Description of Module	
Subject Name	Food Technology
Paper Name	Unit Operations in Food Processing
Module Name/Title	Introduction to material and energy balance
Module Id	FT/UOFP/3
Pre-requisites	Basics of different food processes, block diagrams
Objectives	To understand the system and boundary; the material and energy balance inside a system and the principle underlying it.
Keywords	System, mass balance, energy balance, law of conservation of mass, batch and continuous process

Introduction to Material and Energy Balance

3.1 Introduction

Material and energy balance in food processing is a useful tool for product formulation, process design, cost estimation and process efficiency calculation. Material balance is the tracking of inflow material to a process, out flow from the process and the accumulation amount of the product. The selection and sizing of process equipment is made based on the material balance. The required quantity of a component in a formulation can be calculated from material balance. The information on energy inflow, out flow and loss or conversion enables us to design a process in terms of thermal, mechanical energy and to select the suitable source of energy for the process of concern. Moreover, a process engineer gains the ideas as to where loss of energy taking place and find out the alternative ways to remedied it.

3.2 Law of conservation of mass and energy

Law of conservation of mass and energy states that, mass and energy can neither be created nor be destroyed. It can be transformed from one form to another. So, the total mass or energy applied to a process remains same. If one kilogram of mango pulp is put in a dryer, the sum of the amount of dried pulp and the water evaporated will be one kilogram. The general formula for mass and energy balance adopted in chemical or food processes is given below.

$$Inflow = Out\ flow + Accumulation$$

Accumulation means, the mass or energy absorbed or stored in a process. If the accumulation becomes zero, the inflow will be equal to out flow. This kind of processes are said to be in steady state where as the processes with non zero accumulation are called unsteady state processes. In the process of evaporation of milk, milk passes to the calendria and thick consistent milk comes out leaving the moisture as vapour form. The mass balance around the evaporator will be;

$$Raw\ milk = milk\ accumulated\ inside + concentrated\ milk + vapour$$

The energy equation can be written as;

$$energy\ in = energy\ out + energy\ loss$$

We can calculate the energy efficiency of a process or equipment from the above equation.

$$eficiency, \eta\ (\%) = \frac{energy\ out}{energy\ in} \times 100$$

3.3 System and boundary

A system is necessarily a whole process comprising various operations or a single unit operation or a portion of a unit operation. A system is shown diagrammatically by squares or rectangles around which the material and energy balance is carried out. A boundary is the area outside the system through which the material comes in to the system or goes out. During the drawing of flow diagrams the boundary is shown as dotted lines. It is an imaginary line drawn to differentiate between batch and continuous process or between open and closed system. A system is said to be closed if the material of interest does not crosses the boundary line. It is worthy to mention here that the energy can cross the boundary of a closed system. A batch process can be a closed system. When the material crosses the boundary of a system, it is called open system. The continuous processes are generally of open systems.

3.4 Basis and tie material

A basis of an unknown quantity is considered, the value of which is required to be calculated from a mass or energy balance. In other term, the value of the quantity is not given in a problem. It might be the mass of a raw material entering a process. It could be 100 kg of milk for production of milk powder. A 'tie material' is one of the components of a system or material which does not change during process. Let's have a look to the problem 1. The total solid (TS) in the milk does not change during drying. So, the TS is taken in this problem as tie material.

3.5 Mass balance

3.5.1 Overall mass balance

The sum of the mass streams entering the system through boundary must be equal to the total mass coming out of the system. Of course, the process is a steady process (i.e. accumulation is zero). In the illustration, M_1 and M_2 are the entering mass whereas the M_3 the accumulated mass and M_4 the mass in the vapour comes out of the system. (**Insert the multimedia here**) So,

$$M_1 + M_2 = M_3 + M_4$$

3.5.2 Component balance

The components of a material is expressed either as the fraction of the total mass or as the ratio of the mass of a single component to that of other component of the material. If a mixture consists of components a and b, the mass fraction of component a is expressed as;

$$mass\ fraction,\ X_a = \frac{M_a}{M_a + M_b}$$

Where, M_a and M_b are the mass of component a and b respectively.

