Fundamentals of Heat and Mass Transfer and Design and Development of a General-Purpose Dryer

Neethu K.C.
Engineering Division
ICAR- Central Institute of Fisheries Technology, Cochin
neethu.kc11@gmail.com

Introduction

Heat and mass transfer is a significant and consolidated branch of physics and engineering. Heat and mass transfer studies aims to understand the specific transport phenomena occurring at the fluid boundaries during different unit operations such as cooling, heating, boiling, condensation, evaporation, distillation, drying, frying, etc. Many of these thermal processes are aided by simultaneous heat and mass transfer. It is necessary to understand about heat and mass transfer, to design and develop the processing equipments, to bring out desired changes in the product, and to improve on the equipment's thermal efficiency.

Heat transfer

Heat transfer may be defined as flow of energy from one body to another body by virtue of temperature difference between them. The net flow of energy always occurs from high temperature body towards low temperature body and this flow of heat stops the moment temperature of both the bodies are equal.

Modes of heat transfer

Heat transfer is the study of transmission of thermal energy from a high temperature region to a low temperature region on account of temperature difference. The rate of heat transfer is directly proportional to the temperature difference between the heat exchanging regions/bodies. Three different modes of heat transfer are conduction, convection and radiation. In the conduction and convection modes, heat flows from high temperature to low temperature region/body, whereas, in radiation mode, transfer of heat takes place from both the bodies towards each other. However, net transfer of heat is always from high temperature body to low temperature body.

Conduction

Conduction is a process of heat transfer from a high temperature region to a low temperature region with in a body or between different bodies which are in direct physical contact. In heat conduction, energy is transferred due to exchange of molecular kinetic energy. As the temperature in one region of a body increases, kinetic energy of molecules in that region also increases as compared to that of the molecules of adjacent low temperature region. High energy molecules transfer a part of their energy by impact in case of fluids or by diffusion in case of metals to low energy molecules, thereby resulting in increase in their energy levels, hence temperature.

The basic law of heat transfer by conduction was proposed by the French Scientist J. B. J. Fourier in 1822. One dimensional heat conduction rate equation described by the Fourier Law is written as:

$$q_x = -kA\frac{dT}{dx} \quad \text{or} \quad q''_x = -k\frac{dT}{dx}$$

where,

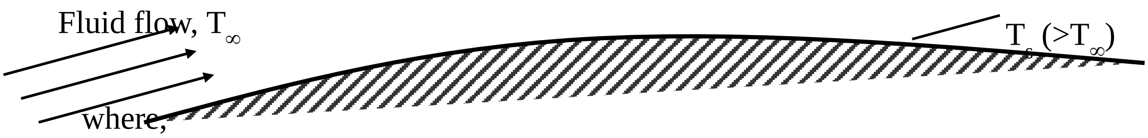
q_x = heat rate in x-direction (W)
q''_x = heat flux in x-direction (W/m^2)
T = temperature (°C or K)
A = area normal to heat flow (m^2)
k = thermal conductivity of material (W/m-K)

Convection

Heat transfer by convection occurs when a fluid (liquid and gas) comes in contact with a solid through direct contact and a temperature difference exists between them. Heat transfer by convection occurs under the combined action of heat conduction and mixing motion. When a fluid comes in contact with a hot surface, energy in form of heat flows by conduction from hot surface to the adjacent stagnant layer of fluid particles, thereby increasing their temperature and internal energy. Due to increase in temperature, density of the fluid particles decreases and they become lighter as compared to the surrounding fluid particles. The lighter fluid particles move up to a region of lower temperature with in the fluid where they mix and exchange a part of their energy with colder fluid particles. Simultaneously, the cold fluid particles move downwards to occupy the space vacated by hot fluid particles. This upward and downward movement of hot and cold fluid particles continues till temperature of the fluid and the surface becomes equal. The upwards movement of hot fluid particles and downward movement of cold fluid particles is called convectional currents. If the convectional currents are set up only due to density differences, then the heat transfer process is termed as natural or free convection. If the convectional currents are caused by some external means such as blower, fan, pump etc. then heat transfer process is called forced convection. It is virtually impossible to observe pure heat conduction in a fluid because as soon as a temperature difference is imposed in a fluid, natural convection currents will occur due to resulting density differences.

