Doc. No. **TG - ITD - 100**

# Technical Guide

# Introduction to H/E Thermal Design

Total **15** sheets with a cover

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|  | Rev. | 0 |
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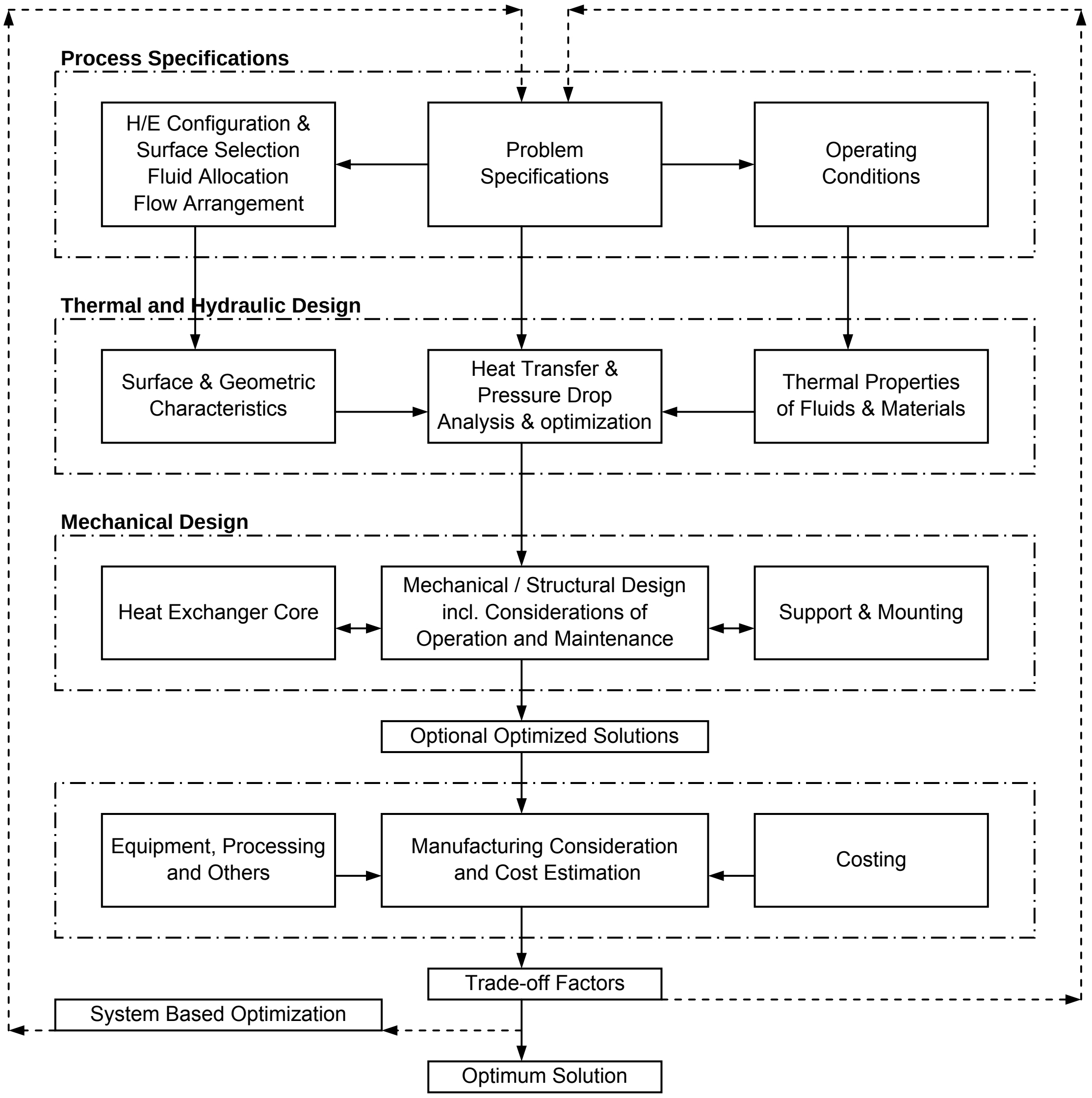
## 1. Introduction

H/E thermal design is an art, where basic heat transfer knowledge is properly used.

