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Engineering Students' Fluid Mechanics Misconceptions: A Description and Theoretical Explanation*

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Even after formal instruction, students struggle with concepts in fluid mechanics, including situations involving pipelines with a changing diameter. Therefore, it is necessary to explore the misconceptions and reasoning that students have with pressurized pipeline flow. Using interview data from three different cohorts of students, this article addresses the following questions: (1) How do students conceptualize pressurized pipeline flow? (2) What misconceptions do they have and how can those misconceptions be explained by existing conceptual change theories? (3) Are those misconceptions consistent across multiple participant groups with varying levels of experience in fluid mechanics and across different problem sets? Answering these questions provides insight into an appropriate theory of conceptual change, which will in turn help instructors achieve conceptual change in the classroom. It is theorized that a combination of an ontological shift theory and "framework theory" provides a more complete understanding of students' misconceptions in fluid mechanics, and provides suggestions on how to implement schema training and active learning to facilitate conceptual change.

Keywords: fluid mechanics; FMCI; conceptual change; mental models; active learning; schema training

1. Introduction

Despite the necessity of fluid mechanics in the civil and environmental engineering curriculum [1], results from the Fluid Mechanics Concept Inventory (FMCI) indicate that students have basic misconceptions related to pipe size, elevation, velocity and pressure [2]. While FMCI results are useful for knowing how students respond to individual questions and groups of questions related to the same concept, they provide little or no insight into students' thinking about concepts related to the questions. Additionally, conceptual change theory research suggests that the context of interview questions influences student responses [2]. Therefore, the purpose of this study is to explore understanding of the fundamental fluid mechanics concepts of pressure and velocity in relation to pipe geometry and the consistency of misconceptions in different contexts and across different populations.

In order to explore these topics, it is useful to critically engage with conceptual change theories. Conceptual change can be understood as exchange of naïve, incorrect knowledge for scientifically correct knowledge [3]. Conceptual change theories are helpful as they allow researchers and educators to go beyond just knowing what concepts students struggle with and understanding why. Applying conceptual change theories will also provide faculty with a better understanding of what can be done to achieve conceptual change in the classroom and help students better understand course material. Conceptual change research has been used extensively to address students' learning and understanding of physics [4-6], heat transfer [5], electricity [7], and biology [8]; however, prior research has not applied learning theories to students' understanding of fluid mechanics concepts.

This article addresses that gap in research by answering the following research questions: (1) How do students conceptualize pressurized pipeline flow? (2) What misconceptions do they have and how can those misconceptions be explained by existing conceptual change theories? (3) Are those misconceptions consistent across multiple participant groups with varying levels of experience in fluid mechanics and across different problem sets?

The article begins with a three-part literature review on the Fluid Mechanics Concept Inventory, prior research on conceptual understanding of fluid mechanics, and two relevant conceptual change

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theories. After describing the research methods, findings on two misconceptions related to pressure are presented: (1) conceptualizing water as a compressible fluid in horizontal pipes, and (2) using hydrostatic pressure for pressure changes in vertical pipes. The misconceptions are discussed with respect to each other and to the explanations provided by the relevant conceptual change theories. Recommendations for teaching and future research are also presented before a summary concluding section.

2. Literature review

2.1 Fluid mechanics concept inventory

Concept Inventories (CIs) were created as assessment tools to provide feedback to instructors on what fundamental concepts students understand and to evaluate teaching effectiveness [9, 10]. When the Force Concept Inventory (FCI) was developed, physics professors deemed the CI questions "too trivial to be informative," but were then shocked to discover how poorly their students answered the FCI questions [10, p. 2]. Researchers found, using the FCI, that even students who did well on exams and homework performed poorly on the FCI questions (qualitative problems) [10]. While CIs can be valuable assessment tools [11], they do have limitations. They are structured questionnaires that do not allow researchers to fully understand the thought process of the participants unless paired with an interview. They also constrain students' responses to the available multiple-choice options. Furthermore, they are not specifically tied to learning theories.

A fluids-specific concept inventory called the Fluid Mechanics Concept Inventory (FMCI) has been created. Development of the FMCI was initiated by asking students and faculty to create a list of ten fluid mechanics topics that they understood or believed to be important and ten topics which they did not fully understand or did not believe to be important [12]. The students were also asked to discuss the list they created as well as answer questions from faculty [12]. To assess the validity of the FMCI the developers administered it to approximately 200 fluid mechanics students at the University of Wisconsin at both the beginning and end of their fluid mechanics course [13]. After assessing the students' responses, the developers revised the FMCI [13]. The FMCI consists of 30 multiple choice questions that cover a broad spectrum of fluid mechanics concepts, including conservation of mass, the Energy equation, momentum, and viscous flow [12, 13].

Unlike prior research that utilized the FMCI, our study overcomes the limitations listed above. In addition to having students solve FMCI questions, our study analyzes their verbal responses about thought process and rationale while solving the problems, and ties those processes and rationales to relevant learning theories, which provides new insights into their conceptual understanding. In addition to using the FMCI, we studied students' responses to an open-ended, pressurized pipe system problem, which provides insight into which misconceptions persist even when students are presented with a more practical situation.

2.2 Conceptual understanding of fluid mechanics

The only research identified relating to students' understanding of fluid mechanics was by Fraser et al. who utilized the FMCI to determine if the application of computer simulations improved students' scores [2]. They had mixed results, with two simulations proving successful and one unsuccessful. Yet, even of the successful ones, they noted that due to the post-test being taken shortly after the computer simulation; students may have performed better than if there was a longer delay between the computer simulations and the post-test. It was also noted that students still struggled to apply what they learned from the computer simulations to problems that were presented in a slightly different context. The computer simulation depicted a horizontal pipeline, when taking the post-test, the number of correct responses improved on horizontal pipe problems; however, when answering questions with a vertical pipeline, there was no significant improvement. This research indicates that although carefully designed instruction can improve students' performance on the FMCI, students will likely struggle to apply their new knowledge to different situations or contexts.

