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Guiding Students in Determining Fluid Velocity Profiles: A Practitioner Research Study Exploring the Role of Kinematics of Fluid Flow in a Foundry-Guided Lesson

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Abstract

In this contribution we expand on the critical role played by kinematic of flow in conjunction with the principle of the conversation of total mass in guiding students towards the observation skills, geometry, flow dimensions and total mass conservation in predicting the type of velocity functions as a prerequisite to the application of momentum conservation equations to determine the actual velocity profile. Adopting a practitioner-based approach, we leverage cycles of inquiry[1] that are guided by the six elements of the Renaissance Foundry Model[2] (herein the Foundry) to explore the role of kinematics of fluid flow as implemented in a undergraduate engineering curriculum. In particular, we identify the Challenge, review the fundamental concepts of the kinematics of the particle to formulate the Organization Tools, and identify related Resources to this challenge. Subsequently, Knowledge Acquisition will guide the understanding of important connections with the kinematic of flow, and then we will apply the Transfer of Knowledge to develop the fundamental aspects of the Prototype of Innovative Technology. This will be centered on a methodology useful to guide students in applying the concepts of kinematics of flows to obtain the fluid velocity *functionality.* The research will be illustrated with a case study relevant to the curriculum in chemical engineering in the context of ChE 3550, Fluid Mechanics, a core course in the chemical engineering curriculum.

Keywords

Kinematic of Flow, Conservation of Total Mass, Geometry, Fluid Flow, Foundry Model

Introduction and Motivation

In general, textbooks focus primarily on the application of the conservation of momentum that begin directly with the calculation of the velocity profile and then jump into a discussion of important constraints that the velocity of the fluids must satisfy. In a recent publication by Tijaro Rojas et. al[3], a methodology termed Systematic and Integrative Sequential Approach (SISA) introduced the systematic incorporation of the constraints (as a building block of knowledge) for the students. However, the independent and important role of the kinematic of fluid flow in guiding students to acquire knowledge and skills to determine the velocity profile was not highlighted in this methodology. In particular, the role of the kinematics of fluid flow coupled with the conservation of total mass on determining the functionality of the velocity profile deserves a more detailed analysis. In short, the understanding of this role by the students is critically important to ultimately, by using the dynamics aspects included in SISA, arrive at the proper velocity fluid profiles.

The identification of the functionality of the velocity profile for a given flow of fluid is a complex task, from a pedagogical point view, and it poses a great challenge for students. In this contribution, we rely on the use of the Renaissance Foundry Model[2] (the Foundry) as an *overall guiding tool* for students to formulate a student-centered learning strategy that will integrate the use of kinematic of flow principles with the conversation principle of total mass to identity the proper function of the velocity profile. In particular, we are interested in the students being able to properly identify which independent variables (of space and time) are relevant for the velocity profile's scalar components. This strategy will guide the students, systematically, to analyze a given fluid flow situation inside a particular geometry to identify first the different velocity components and then, be able to identify suitable functionalities (of the independent variables) of such velocity components. To efficiently guide the students through this strategy, Figure 1 describes a "dual" scale approach that effectively couples the Foundry with the fundamentals of the kinematics of fluid flow. Furthermore, Table 1 describes a 10-point step strategy for the students (i.e., an "organization tool") for facilitating the application of both the Knowledge Acquisition Paradigm to learn more about the key principles related to the kinematics of flow and then the Knowledge Transfer Paradigm to develop the prototype of Innovative Technology (PIT).[2] Finally, Table 2 illustrates the application of the process described in Figure 1 with the results related to the fluid flow challenge sketched in Figure 2.

Context of the Approach: Role of the Renaissance Foundry Model

The Foundry[2] is a student-centered and innovation-driven learning platform that described how to guide students to identify a *Challenge* and apply a series of six elements to develop a *Prototype of Innovative Technology (PIT)*. The theory, pedagogical foundations, and the detailed description of the different elements of the Foundry are beyond the scope of this work and have been described in detail in the open literature.[2,5] Therefore, we present a brief review of how the Foundry works and to describe its role in guiding the student learning process as used in this contribution. The Foundry process of learning followed the six elements that are part of two main paradigms, i.e., the Knowledge Acquisition Paradigm (KAP) and the Knowledge Transfer Paradigm (KTP)[2]. The key coordinating element of the Foundry is the *"Resources"* that are common to both paradigms. Furthermore, the KAP features the *"Learning Cycles",* the *"Organizational Tools"* which follow immediately after the *"Challenge"* identification. The KTP is centrally built on the *"Linear Engineering Sequence, LES"* that is followed by the PIT as the outcome of the leaning platform (please see Figure 1 in Arce et al., 2015). These six elements are key to facilitate the student in identifying a learning challenge and assist in developing a PIT (please see example application sketched in Figure 2).

