Fundamentals of Heat Transfer

Muhammad Rashid Usman

Institute of Chemical Engineering and Technology

University of the Punjab, Lahore.

Figure taken from: http://heatexchanger-design.com/2011/10/06/heat-exchangers-6/ Dated: 17-Jan-2012

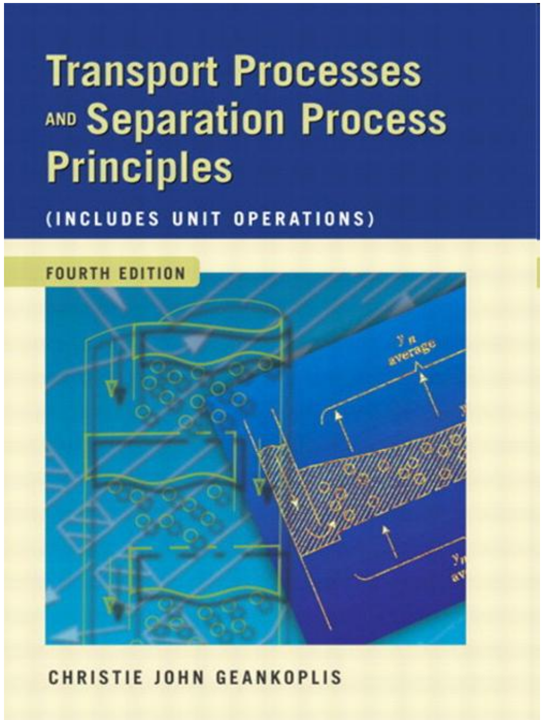
Course contents final term

Convection heat transfer: Free and forced convection. Rate equation for convective heat transfer coefficient. Brief description of hydrodynamic boundary layer and heat transfer coefficient. Units of heat transfer coefficient. Individual and overall heat transfer coefficients: plane wall and hollow cylinder. Numerical problems regarding overall heat transfer coefficient. Determination of heat transfer coefficient. Description of various heat transfer correlations. Log mean temperature difference. Numerical problems involving log mean temperature difference. Heat transfer in coiled and jacketed agitated vessels. Introduction to boiling and condensation. Types of boiling: Pool boiling and film boiling. Critical thickness of insulation. Brief description of heat transfer equipment: Heat exchangers, furnaces, and evaporators.

Radiation heat transfer: Basics of radiation heat transfer. Stefan-Boltzmann Law. Kirchoff's law. Radiation heat transfer coefficient. Radiation to a small object from surroundings. View factors in radiation. Radiation in absorbing gases.

The text book

Please read and consult to know and learn.



Geankoplis, C.J. (2003). Transport processes and separation process principles: includes unit operations. 4th ed. Prentice-Hall International, Inc.

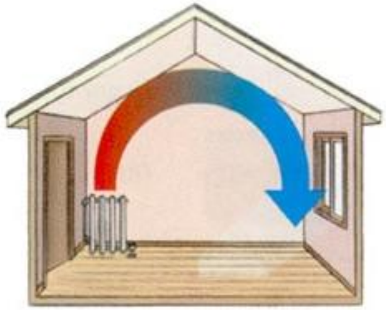
Convection heat transfer

Types of convective heat transfer

- Free or natural convection heat transfer
- Forced convection heat transfer

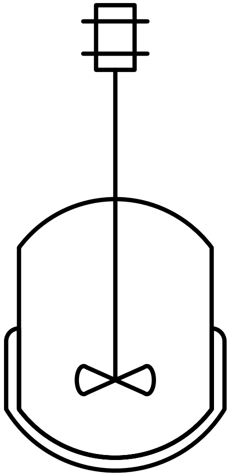
Free or natural convection heat transfer

