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Design and performance evaluation of heat exchangers: The effectiveness – N_{TU} method

Part 2: Performance comparisons and selection of configurations presented in Part 3

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THE PREPARATION OF THIS DATA ITEM

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who undertook the technical work involved in the assessment of the available information and the construction and subsequent development of the original Data Items.

(Continued on inside back cover)

DESIGN AND PERFORMANCE EVALUATION OF HEAT EXCHANGERS: THE EFFECTIVENESS - N_{TU} METHOD

PART 2: PERFORMANCE COMPARISONS AND SELECTION OF CONFIGURATIONS PRESENTED IN PART 3

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DESIGN AND PERFORMANCE EVALUATION OF HEAT EXCHANGERS: THE EFFECTIVENESS - N_{TU} METHOD

PART 2: PERFORMANCE COMPARISONS AND SELECTION OF CONFIGURATIONS PRESENTED IN PART 3

1. NOTATION AND UNITS

Two sets of self-consistent units are given.

		Units	
		SI	British
A	effective surface area of heat exchanger	m^2	ft^2
C^*	thermal capacity ratio (defined in Section 4.2.3 of Part 1)	—	—
c_p	specific heat capacity	J/kg K	Btu/lb °F
E	thermal effectiveness (defined in Section 4.2.1 of Part 1)	—	—
L_b	baffle plate thickness	m	ft
$\dot{M}$	mass flow rate	kg/s	lb/h
N_{TU}	number of heat transfer units (defined in Section 4.2.2 of Part 1)	—	—
N	number of thermal plates in plate-type exchanger	—	—
N_{ch}	number of channels for each stream in plate-type exchanger	—	—
N_p	number of stream passes in plate-type exchanger	—	—
r_f	fouling resistance	$m^2 K/W$	$ft^2 h^\circ F/Btu$
U	overall heat transfer coefficient between streams	$W/m^2 K$	$Btu/h ft^2 °F$
U_b	overall heat transfer coefficient across central baffle of F-shell heat exchanger	$W/m^2 K$	$Btu/h ft^2 °F$
Y	ratio of potential for heat transfer across baffle and between streams in F-shell heat exchanger	—	—
α	heat transfer coefficient	$W/m^2 K$	$Btu/h ft^2 °F$
λ	thermal conductivity	$W/m K$	$Btu/h ft °F$

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Subscripts

<i>b</i>	refers to baffles
larger	larger value of parameter in streams
smaller	smaller value of parameter in streams
1	refers to stream number 1 or location 1
2	refers to stream number 2 or location 2

2. INTRODUCTION

2.1 Purpose and Scope

This is the second of a group of Data Items concerning the effectiveness (E) - number of heat transfer units (N_{TU}) method for the thermal analysis of two-stream heat exchangers.

Aspects of the method presented in the Data Items in the group are as follows.

Data Item Number	Title	Description
98003	Part 1. Introduction	Description and overview of the $E-N_{TU}$ method.
98004	Part 2. Performance comparisons and selection of configurations presented in Part 3	Comparative performance and performance limitations of particular heat exchanger configurations.
98005	Part 3. Graphical and analytical data	Data required to use the method. The range of heat exchangers covered includes pure counter-current, pure co-current, crossflow, shell-and-tube and plate heat exchanger configurations.
98006	Part 4. Case studies	Case studies, incorporating all elements of the method presented.
98007	Part 5. Analytical techniques	Numerical and algebraic techniques for relating heat transfer effectiveness, E , to the number of heat transfer units, N_{TU} .

Comparative performance data are provided for a comprehensive range of crossflow, shell-and-tube and plate-type exchanger geometries.

In addition to providing comparative performance data, this Item extends the $E - N_{TU}$ method to the specification of the thermal performance limitations of particular heat exchanger configurations; hence the suitability of a particular configuration for a particular duty may be ascertained.

2.2 Comparison of Heat Exchangers

Graphical $E - N_{TU}$ data are provided in Part 3 of this group of Data Items for a wide range of practical heat exchanger configurations. For those experienced in heat exchanger design, these types will be familiar but, for the less experienced engineer, the choice of the right type for a required duty can be a major problem.

Data are presented in this Item that allow comparisons to be made of the performance of different heat exchanger configurations or examine the effect of linking heat exchangers together. Such comparisons need to be considered during the design process, together with the effects of cost, pressure drop, mechanical design, geometric constraints and other factors outside the scope of this group of Data Items.

The characteristics of crossflow and serpentine heat exchangers are discussed in Section 3, and the characteristics of shell-and-tube and plate-type heat exchangers are discussed in Sections 4 and 5 respectively.

An important parameter in the analysis of a particular geometry of heat exchanger is the maximum value of effectiveness, E , that can be achieved for a particular value of thermal capacity ratio, C^* , no matter how big the heat exchanger is made. Knowledge of this effectiveness limit provides a means of rapidly discarding from consideration during a design exercise those geometries or categories of heat exchanger that are incapable of achieving a required effectiveness.

In Section 5.1.1 of Part 1 it was shown that for a constant heat capacity ratio, C^* , the effectiveness, E , increases with the number of heat transfer units, N_{TU} , and reaches an asymptotic value as N_{TU} tends to infinity. For some types of heat exchanger, the value of E passes through a maximum before tending to a lower asymptotic value.

Application of the maximum effectiveness criterion to crossflow heat exchanger configurations is discussed more fully in Section 3.8 of this Item and to shell-and-tube configurations in Section 4.6. Maximum effectiveness data are not presented for plate-type exchangers.

2.3 General Assumptions

The $E - N_{TU}$ method, in common with **all** similar methods used in two-stream heat exchanger design, is based on the following assumptions (repeated from Part 1):

- heat exchange with the surroundings is negligible,
- constant specific heat capacities are assumed,
- the overall heat transfer coefficient between the streams is constant throughout the heat exchanger,
- mixing occurs in each stream so that fluid temperature is uniform over any cross section at right angles to the direction of flow,
- where a heat exchanger consists of multiple parallel paths, such as tubes in a row or channels within adjacent plates, the flow rates and heat transfer areas in each path are identical.

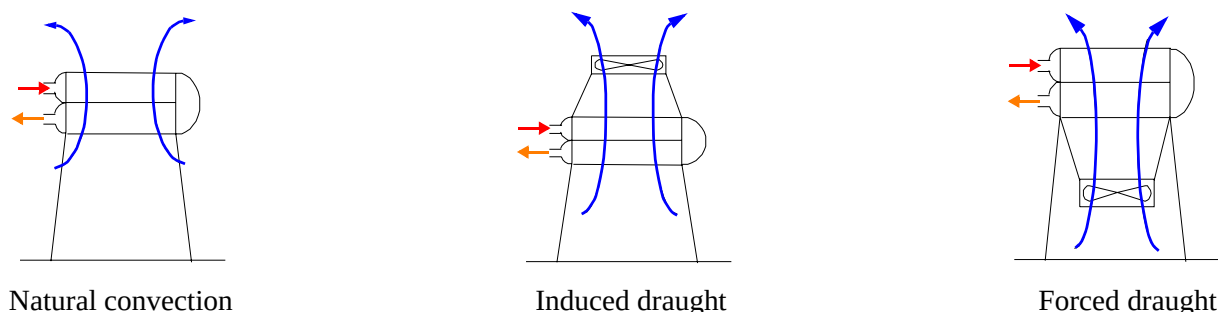
Any further assumptions relating to specific geometries are discussed in detail where data for these geometries are presented.