One limitation of that study, however, is that it utilized multiple-choice test scores rather than in-depth explanations from participants, thus inhibiting the application of conceptual change theories. Results from CIs and educational intervention show whether the instruction or intervention was successful, but do not explain why. A second limitation is that it utilized a homogenous population sample. Our study overcomes both of those limitations, thus advancing prior research by the collection and analysis of detailed interview data with a more diverse population in terms of engineering experience.

2.3 Conceptual change theories

Unlike CI research in science and engineering, previous research on conceptual change has almost wholly utilized interview data [14, 15] because understanding conceptual change for a particular subject requires an in-depth understanding of how students think about concepts related to the subject. There are numerous conceptual change theories [14]. Relying on one established conceptual change theory when studying engineering has proven inadequate to explain and understand engineering-specific contexts. Therefore, combining existing theories is necessary at this point in time, and future work should aim to develop new theories.

In this research, we utilize two theories of conceptual change to explore the meanings of our results: Chi's ontological category approach and Vosniadou's "framework-theory" approach. Both are applicable to fluid mechanics because they incorporate learning from everyday experience with academic learning and have been used to study physical phenomena, such as heat transfer, and students' understanding of the shape of the earth. Both are discussed in more detail in the discussion, to facilitate a clearer link between these theories and how they might explain our results. The goal of this research is to present results of the analysis of in-depth interview data about fluid mechanics concepts from three populations who had different levels of academic experience with fluids mechanics concepts, and to examine the results through the lens of both Chi's and Vosniadou's Conceptual Change Theories.

3. Methods

3.1 Participants and recruitment

As summarized in Table 1, data came from two interview protocols and were collected across three different types of cohorts. Cohort 1 consisted of twenty engineering undergraduate students who had completed an introductory course to fluid mechanics, typically during junior year, prior to the interviews. Cohort 1 was recruited through making announcements in the course about this research and through email contact. Cohort 1 represented approximately equal numbers of students in the top, middle and bottom third of course distribution based on grades. Cohort 1 participants were recruited for purposes of this study, to understand their misconceptions related to the fluid mechanics questions asked and their logic in answering these questions. They were interviewed only once. Cohorts 2 and 3 consisted of current or former civil engineering students, from the same university as Cohort 1, who were interviewed twice. Cohorts 2 and 3 were participants from a larger longitudinal study conducted over three years, tracking their conceptual change over this period. Cohort 2 and 3 participants were recruited through courses they were enrolled in at the start of this study, statics for Cohort 2 and the senior capstone course for Cohort 3. Students in these two cohorts represent a sample of convenience. However, they represent a diverse sample in terms of academic achievement and interests. Cohort 2 consisted of eight engineering undergraduate students. During their first interview (pressurized pipe system), the students were finishing their sophomore year and had not been exposed to the fluid mechanics course; however, they had received some exposure to fluid mechanics concepts via physics, which is a prerequisite for the civil engineering program. During their second interview (FMCI problems), they had just completed the fluid mechanics course. Cohort 3 consisted of nine recent graduates who completed their bachelors of science in civil engineering between the first and second interviews. At the time of their first interview (pressurized pipe system), the participants were in their last semester of their undergraduate program. At the time of their second interview (FMCI problem), cohort 3 had been employed and working as civil engineers for approximately one year. In total, there were 54 interviews.

Together, these cohorts represented very different students in terms of their experience with Fluid Mechanics. Our data therefore provide insight into how persistent or robust a misconception is. A misconception that is shared across cohorts such as these can be considered more persistent or robust than if it had only been identified in one cohort.

3.2 Data collection

Two different interview protocols were utilized. One protocol utilized FMCI questions, depicted in Fig. 1.

Participants from all three cohorts were asked questions 1–3. These questions were selected from the FMCI to help provide insight into participants' understanding of the relationship between pipe diameter, pipe orientation, velocity, and pressure. The interviews were implemented in a semi-structured, clinical format [16–19]. Participants were given each problem and approximately two minutes to determine the correct answer. Afterwards parti-

Table 1. Overview of participants and data collection

Cohort	N	Pressurized Pipe Interview	FMCI Interview
1	20	–	Juniors, after fluid mechanics
2	8	Sophomores, before fluid mechanics	Juniors, after fluid mechanics
3	9	Seniors, after fluid mechanics	Graduated and employed

