M^3) = "; 880

"SPECIFIC HEAT (KJ/KGK) = "; 1.926

"PHYSICAL PROPERTIES OF THE COLD LIQUID"

"THERMAL CONDUCTIVITY (KG/MS) ="; 0.125

"VISCOSITY (KG/MS) = "; 0.003

"DENSITY (KG/M^3) = "; 880

"SPECIFIC HEAT (KJ/KGK) = "; 1.926

The output results are presented below:

INPUT DATA		HOT LIQUID	COLD LIQUID
Type		OIL	OIL
Mass Flow Rate	, KG/S	7.7800	7.7800
Inlet Temperature	, K	383.0	331.0
Outlet Temperature	, K	343.0	371.0
Fouling Factor	, M^2K/W	$57*10^{-5}$	$57*10^{-5}$

PLATE CHARACTERISTICS

Surface Area per Plate	, M^2	0.05000
Thickness	, M	0.00060
Length	, M	0.44500
Width	, M	0.11250
Plate Gap	, M	0.00313

OUTPUT RESULTS

Reynolds Number		23,051.85	23,051.85
Pressure Drop	, KN/M^2	1,913.36	1913.36
Heat Transfer Rate	, KW	599.37	
Overall Heat Transfer Coefficient	, W/M^2K	824.52	
Total Surface Area Required	, M^2	77.72	
Number of Thermal Plates		1,554.31	

The estimated pressure drop is much higher than that allowed in this problem. So the characteristics of the plate must be changed by trials and errors to find a suitable size, as presented below:

INPUT DATA		HOT LIQUID	COLD LIQUID
Type		WASH OIL	WASH OIL
Mass Flow Rate	, KG/S	7.7800	7.7800
Inlet Temperature	, K	383.0	331.0
Outlet Temperature	, K	343.0	371.0
Fouling Factor	, M^2K/W	$57*10^{-6}$	$57*10^{-6}$

PLATE CHARACTERISTICS

Surface Area per Plate	, M^2	0.27000
Thickness	, M	0.00080

Length	, M	0.90000
Width	, M	0.30000
Plate Gap	, M	0.00550

OUTPUT RESULTS

Reynolds Number		8,644.44	8,644.44
Pressure Drop	, KN/M^2	128.42	128.42
Heat Transfer Rate	, KW	599.37	
Overall Heat Transfer Coefficient,	W/M^2K	740.11	
Total Surface Area Required	, M^2	86.58	
Number of Thermal Plates		320.65	

The pressure dropof 128.42 KN/M^2 and totalthe required surface area of 86.58 M^2 agree well when compared to the values of 130 KN/M^2 and 86.4 M^2, respectively, given in the literature [4]. In conclusion, it is recommended to use, for example, plate heat exchanger type PG 12/4 of Stork plate heat exchanger, as presented below:

The Stork range of plate heat exchangers

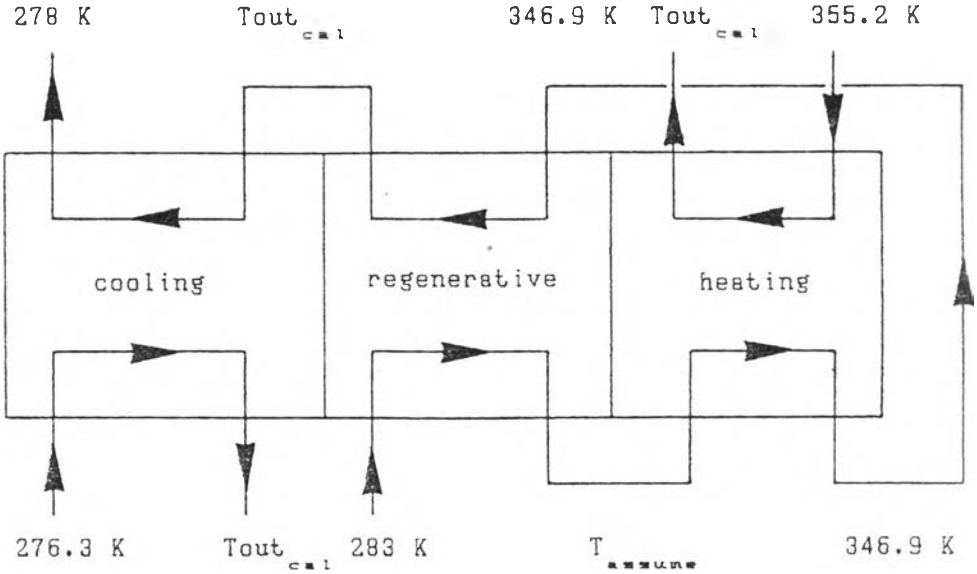
Technical data Type	PG 5/2	PG 9/3	PG 12/4	PG 14/4	PG 16/7	PG 21/8	PG 23/7
Heat transfer area (m^2)	0.043	0.13	0.28	0.4	0.6	0.85	1.0
Plate dimensions (mm)	500 x 125	739 x 242	1,052 x 394	1,360 x 394	1,510 x 540	1,750 x 655	2,230 x 540
Plate thickness (mm)	0.6/0.8	0.6	0.8	0.8	0.6/0.8	0.6/0.8	0.6/0.8
Plate weight (kg)	0.4	1.2	2.4	3.2	5.0	7.7	9.0
Type of frame	130	230	230 320 420	230 320 420	230	230	230
Max. differential pressure (kg/cm^2)	10/20	10/20	10/20	10/20	10/20	10/20	10/20

6.2 Application to Industrial Problem

In the milk industry, one most important operation in milk processing is to destroy the pathogenic agents causing deterioration and or diseases. Minimum temperature and time requirements for pasteurization of milk are based upon the thermal death time of the most heat-resistant pathogen found in milk. Seven temperature-time treatments are currently approved by the U.S. Public Health Service for the pasturization of milk in an indirect heat exchanger. Any combination of temperature and holding time greater than one of these standards is acceptable. All commercial pasteurization heat treatments are achieved by continuous processing. When the 15-second standard is used, the process is called high-temperature short-time (HTST) pasteurization.

The plate heat exchanger is most commonly used for the HTST unit. For each unit (that is, 1,000 gal/hr) of milk product to be pasteurized, approximately 2.5 to 4 units of cooling water at 37 °F is used to cool down the product from 80 to 40 °F, amd 4 to 6 units of hot water is used to heat the product from 140 to 165 °F. The hot-water inlet temperature is normally about 2 to 5 °F above the highest temperature to which the product is to be heated. Heat regeneration involves the use of the heat of the outgoing warm product to increase the temperature of the incoming cold product. Typically, when the incoming milk is at 40 °F and a pasteurization temperatureis 165 °F, the incoming product is preheated to 140 °F, and the pasteurized product is cooled down to 65 °F by regeneration[28].

The present example of industrial application use data from Kasetsart University's dairy processing plant, which employs a plate heat exchanger with has 3 sections and a holding section next to the heating section to increase the holding time to 15 seconds, as required by the standard. The milk feed rate at 283 K (50 °F) is 1000 ton/hr (0.278 kg/s). The hot water inlet temperature is 355.2 K (180 °F) and the cooling water inlet temperature is 276.3 K (38 °F). The heat transfer surface per plate is 0.18 m^2, the length is 0.8 m the width 0.225 m, and the thickness 0.0008 m. The heating section has 5 plates with plate gap of 0.00298 m; the regenerative has 11 plates with plate gap of 0.00343 m; and the cooling section has 11 plates with plate gap = 0.00343 m. Physical properties of the skim milk are; density =1,036 kg/m^3, specific heat = 3.9523 kJ/kgK, thermal conductivity = 0.4559-0.5315 W/mK (68-176 °F), viscosity = 0.000496-0.00128 kg/ms (60 - 153 °F). The outlet temperature from the heating section, i.e. the inlet temperature to the regenerative section, must be 346.9 K (165 °F). The outlet temperature from the regenerative section may be varied to minimize the total number of thermal plates. A simple diagram of the system is shown below.



