Doc. No.	INT-HETD-100

Introduction to H/E Thermal Design

Total 18 sheets with a cover

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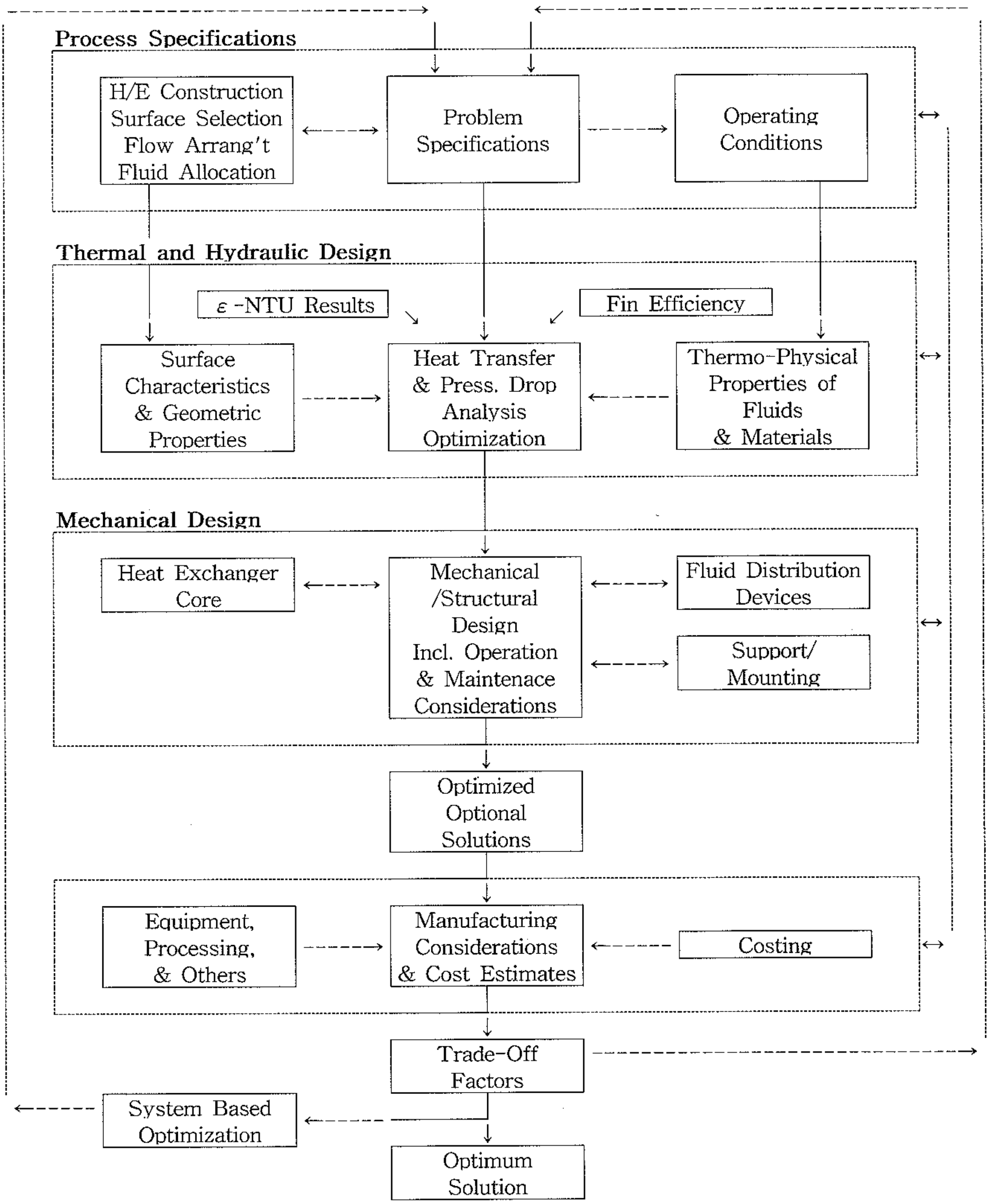
1. H/E Design Methodology



H/E Overall Design Methodology (by Shah)

2. Thermal Design Method

2.1 Design Problem

1) Sizing

It is to determine the H/E size and surface area of a new H/E to meet the specified process requirements.

The sizing problem is also sometimes referred to as the design problem.

2) Rating

It is to determine heat transfer and pressure drop of an existing H/E or an already sized H/E.

The rating problem is also sometimes referred to as the performance problem.