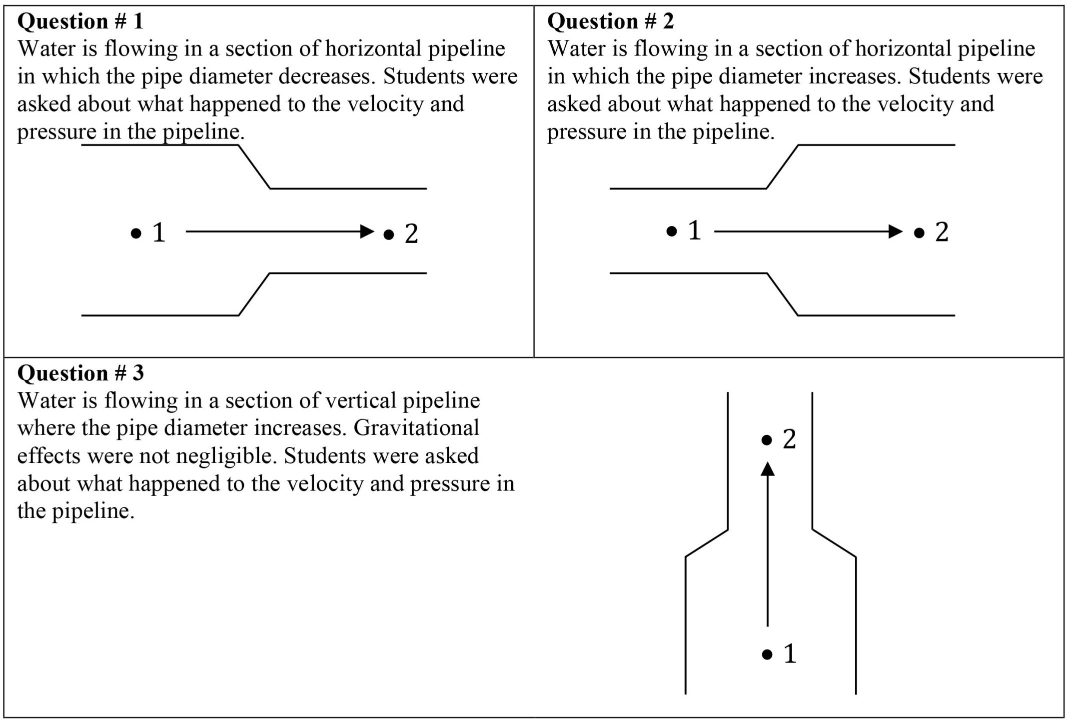


Fig. 1. Diagrams from the FMCI.

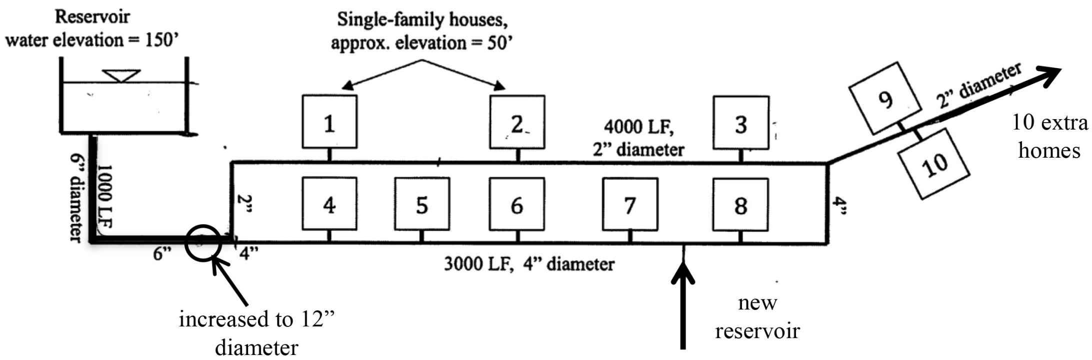


Fig. 2. Pressurized pipe system diagram.

cipants explained why they selected their answer, during which the interviewer asked probing questions to elicit a complete response that demonstrated their understanding of the material. Some participants wrote on the handouts of the questions when explaining their reasoning.

The second protocol utilized a pressurized pipe system drawing. Participants in cohorts 2 and 3 were given a schematic drawing of the pressurized pipe system seen in Fig. 2.

The interview protocol was designed to investigate participants' understanding of how pressure, velocity, and energy vary in, and are affected by, the system utilizing a semi-structured, clinical interview approach [16–19]. The questions were related to pressure, velocity, and energy in the pipeline, and any additional questions were probing questions (e.g., Can you explain why the system will react that way?). Participants were allowed to draw or write anything down on the handout that they felt was useful. They were asked the following questions:

1. What do you think the source of pressure is in the system?
2. Where is pressure greatest?
3. Where is velocity greatest?
4. Where is energy greatest?
5. Residents at house 3 complain about not having enough water pressure. They want their water pressure to increase, but they do not water to come out of the faucet any faster. How might you solve their problem?
6. How would you increase pressure near house 1?

7. How would you increase velocity near house 1?
8. How might the system change if an extra reservoir is added near house 7?
9. How might the system change if 10 new homes were added after house 9 and 10?
10. How might the system change if the entire 6" pipe was replaced with a 12" pipe?

3.3 Data analysis

All interviews were audio recorded and professionally transcribed. The interview transcripts and handouts used in the interviews were analyzed utilizing the qualitative data analysis software Atlas TI [20, 21]. Data analysis began with a quantitative analysis of the FMCI data. This consisted of determining how many participants from each cohort chose the correct answers to each question. The problems were also broken down to determine how many participants from each cohort got the velocity and pressure change portions of the answers correct. The intent of this quantitative analysis was to compare the FMCI results across the cohorts. The qualitative data analysis process developed over six phases and followed the guidelines for thematic analysis outlined by Braun and Clarke [22], focusing on finding patterns or themes within a data set [20, 22]. During the first phase, interview transcripts were read in order to become familiar with the data [22]. This was followed by an initial coding phase where codes, such as 'water condenses' and 'more water in a small pipe area,' were applied to "interesting features" in the transcripts [22, p. 87]. In the third phase of thematic analysis, codes were collated "into potential themes" [22, p. 87]. In the fourth phase, the themes were reviewed to determine if they were applicable and relevant to the data extracts (the coded sections of the interview) as well as the entire data set [22]. The fifth phase was a continuous analysis of the themes and an iterative process of naming and defining the themes, and the sixth phase involved creating the report [22]. While these last two phases may not intuitively be a part of data analysis, they imply that researchers should continue thinking about and analyzing the data throughout the writing process to ensure that all ideas and interpretations are allowed the chance to sprout and grow before a report is finalized.

