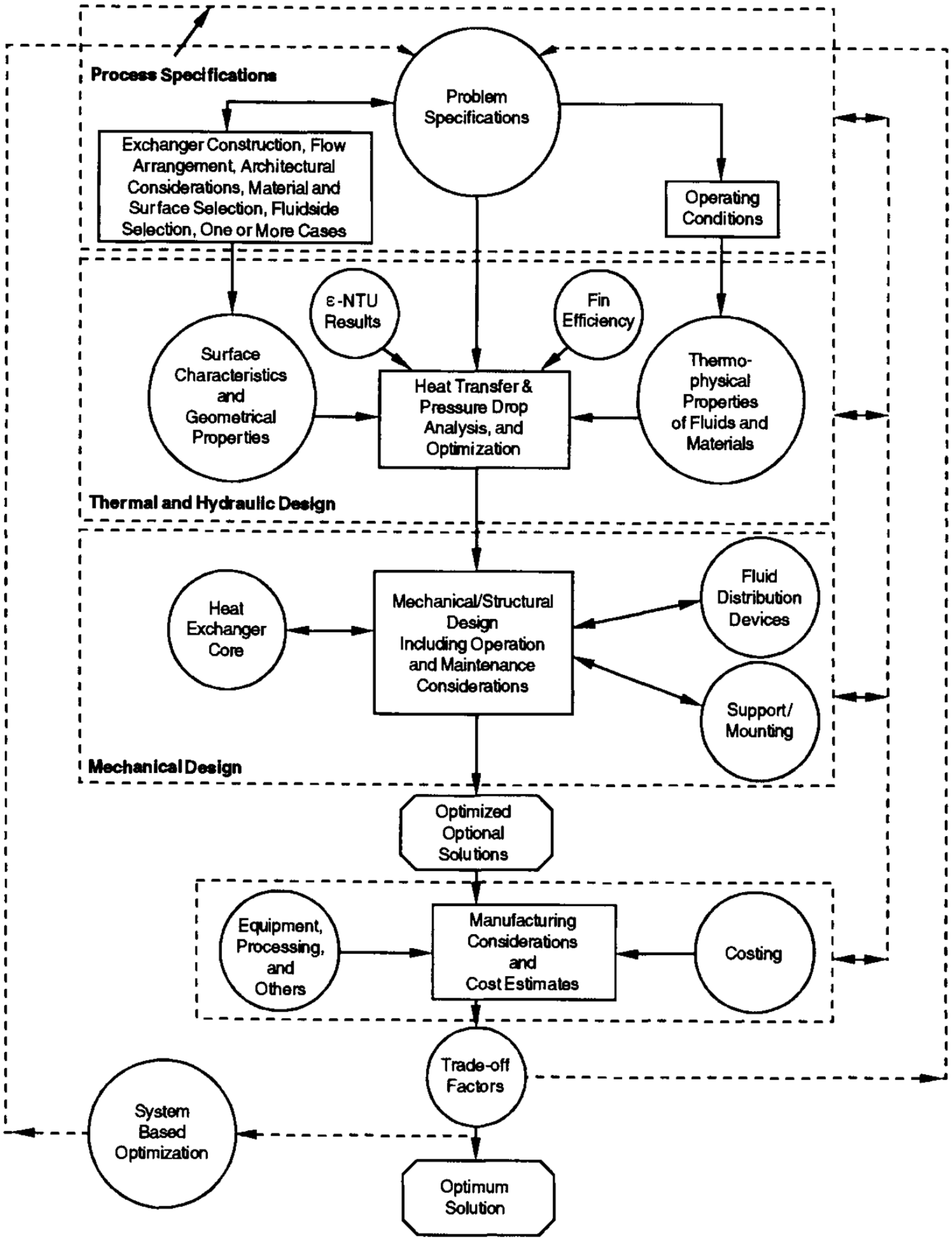
Design of heat exchangers

Exchanger Design Methodology

The problem of heat exchanger design is complex and multidisciplinary. The major design considerations for a new heat exchanger include: process/design specifications, thermal and hydraulic design, mechanical design, manufacturing and cost considerations, and trade-offs and system-based optimization as shown in figure, with possible strong interactions among these considerations as indicated by double-sided arrows The thermal and hydraulic designs are mainly analytical and the structural design is to some extent. Most of the other major design considerations involve qualitative and experience-based judgments, tradeoffs, and compromises. Therefore, there is no unique solution to designing a heat exchanger for given process specifications.