3. CROSSFLOW AND SERPENTINE EXCHANGER TYPES

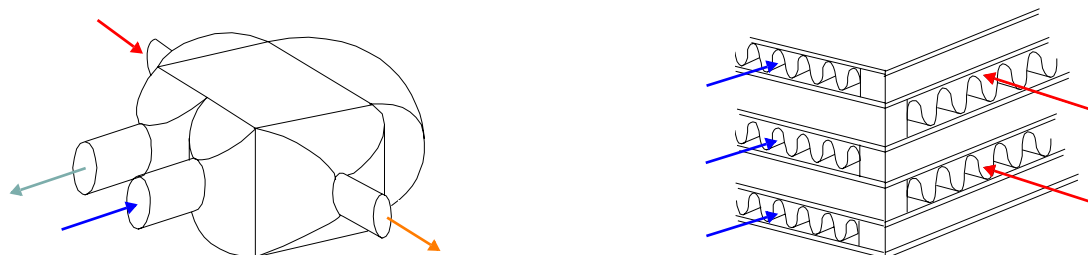
3.1 Description

Crossflow heat exchanger types include X-shells (in which the shellside flow is in pure crossflow, resulting in an extremely low pressure drop), tube banks in ducts, air-cooled types (see ESDU 94043⁷), heat exchangers in domestic refrigerators, boiled feed water preheaters and economisers, carbon block exchangers and plate-fin exchangers (see ESDU 97006⁹). Many common applications involve heat transfer between a gas and a liquid, such as heat rejection in process plants or air conditioning systems. The most widely used crossflow heat exchanger is the car radiator.

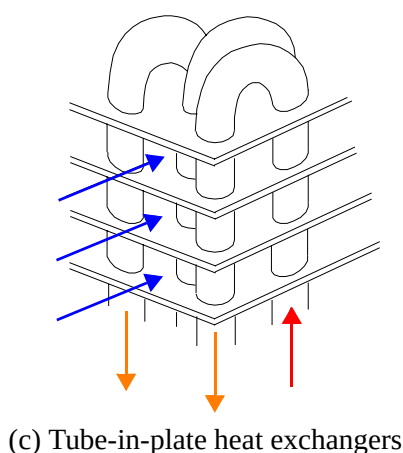
A wide range of designs is possible, particularly when multiple pass configurations are employed. Some of the many types of heat exchanger that may be classified as multi-pass and crossflow are illustrated in Sketch 3.1.



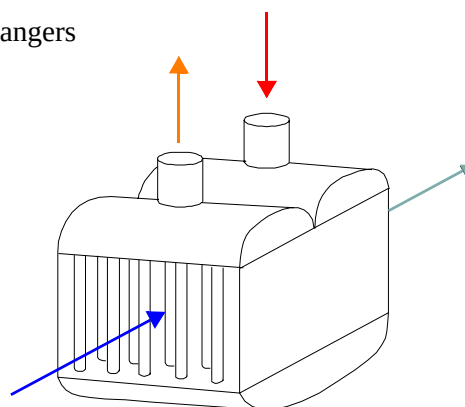
(a) Air-cooled heat exchangers



(b) Plate-fin heat exchangers



(c) Tube-in-plate heat exchangers



(d) Tube-in-duct heat exchangers

Sketch 3.1 Types of multi-pass crossflow heat exchangers

The essential feature of each design is that heat is transferred between two streams flowing at right angles to one another. For example, one stream flows within a series of tubes and the other stream flows at right angles over the tubes. Alternatively, in the plate-fin or printed-circuit heat exchanger, both streams flow in channels arranged at right angles to one another and exchange heat through the plates dividing the streams.

Effectiveness- N_{TU} data are presented in this group of Data Items for a wide range of tubular geometries (see Section 3.2.2.1) and certain plate-type applications in crossflow (typified by the plate-fin type, see Section 3.2.2.2).

3.2 General Assumptions for Crossflow Exchangers

3.2.1 Flow distribution

In the analysis of cross-flow exchangers it is assumed that the **flow distribution is uniform**. This uniformity applies to the distribution of flow between tubes fed from a header and to the distribution of flow passing over a bank of tubes or over a plate.

Serious departures from uniform distribution could occur with poorly designed headers, tube bundles placed in ducts immediately downstream of bends or valves or in forced draught air cooled heat exchangers where insufficient depth is allowed in the plenum between the fan and tube bundle. The effects of maldistribution will generally be to reduce heat transfer performance. Such reductions are not considered in this Item.

3.2.2 Stream mixing assumptions

The following stream mixing assumptions are made.

- (i) **The temperatures of both streams are uniform across their inlet planes to the exchanger.**
- (ii) **In all planes normal to the direction of its flow, each stream is assumed to be either *fully mixed* or *unmixed*.**

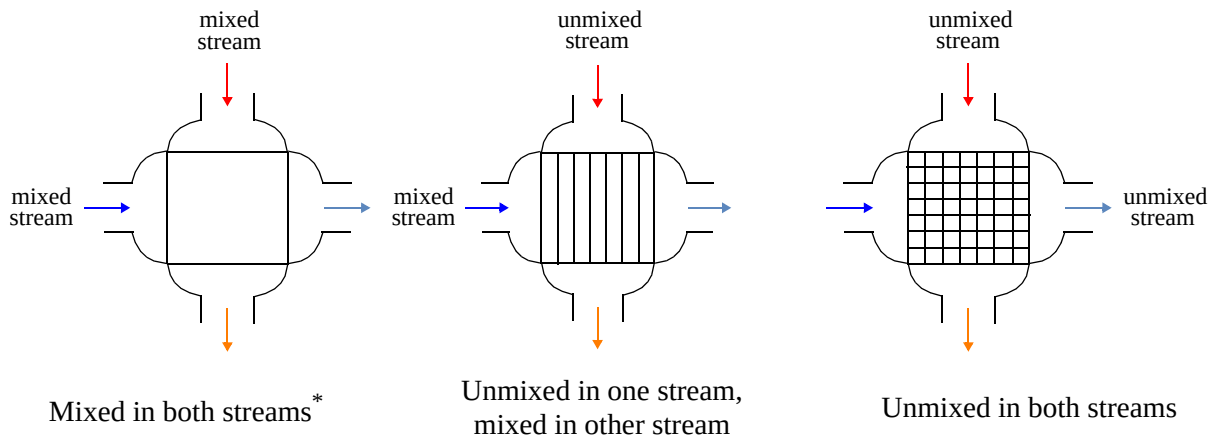
Fully mixed

A characteristic of a fully mixed fluid is that its temperature is uniform across any section and varies only in the direction of flow.

Unmixed

The temperature of an unmixed fluid passing through an exchanger can vary across any section and in the direction of flow.

Sketch 3.2 shows two-dimensional representations of real (three-dimensional) heat exchangers, and illustrates the three options that arise when all combinations of the mixing assumptions are considered for a simple **single-pass** crossflow heat exchanger. The performance of these single-pass crossflow heat exchanger configurations is illustrated in Section 3.3, where it can be seen that peak heat transfer performance is obtained in unmixed/unmixed conditions.



* This arrangement is unlikely to be encountered in conventional heat exchangers.

Sketch 3.2 Single-pass crossflow exchangers with various mixing assumptions

The application of these stream mixing assumptions is discussed in Section 3.2.2.1 with particular reference to tubular crossflow exchangers and in Section 3.2.2.2 for multi-channel or multi-tube types such as plate-fins, in which flow is unmixed.

3.2.2.1 Tubular crossflow and serpentine types

Tubular crossflow heat exchangers include air-cooled, tube-in-plate and tube-in-duct types (see Sketch 3.1).