4. Results

The three cohorts were relatively consistent in their responses and reasoning to the FMCI questions: the results in Table 2 show a maximum difference between cohorts of 25%. However, patterns of correct and incorrect responses were inconsistent across cohorts: cohort 1 improved on question 2, the second horizontal pipe problem, while the percentage of correct responses from cohort 2 decreased, and cohort 3 remained the same. The low percentage of correct responses suggests that many participants struggled with flow in pipelines with a changing diameter, even after formal instruction on this concept in a fluid mechanics course. Furthermore, participants from all cohorts utilized similar approaches and language during both the FMCI and the pressurized pipe system interviews. The consistency of misconceptions across the three cohorts and across the two different protocols is an important finding because it indicates that there are robust misconceptions (discussed below) widely held by engineering students and early career engineers.

Across all three cohorts, many participants were able to accurately predict how velocity would change in pressurized pipeline, but they frequently struggled to predict the change in pressure. For example, Student 106 used the correct approach to determine velocity changes (utilizing the concept of continuity in pipeline flow, which is shown by his mention of constant flow and the equation relating flow, area, and velocity), but then relied only on intuition to determine pressure changes:

> Student 106: Here you have [a] problem where you have—basically it's a pipe with water flowing through it. You have pressure velocity in one section of the pipe, and then the area decreases to a smaller size. And you have pressure velocity in the second portion of the pipe. And you're asked to find which part of the pipe where pressure's greater, which part of the pipe where velocity is greater basically. So I said that pressure and velocity is greater in the smaller portion of the pipe. Velocity is greater because flow has to be constant, and so flow is equal to area times velocity. So since they're constant, the area is smaller for section two of the pipe. And then that means that velocity has to be larger to compensate, basically balance out. So that's how I came up with velocity 2's greater than V1. And then for pressure, basically since it's a smaller—let's see. The way I thought about it is that it's a smaller section but water's still flowing. So pressure's going to have to be greater.

Table 2. Percentage of participants who answered FMCI questions correctly for both pressure and velocity

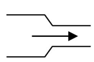
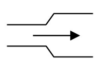
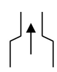
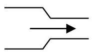
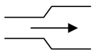
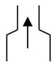
	Question		
	1 horizontal, decreasing diameter	**2** horizontal, increasing diameter	**3** vertical, decreasing diameter
Cohort			
1	40%	50%	45%
2	38%	25%	50%
3	33%	33%	56%

Table 3. Percentage of all participants who correctly got the velocity or pressure component of the FMCI questions correct

	Question		
	1 horizontal, decreasing diameter	**2** horizontal, increasing diameter	**3** vertical, decreasing diameter
Component			
Velocity	95%	84%	76%
Pressure	38%	43%	57%

> Because you have more—And so it's going to be pushing on the cross section of the pipe more.
>
> Interviewer: Okay. So how do you know that?
>
> Student 106: . . . I didn't use a formula for pressure. I just kind of pictured it in my mind how the system would be behaving.

Table 3 shows that less than half of the participants were able to correctly determine pressure, with the exception of question 3. A large portion of the participants answered the pressure portion of question 3 correctly, but their logic in the interview transcripts was not entirely correct. The wider section of the pipe, where pressure would be larger is also the bottom section of the pipe, where participants think pressure is greatest. Two primary misconceptions were found in participants' understanding of fluid mechanics concepts related to pressure: (1) conceptualizing water as a compressible fluid in horizontal pipes, and (2) relying on hydrostatic pressure to determine pressure changes in vertical pipes.

4.1 Conceptualizing water as a compressible fluid in horizontal pipes

In problems with horizontal pipelines, participants commonly expressed a belief that when water travels from a larger to smaller pipe the pressure increases due to more water being "squeezed" or "compressed" in the smaller pipe section. These intuitive responses contradict the premise that water and other liquids are assumed to be incompressible fluids in the context of the majority of engineering problems [23]. Table 4 shows the percentage of participants who conceptualized water as a compressible fluid and who utilized the concept of continuity in their explanations. The following codes, created from participants' explanations, comprised the theme *Water is a compressible fluid*:

- Pushing water into small pipe
- Pressure source is the weight of the water pushing
- Highest pressure at smallest pipe area
- Increase pressure at house 1 with larger pipe before smaller pipe
- More water in small area
- Increase pressure at house 1 with a smaller pipe
- Pressure increases from more water in small pipe area
- Pressure opposite of pipe area
- Pressure depends on volume
- Water compresses
- Water condenses
- Water squeezes
- Water pushed by pressure
- Water pushing
- High pressure pushes water through small area pipe

One of the more common codes was "more water in small pipe area," as seen in the following exchange, which was in response to the first FMCI question, where water flows through a contraction. The participant states that when water flows into a smaller pipe section, it causes the pressure to increase.

> Student 216: I said that the pressure and velocity will be greater in the smaller tube than the bigger tube.

