SINGLE-PASS SHELL & TUBE HEAT EXCHANGER MANUAL-SAMPLE

CENTER OF NUMERICAL ANALYSIS TECHNOLOGY

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1 INTRODUCTION

Fluid processing is an essential operation in any industrial plant. Heating and cooling processes are one of the main operations performed on fluids handled in a plant. Such processes are performed for multiple goals like risk reduction, separation of materials or phases, fluid transport, storage… etc. As a result, temperature control in these processes requires attention to achieve these goals.

Heat exchangers are the core units used in controlling fluid temperatures before and after any operation handling this fluid. Examples of heat exchangers are car radiator, boilers, gas liquefaction units, air-conditioner condensers and many more.

Designers are always required to ensure that the energy capacity of the designed heat exchangers is adequate to remove/add the required thermal energy set for the operations. This capacity determines the exchanger's configuration and its tubing/shell sizes.

1.1 Purpose of Document

This document is developed as a manual for the user to get details of a heat exchanger, considered in the design, including the heat load capacity and the temperature distribution along the tubing and shell sides of the exchanger. The information and steps in this document will briefly guide the end-user to the procedure used in sizing the heat exchanger considering user-defined single-layer tubing and inlet fluid properties for both tubing and shell sides.

1.2 Focus of Document

This document will focus on the following criteria for the heat exchanger analysis:

- The heat exchanger is of a single-pass tube and shell type. The shell is considered cylindrical in shape with the tubing (whether single or bundle) of a single pass and free of fins.
- The tube wall thickness is not changing from its beginning to its end within the exchanger and considered single-layered.
- The heat exchanger shell wall is assumed thermally insulated.
- Inlet fluids at both tube and shell sides are assumed to be of a single-phase each (condensation or evaporation are not accounted for in this document) and their related flows are assumed steady with fixed inlet temperatures and fixed flow rates.
- Only forced convection at the innermost and the outermost tube surfaces is considered. i.e. natural/free convection is not accounted for in this document.
- The heat transfer occurs only across the tube wall with a negligible effect of lateral heat transfer within the internal fluid, the shell fluid and along the tube wall.
- The friction due to the innermost surface roughness is the only roughness-related parameter considered to affect the heat transfer process whenever referenced. That is, other roughness parameters, such as equivalent sand grain roughness, are ignored.
- The effects of fouling or leakage across the baffles are not accounted for in this document.
- Only fluids with Prandtl Number >1 are considered.
- The considered heat exchanger types, based on the shell-side flow, are co-current, counter-current or cross-current with the tube-side flow as schematically illustrated in Figure 1-1.