On the tubeside the following assumptions are made to describe the mixing, as illustrated in Sketch 3.3:

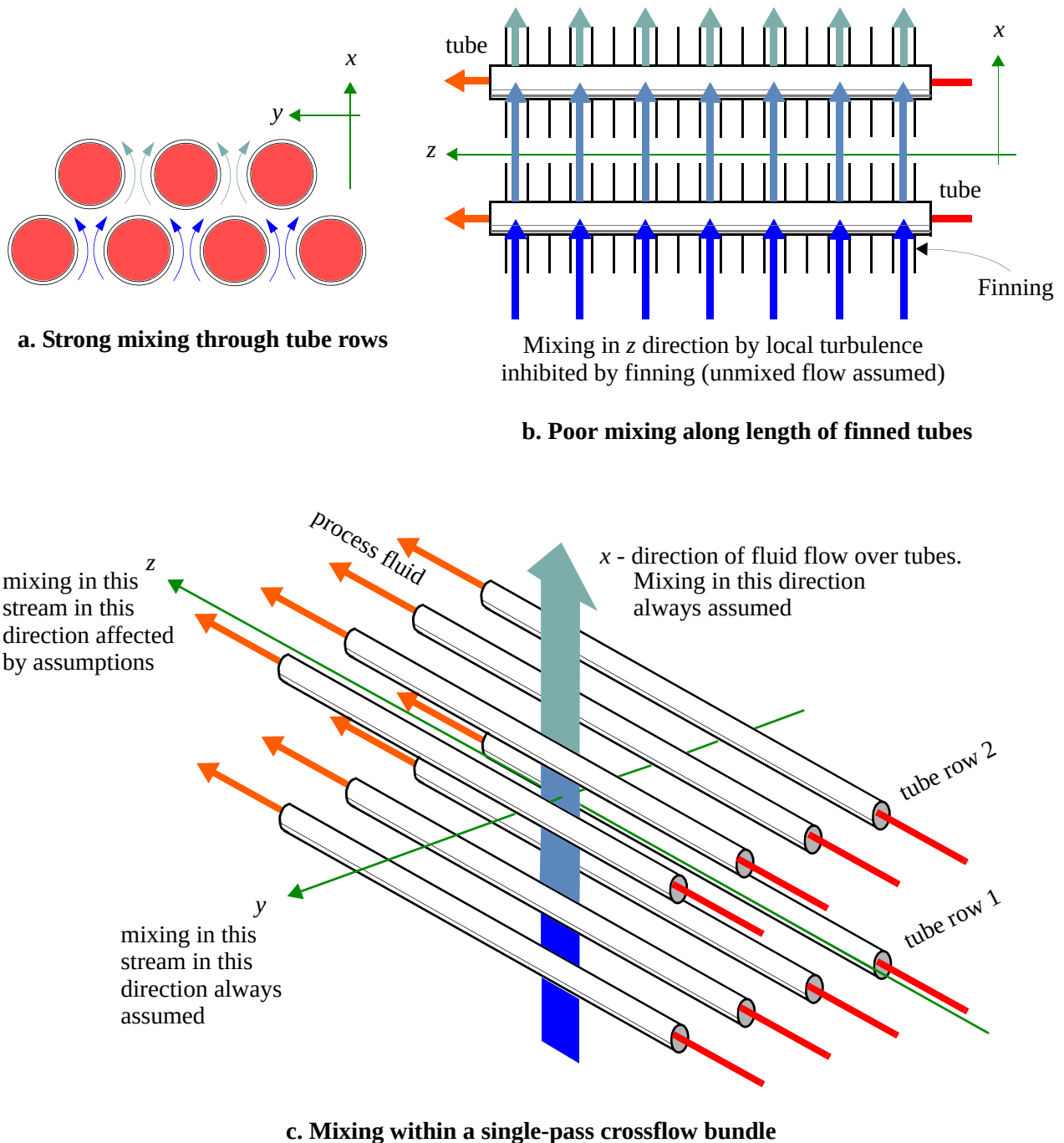
- **Flow within a single row of tubes is fully mixed;** that is, it is assumed that every tube in a row behaves in an identical manner.
- If a heat exchanger consists of more than one row of tubes in a single-pass, then it is assumed that **no mixing occurs between rows** and each row behaves in a distinct manner. The effectiveness increases progressively as the number of tube rows increases and the behaviour moves from the limiting condition of fully mixed (for one tube row) to unmixed (for an infinite number of tube rows). Between these limits the flow is referred to as 'partially mixed'. This behaviour is illustrated in Section 3.3.

Outside tubes the following assumptions are made in each of the three directions x , y , and z , as illustrated in Sketch 3.3.

- In the direction of flow of the fluid passing over the tubes, x , full mixing occurs due to general turbulence and enforced changes of direction (see Sketches 3.3a and c).
- There is also full mixing in the direction normal to the length of the tubes, y (see Sketches 3.3a and c) due to the assumptions of uniform flow distribution and uniform temperature of the tubeside fluid across the inlet plane to the tubes.
- Along the length of the tubes mixing is unlikely to be excessive and it is assumed that **flow over tubes is always unmixed** (see Sketches 3.3b and c).

Circumferential finning, which is a feature of many types of heat exchanger where gas flows outside the tubes, will inhibit significantly any mixing along the tubes (that is, in the direction of the tubes as shown Sketch 3.3) whilst the plates of tube-in-plate designs prevent mixing almost entirely. (There may be small conductivity effects across the plates.)

Flow outside unsupported tubes in the direction of the tubes (that is, in z direction) is always unmixed and may lead to a slight overprediction in performance of plain (unfinned) tubes, but the error is believed to be small in comparison with the overall uncertainties of the method.



Sketch 3.3 Mixing assumptions in crossflow over tubes

For flow both on the tubeside and over tubes, fluid motion in the direction transverse to the main flow and parallel to the direction of the other fluid is alone considered in establishing the mixing characteristics of the streams in crossflow exchanger configurations. By inspection of Sketch 3.3c it can be seen that

- the mixing characteristics of the tubeside flow are defined by the behaviour of the flow in the direction x , and
- the mixing characteristics of flow over the tubes are defined by the behaviour of the flow in the direction z .

3.2.2.2 Types with unmixed flow in exchanger channels or tubes

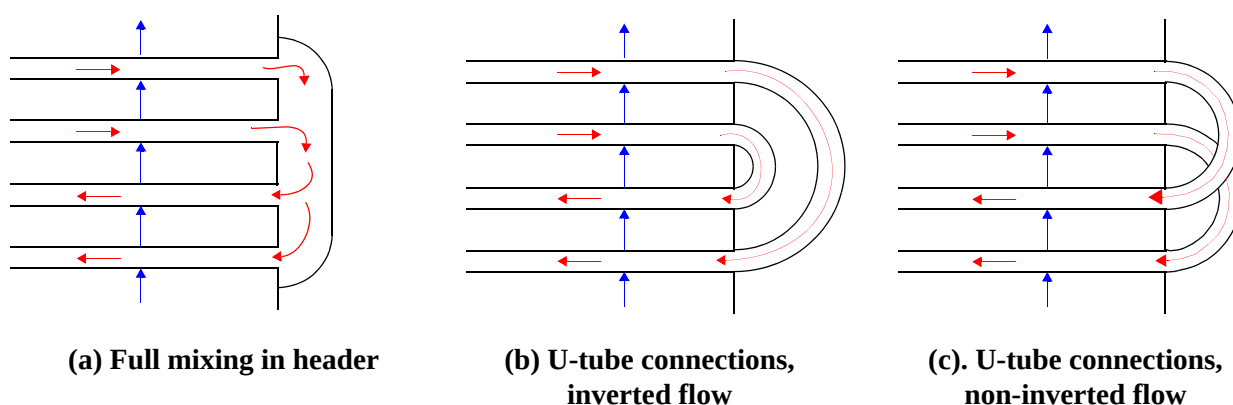
Multi-channel and multi-tube heat exchanger types, typified by the plate-fin (see Sketch 3.1), are the closest approach to the unmixed stream assumption in practice. In a plate-fin exchanger, the flow passages are divided by numerous thin fins that prevent turbulent mixing and no mixing is assumed in either stream. However, even here, some heat transfer can occur on account of conduction through the fins.