The ratio of component a with respect to b can be expressed in percent as given below.

$$mass\ ratio, R_a = \frac{M_a}{M_b}$$

In the context of moisture present in a food material, the moisture component would be expressed either as fraction or as ratio. The fraction of moisture is nothing but the moisture content in wet basis, whereas the moisture ratio is the moisture content in dry basis.

3.6 Batch and continuous process

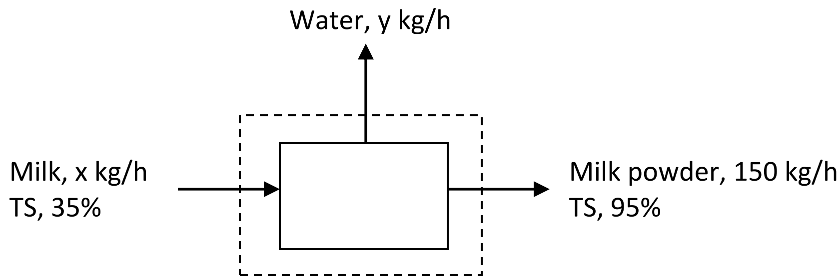
A batch process is one where, the material flows to and from the system is calculated at a particular time or situation. Your parents heat the milk taking a fixed quantity of milk in a bowl. Material neither enters the bowl nor comes out at different time. So there is no exchange of mass between the system and surrounding. In a continuous process, the exchange of material takes place. Take the case of a plate heat exchanger. The milk continuously flows in and out. The mass will be denoted as mass/time (e.g. kg/h). The problem 1 is an example of continuous process.

Problem 1: How much of concentrated milk of 35% total solid is required to produce 150 kg/h of milk powder of 95% total solid?

Solution:

Step 1

Draw a process diagram.



Step 2

Select the tie material and basis.

Tie material: Total Solid of milk

Basis: One hour

Step 3

Write the component and mass balance.

i. Overall mass balance

$x = y + 150$

ii. Component balance (i.e. Total solid balance)

$x \times \frac{35}{100} = y \times \frac{0}{100} + 150 \times \frac{95}{100}$ (Water has no solid content)

Or,

$x \times \frac{35}{100} = 142.5$

⇨ $x = 142.5 \times \frac{100}{35} = 407.14\ kg/h$

And,

$y = 407.14 - 150 = 257.14\ kg/h$

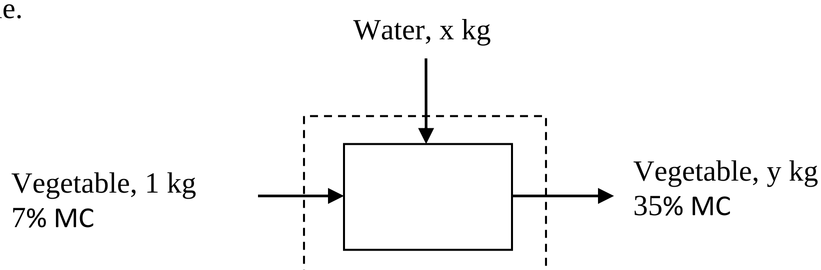
Therefore, 407.14 kg/h milk of 35% TS will yield milk powder of 150 kg/h with 95% TS. The amount of water evaporated from this process will be 257.14 kg/h.

Problem 2: The dried vegetable containing 7% moisture content (wet basis) was conveyed to a water spraying chamber. If the moisture content of the vegetable is required to be raised to 35% (wet basis), find out the amount of water sprayed to the vegetable.