2.2 Design Method

1) MTD Method

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

Here,

Q	Total Heat Transfer Rate 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

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

Here,

ε	Heat Exchanger Effectiveness
Cmin	Minimum of Cc and Ch * 'C' : Heat Capacity Rate, $m \cdot cp$
Thi	Temp., Hot Fluid, Inlet
Tci	Temp., Cold Fluid, Inlet

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

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

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

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

2.3 Heat Transfer Analysis

Idealization

1) The H/E operates under steady-state conditions.
(i.e., constant flowrate, and independency of time)
2) The specific heats of each fluid are 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 losses to the surroundings are negligible. (i.e., the H/E is adabatic.)
7) The fluid flowrate is uniformly distributed through the H/E on each fluid side.
No flow maldistribution, stratification, by-passing, or leakage occur.

Conservation Equation

Temperature Profile, Counter Flow in section 8. Temperature Relation shall be referred to.

Energy Equation for Fluid Heat Capacity Change

$$dQ = -mh \cdot cph \cdot dTh = \pm mc \cdot cpc \cdot dTc$$

$$= -\ Ch \cdot dTh = \pm\ Cc \cdot dTc$$

By integration,

$$\mathbf{Q = Ch \cdot (Thi - Tho) = Cc \cdot (Tco - Tci)}$$

Rate Equation for Heat Transfer

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

By integration,

$$\mathbf{Q = U \cdot A \cdot \Delta Tm}$$

Here,

$$\Delta Tm = \frac{1}{A} \int (Th - Tc)\, dA$$

3. Basic Heat Transfer Equation

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

Here,

Ao	Required Heat Transfer Surface Area, Outside	m2
Q	Heat Duty	kcal/h
U	Overall Heat Transfer Coefficient, Outside	kcal/m2.h.℃
MTD	Mean Temperature Difference = F · LMTD	℃

Surface Area Margin, %

$$Amgn = \left(\frac{Aa}{Ao} - 1 \right) x\ 100$$

Here, Aa Actual Surface Area

Design Heat Transfer Coefficient (Reduced Value for Safety from the Calculated 'U')

$$Udgn = \frac{Q}{Aa \cdot MTD} = \frac{U}{(1 + Amng/100)}$$

4. 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 temp. or outlet temp.) if any.
    - Find fluid properties.

2) Calculate heat transfer rate on each fluid and determine heat duty, 'Q' if not specified.

3) Select a preliminary design
    - H/E Type
    - Size
    - Flow Arrangement

4) Calculate temperature relations
    - LMTD
    - LMTD Correction Factor, 'F'
    - MTD

5) Calculate flow characteristics
    - Mass Velocities
    - Reynolds Numbers

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), calculation of heat transfer coefficients and pressure drops. Suitable correlations shall be selectively applied to the H/E to be designed.

5. Heat Duty

Procedure

Heat capacity change

In advance, 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 Calculation

Sensible Heat

Liquid

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

Here, cpm Specific Heat, Instantaneous, at Mean Temp.

Gas

$Q = m \cdot cp \cdot dT = m \cdot (cpo \cdot To - cpi \cdot Ti)$

Here, cpo / -i Specific Heat, Mean, at Temp., Outlet / Inlet

Latent Heat

$Q = m \cdot dh = m \cdot (ho - hi)$

Sensible + Latent

$Q = m \cdot cp \cdot dT + m \cdot dh = m \cdot cpm \cdot (To - Ti) + m \cdot (ho - hi)$

6. 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 fo evaluation.

Flowrate

The fluid of lower flowrate may be on the shell side in order to obtain turbulent flow at low Reynolds number.

Viscosity

Laminar flow is to be on the tube side.
The fluid is to be on the shell side if laminar flow can be converted to turbulent flow,

Pressure Drop

Pressure drop on tube side can be calculated with less deviation.
The fluid is to be on the tube side if more accurate prediction is required..

Pressure

High pressure shell is thicker and expensive.
High pressure fluid is to be on the tube side.

Temperature

High temperature reduces the allowable stresses and thus, increases shell thickness.
High temperature fluid is to be on the tube side.

Cleanability

The shell is difficult to clean.
The more dirty fluid is to be on the tube side.

Corrosion

Corrosion may require use of expensive materials.
The more corrosive fluid is to be on the tube side in order to save the cost of the shell.

Hazardous or expensive fluids

The more hazardous or expensive fluid is to be on the tighter side,
That is the tube side of some types of H/E.

7. Flow Arrangement

The attached schematics shall be referred to.

Basic configurations of fluid flow :

- Counter Flow
- Cross Flow
- Parallel Flow

Counter vs. Parallel

Counter flow is desirable for maximum heat transfer.