Designers shall be fully aware of the differences between the idealized conditions for the knowledge and the real conditions for practical heat transfer equipments.

**Overall Design Methodology**



The final design should meet process requirements at lowest operation and maintenance costs as well as installation ( capital ) cost.

Design should not be finalized only on a lowest installation cost.

## 2. Thermal Design Method

### 2.1 Design Problem

1) Sizing Problem

It is to determine H/E surface area and size of a new H/E to meet the specific process requirements.
Sizing problem is also often referred to as " Design Problem ".

2) Rating Problem

It is to determine heat transfer and pressure drop of an existing H/E or an already sized H/E.
Rating problem is also often referred to as " Performance Problem ".

### 2.2 Design Method

1) MTD Method

$$Q = U \times A \times \Delta Tm = U \times A \times F \times LMTD$$

Where,

| | |
|---|---|
| Q | Total Heat Transfer or Heat Duty |
| U | Overall Heat Transfer Coefficient |
| A | Heat Transfer Surface Area |
| ΔTm | Mean Temperature Difference ( MTD ) |
| F | LMTD Correction Factor |
| LMTD | Log-Mean Temperature Difference |

2) ε - NTU Method

$$Q = \varepsilon \times Cmin \times ( Thi - Tci )$$

Where,

| | |
|---|---|
| ε | Heat Exchanger Effectiveness |
| Cmin | Minimum of Chot or Ccold * C Heat Capacity Rate m x cp |
| Thi | Hot Fluid Inlet Temperature |
| Tci | Cold Fluid Inlet Temperature |

The above two methods are equivalent, and differ only in algebraic form of equation.

Which method is selected is up to the designer's preference.

The ε - NTU method is much easier for the rating problem.

The ε - NTU method allows physical interpretation of thermodynamic performance,
which is not provided by the MTD method.

## 2.3 Heat Transfer Analysis

### Idealization

1) The H/E operates under steady-state condition. ( i.e. Constant Flowrate and Independency of Time )

2) The specific heat of each fluid is constant throughout the H/E.

3) The temperature of each fluid is uniform over every flow cross section.

4) The individual and overall H.T. coefficients are constant throughout the H/E.

5) The heat transfer surface area is uniformly distributed on each fluid side.

6) Heat loss to the surroundings is negligible. ( i.e. Adiabatic Condition )

7) The fluid flowrate is uniformly distributed throughout the H/E on each fluid side.
( No flow maldistribution, by-passing or leakage occur. )

### Conservation Equation

#### Energy Equation for Fluid Heat Capacity Change

$$\begin{aligned} dQ &= - mh \times cph \times dTh = mc \times cpc \times dTc \\ &= - Ch \times dTh = Cc \times dTc \end{aligned}$$

By integration,

$$Q = Ch \times ( Thi - Tho ) = Cc \times ( Tco - Tci )$$

#### Rate Equation for Heat Transfer

$$dQ = q \times dA = U \times ( Th - Tc ) \times dA$$

By integration,

$$Q = U \times A \times \Delta Tm \qquad * \ \Delta Tm = \frac{1}{A} \int ( Th - Tc ) \, dA$$

| Where, | | |
|---|---|---|
| | m | Mass Flowrate |
| | h | Hot Fluid |
| | c | Cold Fluid |
| | cp | Specific Heat |
| | C | Heat Capacity Rate |
| | i | Inlet |
| | o | Outlet |
| | q | Heat Flux |

## 3. Design Procedure

The following is a step-by-step procedure for the sizing problem.

1) Determine process conditions. ( Flowrates, Temperatures and Pressures )

   Calculate the unknown parameter ( Flowrate, Inlet or Outlet Temperature ), if any.
   Find fluid properties.