Table 4. Percentage of participants who conceptualized water as a compressible fluid

	Fluid Mechanics Experience		
Code Group	**Pre-Instruction**	**Post-Instruction**	**Degree Conferred**
All Interviews			
Compressible Fluid	50%	43%	33%
Continuity	13%	68%	78%
Pressurized Pipe System			
Compressible Fluid	50%	11%	–
Continuity	13%	56%	–
FMCI, Question 1			
Compressible Fluid	–	46%	33%
Continuity	–	57%	67%
FMCI Question 2			
Compressible Fluid	–	29%	0%
Continuity	–	57%	67%

> Interviewer: Okay. Why is that?
>
> Student 216: Because *when it bottlenecks it has less area for the water*. So the pressure will go up. And then it causes the velocity to go faster if it's steady flow.
>
> Interviewer: And why would the pressure go up?
>
> Student 216: Because if they're trying to press the volume, basically, the flow here needs to stay the same here in a smaller area. So with the velocity increasing the pressure So *more water has to go in that small area or go through it.*

A related misconception was that ''water compresses.'' Participants believed that more water was able to fit into the smaller pipes because the water must be compressed when it reaches contractions in the pipeline. The pressure in the smaller pipelines increases because, when compared the larger pipeline sections, there is more water.

> Student 107: The highest pressure, probably from right here, these two-inch pipe or this two inch pipe *because it's thinner and there's more water going through it. . . .*
>
> Interviewer: Okay. And why would it be there?
>
> Student 107: My reasoning is because, actually, because it's going from all this water has to be pumped from six inches or six inch diameter pipe to four inch diameter pipe and then to a two inch diameter pipe. So all the pressure is being—*all the water's being compressed when it gets to these changes in diameter*, so it has to—so it experiences more pressure as it goes through the pipe.

Thus, participants believed that as water conforms to the size of the pipeline the volume of water will change, or that water is a compressible fluid. This misconception led the participants to believe that pressure would increase in smaller pipe sections.

A second code group relating to velocity, which was frequently determined utilizing the concept of continuity, was also created.

Equation (1) was commonly referred to as the continuity equation by many of the participants and was one of the ways in which participants frequently predicted velocity changes in the pipeline. It is a simple relationship between velocity and pipe cross-sectional area. When participants utilized Equation (3) and stated that the flow rate was same throughout the pipeline it becomes the more appropriate version of the continuity equation that is shown in Equation (1).

Equation (1): $Q = VA$

Where,

Q: volumetric flow rate (ft^3/s)
V: fluid velocity (ft/s)
A: pipe cross-sectional area (ft^2)

The continuity equation was not used by participants who had not taken fluid mechanics, but it was used by these same participants in their interview after completing fluid mechanics. Because it may not be a part of intuitive knowledge about pipeline flow and because it is presented in fluid mechanics courses as a part of the concept of continuity, it is included in this theme of 'continuity.' Furthermore, in order to derive the continuity equation an assumption of the fluid being incompressible must be made [23]. This conflicts with how participants described water in the pipeline for determining pressure changes. Table 4 shows the percentage of participants who made comments belonging to the 'compressible fluid' and 'continuity' code groups. The decrease in 'compressible fluid' codes in the second FMCI question is likely due to the fact that not all participants stated that they would repeat the same process they used in the first FMCI question. In this case, because it was not explicitly known what the student was thinking, there are fewer 'compressible fluid' codes for the repeat question.

4.2 Relying on hydrostatic pressure for pressure changes in vertical pipes

Participants commonly did not utilize the concept of conservation of energy in the vertical pipelines. Instead, they tended to focus only on hydrostatic pressure. It was more common for participants who had not taken fluid mechanics to make comments relating to hydrostatic pressure than it was for participants who had graduated with a civil engineering degree. However, many participants who had completed fluid mechanics, but not graduated, relied on hydrostatic pressure. Table 5 shows the percentage of students who relied on hydrostatic pressure. The following codes, created from participants explanations, comprised the theme *Hydrostatic pressure*:

- Pressure affected by water density
- Highest pressure at lowest elevation
- Highest pressure at bottom of vertical pipe

Table 5. Percentage of participants who relied on hydrostatic pressure

	Fluid Mechanics Experience		
Interview	**Pre-Instruction**	**Post-Instruction**	**Degree Conferred**
All Interviews	63%	43%	33%
Pressurized Pipe System	63%	22%	–
FMCI Question 3	–	50%	33%

- Highest pressure where most water weight is above
- Increase pressure at house by lowering its elevation
- A larger vertical pipe creates more pressure due to water weight
- Pressure increases with depth
- Pressure is source of gravity
- Pressure is source of water weight
- Hydrostatic pressure
- Pressure affected by gravity

The following were responses to the third and fourth FMCI questions. In the third FMCI question water flows upwards through a contraction, and in the fourth it flows downwards through an expansion. In both questions the participant stated that pressure would be greater in the bottom section of the pipelines due to hydrostatic pressure.

> Student 020: Okay. So Q = VA. Area decreases, velocity increases, so V2 is greater than V1. So I'm going to cross out C and cross out E because they say V2 is less than V1. Then, for the pressure difference, I'm going to go with P1 is greater because of gravitational so—or *hydrostatic pressure* and that would be B.
>
> Student 020: Okay. So, again, Q = VA. Area increased, velocity decreased so V2 is less than V1, process of elimination, cross out A, B and D. Then I'm going to go with C as my answer *because of the buildup hydrostatic pressure*. . . .

In response to the fourth FMCI question, where water flows downwards through a pipe expansion, another student reasoned that pressure was affected by water density and gravity, and increases with depth.

> Student 009: Okay. So obviously P2 is going to be greater than P1.
>
> Interviewer: Okay, and why?
>
> Student 009: Gravity, you have the static head and then the pressure head above it. I should write that out. So say there's a point there, you'd have the static head and the pressure head. . . . So I'm going to say P2 is bigger and V1 is bigger. V1 is bigger because of the smaller cross-sectional area. P2 being bigger *because of the gravitational effects and the pressure head due to the depth and density of the water*. . .