The Foundry is designed to work with student teams. These teams work in collaboration to identify the challenge associated with their project or tasks; the challenge could be either societal or technological and the students learn key aspects about the challenge and tools by using the KAP, and then they apply the KTP to work on addressing the challenge and developing or constructing a PIT. One key aspect of the Foundry is that this application is not a simple "linear" strategy from the challenges towards the PIT but, instead, student-teams are required to use an approach that involves the iterative application of the two paradigms: this mimics the action of the pistons of a two-cylinder engine. During this strategy, student-teams will identify a plan on how to conduct the process (Organization Tools), they will integrate needed Resources, apply the plan to acquire knowledge (Learning Cycles) and perform the transfer of this knowledge to the challenge (Linear

Engineering Sequence, LES) always towards the development of the PIT. In this particular contribution, students use the Foundry as the *overall*, or "macroscopic" level strategy in the learning and the finer details related to the application or subject matter (the modeling of the fluid velocity profile) are guided by the kinematics of fluid flow that works as the "microscopic" level of the application to the learning topic (please see Figure 1). More details about the learning process and how it works are presented in the sections below.

A Dual Level Learning Approach through a Practitioner's Lens

Research Framework

This work adopts a practitioner research methodology that reflects a praxis-based approach that identifies challenges in the classroom and leverages effective practices to enhance student learning.[1] Manfra and colleagues[1] indicate that, "Practitioner research is grounded in notions of reflective inquiry and experiential education…(and) reflection-in-action" (p. 6). Specifically, this work is inspired by practitioner reflections and observations of student challenges with the understanding of by kinematic of flow in conjunction with the principle of the conversation of total mass. Student involvement in finding a potential solution through praxis was pivotal to addressing this challenge. In the following, we feature the pedagogical approach applied to Kinematic of Flow; this is followed by a case study which illustrates student reflections on the overall strategy and insight on the ways in which the Foundry helped them to make connections to their learning.

Learning Context Overview

As part of this collaboration, it was identified that the learning process can be potentially driven by two levels of guiding tools. In Figure 1, we present an overview of the key levels of the processes integrated in this learning approach. The students guided by the Foundry follow an *overall strategy* to learn and apply concepts related to the modelling of fluid velocity profile; *the details* on how to apply the principles associated with the different aspects involved in the use of kinematics of fluid flow principles. [4] The end result is a dual level PIT: a)-a "new" model for the fluid velocity profile (microscopic level) and b)-a higher level of skills acquired by the student researcher or learner (overall or macroscopic level).