Convective heat transfer rate is governed by Newton's law of cooling and is expressed as:

$$q'' = h(T_s - T_\infty) \quad \text{or} \quad q = hA_s(T_s - T_\infty)$$



where,

q'' = heat flux normal to surface
q = heat rate from or to surface A_s
T_s = surface temperature
T_∞ = freestream fluid temperature
A_s = surface area exposed to fluid
h = convection heat transfer coefficient (W/m^2-K)

Radiation

Heat exchanged between two bodies or mediums, which are separated and are not in contact with each other is called radiation heat transfer. Radiation heat transfer does not require presence of an intervening medium between the two bodies as in case of conduction and convection and it takes place most effectively in a vacuum.

Thermal radiation is the energy emitted by a body in the form of electromagnetic waves due to changes in the electronic configuration of the constituent atoms or molecules of the body. When electromagnetic waves come in contact with a body, energy is transferred to the body as thermal energy which is partly absorbed, reflected and transmitted. Energy emitted per unit area as thermal radiation is called emissive power of a body and the maximum energy emitted as radiation by a body at a particular temperature is governed by Stefan-Boltzmann law which is expressed as:

$$E_b = \sigma A T_s^4$$

At a given temperature, maximum radiations are emitted by an ideal emitter called black body. The energy emitted by non-black bodies are less as compared to that of the ideal body when both the bodies are maintained at same temperature. Energy emitted by a non-black body maintained at temperature 'T' is given as:

$$E = \varepsilon \sigma A T_s^4$$

where,

E = Energy emitted per unit time (W)

A = Surface area (m^{2})

σ = Stefan-Boltzmann constant = 5.67x10^{-8} W/m^2K^4

ε = emissivity (0< ε<1) of surface

T_s = surface temperature in absolute units (K)

Heat exchangers

A heat exchanger is a device used for efficient transfer of heat between a hot and cold fluid when it is required to heat up a cold fluid or cool down a hot fluid. Heat exchangers are used in wide range of applications such as:

- Heating and air conditioning systems
- Automobile radiators
- Cooling of internal combustion engines by a coolant
- Boilers and condensers of a power plant

Heat exchangers are generally classified on the basis of following parameters.

- Nature of Heat Exchange Process
- Direct contact
- Regenerative
- Relative Direction of Flow of Fluids
- Parallel flow
- Counter flow
- Cross flow
- Mechanical Design of Heat Exchanging Surface
- Concentric tubes
- Shell and tubes
- Multi-shell and tube passes
- Physical State of Heat Exchanging Fluids
- Condenser
- Evaporator

Logarithmic mean temperature difference (LMTD)

In a heat exchanger, thermal potential, responsible for heat exchange between the hot and cold fluids changes throughout the process. The LMTD is the maximum mean temperature difference that can be achieved in geometry of heat exchanger for any given set of inlet and outlet temperatures.

$$\text{LMTD} = \frac{(T_{hi} - T_{ci}) - (T_{ho} - T_{co})}{ln\frac{(T_{hi} - T_{ci})}{(T_{ho} - T_{co})}}$$

where,

T_{hi} = Temperature of hot fluid at inlet

T_{ci} = Temperature of cold fluid at inlet

T_{ho} = Temperature of hot fluid at outlet

T_{co} = Temperature of hot fluid at outlet

The heat transfer rate in a heat exchanger at particular length is calculated by considering the thermal potential at that length which is expressed as:

$$Q = UA\,(T_h - T_c)$$

The overall heat transfer in a heat exchanger is calculated by using average thermal potential and is represented by the term LMTD. Therefore, the overall heat transfer I heat exchanger can be defined as:

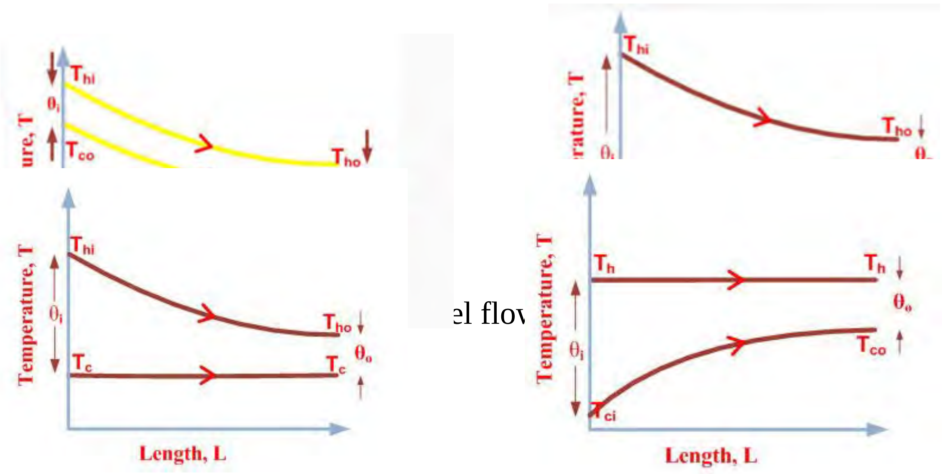
$$Q = UA\,(\Delta T_m)$$

where,

U = overall heat transfer coefficient (W/m^2-K)

A = heat transfer area, m^2

ΔT_m = LMTD



Mass transfer

Mass transfer is defined as the transfer of material from one homogeneous phase to another with or without phase change. It is a complex phenomenon occurs in almost all unit operations. For example, transfer of solute in extraction process, transfer of water molecule in humidification. Drying is another complex process which involves simultaneous heat and mass transfer. Mass transfer is caused by differences in concentration of the substances between two regions. The mass transfer will continue till the concentration differences between two regions exist and will stop when equilibrium is obtained.

Mass transfer basically deals with transport of species:

- within a medium, for example sugar dissolves in a cup of tea to sweeten the entire cup of tea
- across an interface, for example from one medium to another i.e. spreading of food odour in the entire house

There are different types of mass transfer happens during a process. They are diffusion mass transfer, convective mass transfer and phase change mass transfer. Diffusion mass transfer is again classified into molecular diffusion and eddy diffusion. Eddy diffusion happens when one of the fluids in mass transfer is in turbulent condition. Molecular diffusion again classified as ordinary diffusion, in which the diffusion happens due purely due to concentration gradient. Thermal diffusion is due to temperature gradient, pressure diffusion is due to pressure gradient, and forced diffusion is due to the application of mechanical forces.

a) Molecular diffusion in gases

Two gases A and B, separated by a semipermeable membrane, Gas A moves towards chamber B and gas B moves towards chamber A. Concentration of A with distance towards chamber B and B towards A is termed as C_A and C_B. Variation in concentration of component with distance in the system called concentration gradient. Movement of molecule A or B occurs due to concentration gradient known as molecular diffusion.

Molecular diffusion is explained by Fick's law is expressed as:

$$N_A \propto -\frac{dC_A}{dx}$$

Negative sign indicates that concentration decreases with distance.

$$N_A = -D_{AB}\frac{dC_A}{dx}, \text{ for molecule A}$$

$$N_B = -D_{BA}\frac{dC_B}{dx}, \text{ for molecule B}$$

where,

D_{AB}, D_{BA} = Diffusivity of A in B & diffusivity of B in A, respectively (cm^2/sec)

N_A & N_B = Rate of diffusion (g moles/cm^2/sec)

b) Diffusion through stationary, non- diffusing gas

Movement of molecules from liquid or film on drying solids, occurs to a non-diffusing gas. Molecule A is moving from the surface to atmosphere due to concentration gradient in partial pressure, but B is not moving towards the surface. Therefore, rate of mass transfer of A takes place by molecular diffusion and bulk flow.

c) Molecular diffusion in liquids

According to Fick's law, for diffusion in liquid is expressed as:

$$N_A = -D\frac{dC_A}{dx}$$

For equimolar counter diffusion,

$$N_A = -D\frac{C_{A2} - C_{A1}}{x_2 - x_1}$$

where,

C_{A1} and C_{A2} = concentration of A at point x_1 and x_2

Convective mass transfer

The major driving potential for mass transfer process is concentration gradient. But in practical situations, the convective mass transfer in fluids cannot be neglected. The governing equation for convective mass transfer is similar to convective heat transfer equation and is expressed as:

$$m_b = h_{mc}C_{b1} - C_{b2}$$

where,

m_b is the diffused mass component of 'b'
h_{mc} is mass transfer coefficient of component 'b'
C_{b1} and C_{b2} are mass concentrations of component 'b'

Drying

Removal of water by evaporation is known as drying through the application of heat. It can also occur under natural atmospheric conditions. If the material is exposed to air at given temperature and humidity, the material will either lose or gain water until an equilibrium condition is established. Drying results in weight reduction, occupy less space, reduced shipping or transportation or storage costs, convenience in handling, provide definite properties, prevents microbial growth, arrest enzymatic reactions, stops other chemical reactions and helps to improve shelf life.