Two most important heat exchanger design problems are the **rating** and **sizing** problems. Determination of heat transfer and pressure drop performance of either an existing exchanger or an already sized exchanger is referred to as the *rating problem.* The objective here is to verify vendor specifications or determine the performance at off-design conditions. The rating problem is also sometimes referred to as the performance problem. In contrast, the design of a new or existing-type exchanger is referred to as the *sizing problem.* In a broad sense, it means the determination of the exchanger construction type, flow arrangement, heat transfer surface geometries and materials, and the physical size of an exchanger to meet the specified heat transfer and pressure drops. However, from the viewpoint of quantitative thermal-hydraulic analysis, we will consider that the selection of the exchanger construction type, flow arrangement, and materials has already been made. Thus, in the sizing problem, we will determine here the physical size (length, width, height) and surface areas on each side of the exchanger. The sizing problem is also sometimes referred to as the design problem.
The design of heat exchanger is complex task. There are many variables associated with the geometry (i.e., tubes, shell, baffles, front and rear end, and heads) and operating conditions including flow bypass and leakages in a heat exchanger. There are no systematic quantitative correlations available to take into account the effect of these variables on the exchanger heat transfer and pressure drop. As a result, the common practice is to presume the geometry of the exchanger for the determination of the heat duty and the exchanger size calculation. The design calculations can be also performed as a series of iterative rating calculations made on an assumed design and modified as a result of these calculations until a satisfactory design is achieved.
Flue gas heat exchanger and boiler heating surfaces are mainly designed as serpentine tube bundles.

The following is a step-by-step procedure for the "sizing" problem in which we will determine the exchanger dimensions. The key steps of the thermal design procedure for a serpentine tube heat exchanger are as follows:

1. From given parameters calculate unknown inlet or outlet temperatures and flow rates of fluids and heat transfer rate of heat exchanger using **overall energy balance**
2. Select a preliminary flow arrangement (i.e. based on the common industry practice).
3. Design preliminary geometry parameters of heat exchanger. The work includes selection of tube diameter, layout and pitch.
4. Choose fluid flow velocities.
5. Estimate the log-mean temperature difference.
6. Estimate an overall heat transfer coefficient using appropriate methods for heat transfer calculation for designed type of heating surface.
7. Estimate required heat transfer area.
8. Calculate length of tubes, the number of serpentines or passes, baffles etc. (depending on heat exchanger type).
9. Estimate outside dimensions of heat exchangers.
10. Calculate pressure drops for both fluids.
11. Repeat, if necessary, steps 3 to 9 with an estimated change in design until a final design is reached that meets specified requirements.

This step-by-step procedure is consistent with overall design methodology and can be executed as a straightforward manual method or as part of a computer routine. Although the actual design has been frequently carried out using available sophisticated commercial software.

Overall energy balance

For a modern heat exchanger the energy losses to the surrounding air can be neglected, as they are very small. Thus the heat energy given off by the hot fluid is equal to the heat energy absorbed by the cold fluid, i.e. an energy balance.

Two energy conservation differential equations for an overall adiabatic two-fluid exchanger with any flow arrangement are

$$dq = q''dA = -C_h dT_h = +C_c dT_c \qquad [W] \quad (1)$$

Here dq is heat transfer rate from the hot to cold fluid across the surface area dA; C_h and C_c are the heat capacity rates for the hot and cold fluids, and the +/- sign depends on whether dT_c is increasing or decreasing with increasing dA.

The heat capacity rate is

$$C_i = m_i c_i \qquad [W/K] \quad (2)$$

where m_i [kg/s] is mass flow rate and c_i [$Jkg^{-1}K^{-1}$] is specific heat of fluid i at constant pressure.