2) Calculate heat tansfer rate on each fluid and determine heat duty, " Q ", if not given.

3) Select a preliminary design.

   H/E Type and Configuration
   Surface Selection and Sizing
   Fluid Allocation
   Flow Arrangement

4) Calculate temperature relations.

   LMTD
   LMTD Correction Factor, " F "
   MTD

5) Calculate flow characteristics.

   Volumetric and Mass Velocities
   Dimensionless Parameters such as Reynolds Number

6) Calculate performances.

   Heat Transfer Coefficients
   Pressure Drops

7) Calculate overall heat transfer coefficient, " U ".

8) Calculate required heat transfer surface area, " Ao ".

9) Evaluate the results to meet the process requirements.

10) Go to step 3) and repeat for iteration, if necessary.

The central part of the procedure is step 6).
Proper correlations shall be selectively applied to the H/E to be designed.

## 4. Fluid Allocation

Fluid allocation on shell side or tube side requires evaluation of the following factors to arrive at a satisfactory compromise.

One or several factors may be selected for evaluation.

| Factor | Shell Side | Tube Side |
|---|---|---|
| Lower Flowrate | Better for Turbulent Flow at Low Reynolds No. | |
| Viscosity | | Better for Laminar Flow |
| Pressure Drop | | More Accuracy for Press. Drop Cal. |
| Pressure | High press. shell is thicker and expensive. | Better for High pressure fluid |
| Temperature | High temperature reduces allowable stress, and thus increase shell thickness. | Better for High temperature fluid |
| Cleanability | Shell side is difficult to clean. | Better for more dirty fluid |
| Corrosion | Shell maintenance cost is high. | Better for more corrosive fluid |
| Hazardous or Expensive Fluid | | Normally better in some types of H/E |

## 5. Flow Arrangement

Basic Configuration of Flow Pattern

Counter Flow
Cross Flow
Parallel Flow

Counter vs Parallel

Counter flow is desirable for maximum heat transfer.

Paralle flow may be typically selected :

to avoid low temperature corrosion in H/Es such as air preheater.
to lower tube wall temperature in H/Es such as superheater.

Counter or Parallel is meaningless in H/Es with same inlet and outlet temperatures such as condenser.

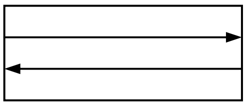
Downward vs Upward

Downward flow is natural for hot fluid, while Upward flow for cold fluid.

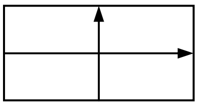
Downward flow shall be assigned to condensing fluid, while Upward flow to boiling fluid.

Schematic Flow Arrangement, Typical

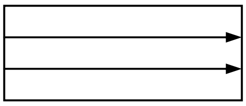
Basic



**Counter Flow**

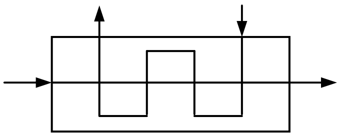


**Cross Flow**

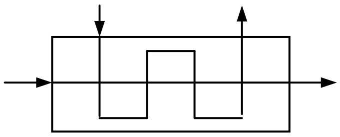


**Parallel Flow**

Multi Pass

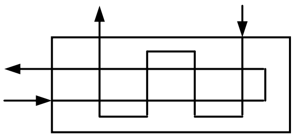


**Cross - Counter Flow**



**Cross - Parallel Flow**

Shell & Tube H/E



**1 Shell Pass & 2 Tube Pass**

## 6. Heat Duty

### Procedure

Heat Capacity Change

First, calculate heat capacity change of each fluid.

Deviation ± 5 % is acceptable. If not, review and correct process data and repeat.

Determination of Heat Duty

The larger of calculated values shall be taken as heat duty, if not specified.

If specified, take that value as heat duty.