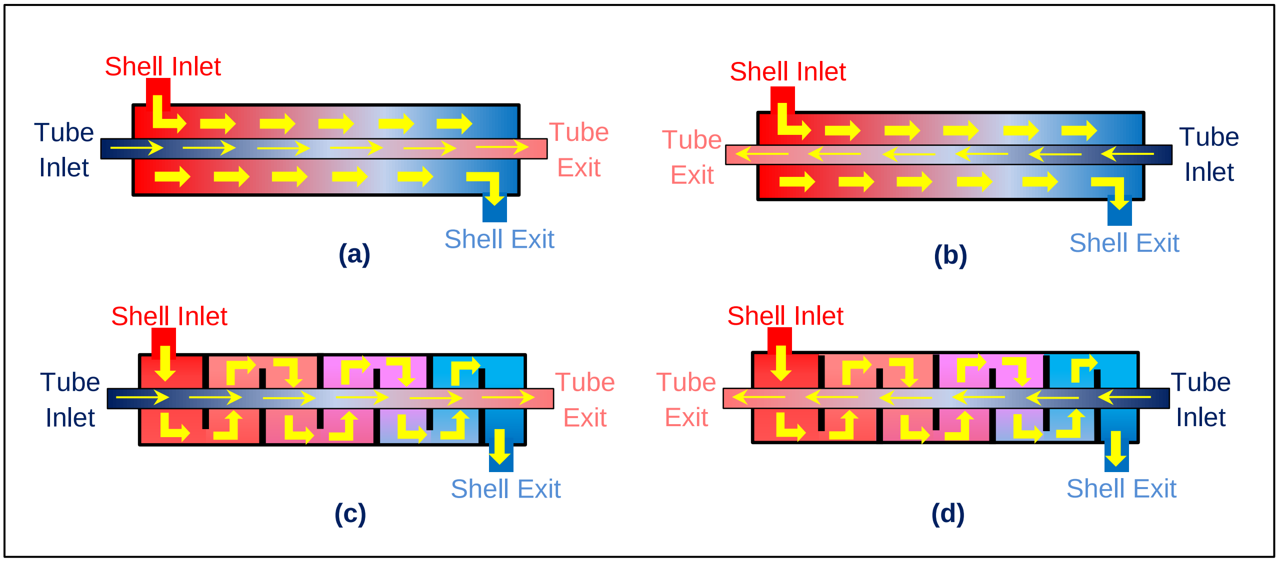

Figure 1-1: Heat exchanger types. (a) Co-current with tube flow, (b) Counter-current with tube flow, (c) Cross-current in the direction of tube flow, (d) Cross-current opposite to tube flow direction

- The bundled tubing is considered for two arrangements (in-lined and staggered) in front of the approaching shell-side flow, as shown in Figure 1-2, that are applicable to all heat exchanger types.

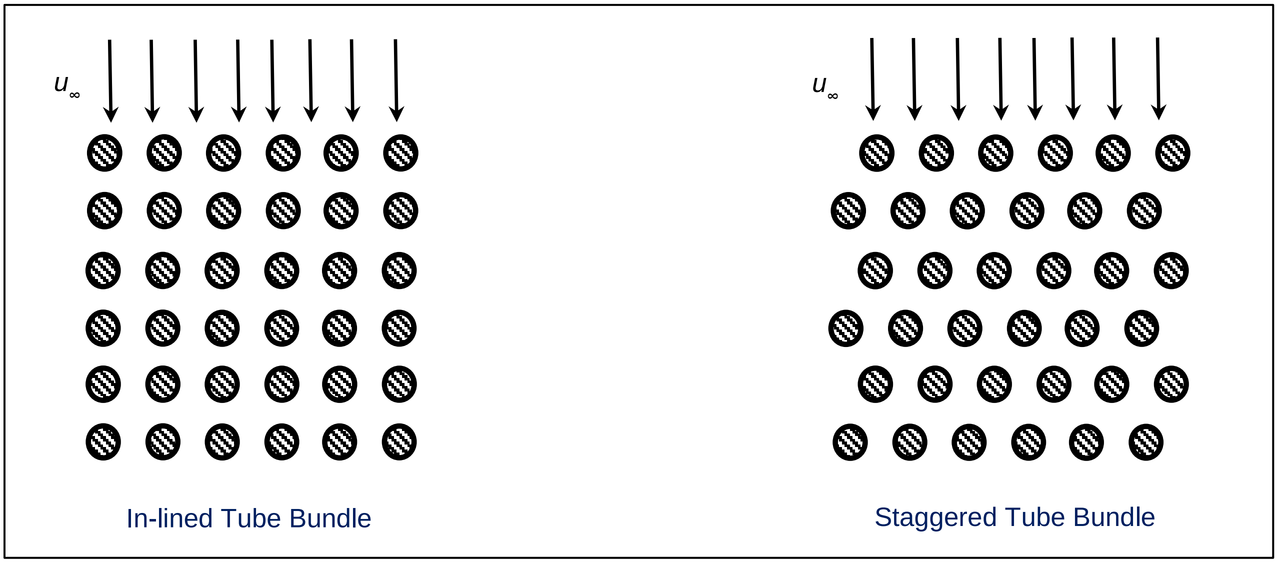

Figure 1-2: Tubing bundle arrangements

1.3 Units and Dimensions

All units and dimensions are applicable in this document. All variables and parameters must be defined on the basis of the same units system. This document does not account for unit conversion.

2 SYMBOLS AND ABBREVIATIONS

Below is a list of symbols and abbreviations that are used in this document. Other specific symbols and abbreviations, if any, will be defined in place.