Drying is a simultaneous heat and mass transfer process occurs due to water vapor pressure gradient. Drying happens in three stages. Initially the moisture from the surface will have enough water to get evaporated, and this will continue till the rate of evaporation from the product surface will be equal to rate of moisture migration to the surface. This is called constant rate drying period. Constant drying rate period lasts till critical moisture content is reached. Then the drying rate decreases as the fraction of wet surface area decreases, is called first falling rate period. At the end of the first falling rate period the fraction of wet surface area decreases to zero. Finally, the subsurface evaporation occurs until the equilibrium moisture content is reached. This stage is known as second falling rate period. During drying, the moisture transfer occurs due to capillary movement, molecular diffusion, thermal diffusion, pressure diffusion and hydrodynamic flow.

Dryers

There are different methods of drying practiced for agricultural commodities. Open air sun drying is traditional method. Many of the developing countries still practice open sun drying method to dry fish and fishery products. It is one of the cheapest methods of drying, in which heat energy is freely available, renewable and abundant. Sun drying involves direct exposure of a commodity to solar radiation and the uses the convective power of the natural wind for drying products. Since the drying conditions are uncontrollable and depends upon weather conditions, it may take longer time for drying and yield inferior quality products. The open conditions may cause contamination with dust, insects, pests and microorganisms.

In order to overcome the drawbacks of open sun drying methods, mechanical dryers with electric heating systems are developed. But this involve running costs due to high electricity consumption and are not recommended due to exploitation of non-renewable sources of energy. Hence, the recent efforts are made to improve the open sun drying and has been led to adoption of solar drying method which is one of the best solutions to the overcome the drawbacks of open sun drying. Solar drying involves a design to capture and magnify the heat from the sun, as well as to help protect the material from infestation of dusts, insects, pests and other foreign bodies. Shorter drying times reduce the risks of spoilage or microbial growth. Even for many centuries farmers were using open-sun drying, solar drying has been taken over open sun drying, as it is more effective and energy efficient. Solar dryers use solar energy which is a renewable energy and freely available. It is clean and green energy and therefore the effective utilisation of solar energy in drying process makes the dryer operated at low cost with maximum energy efficiency. Solar dryers are classified as direct dryers, indirect dryers, greenhouse solar dryers, hybrid solar dryers, solar dryers with energy storage systems etc.

Solar dryer can perform drying only during sunny days, and hence the drying rate depends mainly on climatic conditions and the season. Hybrid solar dryers are therefore, more reliable as there is a back-up system to provide heating in it. Solar-electrical hybrid dryer is more trustworthy as auxiliary system is electrical heating coil.

Design and Development of Dryer

The choice of the best type of dryer to use for a particular application is generally dictated by the following factors such as the nature of the product (physical and chemical); value of the product; scale of production; available heating mechanisms; product quality considerations; space requirements; nature of the vapor (toxicity and flammability); nature of the product; etc.

A mechanical dryer has different components. They are drying chamber, trays, direct or indirect air heating system, air inlet, air distribution systems (fan and blower), air outlet and a control system. There are many factors to be considered while designing a dryer. They are 1) dryer factors – size and shape of dryer, sample quantity, drying time, air flow pattern and air distribution system; 2) Air factors – velocity, air flow rate, temperature and RH, pressure of air, ambient conditions; 3) Sample factors – type, variety of sample, initial and final moisture content of sample, final usage of sample, latent heat of vaporization; 4) Heating system – type and rate of fuel, type of heat source, heat distribution system.

A mechanical dryer with electrical heating coil system was considered for the humid climatic conditions of Kerala, India. The dryer was designed to reduce the moisture content of the shrimp from 75% (w.b.) to 15% (w.b.) within 6 h. The drying conditions and assumptions reported in Table 1 were considered for the design and fabrication of the dryer.