3.2.3 Additional mixing assumptions for multi-pass configurations

For **multi-pass** heat exchangers, it is also necessary to consider the conditions between the passes. Again two extremes exist: **fully mixed** and **unmixed**.

It is assumed that any connection between passes that is made by collecting the tube exit flow from one pass into a header and then redistributing the flow from that header into the next pass can be represented by full mixing

Conditions for unmixed flow require the positive separation of flows between passes, the most obvious example being the connection of tube rows by U-bends. Two methods of making such connections are illustrated in Sketch 3.4 and are identified as inverted and non-inverted flow depending upon the resulting order in which the flows in the tubes encounter the flow outside the tubes. From practical considerations, it is assumed that the U-tube method of connection is restricted to designs with two rows of tubes per pass

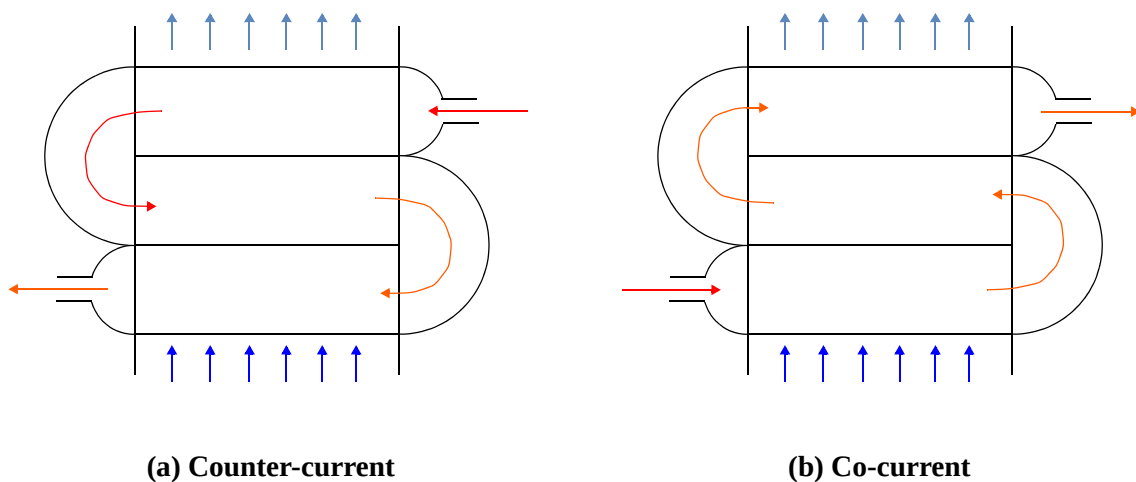


Sketch 3.4 Mixing between passes

Connections between passes on the tubeside of crossflow exchangers are therefore assumed to be either **fully mixed (designs with headers)** or **unmixed (designs with U-tube connections)**. Mixing assumptions for connections between passes outside the tubes can in principle lie anywhere between these two extremes. For plate-fin exchangers, the flow passing axially along the unit will see no disturbance from one pass to another and will remain totally unmixed. Similarly, if the spacing between rows of tubes in an exchanger is the same between passes as within a pass the unmixed assumption can be retained. However,

difficulties would arise if significantly larger gaps between tubes were left between passes since partial mixing could occur. Observations of common designs of multi-pass crossflow heat exchangers suggest that a uniform tube pitch is usual and, therefore, non-mixing between passes outside tubes is assumed in this group of Items.

In addition to opportunities for mixing and non-mixing, multi-pass heat exchangers also provide a variety of options for flow arrangement. The two practical arrangements of counter-current flow and co-current flow are considered here. In counter-current flow arrangements, the first pass of one stream exchanges heat with the last pass of the other stream (see Sketch 3.5a). In co-current flow arrangements, the first pass of one stream exchanges heat with the first pass of the other stream (see Sketch 3.5b).

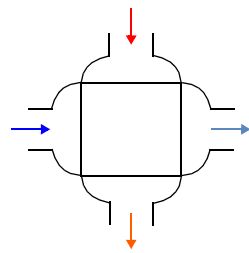


Sketch 3.5 Possible flow arrangements

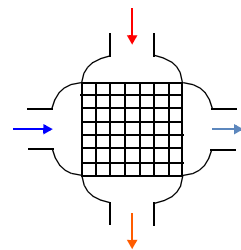
3.3 Comparisons of Performance of Single-pass Crossflow Configurations

The performance of single-pass crossflow heat exchangers is illustrated in Sketches 3.6 and 3.7 for a range of configurations. Sketch 3.6 illustrates the effects on performance estimates of combinations of mixing assumptions. It can be seen that peak heat transfer performance is obtained in unmixed/unmixed conditions. Similarly, Sketch 3.7 shows the heat transfer behaviour for a range of single-pass heat exchangers consisting of one or more rows of tubes. Here it may be seen that the effectiveness increases progressively as the number of tube rows increases, illustrating the benefit of moving from mixed (one tube row per pass) to unmixed (an infinite number of tube rows per pass) flow on the tubeside.

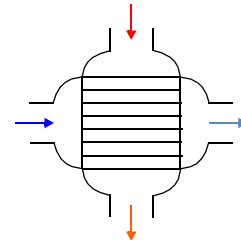
It can be seen in Sketch 3.7 that the performance of a single-pass crossflow configuration with four tube rows is very close to that for an infinite number of tube rows. For practical purposes, for configurations with five or more tube rows the data for an infinite number of tube rows can be used; a slight overestimate of performance will be obtained, particularly at higher values of N_{TU} .



(a) Mixed in both streams
(CRO-MIX/MIX)