a	: Diameter ratio of an annulus configuration
BA_{tube}	: Tubing bundle arrangement
cfac	: User-defined correction factor to control convergence of counter-flow iteration process
$Cp_{fluid-i}$	: Specific heat of fluid-i
D_h	: The hydrodynamic diameter at the shell side
Ex_{type}	: Heat exchanger type
h_{in}	: Convective heat transfer coefficient at the tube-side surface
h_{out}	: Convective heat transfer coefficient at the outer tube surface
ID_{shell}	: The shell inner diameter
ID_{tube}	: The tube inner diameter
k_{tube}	: Thermal conductivity of tube wall
$kf_{fluid-i}$	: Thermal conductivity of fluid-i
L	: Tube overall length
layer	: Tube wall layer name.
$\dot{m}_{in}$	: Overall mass flow rate of the tube-side flow
$\dot{m}_{out}$	: Overall mass flow rate of the shell-side flow
N_b	: Number of baffles dividing the shell
N_{tube}	: Number of tubes in the bundle.
OD_{tube}	: The tube outer diameter
P_L	: The Lateral pitch of the staggered tubing bundle (in line with approaching flow direction)
P_T	: The Transverse pitch of the staggered tubing bundle (Normal to approaching flow direction)
$Pr_{fluid-i}$	: Prandtl Number of fluid-i
$\dot{Q}_{in}$	: Total volume flow rate of tube-side flow
$\dot{Q}_{out}$	: Total volume flow rate of shell-side flow
R_{ex}	: Overall thermal resistance of exchanger per unit length
Re_{in}	: Reynold's Number of tube-side flow
Re_{out}	: Reynold's Number of shell-side flow
SI	: International System of Units
T_b	: Tube-side fluid bulk temperature
T_i	: Tube-side fluid temperature at position/node "i" of the tube
T_{in}	: Inlet temperature of tube-side fluid
$T_{in\ shell}$	: Inlet temperature of shell-side fluid
$T_{s-(i)}$	: Shell-side fluid temperature at position/node "i" of the tube
t_{tube}	: Tube wall thickness
U_{ex}	: Overall thermal conductivity of exchanger
u_{∞}	: Shell-side Flow velocity away from tubing.
ε	: Tube inner surface roughness
$\mu_{fluid-i}$	: Dynamic viscosity of fluid-i
$\rho_{fluid-i}$	: Density of fluid-i
ΔL	: Tube elemental length

3 ANALYSIS PROCEDURE

3.1 General

The analysis procedure is based on calculating the amount of transferred heat energy across the tube wall as the internal fluid flows from inlet towards the discharge end according to the selected scenario of the shell's fluid flow.

3.2 Concept

The concept of the analysis is to divide the length of the tube into elements across each thermal energy balance is applied starting from the element adjacent to the inlet towards the element adjacent to the discharge end. This elemental energy balance will result in calculating the element discharge temperature after accounting for the effect of the heat energy flow across the tube wall on the element inlet energy. This element discharge temperature will be used as an inlet temperature for the next element and so on until the last element is considered. Meanwhile, this heat energy flow is considered in calculating the discharge temperature of the corresponding shell-side fluid element so that it is considered for the next tube-side fluid element analysis. The transferred heat energy across the tube wall is governed by the overall heat transfer coefficient of the tube wall which depends on the wall layer and the conditions of the inner and the outer flows.

A simple representation of the energy balance within a tube element is schematically shown in Figure 3-1.

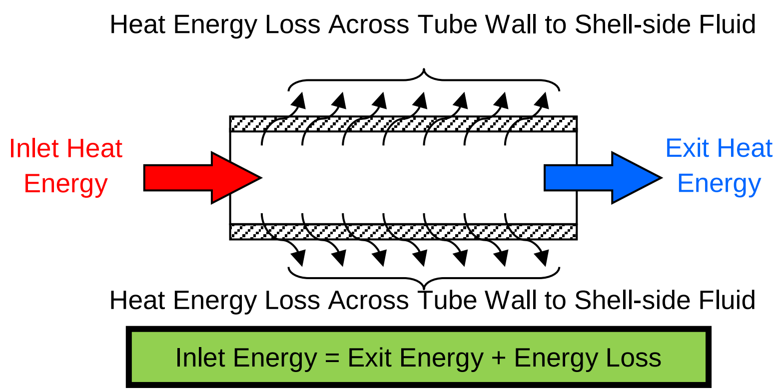

Figure 3-1: A schematic of heat energy balance within a tube element

3.3 Calculations

The computer routine associated with this manual is designed to perform the calculations of the thermal resistances, according to the user-defined tube wall layer and flow conditions at tube and shell sides. Further, it calculates the overall heat transfer coefficient of the exchanger based on the tube outer surface.