The computer code can be used to calculate the number of therm plates of the heating section and the regenerative section by first assuming the outlet temperature (T_{assume}) of the regenerative section at 333 K. The assumed temperature is also the inlet temperature of the cooling section.

Design Procedure:

a. Heating Section

Step 1. "SELECT THE CODE NUMBER OF THE HOT LIQUID ..(1-8).."; 1

1. WATER
2. SYRUP (SUCROSE SOLUTION 20 wt%)
3. SYRUP (SUCROSE SOLUTION 30 wt%)
4. SYRUP (SUCROSE SOLUTION 40 wt%)
5. GLYCERINE 40 vol%
6. GLYCERINE 50 vol%
7. GLYCERINE 60 vol%
8. OTHERS

Step 2. "SELECT THE NUMBER OF COLD LIQUID ..(1-8).."; 8

Step 3. "NAME OF COLD LIQUID"; MILK

Step 4. "THE UNKNOWN OUTLET TEMPERATURE SIDE IS H=HOT OR C=COLD";H

Step 5. "SURFACE AREA PER PLATE,AP(M^2)="; 0.18

Step 6. "LENGTH OF PLATE,LP(M)="; 0.8

Step 7. "THICKNESS OF PLATE, XP(M)= "; 0.0008

Step 8. "WIDTH OF PLATE,WP(M)="; 0.225

Step 9. "PLATE GAP,BP(M)="; 0.00298

Step 10. "FOULING FACTOR OF THE HOT STREAM,FH(M^2K/W)="; 0

Step 11. "FOULING FACTOR OF THE COLD STREAM,FC(M^2K/W)=";0

Step 12. "HOT STREAM FLOW RATE,WH(KG/S)="; 0.278

Step 13. "COLD STREAM FLOW RATE,WC(KG/S)="; 0.278

Step 14. "INLET TEMPERATURE OF THE COLD STREAM(K)"; 333

Step 15. "OUTLET TEMPERATURE OF THE COLD STREAM(K)"; 346.9

Step 16. "INLET TEMPERATURE OF THE HOT STREAM(K)"; 355.2

Step 17. "PHYSICAL PROPERTIES OF THE COLD LIQUID"

"THERMAL CONDUCTIVITY (KG/MS) ="; 0.516

"VISCOSITY (KG/MS) = "; 0.000496

"DENSITY (KG/M^3) = "; 1036

"SPECIFIC HEAT (KJ/KGK) = "; 3.952

The output results are presented below:

INPUT DATA		HOT LIQUID	COLD LIQUID
Type		WATER	MILK
Mass Flow Rate	, KG/S	1.1120	0.2780
Inlet Temperature	, K	355.2	333.0
Outlet Temperature	, K	351.93	346.9
Fouling Factor	, M^2K/W	0	0

PLATE CHARACTERISTICS		
Surface Area per Plate	, M^2	0.18000
Thickness	, M	0.00080
Width	, M	0.22500
Length	, M	0.80000
Plate Gap	, M	0.00298

OUTPUT RESULTS			
Reynolds Number		13,962.61	2,491.04
Pressure Drop	, KN/M^2	20.33	1.89
Heat Transfer Rate	, KW	15.27	
Overall Heat Transfer Coefficient	, W/M^2K	2,989.06	
Total Surface Area Required	, M^2	0.44	
Number of Thermal Plates		2.44	

b. Regenerative Section

Step 1. "SELECT THE CODE NUMBER OF THE HOT LIQUID ..(1-8).."; 8

1. WATER
2. SYRUP (SUCROSE SOLUTION 20 wt%)
3. SYRUP (SUCROSE SOLUTION 30 wt%)
4. SYRUP (SUCROSE SOLUTION 40 wt%)
5. GLYCERINE 40 vol%
6. GLYCERINE 50 vol%
7. GLYCERINE 60 vol%
8. OTHERS

