Solutions for R&D to Design

Influence of Dominant Factors on Overall Heat Transfer Coefficient

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Introduction

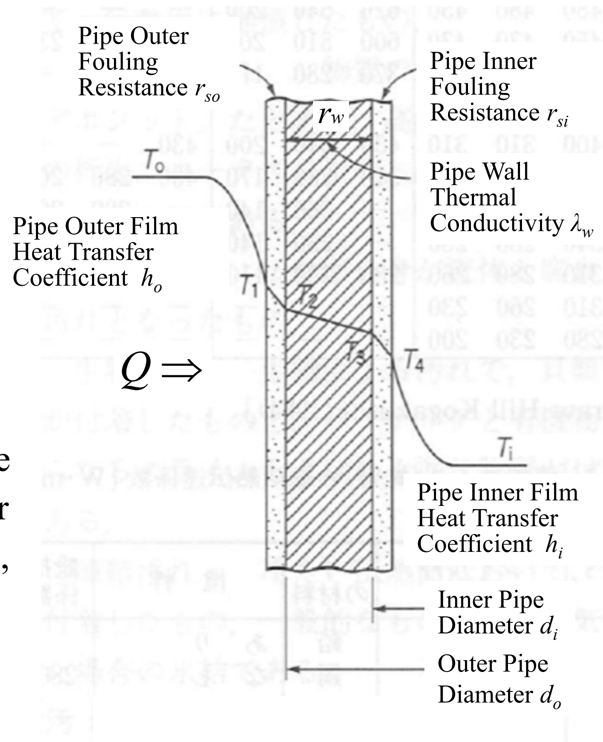
- For the design of multi-tubular heat exchangers, environments are being developed through commercial software enhancements to easily achieve designs that can minimize costs with satisfactory heat transfer performances.
- On the other hand, it is important to estimate the size of a heat exchanger in advance before executing rigorous calculations.
- In this presentation, we will examine the influence of dominant factors (film heat transfer coefficients, and fouling resistance) on the overall heat transfer coefficient.

Heat Transfer Process

In a heat exchanger, heat is transferred from a hot fluid through a tube wall to a cold fluid.

In the right figure, heat from the hot fluid moves near the outer surface of the pipe by convection at temperature To, but it is hindered by the hot side film layer and decreases to temperature (T_1).

Next, heat is transmitted through the fouling layer (T_2) adhering to the outer surface of the pipe, the pipe wall (T_3), and the fouling layer (T_4) adhering to the inner surface of the pipe, propagated through the cold side film layer inside the pipe and finally reaches the cold fluid (T_i).



Heat Transfer Rate

At this time, the relationship between heat transfer and the temperature of each layer is as follows.

1) Heat transfer in hot side film layer

$$q_1 = h_o \cdot A_o \cdot (T_o - T_1)$$

2) Heat transfer in outer surface fouling

$$q_2 = A_o \cdot (T_1 - T_2) / r_{so}$$

3) Heat transfer in pipe wall

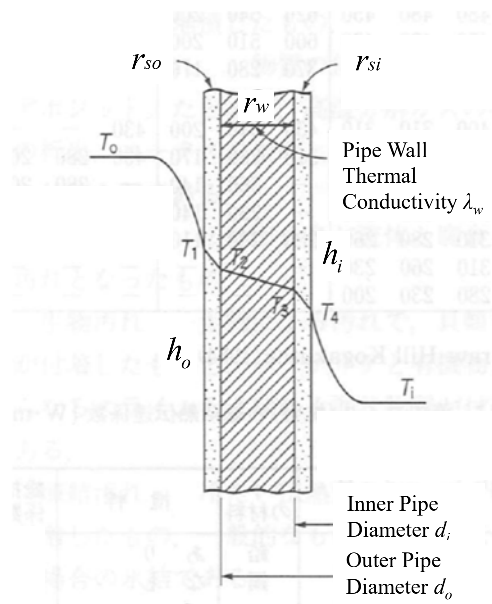
$$q_3 = A_i \cdot (T_2 - T_3) / r_w$$

4) Heat transfer in inner surface fouling layer

$$q_4 = A_i \cdot (T_3 - T_4) / r_{si}$$

5) Heat transfer in cold side film layer

$$q_5 = h_i \cdot A_i \cdot (T_4 - T_i)$$



A_o Pipe outer heat transfer area [m^2]
A_i Pipe inner heat transfer area [m^2]
h_o Pipe Outer Film Heat Transfer Coefficient
h_i Pipe Inner Film Heat Transfer Coefficient
} $\left[\frac{\text{kcal}}{\text{m}^2\text{hrK}}\right]$
r_{so} Pipe Outer Fouling Resistance
r_{si} Pipe Inner Fouling Resistance
r_w Pipe Wall Resistance
} $\left[\frac{\text{m}^2\text{hrK}}{\text{kcal}}\right]$