### Equation for Calcualtion

Sensible Heat

Liquid

$$Q = m \times cp \times dT = m \times cpm \times ( To - Ti )$$

| | | |
|---|---|---|
| Where, | cpm | Specific Heat at Mean Temperature |

Vapor

$$\begin{aligned} Q = m \times cp \times dT &= m \times ( cpo \times To - cpi \times Ti ) \\ &= m \times ( ho - hi ) \end{aligned}$$

| | | |
|---|---|---|
| Where, | cpo | Mean Specific Heat at Outlet Temperature |
| | cpi | Mean Specific Heat at Inlet Temperature |
| | ho | Enthalpy at Outlet Temperature |
| | hi | Enthalpy at Inlet Temperature |

Latent Heat

$$Q = m \times cp \times dT = m \times ( ho - hi )$$

## 7. Temperature Relations

LMTD ( Log-Mean Temperature Difference )

Calculation shall be based on counter flow except for parallel flow.

LMTD Correction Factor, " F "

" P " and " R " shall be calculated on both hot side and cold side basis, and then take larger " P " value, which results in smaller error in finding " F " value on the chart.

Minimum 0.8 is recommended because the curve below 0.8 is steep so that H/E may not be operable under certain conditions.

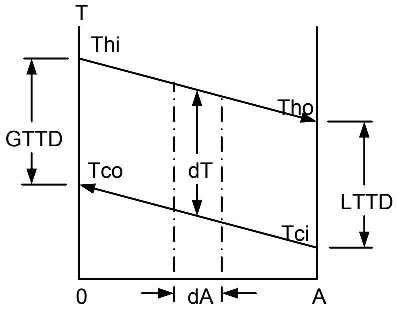
MTD ( Mean Temperature Difference )

All except Parallel Flow MTD = F x LMTDc
Parallel Flow MTD = LMTDp = F x LMTDc * F = LMTDp / LMTDc

Impossible Temperature Change

Hot and cold temperatures both increase or decrease.
Hot and cold temperatures diverge.
Hot and cold temperatures cross.

**Temperature Profile**



**Counter Flow**

Temperature Effectiveness

$$P = \frac{Tco - Tci}{Thi - Tci} \quad \text{or} \quad \frac{Thi - Tho}{Thi - Tci}$$

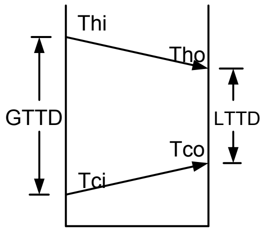
Heat Capacity Rate Ratio

$$R = \frac{Thi - Tho}{Tco - Tci} = \frac{Cc}{Ch} \quad \text{or} \quad = \frac{Tco - Tci}{Thi - Tho} = \frac{Ch}{Cc}$$

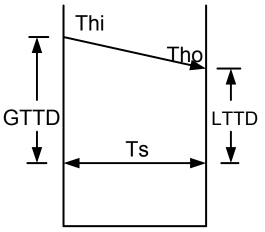
LMTD Correction Factor

F = f ( P, R, Flow Arrangement )

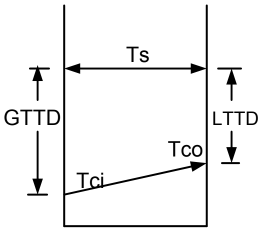
LMTDc = ( GTTD - LTTD ) / ln ( GTTD / LTTD )
LMTD = LMTDc
MTD = F x LMTD = LMTD, if F is 1.