Reference to [1], the performed calculations account for the convective heat transfer coefficients of the tube and shell fluids through the following correlations:

1- Mills correlation for laminar tube-side flow. The same correlation, considering Petukhov & Roizen factorization is also applied for shell-side Co- & Counter- current flows with annulus diameter ratio (a)>3.2 considering Re_{out}, D_h and $Pr_{fluid\text{-}2}$.
2- Gnielinski's correlation for turbulent tube-side flow as long as an approximate range of $3000 \le Re_{in} \le 5x10^6$ is satisfied. The same correlation, considering Petukhov & Roizen factorization is also applied for shell-side Co- & Counter current flows with annulus diameter ratio (a)>3.2 considering Re_{out}, D_h and $Pr_{fluid\text{-}2}$.
3- Dirker & Meyer correlation for shell-side Co- & Counter current flows with annulus diameter ratio (a)≤3.2
4- Churchill-Bernstein correlation for shell-side cross flow type as long as ($Pr_{fluid\text{-}2}$ * $Re_{out\text{-}i}$) ≥ 0.2 and $N_{tube} \le 2$.
5- Zukauskas correlation for shell-side cross flow type when $N_{tube} > 2$ considering the effect of the tube bundle arrangement on Re_{out}.

All required parameters for the above-mentioned correlations are automatically accounted for such as the friction factor at the innermost tube surface, the Prandtl numbers and the Reynolds numbers of the tube-side and the shell-side fluids and flows.

6- The energy balance throughout each tube element results into the nodal tube-side temperature formula that is detailed by eqn. (1).

$$T_i = T_{i\text{-}1} - \Delta L * N_{tube} * \left(T_{i\text{-}1} - T_{s\text{-}(i\text{-}1)}\right) / \left(R_{ex} * Cp_{fluid\text{-}1} * \dot{Q}_{in} * \rho_{fluid\text{-}1}\right), \ m \ge i \ge 1, \ T_0 = T_{in} \qquad (1)$$

When a tubing bundle is considered, the calculated nodal tube-side temperature is assumed to be the same for all tubes in that bundle at the same node location. It should be noted that the calculations are advanced in the direction from tube inlet towards its exit.

7- Since the thermal energy is exchanged between the tube-side fluid and the shell-side fluid, the corresponding nodal shell-side temperature is then calculated using the thermal energy lost/gained by the tube-side fluid element considering the thermal capacity ratio of tube-side and shell-side fluids. Iterations are conducted when counter-current scenarios are considered since the direction of the calculation advancement is always co-current with the tube-side flow.

It should be noted that the elemental temperature difference between the inner flow and the outer flow is assuming that the inner flow bulk temperature of the tube element is the same as the elemental inlet temperature and properties of both internal and external fluids are evaluated at T_b and $T_{s\text{-}(i)}$, respectively. This assumption is acceptable because $T_b \approx T_i$ as the element size becomes smaller. In addition, the properties of the considered fluids are slowly changing over a relatively large temperature range and the applications of such fluids are generally handled below superheated temperatures which justify the evaluation of these properties at T_b and $T_{s\text{-}(i)}$.

Figure 3-2 shows a schematic example of the temperature profile as heat energy transfers between the internal fluid and the external fluid considering the effect of tube wall conductivity and the convection at both the innermost and the outermost tube surfaces.

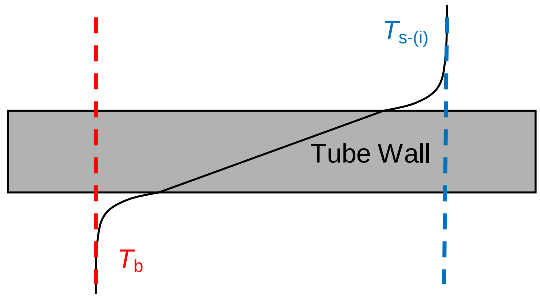

Figure 3-2: A schematic of temperature profile from internal to external fluids across tube wall

4 ANALYSIS ROUTINE

4.1 General

The analysis procedure is translated into a computer routine to generate the temperature distribution along the heat exchanger at both tube and shell sides, the overall heat transfer coefficient of the exchanger and the heat load of the exchanger.

4.2 User Input File

For the computer routine to perform the analysis correctly,

1) The user needs to input the required information as described in the template of Table 4-1.
2) The user needs to maintain the sequence of line numbers as specified without being altered.
3) Maintenance of units' consistency for all input parameters is important.

Upon generating the input file, considering the above-mentioned conditions, the user is to save this file as "16010001301020000101.txt" in the same folder of the executable file.

