Units of Chemical Engineering Operations

Subbarao Duvvuri *and Hilmi Mukhtar,*
Department of Chemical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Tronoh, 31750, Malaysia.

Abstract

Research creates rationale to interconnect existing bits of information which can help effective teaching while opening up new challenges for creative development. Research over the last several decades has expanded the knowledge base exponentially though it has not percolated into the curricula.

Major thrust of chemical engineering education is to teach design and development of process equipment for performing unit operations and reactions. Process equipment are essentially multiphase contactors (and separators) with momentum, heat and mass transfer with or with out reactions between the different phases. Understanding multiphase flow through wide variety of process equipment is needed for rational design. It is interesting to note that all the chemical engineering operations and reactions are carried out in just four types of "units". A course is proposed to organize the vast body of knowledge in terms of "units" of chemical engineering operations.

1 Introduction

Processing of the raw materials to new materials needed by society is the story of human civilization. First step that triggered the story could be controlled combustion of wood / biomass to harness thermal energy. Creativity of mankind has developed many materials of need such as food, clothing, habitat, security/defense, cleanliness and health care, pharmaceuticals, entertainment etc – the list is ever expanding. These developments triggered developments in the fields of transport, communications, security, defense etc and the feed back from these fields has prompted development of more and more new materials.

Chemistry of the materials and their transformations is the basis of development of chemical technology to produce materials needed by society in large quantities. Chemical engineering translates the chemistry into an economically viable chemical technology

Chemical Engineering

Chemistry ⟶ **Chemical Technology**

As newer materials get discovered to satisfy future needs, chemical engineering has to invent, innovate, develop and design process equipment to make the new technologies possible. It is necessary to bring the essence of ever expanding volume of knowledge on the design and development of process equipment in a compact rational format to the next generation to prepare them for future challenges.

2 Unit Operations, Reactions and Transport Phenomena

About a hundred years back, educators recognized the need for engineers who are capable of understanding, operating and developing the chemical industry for processing raw materials to useful products. The task was immense as there were very many chemical industries producing too many products. There were many ways of organizing the material. Arthur D. Little in 1915 observed: “Any chemical process on what ever scale conducted may be resolved into a coordinated series of what may be termed "unit actions" as pulverizing, mixing, heating, drying, roasting, absorbing, condensing, lixiviating, precipitating, crystallizing, filtering, dissolving, electrolyzing, evaporating and so on. The number of these basic unit operations is not large and relatively few of them are involved in any particular process”. Since then, Chemical Engineering education evolved through the concept of unit operations. Concepts of thermodynamic equilibrium and rate processes have shaped the framework for the equipment design of unit operations.

It is interesting to note that some how reactions were not considered as a unit operation though Little (1915) did mention roasting and precipitation also as unit actions. Groggins (1930) organized chemical reactions in terms of “unit processes” such as oxidation, nitration chlorination, sulfonation etc. based on the principles of chemistry. Concept of ideal reactors, such as stirred tank and plug flow reactors, shaped the development of Reactor Engineering. In most applications, reactants are all not in a single phase and challenges of interphase and intraphase mixing of reacting species dominated the developments in reactor engineering. Unit operations, unit processes and reactors add upto quite a number!

In 1960s, methodology of transport phenomena has brought out the physics of the rate processes at micro level in terms of fluid mechanics, heat transfer and mass transfer. Theories of Heat and Mass Transfer and Analogies have brought out the importance of fluid mechanics in understanding the rate processes. Translation of the knowledge of processes at micro level to understand the performance of process equipment at macro level is a formidable challenge as flow through process equipment is multiphase in nature.

One of the major objectives of Chemical Engineering Education is to equip young aspirants with the capability to choose/develop, design, operate, simulate and optimize process equipment with multiphase flow such as reactors, separators, heat exchangers and interconnecting pipes for various technologies. Hence focus should be on the science of process equipment than on the science of the process. An attempt in this direction is presented.

3 A fresh look: UNITS of Chemical Engineering Operations

A typical chemical industry can be expressed in terms of a “Flow Sheet” depicting the flow of materials through various process equipments, such as reactors, separators, heat exchangers etc. The reactors transform raw materials to products and as the reactor conversions are rarely total, the reactants in the out stream are separated from the products for recycle.

Most of the raw materials available in the nature except for air, natural gas, water and petroleum are in solid phase. In reactors, the raw materials in different phases need to be brought together at molecular level for the reactions to take place. After the reactions are complete, separation of the molecules which are in mixed state is not easy. The strategy of separating pure molecules from a mixture is to see that they partition preferentially from one phase to a different phase by diffusion. Later the molecules are recovered from the solvent by phase change techniques such as evaporation and crystallization. Separation of phases is comparatively simpler than separating the molecules directly. For these reasons, more than one phase need to flow through the separators.

