Work in Progress: The "Cilindro Rotador" as a Pedagogical Tool for Complex Engineering Systems

A. Nastasia Allred, J. Robby Sanders, and Pedro E. Arce
Tennessee Technological University Chemical Engineering Department

Abstract

The engineering description of multiphase systems (such as organs within the human body or packed-bed reactors in the petrochemical industry) represents a challenging pedagogical task for the instructor and a steep learning curve for the students. Both students and instructors face a multitude of domains with different scales and with interconnecting interfaces that need an intimate understanding before physical concepts can be put into mathematical models. Such systems usually involve various transport processes (diffusion, convection and/or migration) with either homogeneous or heterogeneous reactions; they reflect different types of geometries that anchor irregular pore shapes, and they are comprised of different types of materials with various properties (e.g., diffusivity, viscosity, thermal conductivity, etc.).

In reaching a successful description, students must bring together "disconnected" concepts from a variety of courses in a coherent manner; they need to assess the assumptions in each phase that match the relevant scale and, therefore, connect them with microscopic or macroscopic models. Their skill set should allow them to identify suitable boundary conditions that capture the interfacial physics. In all, the analysis is a daunting learning task for the students. Within the framework of the Renaissance Foundry Model[1], this study is exploring the use of well-characterized physical or laboratory devices (i.e., a diffusion cell, a simplified reactor, etc.) as pedagogical tools to help the students (and the instructor) acquire the skill set to describe complex systems. In particular, we will present elements and pedagogical functions of the "Cilindro Rotador" to integrate concepts learned in different courses, train the students in the art of simplifying assumptions, identifying suitable scales, and assessing proper conditions for the interfacial boundaries.

Keywords

multiphase, interface, lab model, collaborative learning, Renaissance Engineering

Introduction and Motivation

Chemical engineering is home to many problems in which the student is faced with the task of analyzing multi-phase systems. Heterogeneous catalyst reactors, diffusion cells, sedimentation, and wound healing models are just a few of the numerous examples. Learning how to bring together concepts from various courses is one of the biggest feats students have to overcome in order to analyze these problems. Another task the students have issues with is understanding how to connect domains in a multiphase system through the properties of interfaces. Lastly, understanding multiple scales of a system is a concept that is hard for students to grasp. Using the "Cilindro Rotador" model, we have come up with a way for students to tackle these issues with multiphase systems by applying the concepts found in this one example.

Pedagogical Framework

Active and collaborative learning bring a number of advantages for student learning since, for example, a multi-dimensional learning environment (incorporating different levels of communication, opportunities to get involved in hands-on activities, obtaining different points of view, etc.) can be developed to expose students to a variety of pedagogical pathways.[2] In an effort to organize different aspects of the active and collaborative learning approaches, the Renaissance Foundry Model[1] uses two key learning paradigms (please see Figure 1 of reference one), i.e. the Knowledge Acquisition Paradigm (KAP) and the Knowledge Transfer Paradigm (KTP) that are synergistically connected by the Resources (didactic material, facilitator of learning, lab elements of the model, etc.). From a course design point of view, the Renaissance Foundry is a useful platform that helps both the student and the facilitator of learning to identify a challenge and provide guidelines to find a suitable prototype of innovative technology as a potential solution to the challenge.[1] In their path to achieving the prototype of innovative technology, the students (with the coaching of the facilitator of learning) will iterate as many times as needed between the KAP and KTP to build on previous understanding of the challenge and in order to move the ideas to the development of the prototype of innovative technology.[3] It is here that the availability of practical tools or experimental lab models (in the Resources of the Foundry) are helpful to assist students in gaining knowledge. Extensive discussion on the implementation of the learning protocols suggested by the Foundry Model can be found in reference one. Here we have provided a short overview to frame the potential uses of the "Cilindro Rotador" and its implementation.