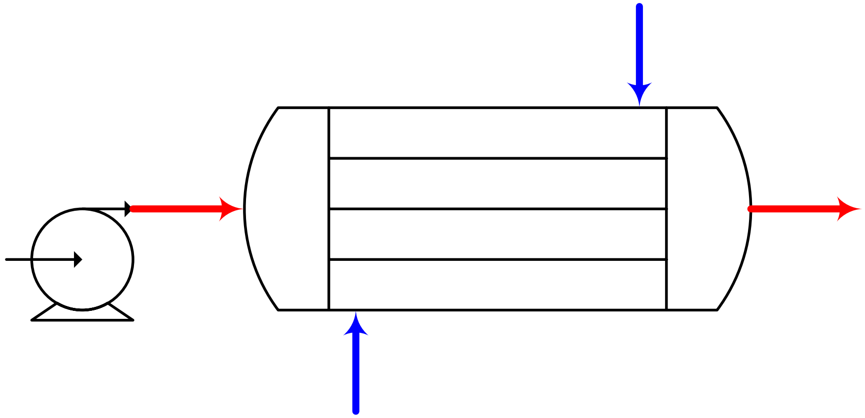
If the fluid motion is caused by itself due to difference in densities at two different points such a process is natural or free convection heat transfer. The density differences may be caused by temperature differences or concentration differences at two locations. In natural convection, no mechanical means are used to produce convective currents and convective mixing is a solely due to natural motion of the fluid. Boiling of milk and water and heating distant parts of a room in the presence of a room heater are common daily examples.



Forced convection heat transfer

If the fluid motion is caused by some external or mechanical means the heat transfer is due to forced convection. Pumps, blowers, fans, agitation devices such as impellers are employed for forced convection heat transfer. Agitation using impellers in reaction vessels and pumping of fluids, at high velocity, in heat exchangers devices are the examples of forced convection.





Free and forced convection heat transfer

In which of the following cases do you expect greater rate of heat transfer?

1. Free convection

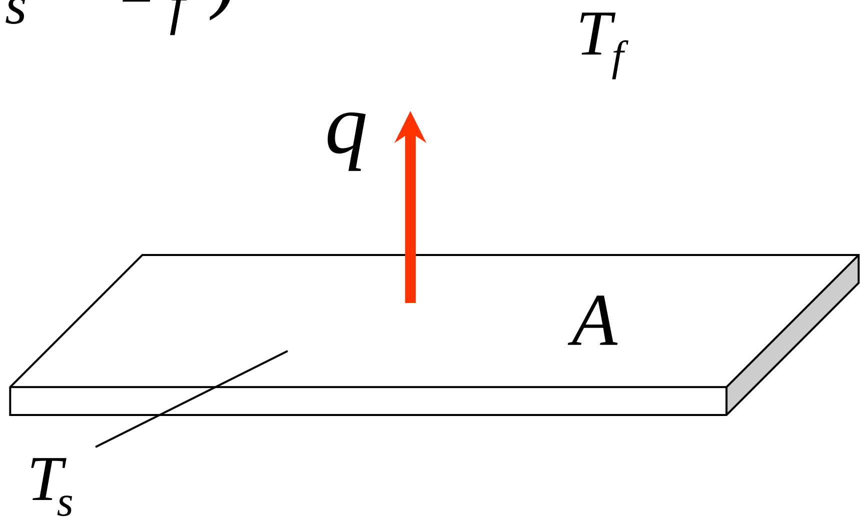
2. Forced convection

Newton's rate equation

Rate of heat transfer per unit area is equal to the product of heat transfer coefficient and temperature difference between the heated surface and fluid far from the surface.