Step 2. "SELECT THE NUMBER OF COLD LIQUID ..(1-8).."; 8

Step 3. "NAME OF HOT LIQUID"; MILK

"NAME OF COLD LIQUID"; MILK

Step 4. "THE UNKNOWN OUTLET TEMPERATURE SIDE IS H=HOT OR C=COLD";H

Step 5. "SURFACE AREA PER PLATE,AP(M^2)="; 0.18

Step 6. "LENGTH OF PLATE,LP(M)="; 0.8

Step 7. "THICKNESS OF PLATE, XP(M)= "; 0.0008

Step 8. "WIDTH OF PLATE,WP(M)="; 0.225

Step 9. "PLATE GAP,BP(M)="; 0.00343

Step 10. "FOULING FACTOR OF THE HOT STREAM,FH(M^2K/W)="; 0

Step 11. "FOULING FACTOR OF THE COLD STREAM,FC(M^2K/W)=";0

Step 12. "HOT STREAM FLOW RATE,WH(KG/S)="; 0.278

Step 13. "COLD STREAM FLOW RATE,WC(KG/S)="; 0.278

Step 14. "INLET TEMPERATURE OF THE COLD STREAM(K)"; 283

Step 15. "OUTLET TEMPERATURE OF THE COLD STREAM(K)"; 333

Step 16. "INLET TEMPERATURE OF THE HOT STREAM(K)"; 346.9

Step 17. "PHYSICAL PROPERTIES OF THE HOT LIQUID"

"THERMAL CONDUCTIVITY (KG/MS) ="; 0.4943

"VISCOSITY (KG/MS) = "; 0.000743

"DENSITY (KG/M^3) = "; <u>1036</u>

"SPECIFIC HEAT (KJ/KGK) = "; <u>3.952</u>

"PHYSICAL PROPERTIES OF THE COLD LIQUID"

"THERMAL CONDUCTIVITY (KG/MS) ="; <u>0.4616</u>

"VISCOSITY (KG/MS) = "; <u>0.00128</u>

"DENSITY (KG/M^3) = "; <u>1036</u>

"SPECIFIC HEAT (KJ/KGK) = "; <u>3.952</u>

The output results are presented below:

INPUT DATA		HOT LIQUID	COLD LIQUID
Type		MILK	MILK
Mass Flow Rate	, KG/S	0.2780	0.2780
Inlet Temperature	, K	346.9	283.0
Outlet Temperature	, K	296.9	333.0
Fouling Factor	, M^2K/W	0	0

PLATE CHARACTERISTIC		
Surface Area per Plate	, M^2	0.18000
Thickness	, M	0.00080
Length	, M	0.80000
Width	, M	0.22500
Plate Gap	, M	0.00343

OUTPUT RESULTS			
Reynolds Number		1,662.03	965.28
Pressure Drop	, KN/M^2	1.37	1.58
Heat Transfer Rate	, KW	54.93	
Overall Heat Transfer Coefficient	, W/M^2K	1,632.82	
Total Surface Area Required	, M^2	3.21	
Number of Thermal Plates		17.85	

c. Cooling Section

Step 1. "SELECT THE CODE NUMBER OF THE HOT LIQUID ..(1-8).."; 8

1. WATER
2. SYRUP (SUCROSE SOLUTION 20 wt%)
3. SYRUP (SUCROSE SOLUTION 30 wt%)
4. SYRUP (SUCROSE SOLUTION 40 wt%)
5. GLYCERINE 40 vol%
6. GLYCERINE 50 vol%
7. GLYCERINE 60 vol%
8. OTHERS