For numerous engineering systems including, for example, heterogeneous reactors in the petrochemical industry, decontamination of water for recycling purposes, pharmaceutical processes in biotechnology, and biomedical applications, understanding of the role of the two (or more) phases is required. Moreover, in order to scale up the process, *interfacial fluxes*, as key factors in determining the mass transfer, must be properly integrated with the up-scaling models. For an expert learner (i.e., the professional design engineer), these tasks are usually considered routine. However, for the novice, i.e. the student, these represent most likely very steep challenges, and learning would be enhanced via assistance regarding a proper handling and assimilation (all part of the KAP of the Foundry model). Therefore, laboratory or physical models that capture the essential aspects of the engineering system at hand are being explored in this contribution as potential useful pedagogical tools to be housed in the Resources element of the Foundry.[1] Lab models, cellular works, and small experimental devices, are abundant in the literature, and researchers have used them for kinetics and mass transfer studies. Among these, lab models such as the Spinning Catalyst Basket Reactor[4], the Single Pellet Reactor[5], the Wicke-Kallenbach diffusion cell[6], and even wound healing models[7] are "precursors" of the "Cilindro Rotador" model. The novelty here is to use them as a pedagogical tool that is potentially beneficial for helping students in gaining knowledge about multiphase systems such as those mentioned above. In the sections below, we will describe the "Cilindro Rotador"; we will present key equations, and we will suggest a potential use as part of the Foundry Model KAP and KTP.

The "Cilindro Rotador" Model: Description and Role in the KAP

The "Cilindro Rotador" is a two-phase laboratory reactor in which there is a "Fluid" phase or fluid? domain (see Figure 1, label 1) and a "Solid" phase or catalytic pellet domain, (see Figure 1, label 2). The spherical pellet domain is housed in a metallic meshed cylinder with the ability to rotate at a fixed speed, **Ω**, (see Figure 1, label 3) in order to promote mixing in the Fluid domain. The Pellet Domain (PD) involves mass transport via diffusion and reaction, while the Fluid Domain (FD) involves convection and has, usually, no "bulk" reaction occurring since we assume a catalytic system. In order to analyze this physical model, we observe each domain separately and relate them using their interfacial characteristics and fluxes. Due to the presence of two domains, there will be two variables for the concentration of species "A" in the system: C_A^P for the PD and C_A^f for the FD, respectively.