Overall Heat Transfer Coefficient

In the steady state, the heat transfer rate of each layer is equal, and the following equation is obtained when it is set as Q:

$$Q = q_1 = q_2 = q_3 = q_4 = q_5$$
$$= h_o \cdot A_o \cdot (T_o - T_1) = A_o \cdot (T_1 - T_2)/r_{so}$$
$$= A_i \cdot (T_2 - T_3)/r_w = A_i \cdot (T_3 - T_4)/r_{si}$$
$$= h_i \cdot A_i \cdot (T_4 - T_i)$$

$$\Delta T = (T_o - T_i) = (T_o - T_1) + (T_1 - T_2) + (T_2 - T_3) + (T_3 - T_4) + (T_4 - T_i)$$

$$\therefore \Delta T = \frac{Q}{h_o \cdot A_o} + \frac{r_{so} Q}{A_o} + \frac{r_w Q}{A_i} + \frac{r_{si} Q}{A_i} + \frac{Q}{h_i \cdot A_i}$$
$$= Q\left(\frac{1}{h_o \cdot A_o} + \frac{r_{so}}{A_o} + \frac{r_w}{A_i} + \frac{r_{si}}{A_i} + \frac{1}{h_i \cdot A_i}\right)$$

$$Q = \frac{\Delta T}{\left(\frac{1}{h_o} + r_{so} + r_w \frac{A_o}{A_i} + r_{si} \frac{A_o}{A_i} + \frac{1}{h_i}\frac{A_o}{A_i}\right) \cdot \frac{1}{A_o}}$$

Overall Heat Transfer Coefficient

Setting $r_{wo} = r_w \frac{A_o}{A_i}, \quad r_{sio} = r_{si} \frac{A_o}{A_i}, \quad \frac{1}{h_{io}} = \frac{1}{h_i}\frac{A_o}{A_i}$

$$Q = \frac{\Delta T \cdot A_o}{\left(\frac{1}{h_o} + r_{so} + r_{wo} + r_{sio} + \frac{1}{h_{io}}\right)}$$
$$= U \cdot A_o \cdot \Delta T$$

$$Q = U \cdot A \cdot \Delta T$$

$$\frac{1}{U} = \frac{1}{h_o} + r_{so} + r_{wo} + r_{sio} + \frac{1}{h_{io}}$$

For heat exchanger design, since the temperature condition and the heat exchange rate are known, the approximate heat transfer area can be obtained if U is known.

r_{sio}	Pipe inner fouling resistance based on pipe outer area	$\left[\frac{m^2 hrK}{kcal}\right]$
r_{wo}	Pipe wall resistance based on pipe outer area	$\left[\frac{m^2 hrK}{kcal}\right]$
h_{io}	Pipe inner film heat transfer coefficient based on pipe outer area	$\left[\frac{kcal}{m^2 hrK}\right]$
U	Overall heat transfer coefficient based on pipe outer area	$\left[\frac{kcal}{m^2 hrK}\right]$

Generally in a circular pipe, the outer area is used as the basis.

Overall Heat Transfer Coefficient Calculation

Here, we want to check the influence of the film heat transfer coefficients and of fouling resistance on the overall heat transfer coefficient.

The overall heat transfer coefficient is calculated under the following conditions.

Inner diameter di = 25.4 mm, Pipe thickness = 1.6 mm.

Pipe inner film heat transfer coefficient h_i	: 6,000	[kcal/m^2/hr/K]
Pipe outer film heat transfer coefficient h_o	: 600	[kcal/m^2/hr/K]
Pipe inner fouling resistance r_{si}	: 0.0002	[m^{2}hrK/kcal]
Pipe outer fouling resistance r_{so}	: 0.0006	[m^{2}hrK/kcal]
Pipe wall resistance r_{wo}	: 0.00008	[m^{2}hrK/kcal]

$$\frac{1}{U} = \frac{1}{h_o} + r_{so} + r_{wo} + \left(r_{si} + \frac{1}{h_i} \right) \frac{d_0}{d_i}$$

$$\frac{1}{U} = \frac{1}{h_o} + r_{so} + r_{wo} + \left(r_{si} + \frac{1}{h_i} \right) \frac{d_0}{d_i}$$

$$= \frac{1}{600} + 0.0006 + \left(0.0002 + \frac{1}{6000} \right) \frac{(25.4 + 1.6 \times 2)}{25.4} + 0.00008$$

$$= 0.00276$$

$$\therefore U = 362.4 \left[\frac{\text{kcal}}{\text{m}^2\text{hrK}} \right]$$

hi =	6000	kcal/m2/hr/K
ho =	600	kcal/m2/hr/K
rsi =	0.0002	m2*hr*K/kcal
rso =	0.0006	m2*hr*K/kcal
rwo =	0.00008	m2*hr*K/kcal
do/di =	1.1260	
1/U =	0.002760	
U =	362.4	kcal/m2/hr/K

Dominant Factors on Overall Heat Transfer Coefficient

The following equation holds for convection heat transfer in turbulent flow conditions:

$$Nu = 0.023(Re)^{0.8}(Pr)^{0.4}$$

It can be seen from the equation that if the Re number is increased, the film heat transfer coefficient will become higher.