Table 4-1: Template for user-input parameters

1	Ex_{type} (a)					
2	ID_{tube}					
3	ε					
4	L					
5	ΔL					
6	ID_{shell}					
7	BA_{tube} (b)					
8	N_{tube}					
9	P_L (c)					
10	P_T (c)					
11	N_b (d)					
0 (f)	---------- (e)					
12	layer (g)	k_{tube}	t_{tube}			
0 (f)	---------- (e)					
13	fluid-1 (h)	$\rho_{fluid-1}$	$\mu_{fluid-1}$	$kf_{fluid-1}$	$Cp_{fluid-1}$	$\dot{Q}_{in}$
14	fluid-2 (h)	$\rho_{fluid-2}$	$\mu_{fluid-2}$	$kf_{fluid-2}$	$Cp_{fluid-2}$	$\dot{Q}_{out}$
0 (f)	---------- (e)					
15	T_{in}					
16	T_{in_shell}					
0 (f)	---------- (e)					
17	cfac					

(a) Set Ex_{type} to: 0: for Co-current Exchanger, 1: for Counter-current Exchanger, 2: for Cross-flow Exchanger co-current with tube flow direction, 3: for Cross-flow Exchanger counter-current with tube flow direction.
(b) Set BA_{tube} to: 0: for an in-lined tube bundle, 1: for a staggered tube bundle.
(c) Takes effect only when $N_{tube} > 2$, Ex_{type} is set to 2 or 3 and $P_T > OD_{tube}$
(d) Takes effect only when Ex_{type} is set to 2 or 3
(e) These dashes are field separators and need to be input as is (10 dashes).
(f) This “0” is a controlling line index for the routine to read input parameters properly.
(g) Name of the tube wall layer (optional to user to name it).
(h) Always consider “fluid-1” to be the internal/tube fluid and “fluid-2” to be the external/shell fluid (optional to user to name the fluid).

4.3 Output File

Upon the execution of the computer routine, the following information are extracted in the output file “16010001311020000101.txt”:

1) The exchanger’s shell-based overall heat transfer coefficient (U_{ex}) per unit area is obtained through the full version of the computer routine or when $N_{tube} \leq 10$.
2) The exchanger’s overall heat load- obtained through the full version of the computer routine.
3) The exchanger’s overall shell-side heat transfer surface area.
4) The convective heat transfer coefficients of the innermost tube surface (h_{in}). (h_{out}) is obtained through the full version of the computer routine..
5) The mass flow rate of the tube-side and the shell-side fluids ($\dot{m}_{in}$, $\dot{m}_{out}$).
6) The temperature distribution profiles along the exchanger (T_i, $T_{s-(i)}$, $m \geq i \geq 0$) is obtained through the full version of the computer routine or when $N_{tube} \leq 10$.

Further, a log file is generated broadcasting the status of the routine execution as to whether completed successfully or terminated due to some errors in the input file information.

4.4 Sample Problem

An actual sample problem is presented herein to familiarize the user with the computer routine and to evaluate its capability in handling similar analysis problems. The problem is to calculate the temperature profiles and other heat transfer parameters of a heat exchanger under four different types of shell-side flow directions to the tube-side flow. The examined exchanger is 4.88 meters long and 0.594 meters in internal diameter. The tube bundle is made of 10 copper-nickel tubes. The tube-side fluid is water and the shell-side fluid is methanol. The exchanger is internally divided by 7 baffles to be considered for cross flow exchanger types. Table 4-2 lists the input file information for the sample problem in SI units system considering all exchanger types and bundle arrangements to be input once at a time.

Table 4-2: Input parameters of the sample problem

1	0,1,2,3					
2	0.016					
3	0.00085					
4	4.88					
5	0.01					
6	0.094					
7	0,1					

8	10					
9	0.025					
10	0.025					
11	7					
0	----------					
12	Copper-Nickel	50.0	0.002			
0	----------					
13	Water	995	0.0008	0.596	4200	0.00192
14	Methanol	750	0.00034	0.190	2840	0.00037
0	----------					
15	25					
16	95					
0	----------					
17	1.0					

Upon the execution of the computer routine for the input file, as detailed in Table 4-2, the temperature profiles and related exchanger's output parameters are shown in Figure 4-1 and Table 4-3, respectively, for the co-current and counter-current exchanger types. The profiles and output parameters related to cross-flow co- & counter- current exchanger types are, respectively shown in Figure 4-2 and Table 4-4.