$$q = h \cdot A \cdot (T_s - T_f)$$

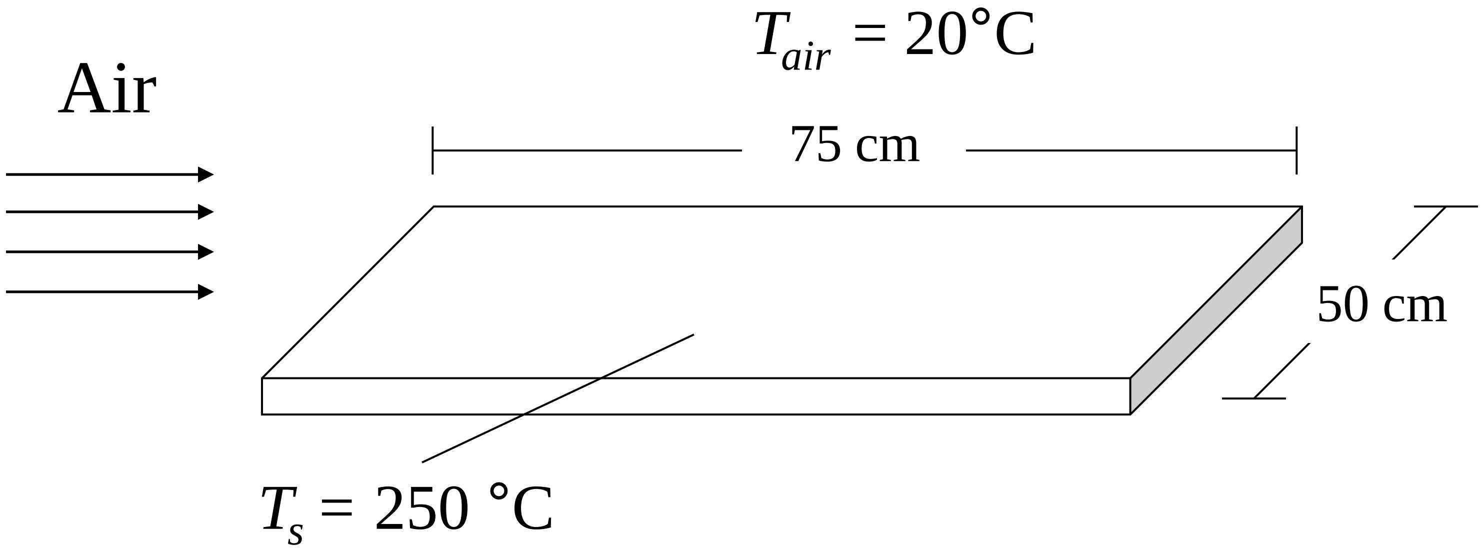
$$\frac{q}{A} = h \cdot (T_s - T_f)$$



1642-1727

Heat conduction through a multilayer (composite) hollow cylinder-4: Problem (modified)-7 [p. 17, 2]

Air at 20 °C blows over a hot plate 50 by 75 cm while maintained at 250 °C. The convection heat transfer coefficient is 25 W/m^2·K. Calculate the rate of heat transfer. What if heat transfer coefficient for the system is very high or very low such as 200 W/m^2·K and 0.1 W/m^2·K respectively. What is the direction of heat flow.



Heat transfer coefficient

From the Newton's rate equation, it may be said that heat transfer coefficient is the ability of the system, for which it is defined, to transfer heat.

What are the units of heat transfer coefficient?

Units of heat transfer coefficient

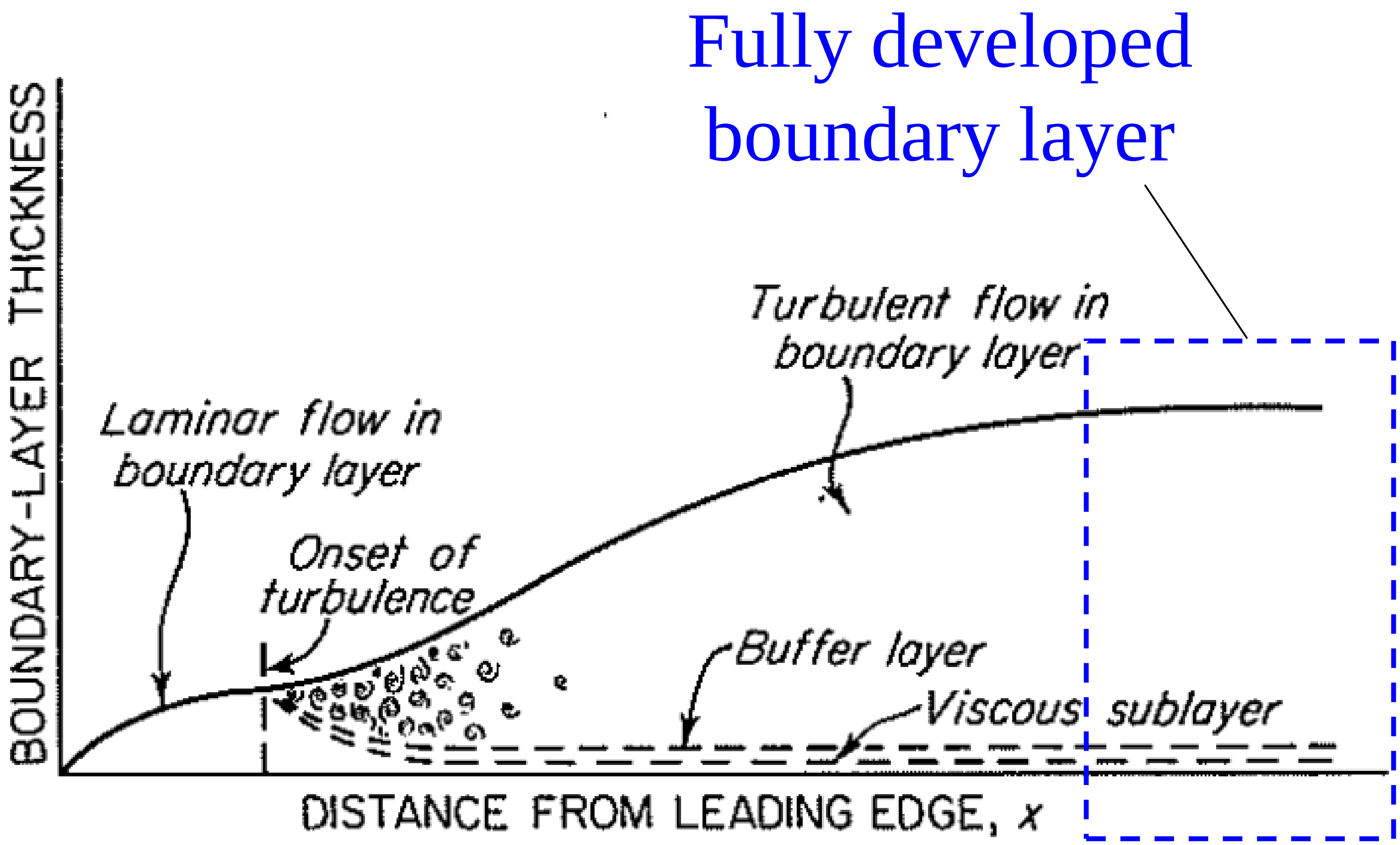
SI units: $J/s \cdot m^2 \cdot K$ or $W/m^2 \cdot K$