Parallel flow may be selected to avoid low temp. corrosion in services such as air preheater.

Counter or parallel is not meaningless for same inlet & outlet temp. such as in evaporating or condensing fluid.

Downward vs. Upward

Downward flow is suitable for hot fluid.

Downward flow shall be assigned in nature to condensing fluid.

Upward flow is suitable for cold fluid.

Upward flow shall be assigned in nature to evaporating fluid.

Flow Arrangement

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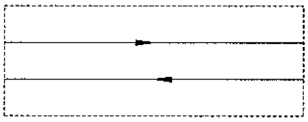
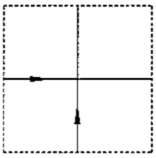
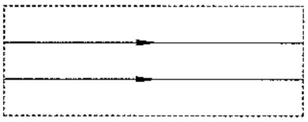
Basic Configuration



Counter Flow

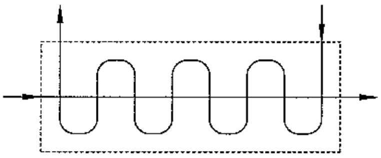


Cross Flow

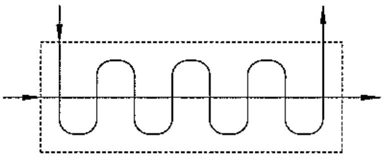


Parallel Flow

Multi-Pass

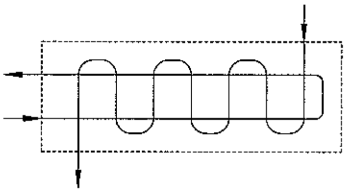


Cross - Counter Flow

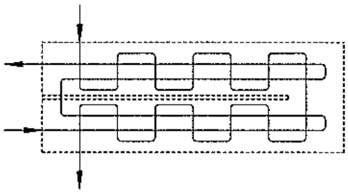


Cross - Parallel Flow

Shell & Tube



1 Shell Pass, Even No. of Tube Passes



2 Shell Passes, 4 or Multiple of 4 Tube Passes

REMARK

1. Other flow arrangements are also available to meet design requirements.
2. For further details, please refer to technical materials such as 'TEMA'.

8. Temperature Relation

The attached 'Temperature Profile' shall be referred to.

LMTD, Log-Mean Temp. Difference

Calculation shall be based on counter flow except parallel flow.

LMTD Correction Factor, 'F'

'P' & 'R' shall be calculated on both hot and cold bases and then, take values on basis of larger 'P' value, which results in smaller error in finding 'F' on the chart.

$Fc = 1 > Fcc > Fc > Fcp > Fp = LMTDp / LMTDc$

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

MTD, effective Mean Temp. Difference

All except below : $MTD = F \times LMTD = F \times LMTDc$

Parallel Flow : $MTD = F \times LMTD = LMTDp$

Impossible Temp. Change

Hot and cold temp. are increasing or decreasing both.

Hot and cold temp. are diverging.

Hot and cold temp. are crossing.

Temperature Profile

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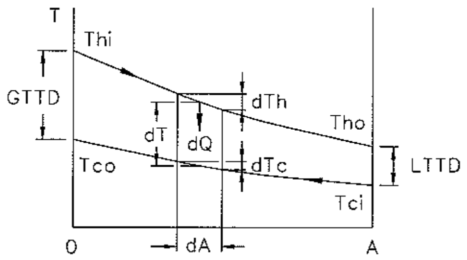


Counter Flow

$$LMTDc = \frac{GTTD - LTTD}{\ln \frac{GTTD}{LTTD}}$$

$LMTD = LMTDc$

$F = 1$

$MTD = F \times LMTD = LMTD$

Relationship

Temperature Effectiveness

$$P = \frac{Tco - Tci}{Thi - Tci} \qquad \frac{Thi - Tho}{Thi - Tci}$$

Heat Capcity Rate Ratio

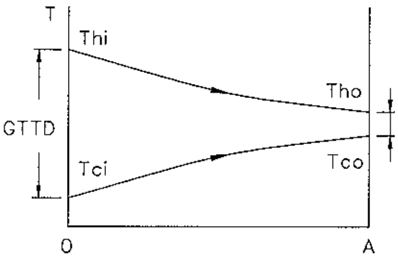
$$R = \frac{Thi - Tho}{Tco - Tci} = \frac{Cc}{Ch} \qquad \frac{Tco - Tci}{Thi - Tho} = \frac{Ch}{Cc}$$

LMTD Correction Factor

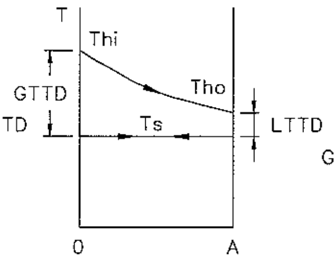
$$F = \phi\ (\ P,\ R,\ \text{Flow Arrangement}\ )$$

'F' is obtained using one of the fllowing.