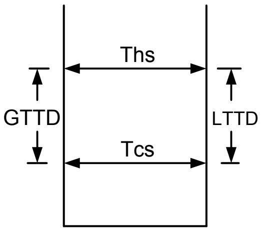
**Parallel Flow**



**Cold Fluid Boiling**



**Hot Fluid Condensing**



**Both Fluids Phage Change**

LMTDp
= ( GTTD - LTTD ) / ln ( GTTD / LTTD )
MTD = LMTDp

LMTD = ( GTTD - LTTD ) / ln ( GTTD / LTTD )
F = 1
MTD = LMTD

F = 1
MTD = LMTD

LMTD = Ths - Tcs
F = 1
MTD = LMTD

## 8. Overall Heat Transfer Coefficient

$$U = \frac{1}{\left[ \left( \frac{1}{h_o} + r_o \right) \frac{1}{\eta} + r_w + \left( \frac{1}{h_i} + r_i \right) \frac{A_o}{A_i} \right]}$$

Where,

| | | MKH Unit |
|---|---|---|
| U | Overall Heat Transfer Coefficient, Outside based | kcal/m2.h.℃ |
| ho | Film Coefficient of Shell Side Fluid | kcal/m2.h.℃ |
| ro | Fouling Resistance on Outside Surface | m2.h.℃/kcal |
| η | Surface Efficiency, where applicable | |
| rw | Resistance of Surface, Outside based | m2.h.℃/kcal |
| hi | Film Coefficient of Tube Side Fluid | kcal/m2.h.℃ |
| ri | Fouling Resistance on Inside Surface | m2.h.℃/kcal |
| Ao | Heat Transfer Surface Area, Outside | m2 |
| Ai | Heat Transfer Surface Area, Inside | m2 |

**Overall Heat Transfer Coefficient, Clean** * ro = 0 , ri = 0

$$U_c = \frac{1}{\left[ \left( \frac{1}{h_o} + 0 \right) \frac{1}{\eta} + r_w + \left( \frac{1}{h_i} + 0 \right) \frac{A_o}{A_i} \right]}$$

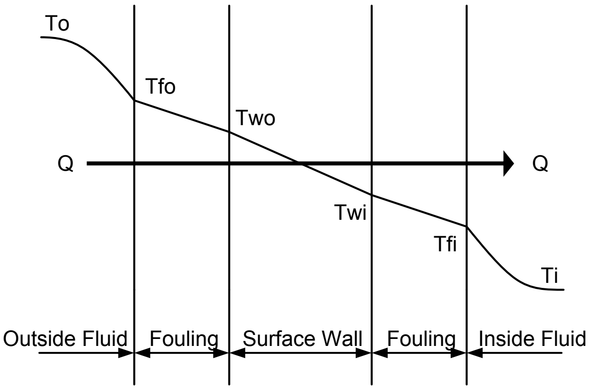
**Cleanliness Factor**

$$F_c = U / U_c \times 100$$

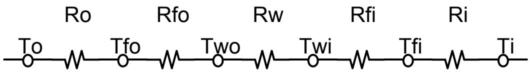
If cleanliness factor is specified as requirement,
" U " shall be calculated as below with fouling resistances ignored.

$$U = U_c \times F_c / 100$$

**Heat Transfer Circuit**



**Equivalent Electric Circuit**



$$Q = U \times (T_o - T_i) \times A_o$$

$$= h_o \times (T_o - T_{fo}) \times A_o$$

$$= \frac{1}{r_o} \times (T_{fo} - T_{wo}) \times A_o$$

$$= \frac{1}{r_w} \times (T_{wo} - T_{wi}) \times A_m$$

$$= \frac{1}{r_i} \times (T_{wi} - T_{fi}) \times A_i$$

$$= h_i \times (T_{fi} - T_i) \times A_i$$

$$Q = \frac{1}{R} \times dT = U \times A_o \times dT$$

Where, R Overall Resistance
UAo Overall Conductance

$$R = R_o + R_{fo} + R_w + R_{fi} + R_i$$

$$\frac{1}{UA_o} = \frac{1}{h_oA_o} + \frac{r_o}{A_o} + r_w + \frac{r_i}{A_i} + \frac{1}{h_iA_i}$$

This equation gives same equation for " U ".

Solving simultaneous equations above results in equation for overall heat transfer coefficient, " U ".