In the separators, different phases are brought into intimate contact for achieving heat and mass transfer followed by separation of the phases; in the reactors different phases are brought into intimate contact for achieving heat and mass transfer with chemical reactions followed by separation of the phases. Application of external force is necessary to bring the different phases together as well as to separate them. Gravitational force is utilized with advantage for dispersion of one phase into another as well as for separation of the phases. Thus, both reactors and separators are essentially multiphase contactors (followed by multiphase physical separation) and the same “units” can be used for carrying out reactions or separations. It is interesting to note that, from process equipment point of view, all the chemical engineering operations are performed in just four basic “units” namely
Pipes
Packed Beds
Suspended Beds
Stirred Tanks.

To develop coherent focus in teaching process equipment design, it is proposed that multiphase flow through "units" of process equipment be organized as a new course. This type of course can rationalize many thumb rules used in the process equipment design. An attempt in this direction is presented in this paper.

4 Multiphase Flow in the UNITS

Single phase fluid mechanics provides information on three essential parameters viz.

- Pumping power required for the fluid to flow through the process equipment
- Heat and mass transfer coefficients across interfaces and
- Residence time (distribution) of molecules in the process equipment.

In the last several decades, fluid mechanics of multiphase contact in various process equipments have been extensively studied. Parameters such as

- pressure drop across the equipment,
- phase holdups,
- size of dispersions,
- area of contact,
- volumetric heat and mass transfer coefficients and
- residence time distributions of each phase

have been measured. In view of the dispersion of phases and complexity of flows, difficulties in the assumption and definition of continuum properties, internal circulatory flows, turbulence and equipment geometries, the traditional approach based on micro balances through Navier Stokes equations are not realistic. In recent times CFD is opening up new vistas in analyzing multiphase flow through process equipment though computational times are prohibitive.

Out of the haze, methodologies to use these information together for modeling performance of various process equipment are emerging. One dimensional meso scale conceptual approach is still of great educational value. The concepts of friction factor/drag coefficient/dispersion number are useful in describing the multi phase fluid mechanics to estimate phase hold ups, size of dispersions, area of contact and residence time distributions. Penetration theory can be adopted to estimate heat and mass transfer coefficients.

5 Course content

Contents of a course with detailed profile of each chapter is given. Synthesis of the concepts for one dimensional steady state performance modeling of reactors and separators is encouraged.

Contents

Ch1 Introduction

Chemistry, Chemical Technology, Flow Sheets, Unit Operations, Reactors, Transport Phenomena,
Basic Units in which Separations and Reactions can take place,
Multiphase Fluid Mechanics, issues of importance
Size distribution of dispersion, Phase holdups, interfacial area of contact,
heat and mass transfer coefficients,
degree of mixing in each phase, Tanks in series models,
Performance modeling

Part I Pipes

Ch2 Single Phase Flow

Fluid Mechanics, Bernoulli Equation,
Laminar flow,Shell balances, Navier Stokes Equation, Turbulence, friction factors
Power for pumping the fluid,
Analogies and heat & mass transfer coefficients, Mixing, RTD, Tanks In series model, Axial dispersion model, Performance model for reactors

Ch3 Two Phase flow

Pseudo homogeneous Model, Viscosity of complex mixtures, non Newtonian fluids
Separated Flow Model, Lokhart-Martinelli correlation
Drift Flux Model, Drag and buoyancy force on a dispersed phase, drag coefficient for a particle, drop and bubble, terminal velocity and slip velocity. effect of presence of other particles on slip velocity
Mechanistic Models

Part II Packed Beds

Ch4 Single Phase Flow

Ergun's Equation, tortuosity factor
Drag coefficient on a particle in a packed bed of particles

Effect of particle size and bed voidage on pressure drop across the bed
Interphase heat and mass transfer coefficients
RTD of fluid

Ch5 Evolution of Packings
- 3D packings
  - Spherical, cylindrical particles, Trilobes
  - Bed Voidage
  - Surface to volume mean particle size
  - Surface area of particles per bed volume
- 2D packings
  - Raschig rings,
  - bed voidage, importance of wall thickness,
  - Ceramic, plastic and metal packings
  - surface to volume mean particle size, surface area of particles per bed volume
  - Berl Saddles, Pall Rings, IMTP packing, intellox saddles etc
  - Structured packing made of sheets
- 1D packings
  - Springs and helical coils
  - Rods and holes, monolith reactors