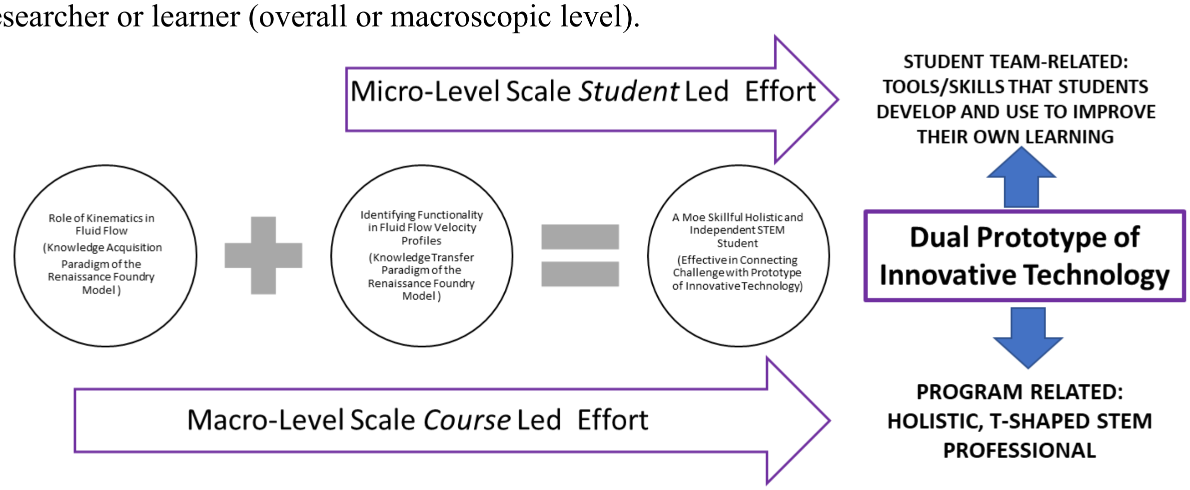

Figure 1: The Dual Learning Process Guided by the Foundry (Overall) couple with the Kinematics of Fluid Flow (Micro/Subject Related)

Inspiration based on the Kinematics of Flow Approach

Prior to the use of the SISA approach, students were left with a very complex challenge of identifying a velocity profile for fluid flow without a detailed and systematic process that guides the students in applying the different hydrodynamic concepts. The detailed understanding of the fluid velocity profile for viscous flow situations is an intricated process that without a guiding protocol becomes easily overwhelming for the students. These include scales, geometries associated with the different scales, shape of the pores or channels of the material, different transport processes present in the control domain where friction takes place, among other things. Students are guided to re-shape the different concepts of the challenge into the elements of the Foundry (see Figure 1). Table 1 describes a list of the potential steps associated to the kinematics of fluid flow and the conservation of total mass that can be effectively integrated into the Foundry elements (see Table 2). The student's training is guided by the KAP of the Foundry in the sense that students acquire useful knowledge on how to conceptualize the different concepts associated with the domain, flows, geometry, and scales. The students do not have to develop the PIT in this KAP process but rather recognize where the different elements of the Foundry play a role and how they work and can help to go through the learning process afterwards when the PIT needs to be developed via the application of the KTP (See example in Table 2).

Fluid Flow Velocity Profile- An Example of Application

After students have been exposed to the kinematics of fluid flow (see Table 1) and trained on how the Foundry works, they are asked to transfer the knowledge to the new application, i.e., the determination of the functionally of the particular case of fluid flow. For example, Figure 2 sketches a typical application of the hydrodynamic mixing of cement in a mixer truck. The first thing the students need to realize is the identification of *the new challenge*: The derivation of the microscopic or local functionally of the fluid velocity profile. As part of *the organization tools*, Table 1 lists 10 key steps that facilitate the key learning aspects needed for moving the challenge into the PIT. Table 2 lists the student key outcome of the application of the protocol of Table 1 by following the strategy of Figure 1. Resources need to be identified and the students need to connect the new challenge with textbooks, student personal notes, lab experiences, instructors, other students etc. The second part listed in Table 2, is centralized on the application of *LES* to transfer the knowledge acquired and develop the new PIT.

Current Work and Ongoing Strategy

This dual approach showed in Figure 1 has been applied to typical case studies of fluid flow similar to the one sketched in Figure 2 to train students in undergraduate research projects as well class special projects during a fluid mechanic focused course. The effort has produced posters or oral presentations either for the annual meeting of the student research presentations in our university or for class presentations. In general, and according to feedback provided by the students, the approach has been useful to guide the student in two important aspects: Acquiring skills and knowledge about modeling complex engineering fluid flow systems in typical hydrodynamic applications and, also, in introducing students to a new subject that usually is not part of the topics delivered in the courses of the curriculum.; i.e., applications of fluid flows in biomedical related areas.[4] A key set of observations by students includes:

Table 1: Key Sequential Steps in the Strategy towards Identifying Fluid Velocity Profiles based on Kinematics' Principles Applied in Hydrodynamics: The Pre-SISA Steps[1]		
Step	**Key Function**	**Student Learning Objectives**
1	Identify your Control Domain	Students should first study and carefully recognize the system they want to study and identify *a proper control domain* to present their study
2	Select the Most Appropriate Geometry	Recognizing the *appropriate geometry* of the control domain is a critically important step for the students to study the system.
3	Anchoring a Suitable Coordinate System	The anchoring of the *System of Coordinate in a point that captures the system symmetry* will be tremendously helpful for the students in the simplification of the model used to describe the hydrodynamics.
4	Characterizing the Type of Flow inside the Control Domain	This characterization may be inferred by studying the characteristics of the flow in the system and the direction/s this flow goes and it will allow students to make decisions, properly.
5	Proposing the Kinematics most Aligned with the Type of Flow of Step 4	Proposing the Kinematics of Flow is based on the characteristics of the flow in the control domain for the geometry selected. Students will be involved in the transfer of knowledge here.
6	Analyzing the Type of Fluids inside the Control Domain	Fluids are usually from a large range of possible behaviors: Liquid, gases, incompressible or not, Newtonian or not, etc. This information is critically important in the next steps of the analysis for the students to make decisions, accordingly.
7	Applying the *Incompressible Flow Condition* to the Kinematics of Step 5	Utilizing the characteristics of the fluid found in Step 6 *into the equation of continuity* provides additional information for the fluid velocity so that students can learn constraints of such profile.
8	Inferring Functionality for the Scalar Component of the Velocity Profile identified in Steps 5 & 7	Incorporating the information from Step 7 by the students into the kinematic information that has been obtained is critically important for detecting spatial functionality of the scalar components of the fluid velocity. The analysis provides what independent variables are not part of velocity profile.
9	Final Result: The scalar velocity component with its proper function of independent variables	This step concisely presents the final result of the functionality of the velocity profile obtained by the students under the assumptions and constrains indicated in the previous steps.
10	Assessment/ Validation of the Final Result	As in any theorical analysis, the assessment of the result to validate the physical consistency of the result is very important. Students must be able to accomplish this task and conclude, accordingly.

[1] Table proposed by Pedro E. Arce, PhD, FRSC in consultation with Dipendra Wagle and Mohammad Seyed Sabour who are serving as the teaching assistants for the course. *Dated:* 2023 Spring Semester, Cookeville, TN-USA.

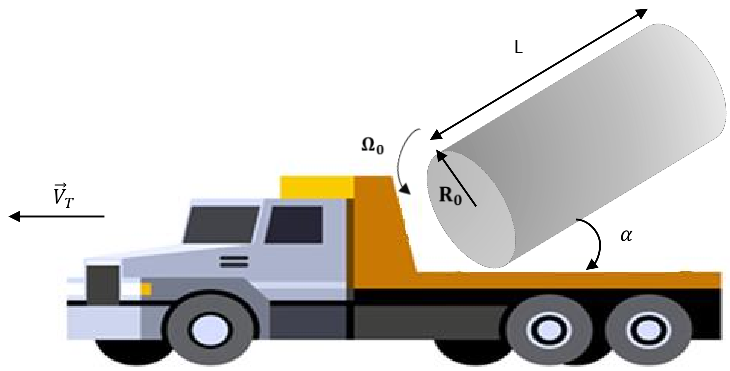

Figure 2: An Example of Application of The Dual Learning Process Guided by the Foundry (Overall) couple with the Kinematics of Fluid Flow (Micro/Subject Related): The Rotating Tank in a Cement Mixer Truck

Table 2: Foundry-Kinematics of Fluid Flow Integration Approach	
Challenge: Identification of the Fluid Velocity Profile Functionality	
Organizational Tools: 10 Steps Based on Kinematics of Fluid Flow and Equation of Continuity (Table 1)	
A-Knowledge Acquisition Paradigm	
1	*Control Domain Identification*: Figure 3a sketches such control domain for the tank
2	*Select Most Appropriate Geometry*: The tank is a cylindrical control domain
3	*Anchoring a Suitable Coordinate System*: Figure 3b shows the selected coordinate system
4	*Characterizing of the Fluid Flow inside the Control Domain*: Key characteristics: Tank is rotating at an angular velocity Ω_o, producing a laminar flow, fully developed, and with a sealed bottom. Tank is under isothermal conditions and the truck moves at a constant velocity V_t.
B-Knowledge Transfer Paradigm	
5	*Proposing Kinematics most Aligned with Flow*: $v_r = 0$; $v_\theta \neq 0; v_z = 0$-Justification: No flow in either the r or z directions as the tank is rotating in the angular direction.
6	*Analyzing the Type of Fluids inside the CD:* The fluid is assumed incompressible as the cement mixture is assumed dilute in water.
7	*Applying the Incompressible Flow Condition to the Kinematics of Flow:* This condition is given by the equation: $\vec{\nabla}.\vec{v} = 0$-By applying the kinematics of step 5 this yields $\frac{\partial v_\theta}{\partial \theta} = 0$ which produces $v_\theta \neq F(\theta)$
8	*Inferring Functionality of the Fluid Velocity Profile:* Based on information of step 7, the fluid velocity is a function of r and z, i.e. $v_\theta = F(r, z)$. However, there is no variation along the z direction of the CD and therefore, symmetry can be assumed.