The overall rate equation on a local basis is

$$dq = q''dA = U(T_h - T_c)_{loc}dA = U\Delta T dA \qquad [W] \quad (3)$$

where U is the overall heat transfer coefficient. Integration of Eqs. 1 and 3 across the exchanger surface area results in overall energy conservation and rate equations as follows.

$$q = C_h(T_{h,i} - T_{h,o}) = C_c(T_{c,o} - T_{c,i}) \qquad [W] \quad (4)$$

and

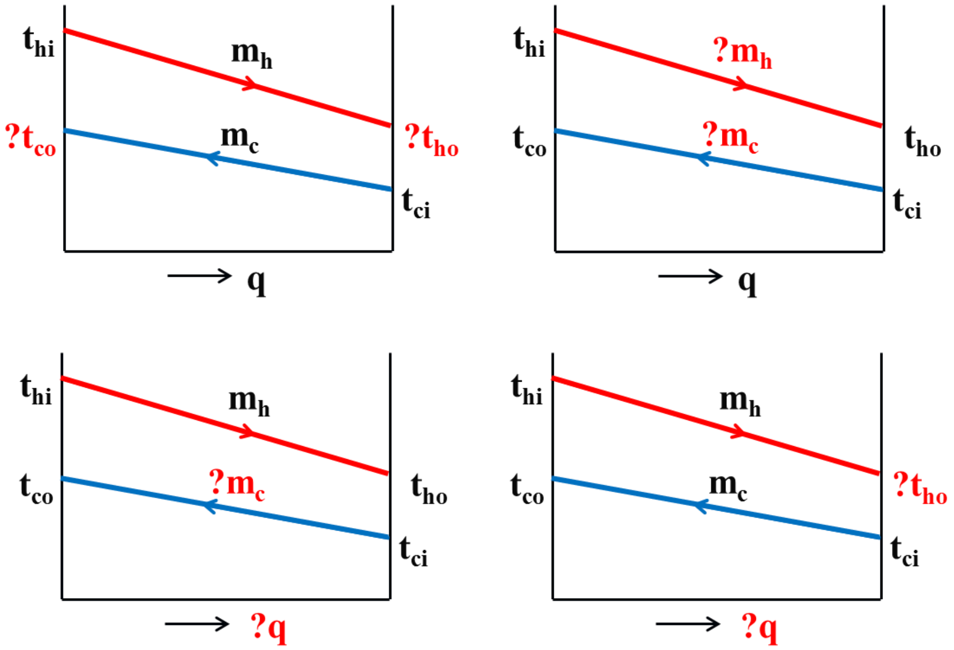
$$q = UA\Delta T_m \qquad [W] \quad (5)$$

Here ΔT_m is the true mean temperature difference dependent on the exchanger flow arrangement.

The required heat transfer rate can be determined from known flow rate, heat capacity and temperature change for either the hot fluid or the cold fluid. Then either the flow rate of the other fluid for a specified temperature change, or the outlet temperature for known flow rate and inlet temperature can be calculated. Aim of overall energy balance is to determine all external parameters describing heat exchanger operation:

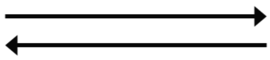
- mass flow rates m_h, m_c
- inlet temperatures $T_{h,i}$, $T_{c,i}$
- outlet temperatures $T_{h,o}$, $T_{c,o}$
- heat transfer rate

Depending on given parameters solving of following tasks is possible:



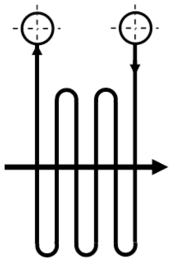
Selection of flow arrangement

Basic flow arrangements of two fluids in heat exchanger are counterflow, parallelflow, single-pass crossflow, multipass crossflow and various combinations.