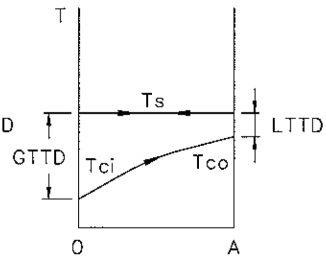
- Graphs
- Analytic Equations



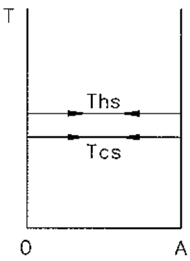
Parallel Flow



Cold Fluid Evaporating



Hot Fluid Condensing



Both Fluids Phase Change

$$LMTDp = \frac{GTTD - LTTD}{\ln \frac{GTTD}{LTTD}}$$

$LMTD = LMTDc$

$F = LMTDp\ /\ LMTDc$

$MTD = F \times LMTD = LMTDp$

$$LMTD = \frac{GTTD - LTTD}{\ln \frac{GTTD}{LTTD}}$$

$F = 1$

$MTD = LMTD$

$$LMTD = \frac{GTTD - LTTD}{\ln \frac{GTTD}{LTTD}}$$

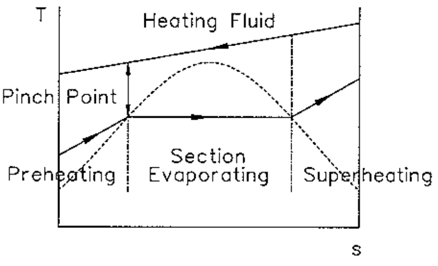
$F = 1$

$MTD = LMTD$

$LMTD = Ths - Tcs$

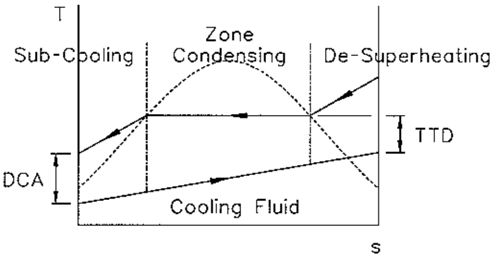
$F = 1$

$MTD = LMTD$



Boiler

* Calc. shall be applied to each section.



Feedwater Heater

* Calc. shall be applied to each zone.

9. Overall Heat Transfer Coefficient

The attached 'Heat Transfer Circuit' shall be referred to for derivation of 'U',

$$U = \frac{1}{\left[\left(\frac{1}{ho} + ro \right) \cdot \frac{1}{\eta} + rw + ri \cdot \frac{Ao}{Ai} + \frac{1}{hi} \cdot \frac{Ao}{Ai} \right]}$$

Here,

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

* $\eta = (Ap + Ef \cdot Af) / A$

Here,

Ap	Primary Surface Area
Af	Fin Surface Area
Ef	Fin Efficiency
A	Ap + Af

Overall H. T. Coefficient, Clean (ro = ri = 0)

$$Uc = \frac{1}{\left[\left(\frac{1}{ho} \right) \cdot \frac{1}{\eta} + rw + \frac{1}{hi} \cdot \frac{Ao}{Ai} \right]}$$

Cleanliness Factor, %

$$Fc = \frac{U}{Uc} \times 100$$

If cleanliness factor is specified as requirement, 'U' shall be calculated as follows. In this case, given fouling resistances are neglected.