$W/m^2 \cdot K$ is equal to $W/m^2 \cdot °C$

English system: $Btu/h \cdot ft^2 \cdot °F$

Compare units of thermal conductivity and heat transfer coefficient.

Heat transfer coefficient based on film model: Hydrodynamic boundary layer [p.58, 6]



Heat transfer coefficient based on film model

Consider thickness of the film as Δx and k as the thermal conductivity of the fluid (material of the film), then it may be written that

$$h = \frac{k}{\Delta x}$$

The main resistance to heat transfer is in this film. The heat transfer coefficient is sometimes called film coefficient.

Note: Liquids and gases have low thermal conductivity.

Heat transfer coefficient based on film model

Consider that a hot fluid is flowing through a circular pipe and a cold fluid is flowing on the outside of the pipe. The heat will flow from the hot fluid to the cold fluid through a series of resistances. Generally, the velocity of the fluid may be considered to be zero at the solid surface and it rapidly increases as we move away from wall surface. It is found that even in turbulent flow where convective heat flow occurs from a surface to a fluid, the thin film of the fluid free of turbulence (viscous sublayer) exist at the wall surface. This thin film of fluid covering the surface is of great importance in determining the rate of heat transfer as all the heat reaching the bulk of cold fluid must pass through the film of fluid by conduction. The thermal conductivities of fluids are very low so that the resistance offered by the film to the heat flow is very large though the film is thin. Beyond this film the turbulence existing brings about rapid equalisation of temperature.

Excerpt (p. 3.2) from Heat transfer by K.A. Gavhana, 8th ed., Nirali Prakashan, Pune (2008).

Heat transfer coefficient based on film model

For convective heat transfer, the film model suggests that where ever a fluid flows past a solid surface there is a film formed adjacent to the wall and that there is no turbulence in this film and this film offers the only resistance to heat transfer.

It is important to mention here that for the film model, in the turbulent region (beyond the film) of a fluid there is no problem for heat transfer, i.e. due to intense mixing, heat transfer is greatly enhanced and there is no temperature differential.