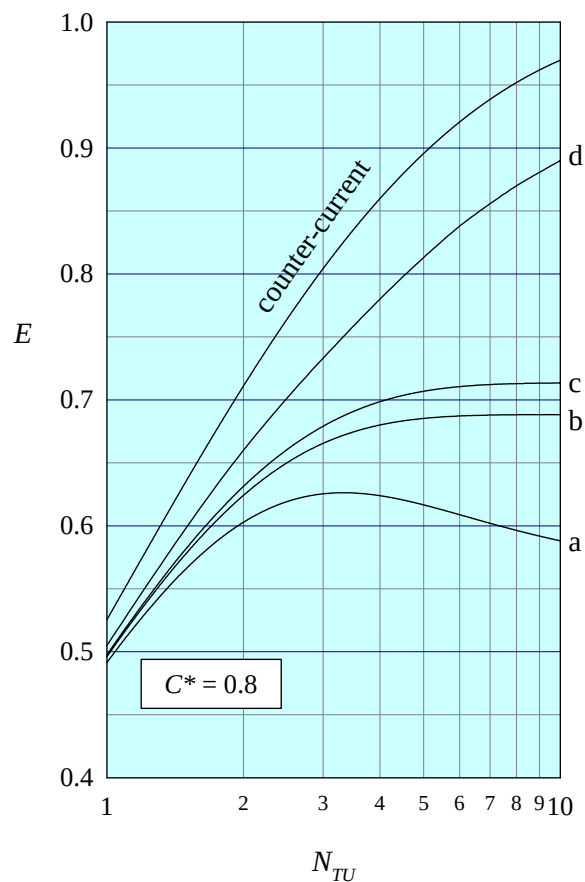
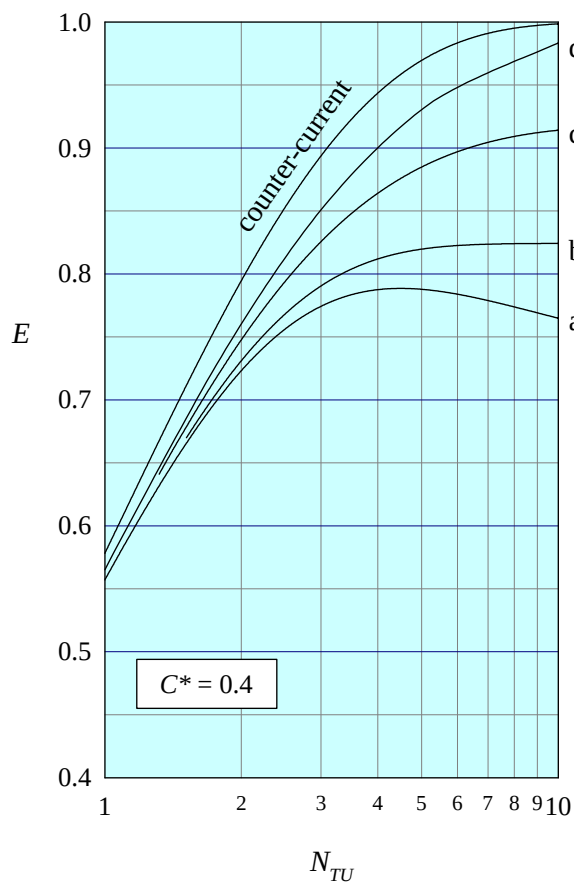


(d) Unmixed in both streams
(CRO-UNMIX/UNMIX)

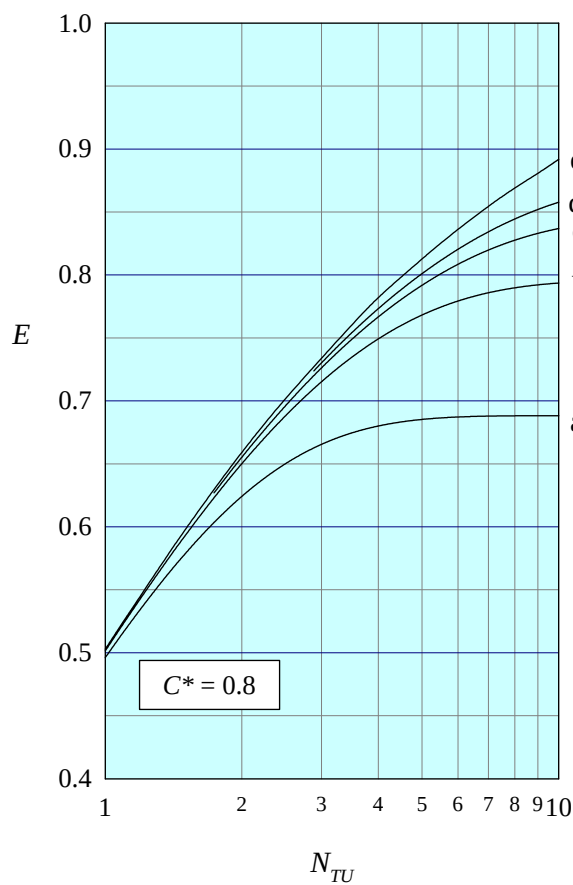
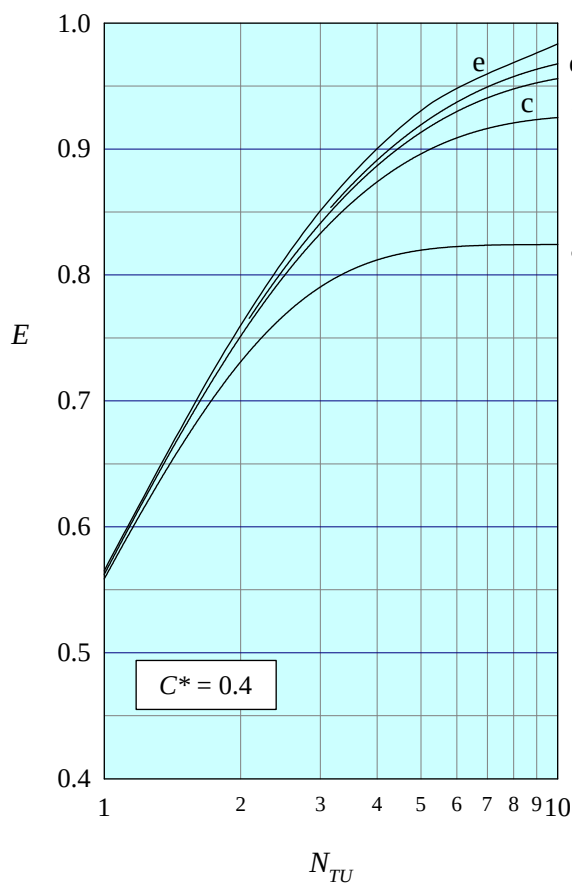
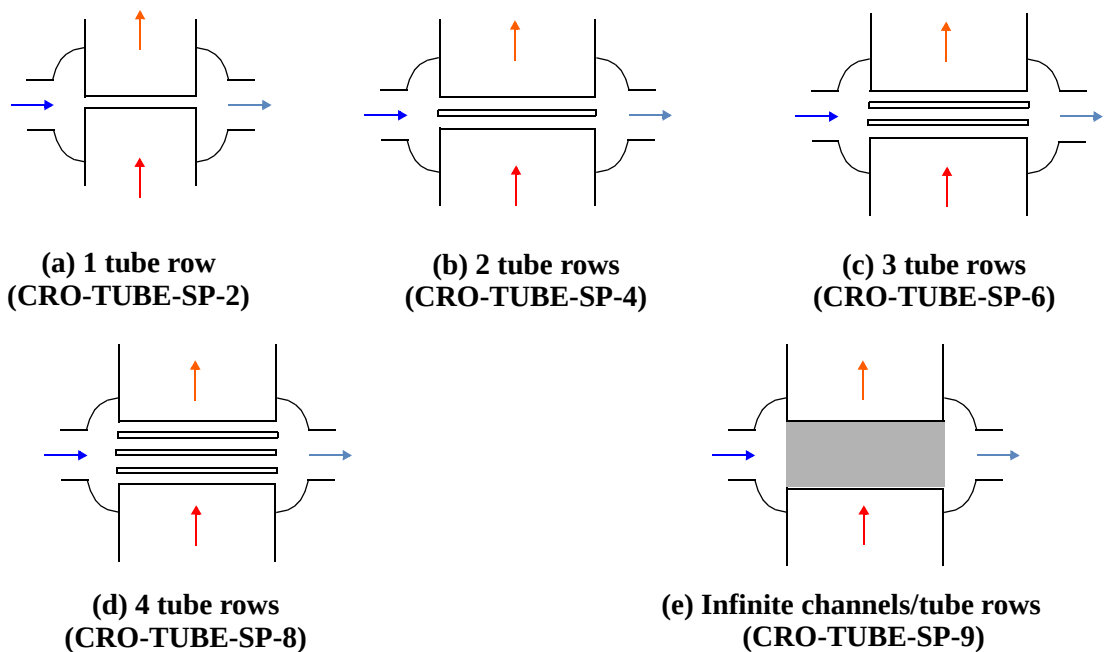