Ch6 Two Phase Flow through packed Beds
- Absorbers and Trickle Bed Reactors
  - Liquid distributors and channeling
  - Liquid holdup, flooding
  - Area of particles, gas-liquid interfacial area
  - Wetting efficiency
  - Two phase flow pressure drop
  - Volumetric mass transfer coefficients
  - RTD of liquid phase and gas phase

Part III Suspended Beds

Ch7 Bubble and Drop Formation
- From single orifice or nozzle
- Models of Davidson and coworkers
- Model of Kumar and Kuloor
- Bubble and drop formation from multiorifice distributors, design of distributors

Ch8 Bubble Columns,
- Homogeneous and heterogeneous/churn turbulent flow regime

Bubble size distribution, Liquid circulation in bubble columns, bubble velocity, gas holdup, gas-liquid interfacial area, volumetric mass transfer coefficient, liquid backmixing, gas backmixing

Packed bubble columns

Slurry Bubble Columns

Ch9 Fluidization

- Minimum Fluidization velocity
- Particulate fluidization, Richardson- Zaki correlation, slip velocity
- Aggregative Fluidization
- Geldart Particle Classification

Ch10 Bubbling Fluidized Beds

- Two Phase theory of fluidization, Bubbles,
- Size of bubbles at the Grid, Grid Design
- Bubble rise velocity, coalescence and growth along the axial direction
- Bubble holdup
- Bubble to Dense phase mass transfer coefficients
- Fast and slow bubbles, Cloud formation and bubble to emulsion phase mass transfer coefficients
- Bubble Wakes and particle turnover in the bed
- Emulsion phase gas velocity
- Bubble assemblage Model for catalytic reactors, non catalytic reactions, physical operations
- Cause of low conversions
- Entrainment, TDH, Elutriation

Ch11 Turbulent, Fast Fluidization and Dilute Transport

- Risers, Elutriation and circulating fluidized beds
- Bubble less fluidization, slip velocities, particle aggregation in the form of clusters,
- Cluster models for axial voidage variation, wall heat transfer and gas to particle mass transfer coefficients
- Particle and gas back mixing
- Reactor Models

Downers,and Emerging technologies

Part IV Stirred Tanks

Ch12 Mixing of liquids

- Options of Equipment, tanks, impellers, baffles

Geometric, kinetic and dynamic similarity
Power number as a function of Reynolds Number
Liquid circulation and mixing times
Jacket/coil wall heat transfer coefficients

Mixing of two Phases
Gas-Liquid Mixing, Gas flow number, flooding, size of bubbles, bubble holdup, volumetric mass transfer coefficients
Liquid-Liquid mixing, droplet size distribution, liquid holdup, volumetric mass transfer coefficients
Liquid-solid mixing, critical stirrer speed, mass transfer coefficients

Mixing of Three Phases
Suspension of particles and simultaneous dispersion of gas, transfer processes

6 Concluding Remarks

The approach being developed in this elective course tries to include the results of research being pursued in the chemical engineering field for the last several decades. An attempt is made to present the various factors together for synthesizing performance models to explain the behavior of reactors and separators. It is expected that the subject matter evolves over next decade. There are many other topics which are of great importance and constraint of time dictates the extent of coverage. However, once the general approach to multiphase flow is delineated, the students will be able to figure out more advanced topics.

Acknowledgements

The authors wish to record their deep sense of appreciation for the financial support by Universiti Teknologi PETRONAS.

References

1. Little A.D., Report on the corporation of M.I.T. as quoted in Silver anniversary Volume, A.I.Ch.E. ,1933, p.7
2. “Unit Operations of Chemical Engineering”, McCabe W.L., Smith J.C. and Harriot. P., 5th ed., McGraw Hill Chemical Engineering series, 1993
3. “Principles of Unit Operations”, Foust. A.S., Wenzel. L.A., Clump. C.W., Maus. L. and Andersen. L.B. 2nd ed. , John Wiley & Sons, 1990.
4. “Unit Operations”, Brown. G.G., New York, Wiley,1950

5. "Unit Processes in Organic Synthesis", P.H.Groggins, 5th ed., McGraw Hill, 1984.
6. "Transport Phenomena", Bird. R.B., Stewart W.E. and Lightfoot. E.N. John Wiley & Sons, 1960
7. "Chemical Reaction Engineering", Levenspiel. O., John Wiley & Sons, 1999
8. "One Dimensional Two Phase Flow", Wallis. G.B.,McGraw – Hill Inc. NY, 1969
9. "Fluidization Engineering", Kunii. D. and Levenspiel. O., Butterworth-Heinemann, Boston, 1991