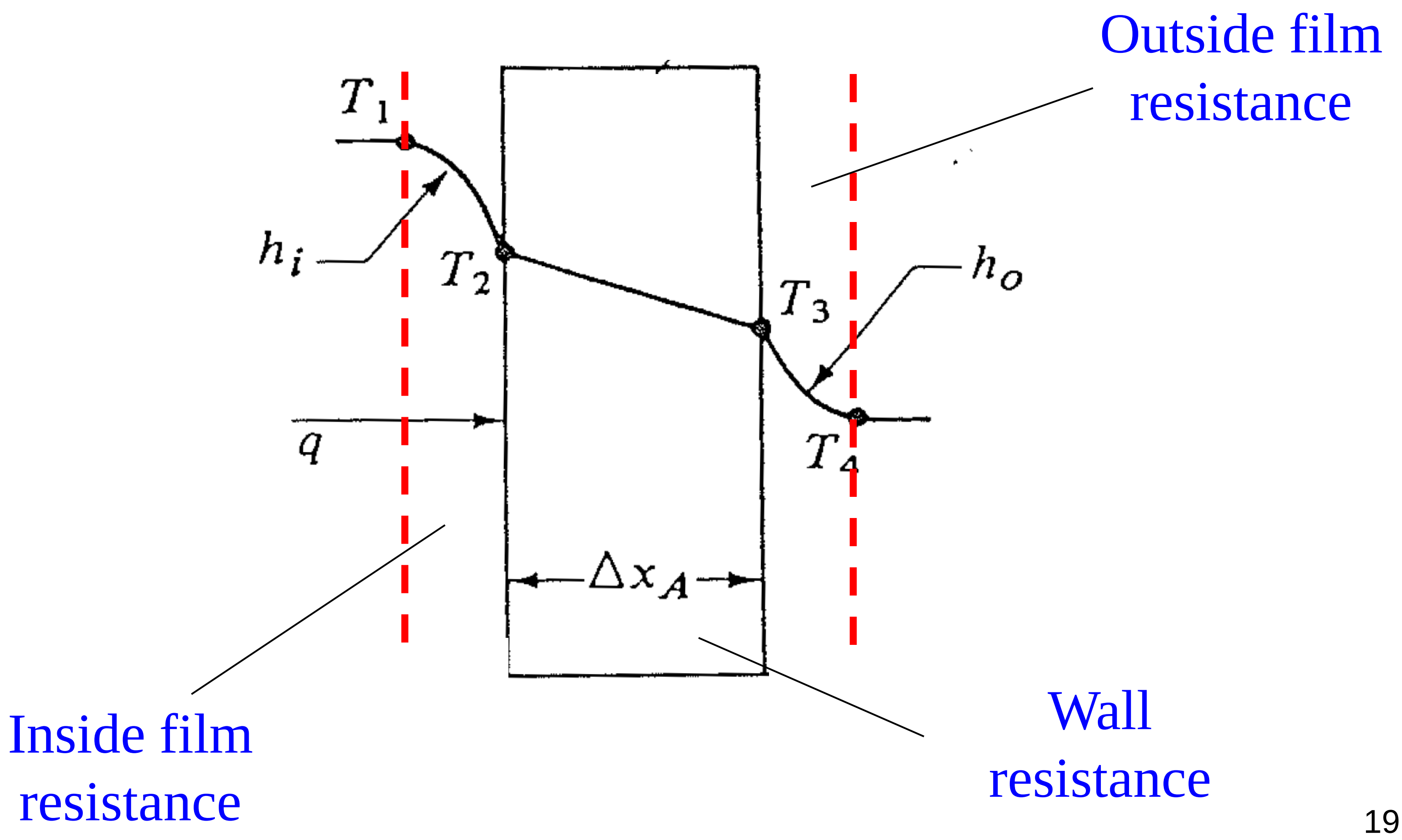
Approximate magnitudes of some heat transfer coefficients [1]

Mechanism	Range of Values of *h*	
	$btu/h \cdot ft^2 \cdot {}^\circ F$	$W/m^2 \cdot K$
Condensing steam	1000–5000	5700–28 000
Condensing organics	200–500	1100–2800
Boiling liquids	300–5000	1700–28 000
Moving water	50–3000	280–17 000
Moving hydrocarbons	10–300	55–1700
Still air	0.5–4	2.8–23
Moving air	2–10	11.3–55

Heat transfer coefficient based on film model

Condensing steam (saturated steam) has high heat transfer coefficient in contrast to superheated steam that is why a process engineer would like to heat a system using condensing steam and not by superheated steam. A superheated steam behaves like a gas and you know gases have low heat transfer coefficients.

Individual and overall heat transfer coefficients: plane wall [p. 249, 1]



Individual and overall heat transfer coefficients: plane wall [p. 249, 1]

For inside film resistance:

$$\frac{q}{A} = h_i \cdot (T_1 - T_2)$$

For wall resistance:

$$\frac{q}{A} = k_A \cdot \frac{(T_2 - T_3)}{\Delta x_A}$$

For outside film:

$$\frac{q}{A} = h_o \cdot (T_3 - T_4)$$

What if we have two walls?

