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Exploring Practicing Engineers' Understanding of Fluid Mechanics Concepts*

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Although it is widely recognized that conceptual understanding is vital to effective engineering education and practice, both practicing engineers as well as students demonstrate misconceptions related to basic engineering concepts. And while a growing body of research has demonstrated the differences in the role and function of concepts across school and work, less is understood about the ways engineers in practice describe the concepts they use. The purpose of this research is to explore the way practicing engineers articulate their understanding of fundamental concepts in fluid dynamics. Using two independent samples, we administered the Fluid Mechanics Concept Inventory (FMCI) to one group of practicing civil engineers and used FMCI to conduct clinical interviews with the other. Our analysis focuses specifically on understanding of pressurized pipeline problems. We performed descriptive statistical analyses alongside the application of an *a priori* codebook informed by prior research with students. Misconceptions revealed through incorrect responses to FMCI are elaborated on by the qualitative clinical interviews. Findings suggest that, much like students, practicing civil engineers still harbor misconceptions concerning fundamental fluid mechanics concepts related to pressurized pipe flow problems. Engineers in this study relied on overly simplified relationships and inappropriately applied principles in ways that echo findings from similar research with students. Given the persistence of such misconceptions, it seems important to consider the meaning of these concepts both at work and in preparing students for work.

Keywords: fluid mechanics; conceptual knowledge; engineering practice; misconceptions

1. Introduction

Concepts and conceptual knowledge play vital roles in engineering problem solving processes [1, 2]. Bridges stand up and pipes carry water because concepts in physics and mechanics and dynamics help us understand and make predictions about the behavior of a range of phenomena. Yet both students who have completed the relevant coursework as well as engineers with practical experience still exhibit what would seem like fundamental misconceptions related to engineering content [3, 4]. While some work has explored these misconceptions in other areas of basic physics and science (e.g., [5]) and provided evidence for their persistence, less is understood regarding misconceptions of engineering concepts (that are arguably built on these more fundamental concepts). Research has demonstrated the presence of robust misconceptions in student learning, but less is known about the way those conceptions are described by practicing engineers. Importantly, however, gaining insight into the nature of particular conceptions offers opportunities for educators to confront, address, and repair misconceptions [6–8].

At the same time, a growing body of literature points to critical differences in the nature of professional engineering work—and therefore the role and function of concepts—when compared to school [9–12]. Engineers use and interact with concepts in practice in ways that can differ significantly from the modes of interaction characteristic of school [13, 14]. However, while that literature illustrates differences in how concepts function [15, 16] and the consequences of those differences [12], relatively little is known about how engineers articulate their conceptual knowledge as they solve problems. With a better understanding of the ways engineers describe their own (mis)conceptions and problem-solving approaches, educators can more appropriately align engineering education with those aspects of practice for which conceptual knowledge is most salient. To that end, the authors explore the following research question:

How do practicing civil engineers describe and conceptualize problems related to pressurized pipeline flow?

To answer this question, the authors present a multi-method, exploratory study that combines quantitative survey data with qualitative clinical interviews conducted with independent samples of practicing civil engineers. One group of participants responded to a quantitative, computer-based version of the Fluid Mechanics Concept Inventory (FMCI) [17] and another group participated in

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clinical, thinkaloud interviews during which they solved selected FMCI problems related to pressurized pipe flow. Using a framework comprised of prior research surrounding student misconceptions in fluid mechanics (i.e., [3, 18]), our results indicate that practicing engineers, much like students, exhibit misconceptions on pressurized pipe flow problems related to issues of compressibility, geometry and orientation, and naïve physical intuition resulting in the conflation of various concepts within the pressurized pipe flow problems. Given that engineers articulate many of the same misconceptions as students, it seems important to consider how practitioners' understanding and articulation of these concepts might inform curricular interventions.

2. Literature and background

Given the role of concepts and conceptual knowledge, it is perhaps unsurprising that a range of research projects have investigated ways to measure or assess knowledge of a concept. Many of these endeavors have resulted in the development of concept inventories—multiple choice assessments designed to isolate single engineering concepts and diagnose misconceptions based on responses to different distractors. These inventories have been influential in a variety of learning and assessment research, and form the basis of the research protocol employed in the present study. Specifically, we turn to the Fluid Mechanics Concept Inventory (FMCI) developed through a collaborative, multi-institutional effort [17]. Fluid mechanics problems in general, and pressurized pipe flow problems in particular, can pose challenges for students, in part because some of the calculations and principles seem to run counter to many individuals' intuitive models of how water ought to move through pipes. The following sections provide a discussion of the development of concept inventories and the FMCI and also review current literature concerning misconceptions in engineering and fluid mechanics.

2.1 Concept inventories

Concept inventories are popular assessments tool within engineering education [17, 19, 20]. They are useful assessments in part because they represent a relatively straightforward, economical approach to gain in-depth understanding of students' conceptual knowledge. Further, these inventories can diagnose particular kinds of misconceptions based on the selection of certain distractors. Most concept inventories in engineering education have been modeled after the Force Concept Inventory (FCI) developed in physics to measure student's understanding of force and motion via qualitative questions about single concepts [21]. In engineering education, the Foundation Coalition began a long-term program on development of concept inventory assessment instruments for various engineering and science disciplines [28]. Some of the examples of topics include Thermodynamics [22], Electromagnetic [23], Signals and Systems [24, 25], Fluid Mechanics [17], Dynamics [26], Statics [27], and Engineering Graphics [19], to name a few.