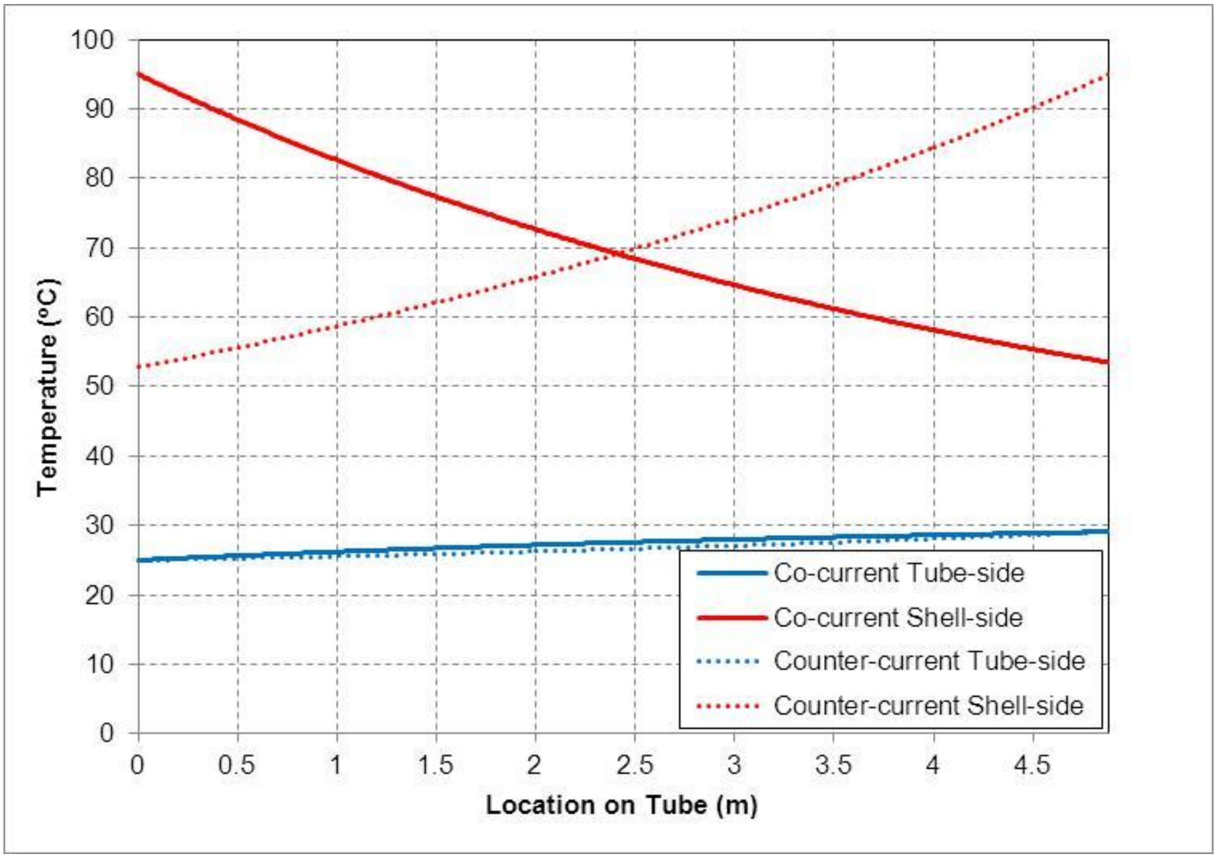

Figure 4-1: Temperature distribution profiles along a sample problem heat exchanger (Co- & Counter- current types)

Table 4-3: Output parameters of the sample problem for Co- & Counter- current types

Parameter	Co-current Exchanger (In-lined & Staggered Arrangement)	Counter-current Exchanger (In-lined & Staggered Arrangement)
U_{ex} "W/(m^2.^{o}C)"	246.3	
Heat Transfer Area "m^2"	3.066	
h_{in} "W/(m^2.^{o}C)"	9650	
$\dot{m}_{in}$ "kg/sec"	1.91	
$\dot{m}_{out}$ "kg/sec"	0.2775	