Individual and overall heat transfer coefficients: plane wall [p. 249, 1]

$$\frac{q}{A} = \frac{T_1 - T_4}{\frac{1}{h_i} + \frac{\Delta x}{k} + \frac{1}{h_o}}$$

$$q = \frac{T_1 - T_4}{\frac{1}{h_i \cdot A} + \frac{\Delta x}{k \cdot A} + \frac{1}{h_o \cdot A}}$$

$$Heat\ rate = \frac{Overall\ temperature\ difference}{Sum\ of\ all\ the\ resistance\ in\ series}$$

Individual and overall heat transfer coefficients: plane wall

Reciprocal of overall resistance is overall conductance and frequently written in terms of overall heat transfer coefficient.

$$U \cdot A = \frac{1}{\dfrac{1}{h_i \cdot A} + \dfrac{\Delta x}{k \cdot A} + \dfrac{1}{h_o \cdot A}},$$

$$U = \frac{1}{\dfrac{1}{h_i} + \dfrac{\Delta x}{k} + \dfrac{1}{h_o}}$$

$$\frac{1}{U} = \frac{1}{h_i} + \frac{\Delta x}{k} + \frac{1}{h_o}$$

$$q = U \cdot A \cdot (T_1 - T_4)$$

Individual and overall heat transfer coefficients: plane wall

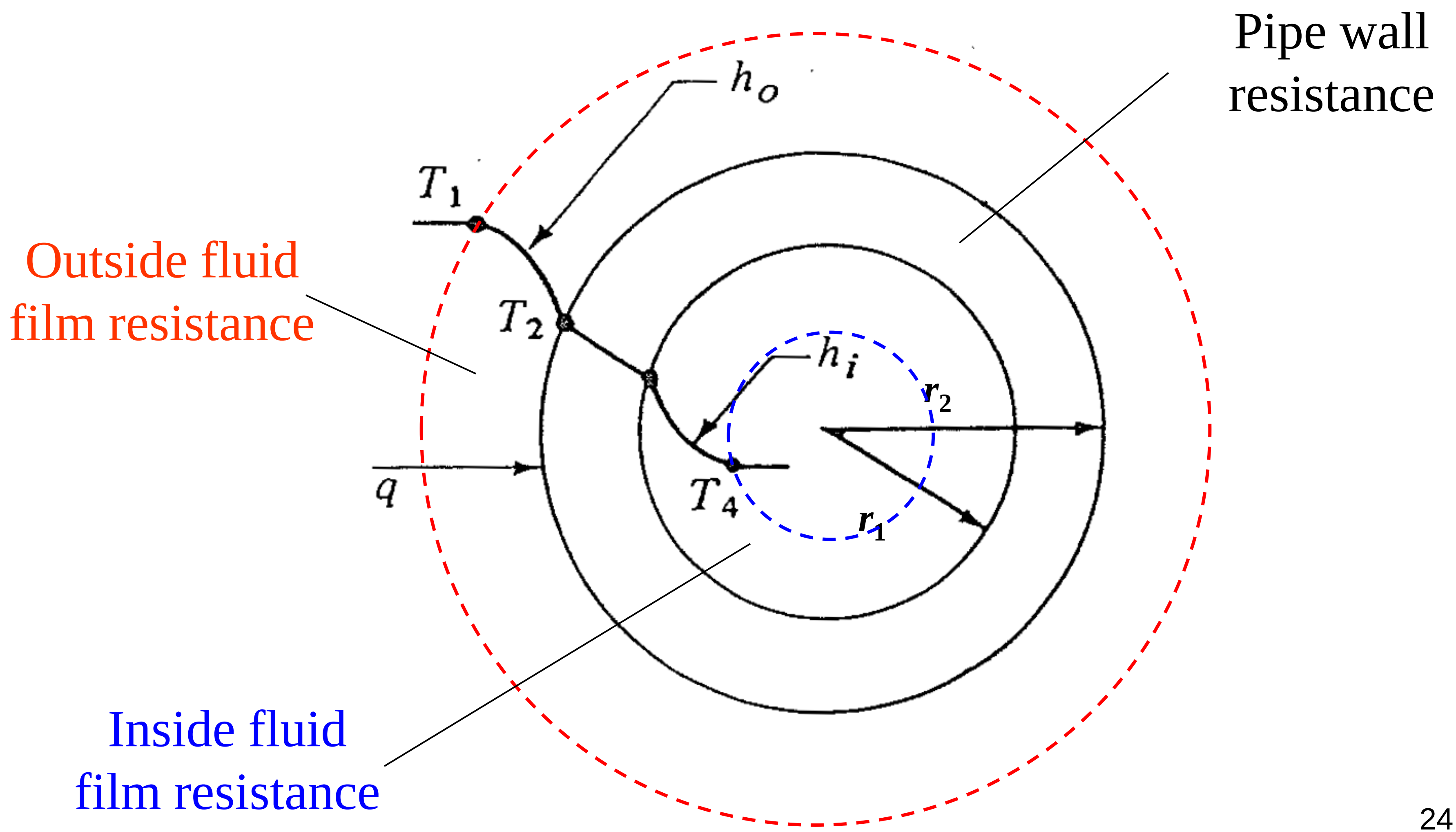
Case 1: What if thickness of the wall with high thermal conductivity is very small?