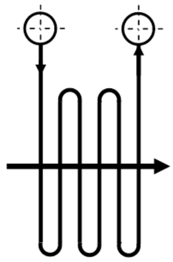


counterflow

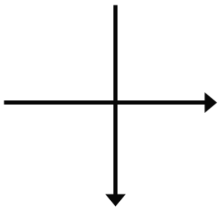
parallelflow



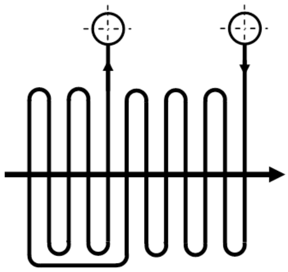
multipass crosscounterflow



multipass crossparallelflow



single-pass crossflow

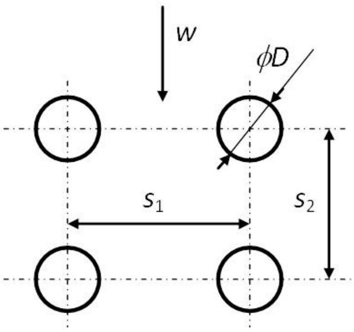


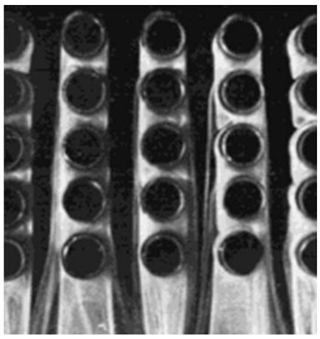
combined multipass crossflow

Preliminary geometrical design

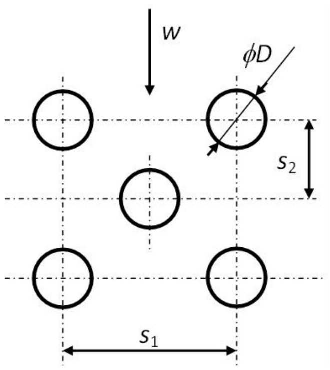
The work includes selection of tube diameter, layout and pitch. Choice depends on many conditions i.e. type of fluid, its velocity, pollution by particles and chemical impurities, design limitations etc. Two layouts of tubes in bundle are:

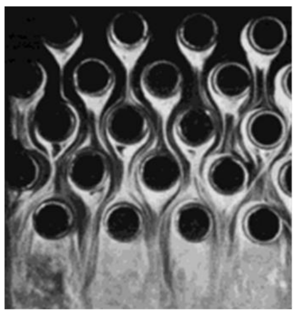
- inline





- staggered





Choice of fluid flow velocities

Choice of fluid flow velocity according to common practice allows reasonable and compromise values of overall heat transfer coefficient and pressure drop already in the first approach to heat exchanger design. Recommended velocities of fluid flows are:

- water in tubes 0,3 – 1,0 m/s
- steam-water mixture in horizontal tubes 1,0 – 3 m/s
- steam in tubes up to 30 m/s
- gases in tubes 10 – 15 m/s
- air, clean flue gas cross tubes 8,0 – 15 m/s
- flue gas with particles cross tubes 5,0 – 10 m/s
- water cross tubes 0,2 – 0,8 m/s

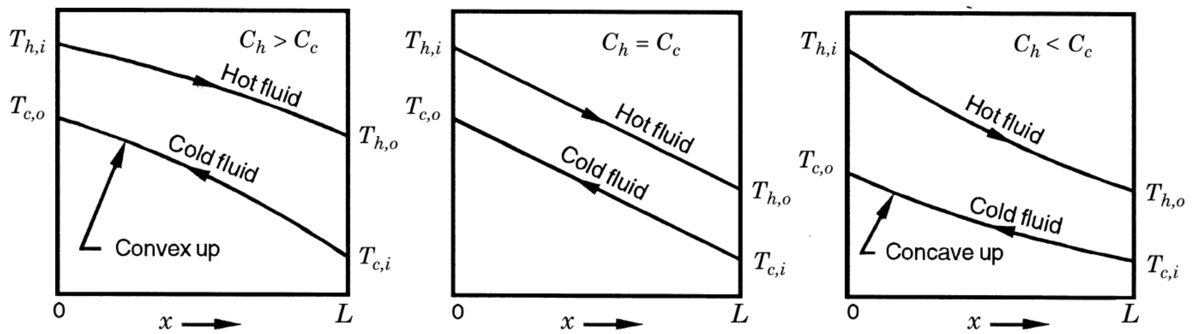
Velocity in tubes determines number of parallel tubes as follows.