(b) Mixed in one stream: $(\dot{M}c_p)_{\text{smaller}}$ unmixed
(CRO-UNMIX/MIX-1)

(c) Mixed in one stream: $(\dot{M}c_p)_{\text{smaller}}$ mixed
(CRO-UNMIX/MIX-2)



Sketch 3.6 Single-pass crossflow exchangers with various mixing assumptions



Sketch 3.7 Single-pass crossflow exchanger with various number of tube rows

3.4 Comparisons of Performance of Two-pass Crossflow Configurations

For two-pass crossflow heat exchangers, Sketch 3.8 shows the behaviour of **counter-current**^{*} flow arrangements with headered connections of the tubes. For single-pass exchangers (Sketch 3.6) it is seen that the curves for finite numbers of tube rows form an ordered relationship between one tube row and an infinite number of tube rows. A similar relationship is observed for counter-current flow of two-pass heat exchangers, with the effectiveness again increasing as the number of tube rows increases. For design or rating calculations, it is recommended that separate data sets should be used for one, two and three tube rows per pass. For more than three tube rows per pass, it is recommended that the solution for an infinite number of tube rows should be used. Comparisons show that the effect on the curves of the position of the stream with the smaller thermal capacity, $(\dot{M}c_p)_{\text{smaller}}$, is negligible.

The behaviour of two-pass crossflow heat exchangers with **co-current**[†] flow arrangement and headered connections is shown in Sketch 3.9. Here there is no ordered progression from one tube row per pass to an infinite number of tube rows per pass, and for N_{TU} values below approximately three the values of E are independent of tube row count. However, increasing the number of tube rows decreases progressively the effectiveness at high values of N_{TU} . In all cases a maximum effectiveness value is observed. Data sets are provided for one tube row per pass, two tube rows per pass and three tube rows per pass. For more than three tube rows per pass, it is recommended that the solution for an infinite number of tube rows is used.

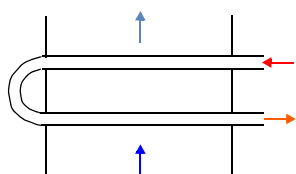
It should be noted that (perhaps surprisingly for co-current flow) the data highlight the onset of reverse heat flows or local temperature cross. This is because, for a single-pass unmixed/unmixed heat exchanger, the heat transfer effectiveness at high values of N_{TU} tends to unity. As a result a temperature cross can occur in the first half of the heat exchanger. This temperature reversal means that some of the heat transferred in the first pass will be transferred back in the second pass. As N_{TU} increases, more and more of the heat transfer in the first pass is reversed, so reducing the performance.

Sketch 3.10 shows the effect of headered and U-tube connections of the tubes for two tube rows per pass and counter-current flow. It can be seen that the connections between passes have virtually no effect upon the effectiveness and it is recommended that design and rating calculations are performed using the relationship for the headered arrangement.

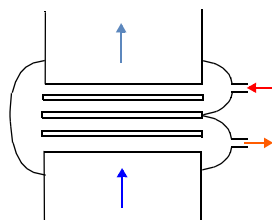
Sketch 3.11 repeats the comparison of two-pass, two tube rows per pass heat exchangers but using co-current flow arrangements. Here, changing the connections between passes has a significant effect upon effectiveness. It is observed that the arrangement with a U-tube connection that does not invert the flow gives the best performance. Detailed investigation of the temperatures of the two streams while passing over the four rows of tubes reveals that the non-inverted flow arrangement produces temperature driving forces at high values of N_{TU} that generate less reverse heat flow than the other two options and hence a higher overall effectiveness. Data sets are provided for U-tube inverted flow connections and U-tube non-inverted flow connections

* In the context of a multi-pass crossflow configuration, a counter-current arrangement is defined as one where the tubeside inlet is located adjacent to the exit of the crossflow stream (see Sketches 3.8 and 3.10).

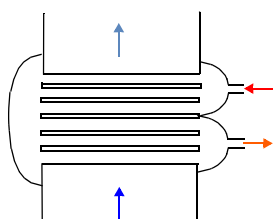
† In the context of a multi-pass crossflow configuration, a co-current arrangement is defined as one where the tubeside inlet is located adjacent to the inlet of the crossflow stream (see Sketches 3.9 and 3.11).



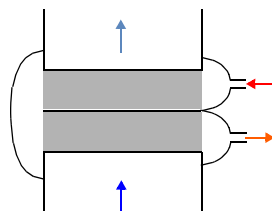
(a) 1 tube row per pass
(SERP-CU-2)



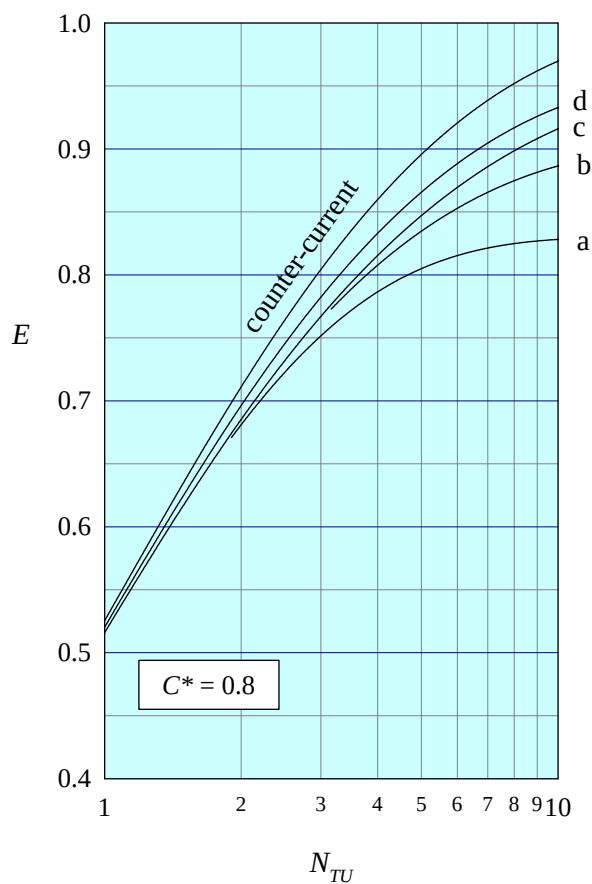
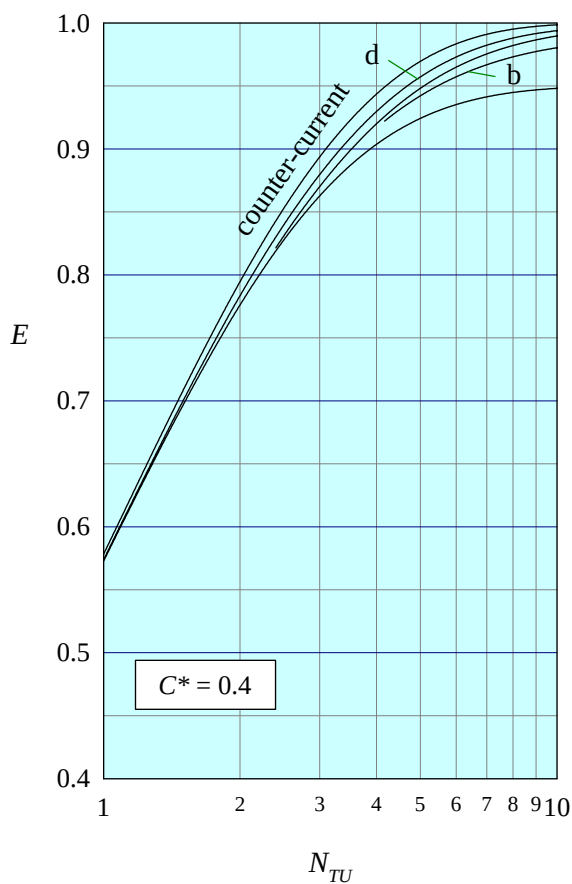
(b) 2 tube rows per pass
(CRO-TUBE-MP-CU-2)