Case 2: If one of the two film coefficients is a small value compared to the other, then major resistance is offered by the one with small value and the coefficient is called as "controlling film coefficient". What will be the form of the heat rate equation if $h_i >>> h_o$?

Case 3: What if there are a number of plane walls in series?

Think other cases!

Individual and overall heat transfer coefficients: hollow cylinder



Individual and overall heat transfer coefficients: hollow cylinder

$$q = \frac{T_1 - T_4}{\dfrac{1}{h_i \cdot A_i} + \dfrac{\ln(r_2 / r_1)}{2 \cdot \pi \cdot k \cdot L} + \dfrac{1}{h_o \cdot A_o}}$$

$$Heat\ rate = \frac{Overall\ temperature\ difference}{Sum\ of\ all\ the\ resistance\ in\ series}$$

Individual and overall heat transfer coefficients: hollow cylinder

$$\frac{1}{U \cdot A} = \frac{1}{h_i \cdot A_i} + \frac{\ln(r_2 / r_1)}{2 \cdot \pi \cdot k \cdot L} + \frac{1}{h_o \cdot A_o}$$

Which *A*? Unlike plane wall, the inside and outside surface areas are different for cylindrical geometry. The overall heat transfer coefficient is therefore has to be defined either on outside or inside surface of the hollow cylinder.

Individual and overall heat transfer coefficients: hollow cylinder

$$\frac{1}{U_i} = \frac{1}{h_i} + \frac{A_i \cdot \ln(r_2 / r_1)}{2 \cdot \pi \cdot k \cdot L} + \frac{A_i}{h_o \cdot A_o}$$

$$\frac{1}{U_o} = \frac{A_o}{h_i \cdot A_i} + \frac{A_o \cdot \ln(r_2 / r_1)}{2 \cdot \pi \cdot k \cdot L} + \frac{1}{h_o}$$

References

1. Geankoplis, C.J. (2003). Transport processes and separation process principles: includes unit operations. 4th ed. Prentice-Hall International, Inc.
2. Holman, J.P. (2010). Heat transfer. 10th ed. McGraw-Hill Higher Education, Singapore.
3. Cengel, Y.A. (2003). Heat transfer: A practical approach. 2nd ed. McGraw-Hill.
4. Incropera, F.P.; DeWitt, D.P.; Bergman, T.L.; Lavine. A.S. (2007) Fundamentals of heat and mass transfer. 6th ed. John Wiley & Sons, Inc.
5. Kern, D.Q. (1965). Process heat transfer. McGraw-Hill International Book Co., Singapore.
6. McCabe, W.L.; Smith, J.C.; Harriott, P. (1993). Unit operations of chemical engineering. 5th ed. McGraw-Hill, Inc., Singapore.
7. Coulson, J.M.; Richardson, J.F.; Backhurst, J.R.; Harker, J.H. (1999). Coulson and Richardson's Chemical engineering: Fluid flow, heat transfer and mass transfer. vol. 1. 6th ed. Butterwoth-Heinemann, Oxford.
8. Staff of Research and Education Association. (1984). The heat transfer problem solver. Research and Education Association, New Jersey.
9. Kreith, F.; Manglik, R.M.; Bohn, M.S. (2011). Principles of heat transfer, 7th ed., Cengage learning.
10. Mills A.F. (1995). Heat and mass transfer. Richard D. Irwin, Inc.