	Thus, the velocity profile component becomes only a function of r- the radial coordinate.
9	*The Prototype of Innovative Technology (PIT):* Based on the information available on step 8, the conclusion is that $v_\theta = F(r)$. This result is the core PIT of the application of the Renaissance Foundry to the fluid flow velocity profile analysis.
10	*Assessment/Validation:* Based on the fluid flow identified in the CD and it constraints, it is reasonable that the velocity be only a function of the radial direction to accommodate the friction effects of the walls of the CD- This aspects are the core items of the SISA Part II- Dynamics Analysis of the flow.

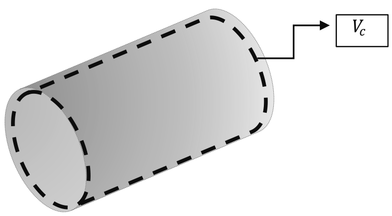

Figure 3a: Control Domain

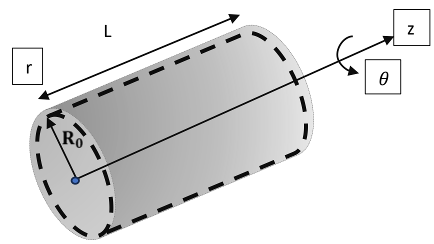

Figure 3b: Coordinate System

Student Reflections on Learning

These observations made by the students were offered after extensive students' practice to implement the strategy in various examples of flows relevant for a typical course in fluid mechanics suitable for the chemical engineering undergraduate or graduate level curriculum. After each one of these exercises, students formally presented their solution approach and engaged in a collaborative discussion with classmates and instructors. Also, on few occasions, other faculty from the department and with expertise in fluid mechanics joined the discussion section and engaged in productive conversations with the students offering their perspectives.

1. The Kinematic of Fluid Flow helped me in gaining a deeper understanding of how fluids move and interact in various flow scenarios. It was interesting to learn that this branch of fluid dynamics focuses on the motion of fluids without considering the forces that cause the motion. By studying the kinematics of fluid flow, I gained insights into the patterns, velocities, and trajectories of fluid particles, which proved invaluable in analyzing real-world fluid flow systems. In short, the Kinematics of Fluid Flow offered me a comprehensive understanding of fluid behavior, velocity distribution, and enabling precise analysis and prediction of fluid movements in physics of transport applications.

2. The systematization of the Kinematics of Fluid Flow was very helpful to learn how to organize the study allowing me to develop practical skills in applying kinematic principles to real-world fluid flow situations. It equipped me with the ability to describe fluid flow behavior, identify key parameters influencing flow patterns, and make predictions about fluid movements in different flow scenarios. The systematization of this knowledge has been instrumental in my educational journey and professional development.

In short, the structured organization of the Kinematics of Fluid Flow (coupled with the Foundry) significantly enhanced my learning on how to analyze and predict fluid moments in various flow scenarios. It also provided a systematic framework for grasping and applying the principles of fluid flow motion, contributing to a more efficient and informed problem-solving approach when the fluid flow velocity profile needs to be calculated.

3. Simplifying complex problems involves breaking them down into more manageable parts and approaching them systematically. The Kinematic Approach has not only deepened our comprehension of fluid dynamics but has also proven to be a versatile tool in addressing challenges across diverse flow scenarios. Its applicability could extend beyond conventional fluid mechanics, highlighting its value in optimizing processes and improving overall system performance in engineering applications.

Future Work

This work-in-progress offers preliminary observations on the applications by students of the Kinematics-based approach paired with the Foundry model. However, a more systematic evaluation is needed to investigate the impact of this pairing on student learning. In future work, we propose the adoption of a mixed methods approach to better understand the ways in which this strategy helps students to improve their skills and the reasons why they show support for the role of strategy when solving problems related to hydrodynamic velocity profiles. As part of this work, we intend to document potential student gains in knowledge about flow behaviors in capillaries or channels through direct learning measures and pre- and post surveys. Furthermore, the role played by the Renaissance Foundry model coupled with the kinematics-based strategy should be studied in more detail to determine how this paired approach assists in guiding the students across the different steps.

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