$$n_t = \frac{4 \cdot m}{\pi \cdot d^2 \cdot w \cdot \rho}$$

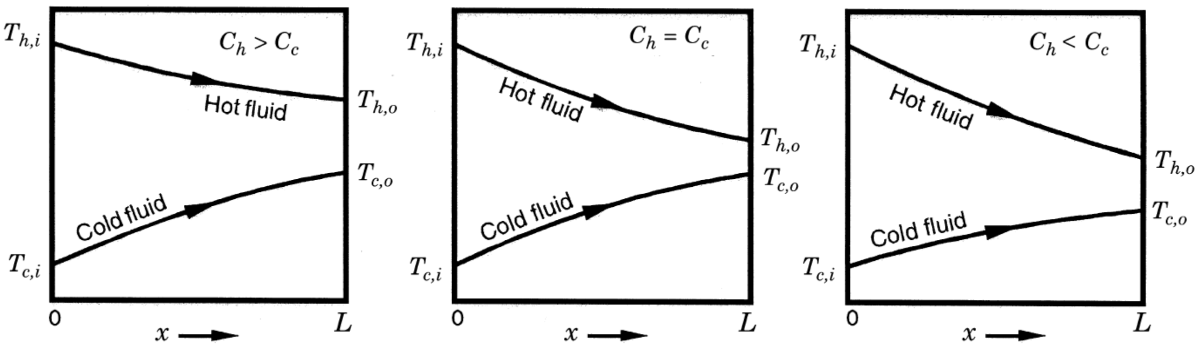
Number of parallel tubes, their layout and pitch influences external dimensions of heat exchanger.

The log-mean temperature difference

The driving force for any heat transfer process is a temperature difference. For heat exchangers temperature difference between two fluids across the heating area is not constant. It depends on heat exchanger arrangement and value of C_h and C_c.



Temperature distributions in a counterflow heat exchanger of single-phase fluids



Temperature distributions in a parallelflow heat exchanger of single-phase fluids

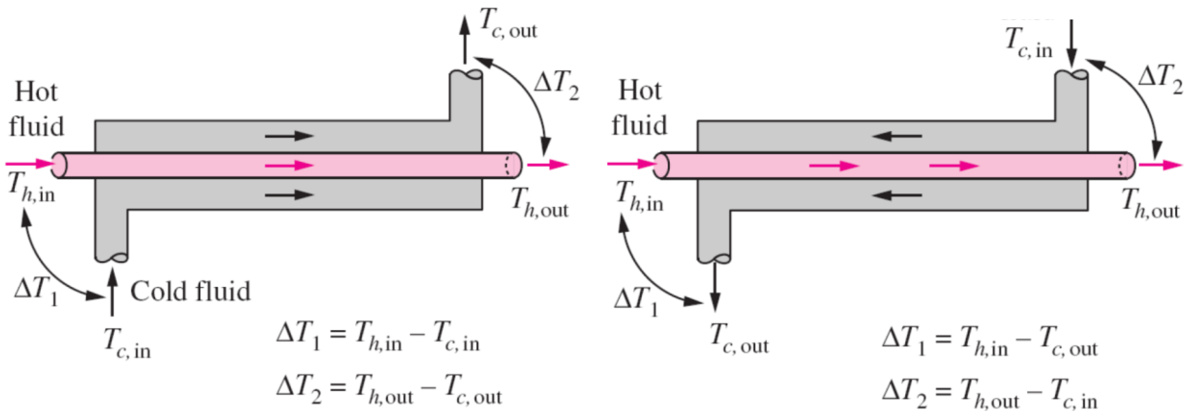
Evaluation of an average temperature difference is necessary for calculation of heat transfer rate. For cases with pure counter and parallel flow the temperature difference is best represented by the log mean temperature difference (LMTD or ΔT_m), defined in equation below.

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

where:

ΔT_2 = the larger temperature difference between the two fluid streams at either the entrance or the exit to the heat exchanger

ΔT_1 = the smaller temperature difference between the two fluid streams at either the entrance or the exit to the heat exchanger