Step 2. "SELECT THE NUMBER OF COLD LIQUID ..(1-8).."; 1

Step 3. "NAME OF HOT LIQUID"; MILK

"NAME OF COLD LIQUID"; MILK

Step 4. "THE UNKNOWN OUTLET TEMPERATURE SIDE IS H=HOT OR C=COLD"; C

Step 5. "SURFACE AREA PER PLATE,AP(M^2)="; 0.18

Step 6. "LENGTH OF PLATE,LP(M)="; 0.8

Step 7. "THICKNESS OF PLATE, XP(M)= "; 0.0008

Step 8. "WIDTH OF PLATE,WP(M)="; 0.225

Step 9. "PLATE GAP,BP(M)="; 0.00343

Step 10. "FOULING FACTOR OF THE HOT STREAM,FH(M^2K/W)=": 0

Step 11. "FOULING FACTOR OF THE COLD STREAM,FC(M^2K/W)=";0

Step 12. "HOT STREAM FLOW RATE,WH(KG/S)="; 0.278

Step 13. "COLD STREAM FLOW RATE,WC(KG/S)="; 0.556

Step 14. "INLET TEMPERATURE OF THE HOT STREAM(K)"; 296.9

Step 15. "OUTLET TEMPERATURE OF THE HOT STREAM(K)"; 278

Step 16. "INLET TEMPERATURE OF THE COLD STREAM(K)"; 276.3

Step 17. "PHYSICAL PROPERTIES OF THE HOT LIQUID"

"THERMAL CONDUCTIVITY (KG/MS) ="; 0.4559

"VISCOSITY (KG/MS) = "; 0.002156

"DENSITY (KG/M^3) = "; 1036

"SPECIFIC HEAT (KJ/KGK) = "; 3.952

The output results are presented below:

INPUT DATA		HOT LIQUID	COLD LIQUID
Type		MILK	WATER
Mass Flow Rate	, KG/S	0.2780	0.5560
Inlet Temperature	, K	296.9	276.3
Outlet Temperature	, K	278.0	285.19
Fouling Factor	, M^2K/W	0	0

PLATE CHARACTERISTICS		
Surface Area per Plate	, M^2	0.18000
Thickness	, M	0.00080
Length	, M	0.8000
Width	, M	0.22500
Plate Gap	, M	0.00343

OUTPUT RESULTS			
Reynolds Number		572.02	1,769.45
Pressure Drop	, KN/M^2	1.80	5.61
Heat Transfer Rate	, KW	20.76	
Overall Heat Transfer Coefficient	, W/M^2K	1,997.19	
Total Surface Area Required	, M^2	2.93	
Number of Thermal Plates		16.28	

The total number of thermal plates is thus 36.57 and the total pressure drop on the milk stream is 6.7 KN/M^2.

When the T_{assume} is varied the number of thermal plates in each changes too. So the minimum of total plates can be found as shown below:

Section	Heating			Regenerative			Cooling		
	T_{in} (K)	T_{out} (K)	P (KN/M^2)	T_{in} (K)	T_{out} (K)	P (KN/M^2)	T_{in} (K)	T_{out} (K)	P (KN/M^2)
Hot side	355.2	351.9	20.3	346.9	296.9	1.4	296.9	278.0	1.8
Cold side	333.0	346.9	1.9	283.0	333.0	1.6	276.3	285.2	5.6
Plates	2.44			17.85			16.28		
Total plates	36.57 (T_{assume} = 333 K)								
Total $\triangle$P	6.7 KN/M^2								
	T_{in} (K)	T_{out} (K)	P (KN/M^2)	T_{in} (K)	T_{out} (K)	P (KN/M^2)	T_{in} (K)	T_{out} (K)	P (KN/M^2)
Hot side	355.2	352.4	20.3	346.9	294.9	1.4	294.9	276.3	1.8
Cold side	335.0	346.9	1.9	283.0	335.0	1.6	278.0	284.3	5.6
Plates	2.15			23.19			15.01		
Total plates	40.35 (T_{assume} = 335 K)								
Total $\triangle$P	6.7 KN/M^2								