Evaporation load calculation

Moisture content of sample was calculated by hot air oven method.

$$\text{Moisture content}(\%\text{w.b.}) = \frac{\text{Weight of moisture}}{\text{Weight of sample}} \times 100$$

The amount of water to be removed from shrimps during drying (M_w, kg) was estimated from the initial moisture content, final moisture content and total mass of the shrimps.

$$M_w = M \times \frac{M_i - M_f}{100 - M} \times 100$$

where,

M_i = Initial moisture content

M_f = Final moisture content

M = Dryer Capacity

Table 1 Design considerations and assumptions for fabrication of electrical dryer

Product	Shrimp
Dryer capacity	10 kg
Initial moisture content of shrimp	75% (w.b.)
Final moisture content of shrimp	15% (w.b.)
Drying air temperature	55±5℃
Ambient air temperature & relative humidity	30℃& 70%
Specific heat of air	1 KJ/kg K

Density of air	1.2 kg/m^3
Latent heat of vaporization	2260 KJ/kg
Drying time	6 h

Heat energy calculations

Energy required to dry the shrimp is calculated by taking into account of mass of material to be dried (kg), mass of water to be evaporated (kg), specific heat (KJ/kg), latent heat of evaporation (KJ/kg) and temperature difference between ambient and drying conditions.

$$Q = MC_p\Delta T + M_w\lambda$$

where,

Q = energy requirement

C_p = Specific heat of water

λ = Latent heat of evaporation

ΔT = Temperature difference between dryer and atmosphere

Power rating of coil

The power requirement of heating coil can be calculated from the energy required to dry the material in specific drying time.

$$P_C = \frac{Q}{D_t}$$

where, D_t = drying time

Drying air flow rate calculation

The total mass of air required to dry the material in 6 h,

$$m_a = \frac{Q}{\Delta T \times C_p}$$

The total volume of air required (kg) for completing the drying process,

$$V_a = \frac{m_a RT}{P}$$

The total volume of air required per hour (m^3/h),

$$V_{ra} = \frac{V_a}{D_t}$$

where,

m_a = mass flow rate of air

V_a = Volume of air

R = Universal gas constant

T = Temperature of air

P = Pressure of air

The blower capacity can be decided accordingly for the volumetric flow rate of the air.

Drying Chamber size

By doing preliminary experiments, the area required to spread 1 kg shrimp can be calculated. The drying area requirement for loading a definite weight of shrimp can be found out. The area of each tray and total no. of trays can be calculated from this data and accordingly the drying chamber dimensions can be worked out.

Fabrication of electrical dryer

The materials used for fabrication of electrical dryer are stainless steel (SS 304 for drying trays), mild steel (MS) angles for frame, galvanized iron (GI) for supporting structure, polyurethane foam (PUF) for insulation, glazing, blowers and exhaust fans. The dryer consists of drying chamber and heating coils. The base frame of the structure was fabricated using GI pipes and drying chamber supporting frames were made of stainless steel. Initially GI and SS base supporting frames are welded to drying chamber to enable loading and unloading of material. Drying chamber is insulated with PUF material. The drying chamber is designed to hold 5 trays for 10 kg fresh shrimp. The drying trays were made of perforated SS 304. There should be a spacing provided between each tray to provide efficient air movement between trays. A blower is placed on the top of the drying chamber of 0.5 hp capacity. That blower supplies air in to the heating coil, then the heated air comes inside the chamber from the vent at the bottom of drying chamber. Then the hot air went outside through two exhaust fans 0.03 hp on both top sides of the drying chamber. The cost of electrical dryer is estimated considering the cost of drying chamber, frames or stands, control panels, electrical heating coil.

Drying efficiency

The performance of a dryer was evaluated by calculating its drying efficiency. The drying efficiency is defined as the ratio of total heat energy required to the total heat energy supplied by the dryer to remove the moisture from the material.

$$Drying\ efficiency = \frac{Energy\ required}{Energy\ supplied\ by\ heating\ coil + Energy\ supplied\ by\ solar\ collector}$$

Shrinkage

Shrinkage is one of the key parameters to be checked during drying of shrimps. It was calculated by measuring the of dimensions of shrimps using vernier caliper before and after drying. Shrinkage of shrimp may be calculated from the geometric mean dimensions using the formula:

$$Shrinkage = \frac{Avg\ GMD\ before\ drying - Avg\ GMD\ after\ drying}{Avg\ GMD\ before\ drying}$$

Rehydration ratio

About five grams of dried shrimp samples were soaked in 200 mL of distilled water at ambient conditions. After 30 minutes of soaking, samples were removed, then weighed and immediately returned to the soaking water and process continued till the weight of samples become constant.

$$Rehydration\ ratio = \frac{weight\ of\ rehydrated\ sample}{weight\ of\ dried\ sample}$$