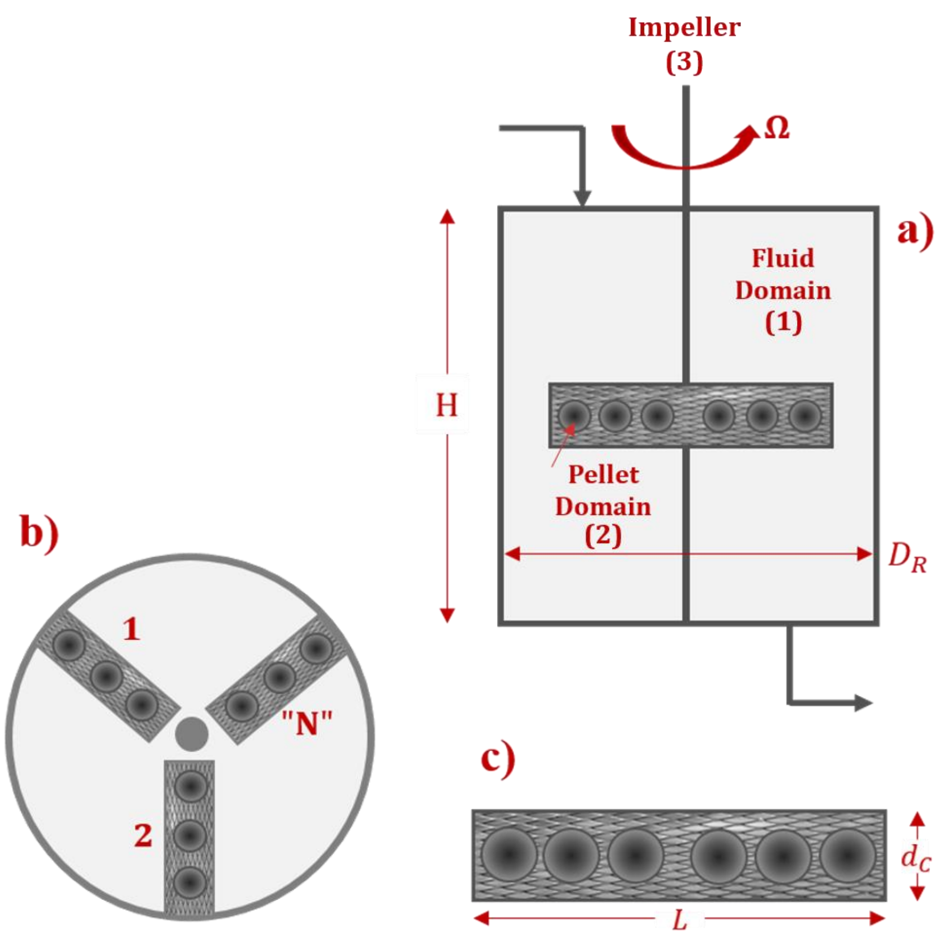

Figure 1: "Cilindro Rotador" Sketch: A) The side view of the tank B) The top view showing "N" cylinders on the rotating axis C) The mesh of the cylinder holding the catalytic pellets

For the PD we make the following assumptions: diffusion in the r direction (in fact, the pellet is under the long channel approximation, $d_c/L<<1$), steady state, 1st order "bulk" reaction within the pellet leading to an "effective" view of the phase, and assume the system is isothermal. Furthermore, the FD is assumed steady state, convection driven only, with no bulk reaction, and once again, we are assuming the system is isothermal. In the case of a non-isothermal system, an energy balance would be required on each domain. The summary of equations associated with the two domains of the "Cilindro Rotador" is presented in Table 1.[8] Clearly, the scale used for the PD is the microscopic or the "local" scale since in this domain we have the chemical reaction while for the FD the macroscale or global scale is more appropriate (see below).

The model described in Table 1 is clearly a rich pedagogical tool to help instructors to assist students in identifying domains that interact via an interface and with different levels of potential suitable assumptions. The different domains of the systems do not need to show the same scale of operation either. For example, the PD is more suitable for a *microscopic scale* since the reaction is taking place there. The FD is more realistic in a *macroscopic scale* since input and output concentrations are needed for the reactor conversion. The differential model/s associated with the PD requires the formulation of proper boundary conditions to handle the interfacial mass transfer with the integration of the associated driving forces. A good understanding of the different physical aspects and their roles in determining the proper mathematical description is an important aspect in the KAP for the students. Furthermore, a good foundation in these concepts will be a catalysis for the KTP when students are faced with a real engineering system such as those identified above.

Table 1: Summary of Equations for the "Cilindro Rotador" Model

	Pellet	Fluid
Species Mass Conservation Equation (SCE)	$\frac{\partial C_A^p}{\partial t} = \vec{\nabla} \cdot \overrightarrow{N_A^p} + R_A^p\left(C_A^p, T\right)$	$\frac{\partial C_A^f}{\partial t} = \vec{\nabla} \cdot \overrightarrow{N_A^f} + R_A^f\left(C_A^f, T\right)$
Assumptions	Bulk reaction (1st order) Diffusion in r Steady State Isothermal	Convection Well-mixed No reaction Steady State Isothermal
Simplified SCE	$\frac{D}{r^2}\frac{d}{dr}\left(r^2\frac{dC_A^p}{dr}\right) + kC_A^p = 0$	$\vec{\nabla} \cdot \overrightarrow{N_A^f} = 0$
Boundary Conditions	$-D\left.\frac{dC_A^p}{dr}\right\rvert_{r=R_p} = k_g[C_A^p\rvert_{r=R_p} - C_A^f]$ $\left.\frac{dC_A^p}{dr}\right\rvert_{r=0} = 0$	Student must assess the role of the boundary conditions in the Up-Scaling process of the FD and how the two domains play a role in the "completion" of the scaling.
Solution	$C_A^p(r) = AY_1(r) + BY_2(r)$	
$C_{A_S}^p(r) = \frac{C_{A_R}^p(r)}{r}$	$C_A^p(r) = \frac{k_g\left[C_A^p\rvert_{r=R_p} - C_A^f\right]}{rD\sqrt{\frac{k}{D}}\sinh\left(\sqrt{\frac{k}{D}}R_p\right)}\cosh\left(\sqrt{\frac{k}{D}}x\right)$	The solution from the PD is crucial to complete the Up-scaling of the FD as it is observed in the equation for FD, below.
Up-scaled Equation		$Q\left[\langle C_A^f\rangle - \langle C_A^o\rangle\right] = Nk_g[C_A^p\rvert_{r=R_p} - \langle C_A^f\rangle]$