Solution:

Basis: 1 kg vegetable fed to chamber

Total material balance:



$1 + x = y$ ….. (1)

Moisture balance:

$$1 \times \frac{7}{100} + x = y \times \frac{35}{100}$$

Or,

$0.07 + x = 0.35\, y$ -------- (2)

Putting the value of y from equation (1) in (2),

$$0.07 + x = 0.35\,(1 + x)$$

⇨ $x = 0.43\, kg$

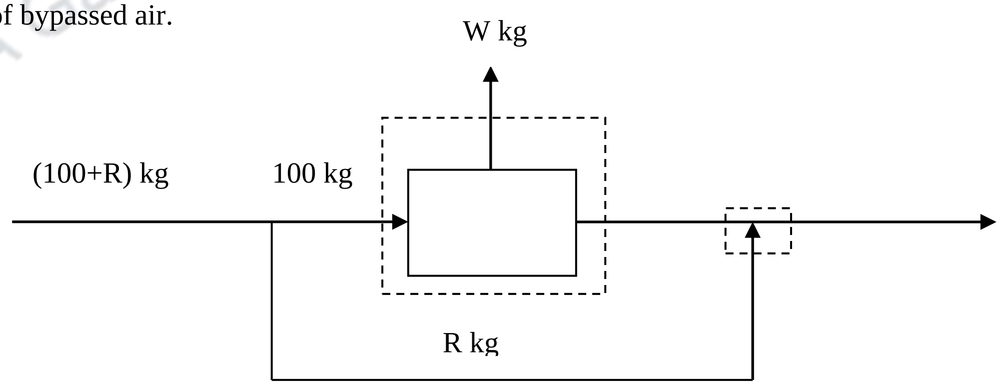
Therefore, the amount of water to be sprayed to the vegetable is at the rate of 0.43 kg per kg of vegetable. The final weight of the vegetable would be 1.43 kg.

3.7 Recycle and Bypass of a process

Recycling of the flow of material is practiced for the purpose of higher yield, complete degradation of a component, conservation of energy or to maintaining a particular concentration in feed material. Bypass is the diversion of a stream from a process or system.

Problem 3: Dehumidified air of 0.008 kg H_2O/kg air is required to be fed to a dryer. The atmospheric air has the absolute humidity of 0.02 kg H_2O/kg air. Therefore, the air is passed through a dehumidifying system that reduces the absolute humidity to 0.004 kg H_2O/kg air. So, part of the fresh atmospheric air is bypassed to dehumidifying unit. Find out the mass of water removed per 100 kg of dry air feed and the percentage of bypassed air.

Answer



Basis: 100 kg dry air entering the dehumidifier.

Since we are taking dry air as the basis the dry air quantity will be constant at the outlet of the dehumidifier.

Moisture balance in the dehumidifier:

$100\ kg\ dry\ air \times 0.02\ \frac{kg\ H_2O}{kg\ dry\ air} = W\ kg\ H_2O + 100\ kg\ dry\ air \times 0.004\ \frac{kg\ H_2O}{kg\ dry\ air}$

So, the rate of water removal is $W = 1.6\ kg$ per 100 kg of dry air.

Assume, R kg dry air bypassed the dehumidifier.

Taking the mass balance of water at the point of mixing of fresh air with dehumidified air;

$$R\ kg\ dry\ air \times 0.02\ \frac{kg\ H_2O}{kg\ dry\ air} + 100\ kg\ dry\ air \times 0.004\ \frac{kg\ H_2O}{kg\ dry\ air} = (100 + R) kg\ dry\ air \times 0.008 \frac{kg\ H_2O}{kg\ dry\ air}$$

Simplifying the equation,

$$0.02 \times R + 0.4 = (100 + R) \times 0.008$$

⇨ $R = 33.33\ kg\ dry\ air$

Total dry air before bypass line is, (100+R) kg i.e. 133.33 kg. So the total quantity of humid air will be

$$133.33 + 133.33 \times 0.02 = 136\ kg$$

And the quantity of humid air bypassed will be

$$33.33 + 33.33 \times 0.02 = 34\ kg$$

So, the percentage of bypass air will be

$$\frac{air\ bypassed}{total\ air\ used\ in\ the\ system} \times 100 = \frac{34}{136} \times 100 = 25\%$$

Hence, the amount of water removed is 1.6 kg per 100 kg dry air and the bypass air is 25% of the total air.