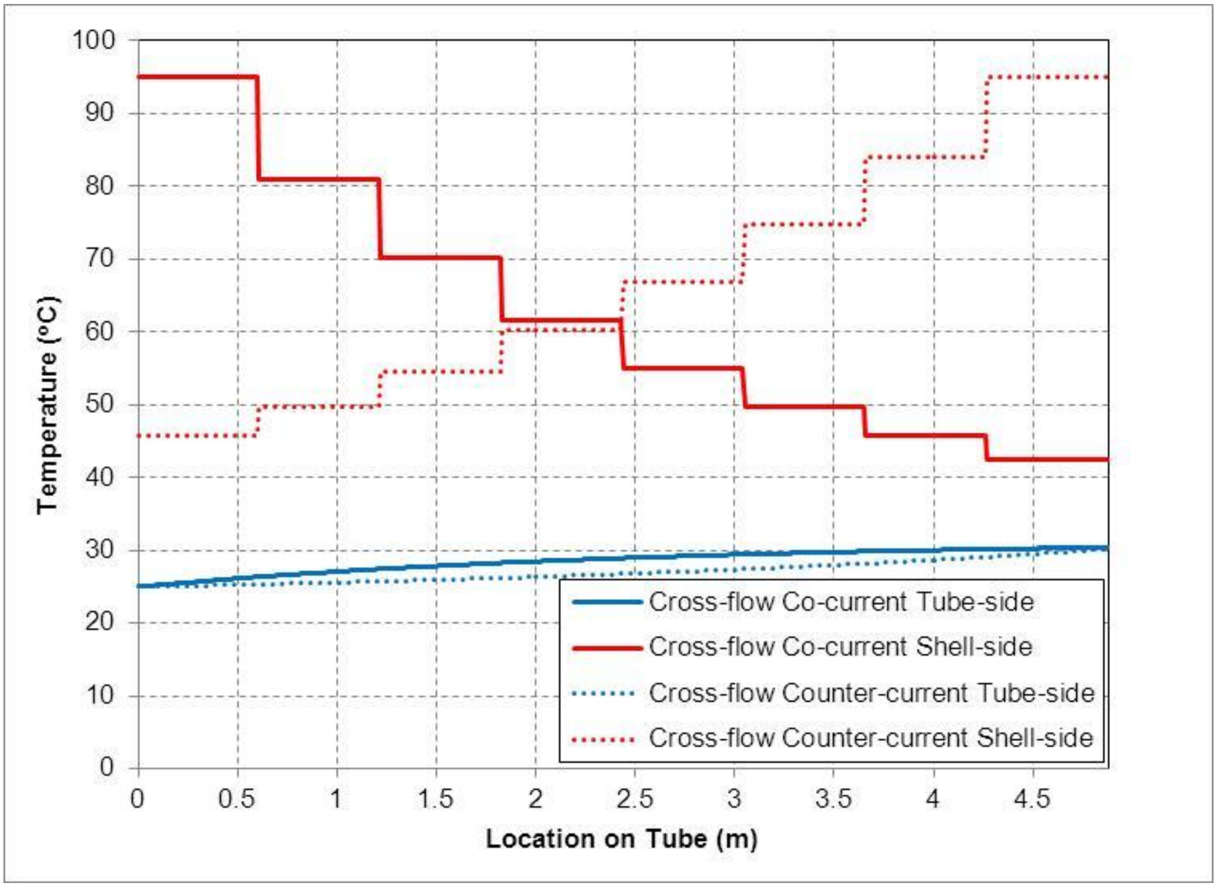

Figure 4-2: Temperature distribution profiles along a sample problem heat exchanger (Cross-flow Co- & Counter- current types)

Table 4-4: Output parameters of the sample problem for Cross-flow Co- & Counter- current types

Parameter	Cross-flow Co-current Exchanger (In-lined/Staggered Arrangement)	Cross-flow Counter-current Exchanger (In-lined/Staggered Arrangement)
U_{ex} "W/(m^2.^{o}C)"	414.3/430.6	
Heat Transfer Area "m^2"	3.066	
h_{in} "W/(m^2.^{o}C)"	9650	
$\dot{m}_{in}$ "kg/sec"	1.91	
$\dot{m}_{out}$ "kg/sec"	0.2775	
Shell Exit Temperature ($T_{s-(m)}$) "^{o}C"	40.07/39.33	42.25/41.43

5 REFERENCES

[1] CNAT Doc. No.: 1601000110002000010A, “Single-Pass Shell & Tube Heat Exchanger Manual”.