PRINCIPLES OF MOMENTUM, MASS AND ENERGY BALANCES

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Contents

Summary

Balance of the entity producing accumulation is, particularly, a basic source of quantitative models of phenomena or processes. The concept of balance of momentum, mass, and energy defined in the chapter is used for elaboration of the algebraic or differential equation which describes processes at the macroscopic or microscopic levels of observation. The procedure of macroscopic balancing for continuous and batch processes is presented. Differential balance equations are formulated for momentum, mass, and energy through the contribution of local rates of transport expressed by principal Newton's, Fick's and Fourier's laws. For description of more complex systems in which strong turbulence of the fluid flow and/or vessel geometry are involved and characterization of the product property is necessary, the population balances are required. Concepts of the age distribution function and the intensity function are introduced and incorporated into the general population balance simultaneously with function of birth and death of balanced entity. Finally, the general microscopic population balance in the geometric space is formulated.

1. Introduction

Balance of an extensive entity is the reference state for comparison of any effects and achievements in which the entity is involved. Balance, as a tool, has been commonly used in many fields of human activity, systematically since the time of Ancient Greeks.

Balance of the entity producing accumulation, in the system under consideration, is (particularly) a basic source of quantitative models of phenomena or process for scientists and engineers.

Depending on the purpose of the balance, different scales of observations are used. Physicists direct their activity toward explanation of concepts by possibly small number of more elementary concepts reducing description down to molecular or atomic scale. For engineers such concepts are too elementary. They would like to build models up into more elaborate concepts. Both, physicists and engineers, perform the same type of analysis. Base on collected information they develop rules at chosen scale of observation.

The basic principle used in modeling of chemical engineering process is a concept of balance of momentum, mass and energy, which can be expressed in a general form as:

$$A = I + G - O - C \quad (1)$$

where

A : **Accumulation** builtup within system
I : **Input** entering through system surface
G : **Generation** produced in system volume
O **: Output** leaving through system boundary
C **: Consumption** used in system volume

The form of the expression depends on the level of description of the process phenomenon. Chemical engineers use in their activity macroscopic and microscopic mathematical models, resulting from the balance principle. Both types of models are very useful for particular purpose of application.

2. Macroscopic Balances

Chemical engineers do a mass balance to account for what happens to each of the compounds used in a chemical process. For such a purpose, the general principle of balancing is reduced to the bookkeeping procedure. Mathematical formula derived from Eq. (1) has a form of an algebraic equation or first order differential equation, depending on the process classification.

2.1. Process Classification and Types of Balances

Base on how the process takes place in time, *the steady-state processes* and *unsteady-state processes* are distinguished.

For the first type of processes all variables have the same values at any instant of the time. For the unsteady-state processes variables have different values at any time of process running. Base on how the process was built to operate, a *continuous* and *batch* processes are distinguished.

A ***continuous process*** is a process that has the feed streams and product streams moving chemicals into and out of the process all the time. At every instant the process is fed and product is produced.

A ***batch process*** is a process where the feed streams are fed to the process to get it started. The process is fed and products result only at specific times.

Differential balance is taken at a specific instant in time and is generally applied to a continuous process. It is applied to steady-state continuous processes. Each term in a differential balance represents a process stream and the mass flow rate of chemicals in that stream.

Integral balance is taken at two specific instants in time. It is applied to batch processes.

2.2. Mass Balances

A mass balance can be written using the total mass in each process stream (total balance) and/or for each component involved in the process. Mass and concentrations are the variables used in the procedure of balancing.

Procedure for material balances

This is only a guideline, not a rigid set of rules. An engineer must be creative and remain flexible.

1. Analyze and understand the problem.
2. Draw process flow chart, including unknown variables.
3. Choose basis for calculation.
4. Label unknown stream variables.
5. Do problem bookkeeping.

1. The major question arises: does the problem have a solution? i.e. determining if the number of unknowns on the flow sheet is the same as the number of available equations, which relate these unknowns:

    a. What equations can be written?