$$U = Uc \times \frac{Fc}{100}$$

Heat Transfer Circuit

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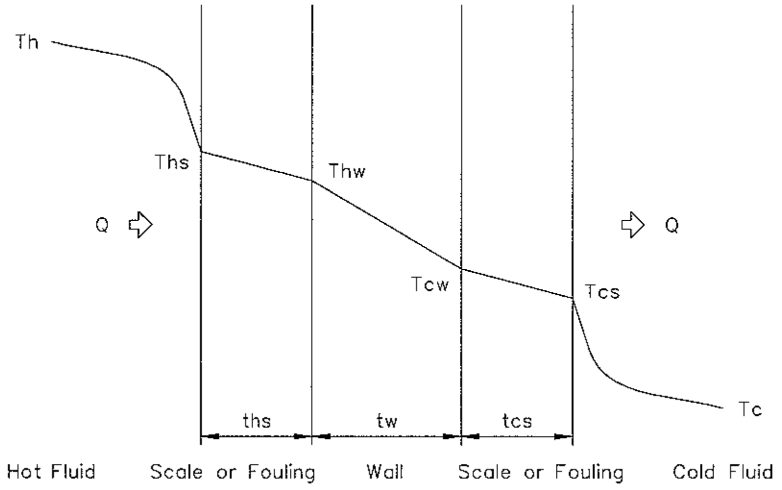
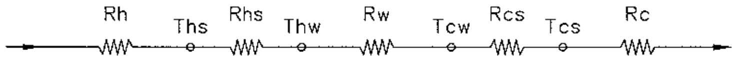


Thermal Circuit



Electric Circuit

Local Heat Transfer

$$Q = ho \times (Th - Ths) \times Ao$$

$$= \frac{1}{ro} \times (Ths - Thw) \times Ao$$

$$= \frac{kw}{tw} \times (Thw - Tcw) \times Am$$

$$= \frac{1}{ri} \times (Tcw - Tcs) \times Ai$$

$$= hi \times (Tcs - Tc) \times Ai$$

$$Q = U \times Ao \times (Th - Tc)$$

By solving simultaneous equations above,

$$U = \frac{1}{\frac{1}{ho} + ro + \frac{tw}{kw} \times \frac{Ao}{Am} + ri \times \frac{Ao}{Ai} + \frac{1}{hi} \times \frac{Ao}{Ai}}$$

Thermal Resistance

$$Q = U \times Ao \times dTm = \frac{1}{R} \times dTm$$

Here, UAo Overall Thermal Conductance
R Overall Thermal Resistance

$$R = Rh + Rhs + Rw + Rcs + Rc$$

$$\frac{1}{UAo} = \frac{1}{hoAo} + \frac{ro}{Ao} + Rw + \frac{ri}{Ai} + \frac{1}{hiAi}$$

This equation gives same result as left.

10. Wall Temperature

Wall temperature shall be calculated, if required, to check the following.

Temperature limit of tube material

Low temperature corrosion

'Heat Transfer Circuit' shall be referred to, again.

Wall temperatures are simply derived **if fouling resistances = 0.**

Hot Wall Temp. (Hot Temp. Base)

$$Q = ho \cdot (Th - Thw) \cdot Ao = U \cdot Ao \cdot (Th - Tc)$$

$$Thw = Th - \frac{U}{ho} \cdot (Th - Tc)$$

Cold Wall Temp. (Cold Temp. Base)

$$Q = hi \cdot (Tcw - Tc) \cdot Ai = U \cdot Ao \cdot (Th - Tc)$$

$$Tcw = Tc + \frac{U}{hi} \cdot \frac{Ao}{Ai} \cdot (Th - Tc)$$

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 as modes, **conduction**, **convection**, and **radiation**.

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

Conduction is the heat transfer form 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 the fundamental differential equation.

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

Here,	q	Heat Flux Heat Transfer Rate per unit area normal to direction of heat flow
	k	Thermal Conductivity
	T	Temperature
	x	Distance in the direction of heat flow

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

Newton's law of cooling is the the fundamental equation.

$$q = h \cdot dT$$

Here,	q	Heat Flux
	h	Heat Transfer Coefficient
	T	Temperature

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

The presence of a material medium is not required. Radiation occurs most efficiently in a vacuum.

Stefan-Boltzmann law is the the fundamental equation.

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

Here,	e	Energy Flux Emissive Power by an Ideal Radiator (Blackbody)	
	σ	Stefan-Boltzmann Constant	kcal/m2.h.℃^{4}
	T	Absolute Temperature	K

12. Some Special Topics

Heat Transfer Enhancement

Technique : Passive or Active which requires external power.

Many techniques are available for improvement of various mechanisms of heat transfer.

Design correlations are being established.

Special Fluid

Cryogenic Fluid

Similar conventional heat transfer correlations are formulated.
H/E are of more sophisticated type.

Non-Newtonian Fluid

Fluids that do not follow Newton's law of viscosity, $\tau = \mu \cdot du/dy$, are called Non-Newtonian fluid.

Typical Application : Food Processing, Biochemical Industries

Liquid Metal

Prandtl No. is very low.

Conventional heat transfer correlations can not be applied.

Direct Contact

Typical Application : Cooling Tower

Packed Bed

Typical Application : Wet Scrubber with Packing

Solid Processing

Typical Application : Dryer