Section	Heating			Regenerative			Cooling		
	T_{in} (K)	T_{out} (K)	P $(\frac{KN}{M^2})$	T_{in} (K)	T_{out} (K)	P $(\frac{KN}{M^2})$	T_{in} (K)	T_{out} (K)	P $(\frac{KN}{M^2})$
Hot side	355.2	351.5	20.3	346.9	298.9	1.4	298.9	278.0	1.8
Cold side	331.0	346.9	1.9	283.0	331.0	1.6	276.3	286.1	5.6
Plates	2.72			14.20			17.35		
Total plates	34.27 (T_{assume} = 331 K)								
Total $\triangle$P	6.7 KN/M^2								
	T_{in} (K)	T_{out} (K)	P $(\frac{KN}{M^2})$	T_{in} (K)	T_{out} (K)	P $(\frac{KN}{M^2})$	T_{in} (K)	T_{out} (K)	P $(\frac{KN}{M^2})$
Hot side	355.2	350.8	20.4	346.9	301.9	1.4	301.9	278.0	1.8
Cold side	328.0	346.9	1.9	283.0	328.0	1.6	276.3	287.4	5.6
Plates	3.11			11.14			18.89		
Total plates	33.14 (T_{assume} = 328 K)								
Total $\triangle$P	6.7 KN/M^2								

Section	Heating			Regenerative			Cooling		
	T_{in} (K)	T_{out} (K)	P (KN/M^2)	T_{in} (K)	T_{out} (K)	P (KN/M^2)	T_{in} (K)	T_{out} (K)	P (KN/M^2)
Hot side	355.2	350.1	20.4	346.9	304.9	1.4	304.9	278.0	1.8
Cold side	325.0	346.9	1.9	283.0	325.0	1.6	276.3	289.0	5.5
Plates	3.46			8.75			20.21		
Total plates	32.42 (T_{assume} = 325 K)								
Total $\triangle$P	6.7 KN/M^2								

Section	Heating			Regenerative			Cooling		
	T_{in} (K)	T_{out} (K)	P (KN/M^2)	T_{in} (K)	T_{out} (K)	P (KN/M^2)	T_{in} (K)	T_{out} (K)	P (KN/M^2)
Hot side	355.2	348.9	20.4	346.9	309.9	1.4	309.9	278.0	1.8
Cold side	320.0	346.9	1.9	283.0	320.0	1.6	276.3	291.3	5.5
Plates	3.97			6.09			22.05		
Total plates	32.11 (T_{assume} = 320 K)								
Total $\triangle$P	6.7 KN/M^2								

Section	Heating			Regenerative			Cooling		
	T_{in} (K)	T_{out} (K)	P $(\frac{KN}{M^2})$	T_{in} (K)	T_{out} (K)	P $(\frac{KN}{M^2})$	T_{in} (K)	T_{out} (K)	P $(\frac{KN}{M^2})$
Hot side	355.2	347.7	20.5	346.9	314.9	1.4	314.9	278.0	1.8
Cold side	315.0	346.9	1.9	283.0	315.0	1.6	276.3	289.0	5.4
Plates	4.41			4.27			23.47		
Total plates	32.15 (T_{assume} = 315 K)								
Total $\triangle$P	6.7 KN/M^2								
	T_{in} (K)	T_{out} (K)	P $(\frac{KN}{M^2})$	T_{in} (K)	T_{out} (K)	P $(\frac{KN}{M^2})$	T_{in} (K)	T_{out} (K)	P $(\frac{KN}{M^2})$
Hot side	355.2	346.5	20.5	346.9	319.9	1.4	319.9	278.0	1.8
Cold side	310.0	346.9	1.9	283.0	310.0	1.6	276.3	296.0	5.4
Plates	4.78			3.19			24.65		
Total plates	32.15 (T_{assume} = 310 K)								
Total $\triangle$P	6.7 KN/M^2								

We may conclude from the above table that the value of T_{assume} around 320 K gives the minimum total number of 32.1 plates.

In the case of the HTST process at Kasetsart University, it has 5, 11, and 11 in the heating, regenerative and cooling sections, respectively. It has been found that if T_{assume} is chosen to be 325 K, the obtained design consists of 3.46, 8.75 ans 20.21 plates, respectively. Furthermore, if the flow rate of the chilled water in the cooling section is increased to 4.2 times that of the product flow rate, the required number of plates for this section becomes 9.71 plates. This means that if a safety factor of 1.2 is used with T_{assume} being 325 K and the chilled water flow rate is increased as above, the final design consists of 4.2, 10.5, 11.7, plates, respectively. The result is satisfactorily close to that actually used in the above process.