        - Material balances,
        - Process specifications; or relations between streams,
        - Physical properties and laws,
        - Physical constrains,

- Chemical properties and laws; stoichiometric proportion, reaction equilibrium, selectivity, fractional conversion, excess reactants, selectivity.

b. Does number of unknowns is equal number of equations?

If yes – unique solution is available
If no – more unknowns than equations $\rightarrow$ multiple solutions $\rightarrow$ check to see that all possible equations have been identified
If no – more equations than unknowns $\rightarrow$ check to see that all equations are independent.

2. Convert all terms to either molar or mass basis with the same units (mass, mass fraction, mass flow rate).
3. Convert process specifications and other information into equations in terms of flow sheet variable.
4. Write all independent material balances.
5. Solve equations.
6. Write results on flow sheet in desired form.

2.3. Energy Balances

In addition to analyzing the transfer of mass, chemical engineers are also concerned with the ***transfer of energy***. Mass transfer problems are typically coupled with energy transfer. General property of energy balance is the same as mass balance.

The first law of thermodynamics is a basis for energy balance, and it states that energy is neither created nor destroyed. Energy can only be converted between forms.

Energy can be input or output from a system by:

- Mass transfer (mass carries energy),
- Its heat Q; energy flow in response to ΔT (temperature difference),
- Its work W; energy flow in response to any driving force besides ΔT, e.g. Force, torque, voltage difference.

System's mass accumulates energy as kinetic energy E_{k}, potential energy E_{p}, internal energy *U*.

The general energy balance can be expressed as:

$$\begin{aligned}
&\textit{Accumulation of } E_{\mathrm{k}},\ E_{\mathrm{p}}, U \textit{ within the system}\\
&= E_{\mathrm{k}},\ E_{\mathrm{p}}, U \textit{ entering the system by mass transfer}\\
&-E_{\mathrm{k}},\ E_{\mathrm{p}}, U \textit{ leaving the system by mass transfer}\\
&+Q, W \textit{ entering system areas boundary}\\
&-Q, W \textit{ leaving system areas boundary} \qquad (2)
\end{aligned}$$

The procedure of macroscopic energy balance is the same as the above indicated procedure of mass balance which is always prior to energy balance.

The macroscopic balances of momentum in chemical engineering systems are realized through energy balances or as the results of integration of the microscopic momentum balances.

3. Microscopic Balances

The general principle of balancing can be applied for smaller scale of description than macroscopic, but larger than molecular one. It is ***microscopic scale***, which involves a phenomenological approach for system analysis. For such a description we assume, that system is represented by a continuum. Differential balance equations are formulated for momentum, mass energy as results of application of the preservation law. The distinguishing between balances of mentioned entities is given through the contribution of local rates of transport expressed by principal Newton's, Fick's and Fourier's laws for momentum, mass and energy balances, respectively.

Because the idea of continuum is a basis for derivation of balance equations, in the next section we will focus our attention on the properties of this concept and we will derive the general balance equation for continuum.

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Biographical Sketch

Leon Gradon was born in Szczekociny, Poland. He obtained his Master of Science in Chemical Engineering (1969) at the Faculty of Chemistry, Warsaw University of Technology and another Master of Science in Mathematics (1975) at the Faculty of Mathematics and Mechanics, University of Warsaw, Poland. In 1976 he obtained his Ph.D. in Chemical Engineering within Heat and Mass Transfer area from the Warsaw University of Technology, Poland. Dr. Leon Gradon has been full professor since 1990 at the Faculty of Chemical and Process Engineering, Warsaw University of Technology. He was dean of the Faculty in period 1999-2005. Dr. Leon Gradon's work focus on the transport phenomena in a human respiratory system, drug delivery via inhalation, controlled drug delivery, aerosol mechanics, separation processes, particularly depth filtration and membrane technology. He is an author or co-author of 15 monographs and chapters in monographs and 6 academic textbooks, as well as over 160 papers published in per-reviewed international journals and over 180 presentations of international conferences published in transactions or proceedings of conferences. He is also author of 63 patents and many technological applications of his innovation. He worked as a visiting professor at Universities in USA, Europe and Japan. Dr. Gradon is a member of Editorial Boards for four international journals. His work was distinguished with high ranks scientific awards.