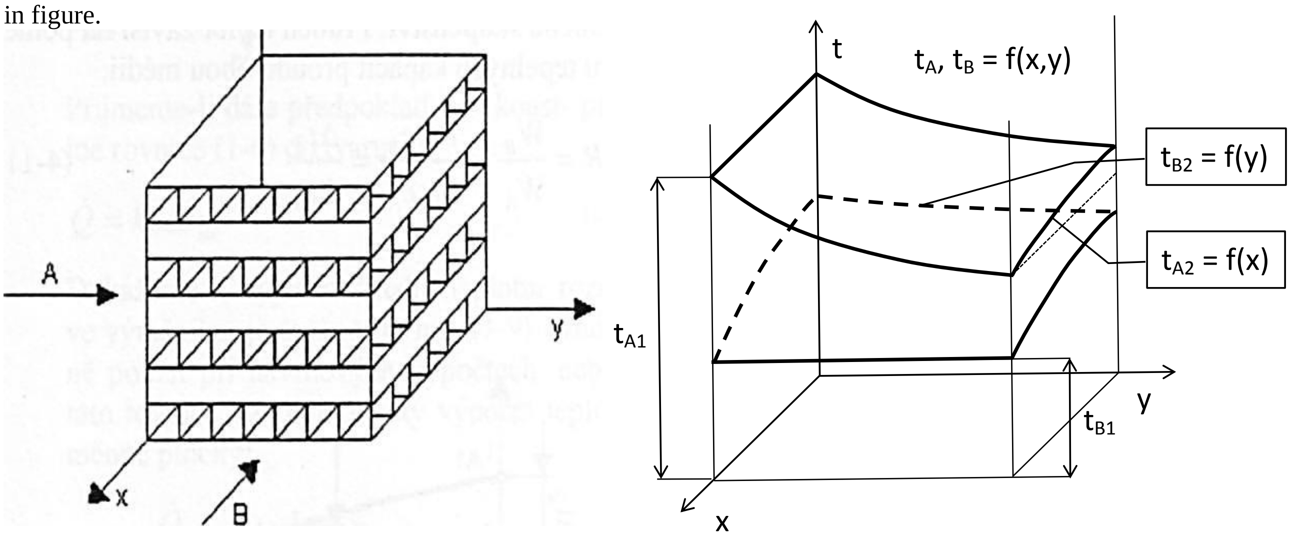
Use of log mean temperature difference for evaluation of heat transfer ration is valid on following conditions:

1. The heat exchanger is at a steady state.
2. Each fluid has a constant specific heat.
3. The overall heat transfer coefficient is constant.
4. There are no heat losses from the exchanger.
5. There is no longitudinal heat transfer within a given stream.
6. The flow is either parallel or counter.

The assumptions are commonly satisfied in practice. It should be noted that an isothermal phase transition (boiling or condensing a pure component at constant pressure) corresponds to an infinite specific heat, which in turn satisfies the second assumption very well.

Cross flow heat exchangers

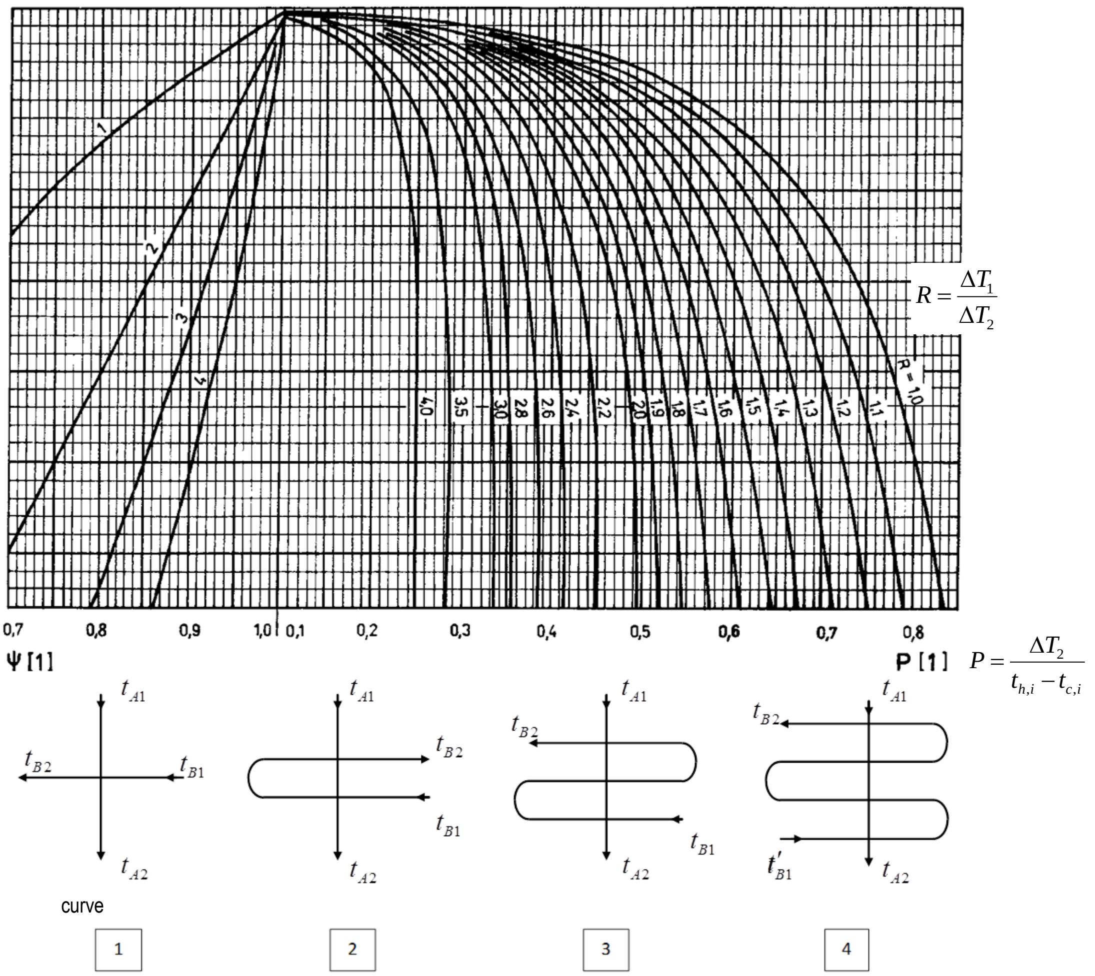
In case of cross flow heat exchanger, fluid temperature differences are illustrated as three-dimensional as shown in figure.