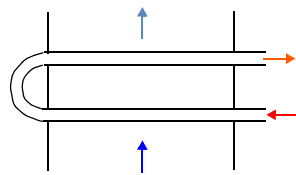
(c) 3 tube rows per pass
(CRO-TUBE-MP-CU-3)



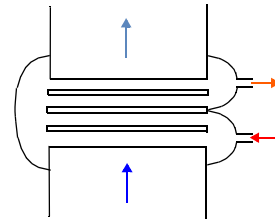
(d) Infinite channels/tube rows per pass
(CRO-TUBE-MP-CU-4)



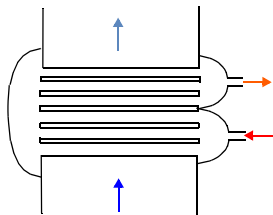
Sketch 3.8 Two-pass crossflow exchangers with mixing between passes and counter-current flow arrangement



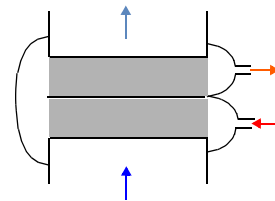
(a) 1 tube row per pass
(SERP-CO-2)



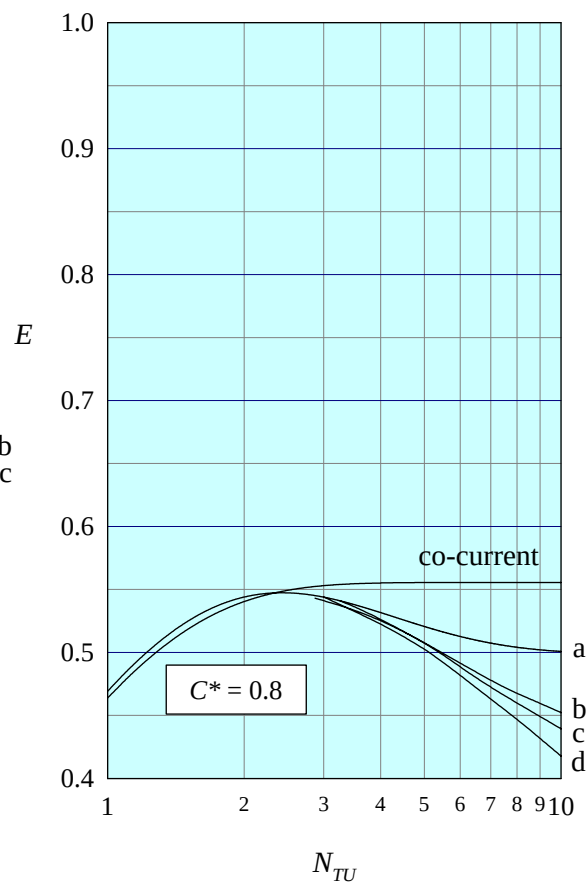
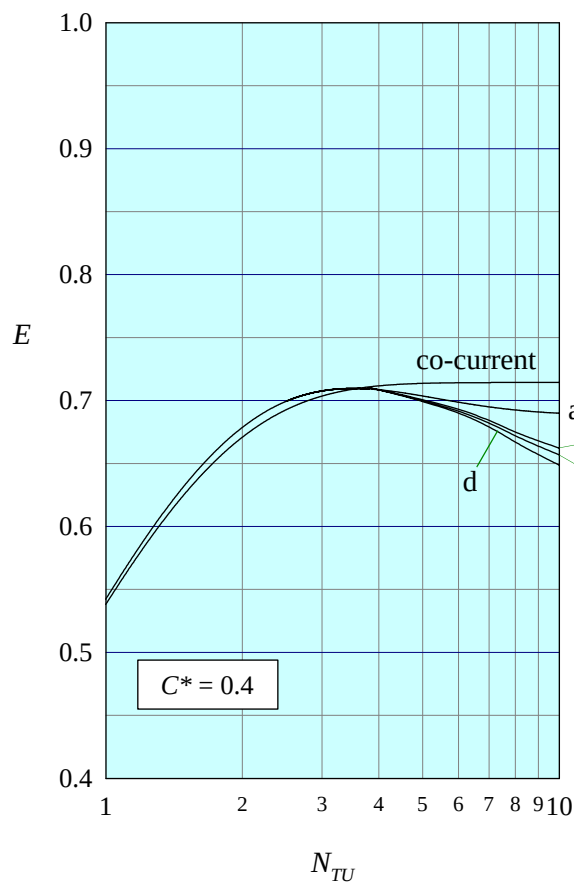
(b) 2 tube rows per pass
(CRO-TUBE-MP-CO-2)



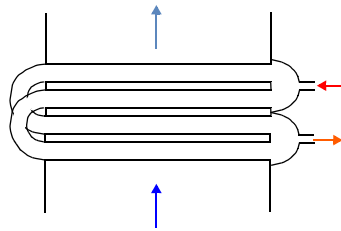
(c) 3 tube rows per pass
(CRO-TUBE-MP-CO-8)



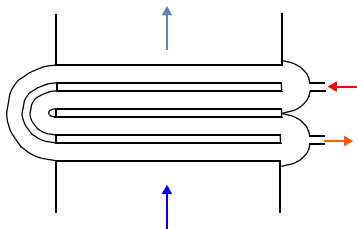
(d) Infinite tube rows per pass
(CRO-TUBE-MP-CO-10)



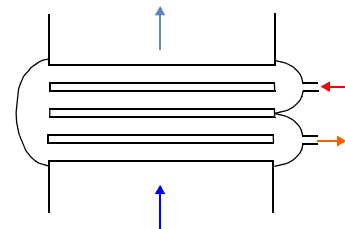
Sketch 3.9 Two-pass crossflow exchangers with mixing between passes and co-current flow arrangement