Here, we will compare the influence of doubling the inner and the outer the pipe flow velocities on the overall heat transfer coefficient.

$$Nu = \left[\frac{\text{Heat transfer velocity}}{\text{Conduction heat transfer velocity}}\right] = \left[\frac{h \cdot L}{\lambda}\right]$$

$$Re = \left[\frac{\text{Inertial forces}}{\text{Viscous forces}}\right] = \left[\frac{d \cdot u \cdot \rho}{\mu}\right]$$

$$Pr = \left[\frac{\text{Momentum diffusivity}}{\text{Thermal diffusivity}}\right] = \left[\frac{\mu \cdot C_p}{\lambda}\right]$$

h : Film heat transfer coefficient [J/m²/sec/K]
L : Characteristic length[m]
λ : Thermal conductivity[J/m/sec/K]
d : Characteristic length[m]
u : Flow velocity[m/sec]
ρ : Fluid density[kg/m³]
μ : Viscosity[Pa·sec]
C_p : Specific heat[J/kg/K]

Dominant Heat Transfer Coefficient

Assuming that the convection heat transfer equation holds, it can be expected that the film heat transfer coefficient will roughly rise to the power of 0.8 with respect to a change in flow velocity.

$$\frac{hd}{\lambda} = 0.023\left(\frac{du\rho}{\mu}\right)^{0.8}\left(\frac{c_p\mu}{\lambda}\right)^{0.4}$$

$$h_i = 6000 \times (2)^{0.8} = 10446.6$$

$$h_o = 600 \times (2)^{0.8} = 1044.7$$

Case	U [kcal/m2/hr/K]	Variation Ratio
Base case	362.4	
U(hi up) =	373.2	2.98%
U(ho up) =	487.8	33.60%

Even if the inner pipe flow velocity which has a high heat transfer coefficient is doubled, the value of U rises only by about 3%, but when the outer flow velocity is doubled the U value increases by more than 30%. In this way, when one heat transfer coefficient is significantly low, this heat transfer coefficient is called the dominant heat transfer coefficient. No significant improvement can be expected without focusing on improving this value.

Dominant Factors for Overall Heat Transfer Coefficient 2

Consider a case where the fouling resistance is large.

Using the base case conditions, let us change only the outer fouling resistance r_{so} to 0.01 [m^2 hr K/kcal] and examine how much this affects the overall heat transfer coefficient when the external flow velocity is doubled.

hi =	6000	kcal/m2/hr/K
ho =	600	kcal/m2/hr/K
rsi =	0.0002	m2*hr*K/kcal
rso =	0.0006	m2*hr*K/kcal
rwo =	0.00008	m2*hr*K/kcal

Base case

hi =	6000	kcal/m2/hr/K
ho =	600	kcal/m2/hr/K
rsi =	0.0002	m2*hr*K/kcal
rso =	0.01	m2*hr*K/kcal
rwo =	0.00008	m2*hr*K/kcal

Case with large external fouling

Dominant Fouling

When the pipe outer fouling resistance is large

Case	U [kcal/m2/hr/K]	Variation Ratio
Base case	362.4	
rso=0.01 case	82.24	
U(ho up) =	87.34	6.20%

1/hi =	0.00017	m2*hr*K/kcal
1/ho =	0.00167	m2*hr*K/kcal
rsi =	0.00020	m2*hr*K/kcal
rso =	0.01000	m2*hr*K/kcal
rwo =	0.00008	m2*hr*K/kcal

Dominant Factor

- In the case where the fouling resistance is large, even if the outer flow velocity of the pipe with the small film heat transfer coefficient is doubled as in the previous case, the effect on the overall heat transfer coefficient is very small at about 6%. This is because fouling has become the dominant factor of heat transfer resistance.
- When fouling is dominant like this, it does not make much sense to try to improve the heat transfer coefficient, and focusing on such design is often a waste of time. This also applies during operation when fouling contamination accumulates.

Conclusion

- In heat exchanger design, it is important first to identify the dominant factor of heat transfer resistance and to get a grasp of the approximate heat transfer area.
- If the dominant factor is extremely large compared to other factors, it can be considered that improving other factors will have no significant effect.
- If the dominant factor is the film heat transfer coefficient, it is possible to raise the value of U by increasing the flow velocity. However, if the flow velocity is too high, caution is required because problems may occur such as tube vibration, increased pressure loss, and erosion.
- If the dominant factor is fouling or tube wall resistance (depending on the material), it is not possible to expect any significant improvement in the design of the heat exchanger, so it is not necessary to take much time to improve its efficiency.