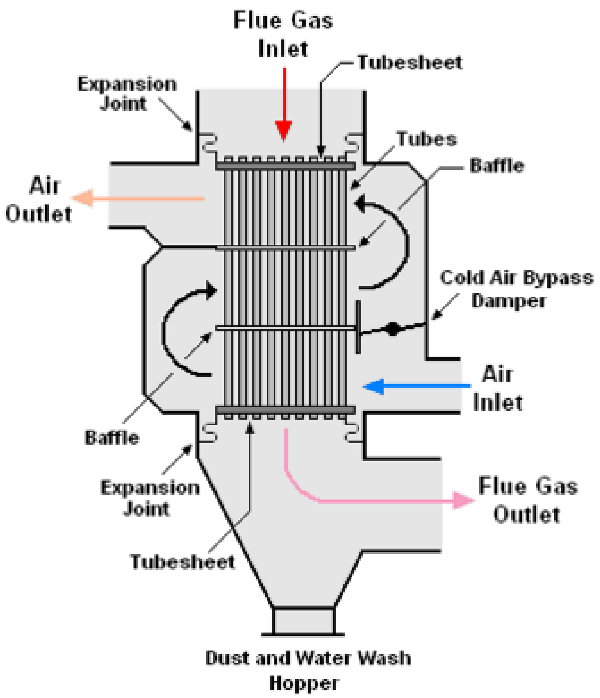


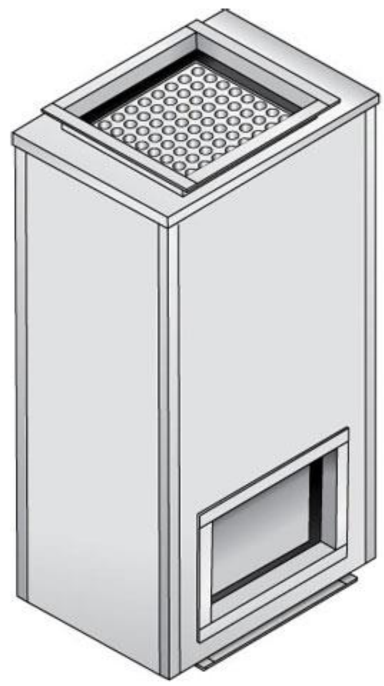
In these heat exchangers, the temperature difference is not possible calculate by previous method, the correction factor is usually used where the log mean temperature difference is expressed as

$$\Delta T_m = \Psi \, \Delta T_{m,\,CF}$$

where Ψ is the correction factor and $\Delta T_{m,\,CF}$ is the log mean temperature difference for a *counter flow heat exchanger*. Value of correction factor is usually determined from diagrams relating to crossflow heat exchanger arrangement. Example of one of such a diagram is shown in following figure.







Tubular flue gas air preheater