The Instructional Role of the Cilindro Rotador in the KTP: Brief Overview

The role of the "Cilindro Rotador" model within the Foundry Model (beyond the KAP) is to assist the students in the KTP when they are faced with a real system. As mentioned above, there are numerous problems in the engineering application fields where the CR is an ideal tool to learn about the system modeling and its behaviors. Few illustrative examples include: a- Setting the model equations for a (tubular) style packed-bed-reactor; b- Mass transfer and chemical reactions processes in a honeycomb catalytic converter; c- Formulation of the convective-diffusion process in wound healing; and d- Stenosis development in human arteries. Several pedagogical strategies will be illustrated in the presentation of the meeting to show how students can accurately analyze the multiple domains and scales and to be able to apply them to these real-world examples. Guidelines for these strategies are available in Arce (2001)[9] and in Tijaro-Rojas et al. (2016)[10].

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A. Nastasia Allred

Nastasia Allred is currently a second-year PhD student working under Dr. Pedro E. Arce in the chemical engineering department at Tennessee Technological University. Nastasia received her Bachelors of Science degree in chemical engineering from Tennessee Technological University in the spring of 2015. Her research focus is modeling the electrokinetic aspect of the kidney's function via a macro-transport theory approach. Components of the research include mathematically modeling the fluid and mass transport phenomena present in the kidney's filtration, and in the future, using a lab-on-the-chip device for modeling an artificial nephron.

J. Robby Sanders

Dr. Robby Sanders is currently an Assistant Professor at Tennessee Technological University in the chemical engineering department. He obtained his Bachelors of Science in Mechanical Engineering from Tennessee Technological University in 1995, and he obtained his Master's degree and his PhD in Biomedical Engineering from Vanderbilt University in 1998 and 2001, respectively. His research interests include biomolecular medicine, including bioassay development, drug delivery and barriers to gene therapy, wound healing, engineering education, and micro-fluidics/lab-on-a-chip applications for clinical diagnostics. Recent courses taught by Dr. Sanders include Transport in Biochemical and Biological Processes, Clinical Immersion at Disciplinary Interfaces, Hemodynamics & Micro-rheology of Blood Suspensions and Other Bio-fluids, and Transport Science I: Heat Transfer.

Pedro E. Arce

Dr. Pedro E. Arce is currently a University Distinguished Faculty Fellow-Professor and the Department Chair of the Chemical Engineering Department at Tennessee Technological University. He obtained his Chemical Engineering Degree from the Universidad Nacional del Litoral (UNL), Santa Fe, Argentina, 1977 (minor in heterogeneous catalysis), and his Master's degree and PhD in Chemical Engineering from Purdue University in 1987 and 1990, respectively. His key areas of research included: A- *Nanostructured Materials* and B- *Environmental Catalysis* with applications in health care engineering, energy systems and advanced oxidation technologies. Dr. Arce has a life-interest in *Engineering Education* (collaborative-, creative- and innovation-driven learning; constructionist approaches and transformational approaches to academic organizations). Classes recently taught by Dr. Arce include Physics of Transport-I, Electrokinetic Hydrodynamics, Advanced Kinetics, Transport Science II: Fluid Dynamics, and Team-based Learning (College of Education, TTU).