While this participant mentions static and pressure head, he does not elaborate on what each of these means or represents. However, at the end of this quotation he succinctly states that in addition to depth, pressure is affected by other variables: gravity and water density. Depth is the only variable that will change throughout the vertical pipeline. Another participant believed that the highest pressure was where the most water weight was above. When asked how the system would change if the 6-inch diameter pipe was replaced with a 12-inch diameter pipe in the pressurized pipe system interview, Student 101 said: "Pressure will increase because there's more mass and water weighs a lot so there's more mass coming out of this pipe so there's a lot of mass coming down, and so there's more pressure, yeah. Pressure will increase . . . obviously on this system." This quotation expresses the relationship between pressure and the weight of the water that exists in the participant's mind. Expanding on this participant's explanation, pressure would also increase due to depth since more water, and therefore more mass and more weight, will exist above a specific point in the pipeline.

Similarly, Student 208 reasoned that pressure increases with depth. "The highest pressure is going to be down at these houses as opposed to up here because pressure increases as you go down in elevation." This response expresses the belief that pressure is directly related to depth: when depth increases the pressure will increase. This type of response was the most frequently used for problems relating to vertical pipelines.

The point here is that participants did not look at the overall energy in the pipeline system to predict changes in pressure. While the concept of pressure being dependent on depth is in fact a true statement, the problem is that participants focused on the simple relation of pressure and depth. If contraction or expansions in the FMCI interview questions are assumed to be sudden, then changes in velocity will have more of an effect on the pressure change than changes in elevation. In the pressurized pipe system interview where there is a larger pipeline system, the elevation will have a significant effect on pressure. The contractions in the pipeline at the lower elevation will also impact where the highest pressure will exist in the system. Participants are technically correct to relate pressure to depth. However, based on how infrequently participants utilized conservation of energy to determine changes in pressure, it is likely that they were not considering the overall energy in the system.

5. Discussion

In Chi's ontological category approach to conceptual change, misconceptions exist because concepts have been "ontologically miscategorized," [24, p. 72]. In other words, something is conceptualized as being one type of thing, when it is actually a different type of thing. Ontological categories are the "basic categories of realities or the kinds existent in the world, such as concrete objects, events, and abstractions" [8, p. 163]. Essentially, they are the categories an individual uses to organize and make sense of the world around them. Chi has developed three primary ontological categories (matter, processes, and abstractions), but recognizes that other ontological categories may exist [25, 26]. Using this theory, conceptual change requires that students become aware of their miscategorization of a particular concept [14]. Chi contends that robust misconceptions, which are misconceptions that persist after formal education, form because concepts have been placed in the wrong ontological category [8, 25–27]. According to this theory, conceptual change, specifically related to robust misconceptions, requires shifting a concept from the incorrect ontological category to the correct one [8, 25-27]. Others have applied the ontological category approach to conceptual change to study the concept of electric current [7].

Vosniadou's self-labeled "framework theory" incorporates the effects of culture and context on an individual's knowledge, contending that misconceptions are formed when individuals try to reconcile "scientific information within an existing framework theory that contains information contradictory to the scientific view" [5, p. 46]. Conceptual change in this approach does not, ultimately, focus on fixing the misconception, but rather on correcting the "naïve, intuitive . . . theories constructed on the basis of everyday experience under the influence of lay culture" [28, p. 58]. Within the "framework theory," beliefs are created based on the everyday observations individuals make about the world around them, and contribute to the "beliefs that describe the properties and behavior of physical objects" [5, p. 47]. Misconceptions form when individuals attempt "to reconcile the inconsistent pieces of information and produce a synthetic mental model" that is scientifically incorrect, but helps them rationalize their beliefs [5, p. 50]. Conceptual change is achieved by correcting the presuppositions and beliefs that exist in a framework theory [28]. This "framework theory" has been applied in research on heat transfer [5].

In horizontal pipe problems, responses indicated a belief that water is squeezable or compressible, based on the frequent comments about water squeezing, condensing, and pressure being inversely related to pipe area. Chi's conceptual change theory can provide insight into and help explain why students conceptualize water as a compressible fluid, even after formal instruction: the misconception stems from thinking in terms of *matter* rather the *processes*. Changes in velocity and pressure in pressurized pipeline flow should fall into the ontological category of processes. Attributes of this category include being abstract, invisible, non-tactile, and continuous. Using Chi's ontological category shift theory, we can posit that the participants are operating in a physical substance category when they should be in a process category. The data indicate that the misconception of water being a compressible fluid is likely "robust" [8] because students who completed fluid mechanics and completed their undergraduate education in civil engineering continued to make comments that indicate this belief.

In vertical pipes, many participants discussed changes in pressure in terms of a single variable problem. The phrases "because the pipe area increases/decreases, the velocity will decrease/increase" and "because the pipe area increases/decreases, the pressure in the pipe will decrease/increase" were common ways in which participants explained the reasoning for their answers. Even when probed for further explanation some students did not provide a more in-depth response, and often times those that did had misconceptions. Since the participants provided limited explanations, they likely did not understand what was happening in the system. In the vertical pipe problems, the single variable problem attribute can be seen in the participants' simple explanations that pressure increases with depth. The elevation component of the energy equation also expresses this idea of hydrostatic pressure, but in terms of energy. The simple relation of pressure and depth was the most frequent way in which participants solved for pressure changes in vertical pipelines. Pressure simply does not change due to one specific variable, such as a change in pipe diameter; instead it changes due to the interaction of the changes in velocity and elevation, which occur simultaneously. It is inappropriate for participants to rely only on hydrostatic pressure to determine pressure changes and ignore any effects on pressure change due to velocity changes. Any hydrostatic pressure effects in vertical pipelines would be significant only in large sections of vertical pipes. However, it has less of an effect when the change in elevation is minimal, as with the sudden expansions or contractions in the FMCI interview questions.