3.8 Energy balance

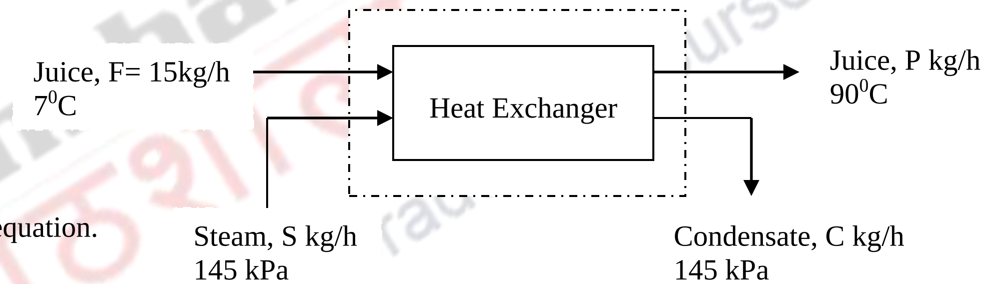
Heat transfer in food processing is a vital area where the energy is transferred from the heating medium to the food product. So, an energy balance within a system would help us know the amount of heat penetrated to the food material, as well as the heat efficiency of a system. A design engineer would get information on heat transferred based on which he/she select the heating medium, design the thickness of the exchanger wall and so on. In the illustration, Q_1 is the total heat of steam given to the juice, Q_2 the heat content of condensate, Q_3 the heat absorbed in juice, Q_4 the heat radiated through the wall of vessel and Q_5 the heat escaped through the vapour. Hence,

$Q_1 = Q_2 + Q_3 + Q_4 + Q_5$

Problem 4: Fruit juice is fed to a heat exchanges at the rate of 15 kg/h. Saturated steam at 145 kPa pressure is used to heat the juice from 7^0C to 90^0C. Assuming the heat capacity of juice 5kJ/kg^{0}C, find out the quantity of steam required for the operation.

Answer:

Step 1: Draw a flow diagram.



Step 2: Write the energy balance equation.

$FH_F + SH_S = PH_P + CH_C$ …..(1)

Since, quantity of steam entering the exchanger S kg/h is equal to the quantity of condensate formed C kg/h (i.e. S=C), $S\ (H_S - H_C) = S\lambda_s$, where λ_s is the latent heat of condensation.

The enthalpies of saturated steam and water at 145 kPa can be found in steam table.

Equation (1) can be rewritten as, $Fc_F(T_i - T_o) + S\lambda_s = 0$ (Since F=P)

Or, $15\frac{kg}{h} \times 5\frac{kJ}{kg°C} \times (90 - 7) + S \times 2229 = 0$

Or, $S = \frac{6625}{2229} = -2.97$

The negative sign indicates the heat is given from the steam to juice.

Hence, the amount of steam required is 2.97 kg/h for raising the temperature of 15 kg/h fruit juice from 7 ^{0}C to 90^0C.

3.9 Summary

Material and energy balance is the heart of process design. The material and energy balance is worked out quantitatively knowing the material and energy entering the system. The nature of process decides the new material generation or loss. A chemical process in a system is always associated with some new component formation. The principle of mass and energy balance is the basis of material and energy balance. The mass/energy entering the system plus mass/energy generated and accumulated equals the mass/energy out plus mass/energy lost. The batch and continuous process is defined based on the material flow. A basis is decided in material/energy balance for quantifying an unknown variable. A tie material is one which does not change during the process. The mass and energy flow in a continuous process quantified with respect to time, i.e. the rate of flow. The overall mass balance and concerned component/constituent balance is carried out in any food processing problems.

References:

1. *Introduction to food process engineering*, P.G. Smith, Springer, 2nd edn., 2010.
2. *Solving problems in food engineering*, Stavros Yanniotis, Springer, 1st edn., 2007.
3. *Fundamentals of food process engineering*, Romeo T. Toledo, Springer, 3rd edn., 2007.