## 9. Basic Heat Transfer Equation

$$Ao = \frac{Q}{U \times MTD}$$

| Where, | | | MKH Unit |
|---|---|---|---|
| | Ao | Required Heat Transfer Surface Area, Outside | m2 |
| | Q | Heat Duty | kcal/h |
| | U | Overall Heat Transfer Coefficient, Outside based | kcal/m2.h.℃ |
| | MTD | Mean Temperature Difference<br>$= F \times \_MTD$ | ℃ |

**Surface Area Margin**

$$Ma = \left( \frac{Aa}{Ao} - 1 \right) \times 100$$

Where, Aa Actual Surface Area

**Service Heat Tranfer Coefficient** ( Reduced Value for Safety form calculated " U " )

$$Us = \frac{Q}{Aa \times MTD} = \frac{U}{(1 + Ma / 100)}$$

## 10. Wall Temperature

Wall temperatures should be calculated to check the following, if required.

Low Temperature Corrosion
Temperature Limit of Tube Materials
Tube Thermal Expansion

Wall temperatures can be calculated using equations shown under " Heat Transfer Circuit " on sheet 9.

Tube Outside Wall Temperature

$$Two = To - U \times \left( \frac{1}{ho} + ro \right) \times ( To - Ti )$$

Tube Inside Wall Temperature

$$Twi = Ti - U \times \left( \frac{1}{hi} + ri \right) \times \frac{Ao}{Ai} \times ( Ti - To )$$

## 11. Heat Transfer Mode

Heat is energy transferred by virtue of temperature difference.

It flows from higher temperature to lower temperature parts.

There are three basic types of heat transfer mechanisms, referred to as mode.

All three modes may occur individually or at the same time.

### Conduction

This is heat transfer from one part of a body to another part of the same body,
or from one body to another body in physical contact without displacement of the particles of the body.

**Fourier's Law** is the fundamental equation.

$$q = - k \frac{dT}{dx}$$

| Where, | | |
|---|---|---|
| | $q$ | Heat Flux<br>Heat Transfer Rate per unit area normal to direction of heat flow |
| | $k$ | Thermal Conductivity |
| | $T$ | Temperature |
| | $x$ | Distance in direction of heat flow |

### Convection

This is heat transfer from one point to another point within a fluid, liquid or gas
by mixing one portion of the fluid with another.

**Newton's Law of Cooling** is the fundamental equation.

$$q = h \times dT$$

| Where, | | |
|---|---|---|
| | $q$ | Heat Flux |
| | $h$ | Heat Transfer Coefficient |
| | $T$ | Temperature |

### Radiation

This is heat transfer from one body to another body, not in contact, by means of wave motion through space.

**Stefan - Boltzmann Law** is the fundamental equation.

$$e = \sigma \times T^4$$

| Where, | | |
|---|---|---|
| | $e$ | Energy Flux<br>Emissive Power by an Ideal Radiator ( Blackbody ) |
| | $\sigma$ | Stefan - Boltzmann Constant |
| | $T$ | Temperature |

## 12. Some Special Topics

### Heat Transfer Enhancement

Many techniques are available to improve mechanisms of heat transfer.
Typical is finned tube adopted in H/Es such as Steam Air Heater ( SAH ) and Air-Cooled H/Es ( ACHE )

### Special Fluids

#### Cryogenic Fluid

Heat transfer correlations are similar to conventional ones.
H/Es are of more sophisticated type.

#### Non-Newtonian Fluid

Fluids that do not follow **Newton's Law of Viscosity,** $\tau = \mu \times du / dy$, are called Non-Newtonian Fluid.

Typical Application : Food Processing
Biochemical Industry

#### Liquid Metal

Conventional Heat transfer correlations can not be applied.

### Direct Contact of Fluids

Typical Application : Deaerator
Cooling Tower

### Packed Bed

Typical Application : Wet Scrubber with Packing

### Solid Processing

Typical Application : Dryer