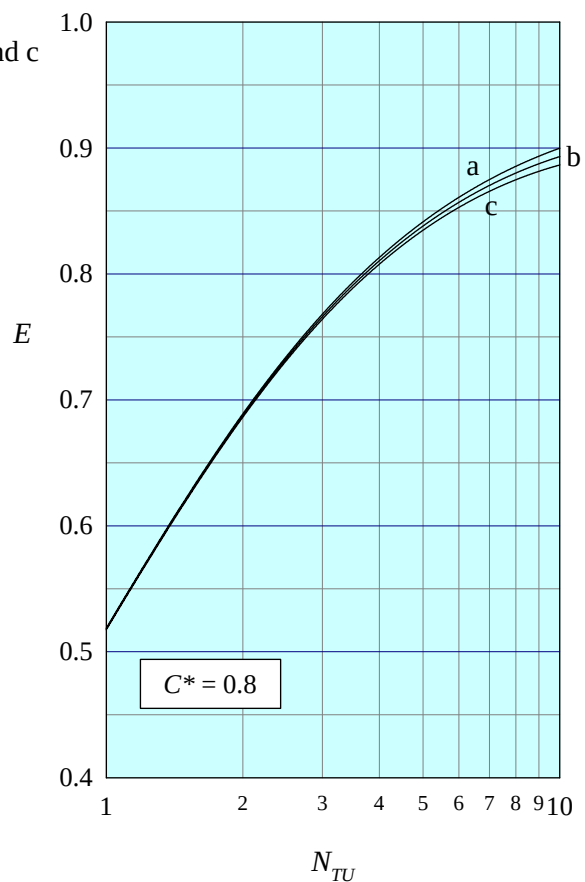
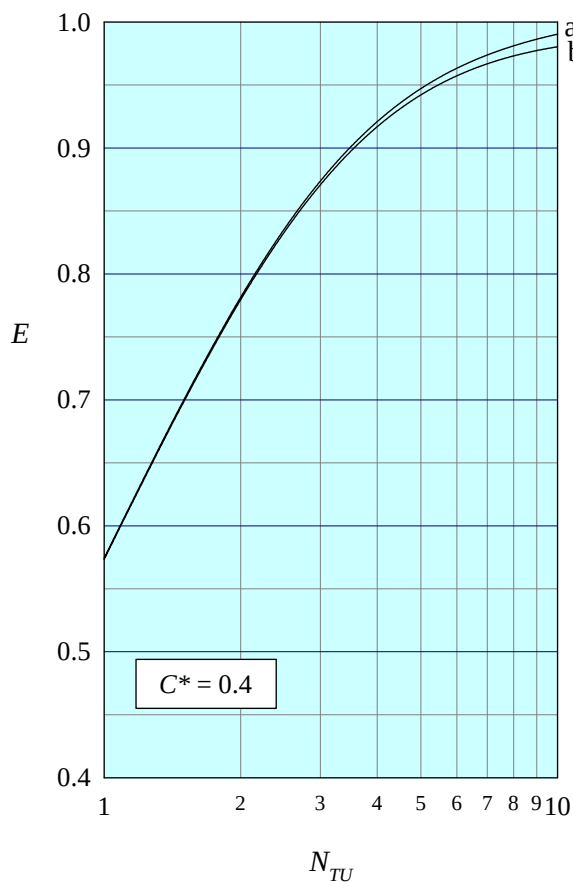
(a) U-tube connections with non-inverted order
(CRO-TUBE-MP-CU-2)



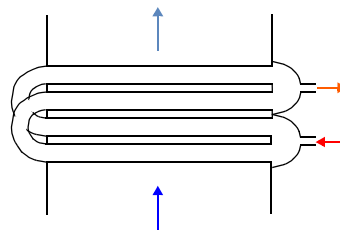
(b) U-tube connections with inverted order
(CRO-TUBE-MP-CU-2)



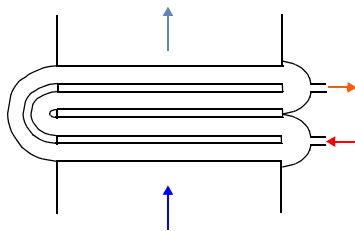
(c) Mixing between passes (headered)
(CRO-TUBE-MP-CU-2)



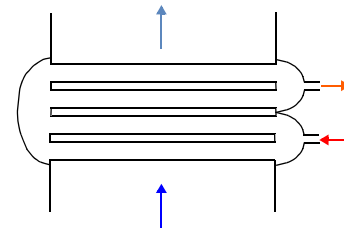
Sketch 3.10 Two-pass crossflow exchangers with two tube rows per pass and counter-current flow arrangements



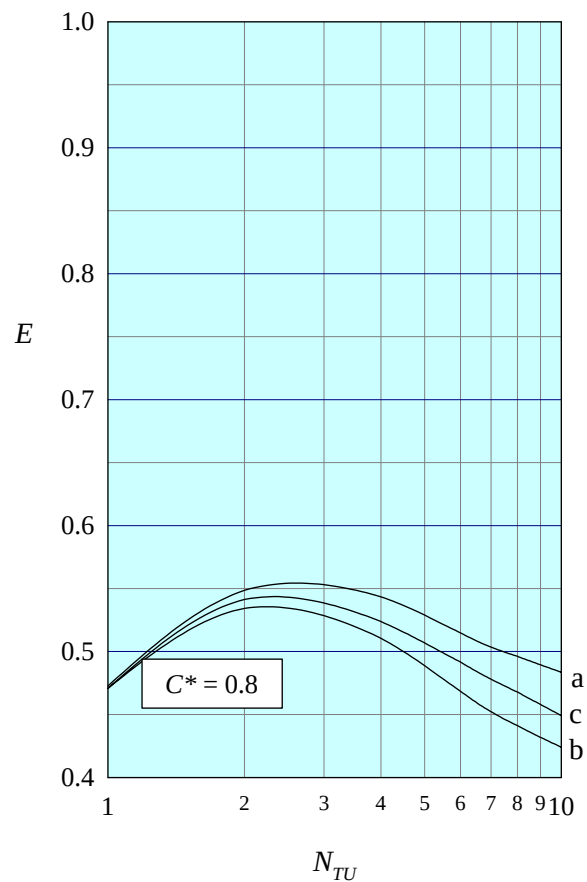
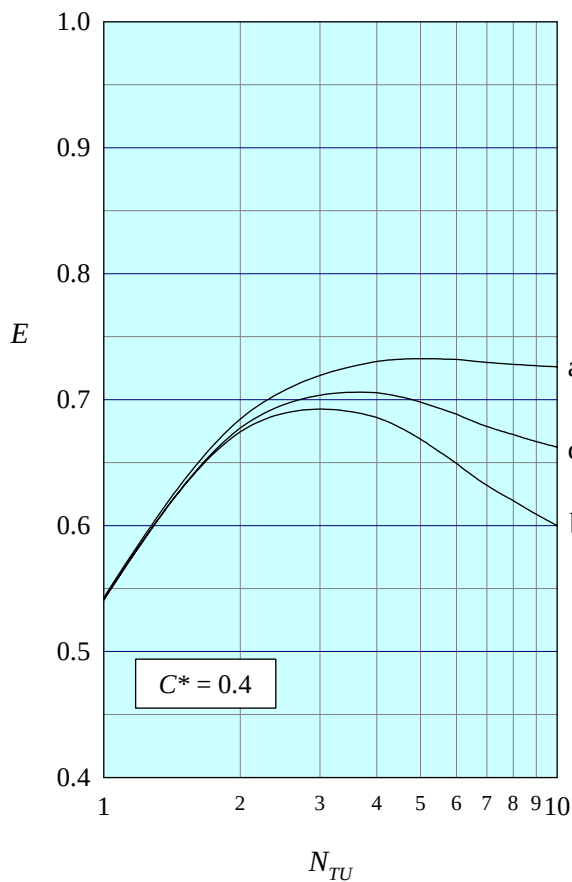
**a. U-tube connections with non-inverted order
(CRO-TUBE-MP-CO-6)**



**b. U-tube connections with inverted order
(CRO-TUBE-MP-CO-4)**



**c. Mixing between passes (headered)
(CRO-TUBE-MP-CO-2)**



Sketch 3.11 Two-pass crossflow exchangers with two tube rows per pass and co-current flow arrangements