As with conceptualizing water as a compressible fluid in horizontal pipes, using Chi's ontological category shift theory, we can suggest that the participants are operating in a physical substance category when they should be in a process category for the vertical pipe problems. Utilizing Chi's conceptual change theory, participants who had issues accurately determining the pressure in pipeline flow used phrases that implied they were thinking about the problems from the ontological category of physical substance. To properly understand horizontal and vertical pipeline flow, students must shift their way of thinking from the physical substance with single variable problems category to the process category with multi variable problems.

Another important finding was that context played a determining role in participants' thinking, as evidenced by the fact that they conceptualized horizontal and vertical problems differently. Like Fraser et al. [2], our findings indicate that the context in which a problem is presented has a notable effect on how students reason/conceptualize about it. A few participants expressed that they had never seen or did not remember working with vertical pressurized pipelines, despite working with horizontal pipes within the same interview. Others mentioned that gravity not being negligible in the problem statement also made it difficult for them to solve the FMCI problems. In addition to how students approach pressure changes, a portion of participants also changed how they approached solving for velocity. To include the gravitation effects in vertical pipe problems on the FMCI some participants began to express a belief that water flowing upward would slow down or go faster if flowing downward. Such sources of confusion indicate that the context in which a problem is presented can heavily influence students' conceptual understanding of pipelines. Even though the problems are conceptually the same and solved using the same process, participants drastically changed how they thought about the problems: from talking about water as a compressible fluid to talking about hydrostatic pressure.

Vosniadou's "framework theory" can help explain the dramatic shift in participants' conceptual understanding of pressure between horizontal and vertical pipelines because that theory highlights the salience of context and intuition in conceptual understanding. Although participants' thinking about horizontal and vertical pipes is both from a physical substance category, Chi's ontological category theory cannot fully account for the differences in participants' understanding of horizontal and vertical pipelines. Therefore, engaging another conceptual change theory, in this case Vosniadou's, is also helpful.

6. Study limitations

The limitations of this study relate to the sample of study participants and the characteristics of the problems they solved. This study included 37 participants with different levels of experience in fluid mechanics and at different stages in their engineering careers. The sample does not necessarily represent the population from which it was drawn nor the broader population of civil engineering students and professionals. More research is necessary to understand in what ways these results would be consistent with other populations. The problems that participants solved have particular language and drawings that may have affected participants' responses to the interview questions. Our data is insufficient to determine the extent of this effect. More research is necessary to understand if changes in the language or drawings of these problems would change participant responses. It is possible that the courses and instructors, and engineer's work experience may have influenced responses. The results do, however, help us understand student and professionals understanding of fluid mechanics and how these relate to conceptual change theories.

7. Implications for teaching

Based on our findings, several pedagogical recommendations (drawn from the two theories found to be relevant) can be made. First, given the finding that some misconceptions stem from ontological category confusion of thinking in terms of matter rather than process, "schema training" is recommended. Schema training has been beneficial in repairing students' misconceptions of electricity [29] and heat transfer [30]. This approach employs an emergent process training module to shift students' understanding of electricity from a material substance ontological category to a process category [29]. In this approach, it is recommended that professors "should not try to "bridge the gap" between students' misconceptions and the" scientifically correct conception "as there is no tenable pathway between distinct ontological conceptions" [29, p. 286]. Instead, they should focus on "explicitly draw[ing] attention to fundamental (ontological) aspects of the concepts in order to help students formulate new conceptions that adhere. . .to the scientifically normative view" [29, p. 287]. In other words, to achieve conceptual change students must be confronted with the idea that there is another, ontologically different, way to think about concepts and, if shown how, this new way of thinking can accurately and appropriately explain scientific phenomena. A computer simulation similar to the one used by Slotta and Chi may be successful [7].

Second, given the finding that context and intuition informed participants' reasoning about pressure changes, active learning approaches can be recommended. Vosniadou's theory offers some general suggestions to implement conceptual change in the classroom [5, 23, 31]. In order to make students aware of their naïve presuppositions and beliefs, Vosniadou suggests that (1) students are put into a situation where they can actively engage in science experiments, (2) students are encouraged to "provide verbal explanations of phenomena" with other students so that they can defend and compare different beliefs, and (3) students express their mental models so that they can manipulate, test, and revise their beliefs and presuppositions [5, p. 67]. Encouraging students to converse with, listen to, and challenge one another helps to create the sociocultural environment necessary for meta-conceptual awareness and conceptual change [31, 32].

Active learning can be implemented with small group work either in class or in a lab outside of regular lectures. This group work should focus on inter-group discussions about concepts in fluid mechanics that students struggle with, including pressurized pipeline flow. During these discussions, individuals, or small groups, should form and test a hypothesis utilizing either actual lab set-ups or computer simulations. Afterwards, students should determine if their hypothesis was valid, as well as if the logic behind their hypothesis was correct. This final part may help students learn what happens in fluid mechanics systems beyond memorizing rules of thumb. Such approaches have proven successful with physics and open channel flow concepts [33, 34].

Third, long-term curriculum planning is needed. Because conceptual change can be a long and gradual process, simply instructing students that a single naïve concept is in conflict with the correct scientific concept will not be effective in most classrooms [31]. This was exemplified by participants' misconceptions of pressurized pipeline flow after formal education in fluid mechanics. A better way to foster conceptual change is with a long-term curriculum that includes "carefully planning the sequence of concepts to be taught by identifying the points at which conceptual change is necessary" [31, p. 26]. Students will frequently revisit portions of fluid mechanics throughout their engineering programs: a civil engineering student will typically first encounter fluid mechanics concepts in school in their physics class, then revisit it more in-depth in fluid mechanics, and again revisit some aspects in water resources. Due to this and the variations in educators' teaching style, a carefully planned, long-term curriculum may be difficult to design, but should be a priority.

8. Implications for research

In addition to implications for teaching, our findings highlight several directions for future research. Such research would help advance existing bodies of knowledge on fluid mechanics, conceptual learning, and concept inventories [35–40]. First, if the FMCI is used in future research, the multiple choice options should be altered. We found that some participants wanted to choose a non-existing option of pressure being constant, or not changing, and that some did not believe any of the available multiple-choice options were correct, but felt forced to choose one. Replacing the multiple-choice options with the two part answers shown in Table 6 would make every possible response available, thus providing more nuanced understanding of where exactly misconceptions exist.

Table 6. Recommended two-part multiple-choice options for FMCI questions

Velocity Answers	Pressure Answers
(A) V_2 is less than V_1	(D) P_2 is less than P_1
(B) V_2 is equal to V_1	(E) P_2 is equal to P_1
(C) V_2 is greater than V_1	(F) P_2 is greater than P_1

Second, future research should aim to determine if students have different understandings based on the type of interview question. The interview questions used in this research utilized aspects of fluids systems to explore student understanding, but did not include explicit questions about the assumptions that affect the analysis of these problems. For instance, although we observed the compressible fluid misconception in participants' explanations, would students state that water is a compressible fluid if directly posed that question? If this is a fundamental barrier to student understanding, then we need to conduct future research to attempt to understand students' fundamental beliefs and their consistency depending on how interview questions are asked. This finding is particularly interesting because discussions of compressible fluids and the assumptions of incompressibility as it relates to some of the concepts and equations used in water problems in fluid mechanics is commonly the first chapter in books, and only covered very quickly in class. Perhaps these fundamental assumptions should be examined more closely by students in a variety of contexts to help with developing correct understanding of later concepts.

Third, future research on students' conceptual understanding of pressurized pipeline flow should continue to focus on applying conceptual change theories to robust misconceptions. This will ensure that the most appropriate teaching methods can be applied to fluid mechanics curricula. However, theories should not be applied uncritically, as they often are in engineering education [41–43]. Researchers need to critically examine where theories work, as well as where they do not, and begin to propose new, engineering-specific, theories that address those limitations. We found that we needed to engage two theories to explain our results, and we were able to begin to propose an engineering-specific "framework theory" to explain why participants conceptualize water as a compressible fluid. By critically engaging theories, engineering education researchers will also be able to refine them in ways that make them more useful to engineering contexts. For example, it may be the case that the ontological category confusion experienced by students does not in fact map neatly on to Chi's categories of matter and process. The hierarchy of concepts and categories utilized by a researcher may impact how misconceptions would be addressed in order for students to form the correct conceptions. It is possible that instead of shifting from one broad ontological category to another, a shift from a more specific category is necessary. Others have already noted that Chi's ontological categories, specifically *processes*, may be problematic [5].

Fourth, to further explore the dramatic change in participants' thought processes of solving for pressure in vertical pipes compared to horizontal pipes, future research should focus on determining why it occurs. A possible reason may be due to the isolation of the pipeline from the assumed system that it is connected to. The pictures that were provided to students show the ends of the pipes being open to the atmosphere, but it is assumed in these pictures and similar ones used widely in fluids mechanics courses that the pipe is connected to a larger system. As an example, similar to how a free body diagram of a beam can be a simplified, isolated component of an entire building, the vertical and horizontal pipes in the FMCI interview would be a small section of a larger system. Students' incorrect understanding may be related to a misinterpretation of the boundary conditions. A few participants struggled with understanding that the vertical pipeline segment was part of a larger pressurized pipeline system. This would emphasize the importance of context, in this case the picture, or representation provided to students, on altering students' conceptions. To explore both of these ideas, future research should be structured to question students about how a pipeline segment might fit into a larger system, or to have students explain what happens after the pipeline segment. Another possibility would be to alter the drawings of the pipe segments to be explicitly obvious that the pipe segment is "broken off" from a larger pipe system. Such research would help determine where and why students hold different misconceptions about pressurized pipeline flow.

9. Conclusions

Students frequently hold misconceptions about pressurized pipeline flow, even after formal instruction. In horizontal pipes, they incorrectly believe that water is a compressible fluid that has to squeeze or compress into small pipe sections. In vertical pipes, they rely on hydrostatic pressure when predicting pressure changes in vertical pipes. Using Chi's ontological category shift approach to conceptual change, we can posit that participants appear to be operating in a physical substance category when they should be in a process category. This approach, however, is unable to explain why participants shifted their thought process about pressure changes between horizontal and vertical pipelines, which are conceptually similar problems. Vosniadou's "framework theory" approach is able to explain this dramatic shift in the participants' conceptual understanding. Using this approach, the context in which these problems are presented (horizontal versus vertical orientation) affects how participants think about and approach the problem. To help students form the correct conceptions about pressurized pipeline flow, schema training can be implemented to help shift students' conceptualization from a physical substance category to a process category, and an active learning approach to encourage conceptual change should be utilized. Students should be encouraged to create, defend, and test hypotheses with classmates to evaluate their beliefs and understanding of fluid mechanics, or other subject areas. Future research should: explore fundamental assumptions of fluid mechanics and their role in misconceptions, critically engage conceptual change theories, and focus on the role of context in students' conceptualization of pressurized pipelines.

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