Concept inventories are designed to isolate individual concepts and therefore probe for knowledge of specific concepts. The Fluid Mechanics Concept Inventory (FMCI) was developed to assess engineering students' knowledge of what were recognized as fundamental or essential fluid mechanics concepts. The essential conceptual topics for the inventory were identified by experienced faculty in the field and reviewed by students who completed fluid mechanics [17]. The FMCI underwent validity and reliability testing, and as a result, was revised and now is comprised of 30 multiple choice questions that focus on basic concepts, such as fluid properties and boundary effects, as well as fundamental fluid relations, such as conservation of mass, energy, and momentum [28].

2.2 Fluid mechanics misconceptions

Research surrounding conceptual understanding of fluids originated in the physics education community. One notable example is the work of Psillos [29], who explored students conceptions of pressure as it related to notions of force. Through their application of a constructivist teaching approach to fluids concepts, they traced the conceptual evolution of students' understanding of pressure from a simplistic model of force and points of application to a more sophisticated understanding of the internal pressure forces within a fluid. A similar 'pressure-force' model emerged in a study by Loverude, et al. [30], where interviews with undergraduate students revealed consistent incorrect reasoning about hydrostatic pressure in terms of the weight of liquid above a point. These misconceptions about the behavior of fluids in different situations seem to be learned or intuited through experience with the world, but nonetheless result in incorrect calculations and predictions.

Moreover, difficulties in understanding of particular fluid concepts frequently persist in students regardless of how many courses on the topic they completed [31]. Prior research on conceptual understanding of fluid mechanics identified student misconceptions with pressurized pipeline flow. For example, Baghdanov and Adam [32] and Brown, et al. [3] conducted thinkaloud interviews with engineering students as they solved FMCI problems. Their findings provided evidence that students often (incorrectly) conceptualize water as a compressible fluid and also rely on hydrostatic pressure in ways that unduly influence their problem solving approaches regarding pipe flow. Relatedly, Montfort et al. [18] interviewed undergraduate engineering students using FMCI questions to test their understanding of fluid mechanics. Findings showed that students tend to inappropriately group dissimilar phenomena, processes, or features and use simplified causal relationships when talking about fluid flow. Students' frequently conflated concepts of pressure and velocity in their responses instead of considering fluid flow as a dynamic equilibrium of mass and energy (p. 1594). In other examples, students assume that flow's velocity is caused by features of the channel or pipe, rather than discussing the dynamic balance between overall system components. An earlier study by Fraser, et al. [33] also demonstrated the persistence and robustness of these misconceptions following conceptual instruction. Students were provided computer simulation tools for fluid mechanics in an effort to confront and address misconceptions related to pressure in vertical pipelines with a changing diameter. While some simulations seemed to remedy aspects of students' misconceptions, in general they appeared to persist. In general, student misconceptions related to fluid mechanics appear resistant to change throughout school, but relatively less is understood regarding how conceptions might change or evolve as engineers engage in professional practice.

3. Methods

3.1 Data collection

Data for this current research was collected at two different times as part of a larger project exploring conceptual understanding and situated cognition in engineering education [34]. For this particular study, we focus on practicing engineers' responses—both quantitative and qualitative—to questions concerning changes in fluid velocity and pressure through fully pressurized, laminar pipe flow problems. The questions are intended to assess respondents' understanding of concepts such as conservation of mass, conservation of energy, Bernoulli's principle, and continuity. Approval for human subjects research was obtained through the institutional review board (IRB # 5963) prior to any collection or analysis.

3.1.1 Quantitative data collection

For the quantitative portion of the present research, data was collected between 2015–2017 from a sample of 96 practicing civil engineers in the Pacific Northwest region of the United States. Participants were recruited via email through contacts of co-author Brown. Most participants were male (72.9%, $N = 96$) and had at least undergraduate engineering education (61.6%) or higher (38.5%) in one of the civil engineering fields. Eighty-two percent of the engineers worked for companies with over 100 employees while the rest were employed at smaller (less than 100 employees) companies. The engineers had an average of 10.75 years of experience (SD = 10.3, $N = 96$), varying from one month to 39 years. Table 1 provides a more detailed overview of the participants who provided the quantitative data in this study.

Individuals at engineering firms were asked to help facilitate data collection by either sending out a notice to their firms requesting civil engineers complete the online survey or for the researchers to visit the firm to collect data. Engineers in this sample were provided a description of the FMCI and offered an incentive of $20. Participants who completed the FMCI at their work were provided a dedicated computer in a conference room on which to take the FMCI. Participants completed the FMCI in between 10 and 30 minutes. As noted, only responses to questions related to pressurized pipe flow were considered for analysis.

Table 1. Demographic information of FMCI survey respondents

		Gender		Degree		Company size	
Engineering expertise	**Total**	**Female**	**Male**	**Bachelor**	**Master**	**<100**	**>100**
Civil Engineering	30	8	22	25[b]	5	3	27
Water Resources	8	1	7	2	6	2	6
Structural Engineering	15	4	11	6	9	0	15
Multidisciplinary[a]	43	13	30	26[c]	17[d]	12	31
Total	96	26	70	59	37	17	79

Note:
[a] Engineers who claimed to have more than one civil engineering expertise, including Civil Engineering, Construction management, Geotechnical Engineering, Environmental Engineering, Structural engineering, Water Resources, and others.
[b] Included one engineer with high school education.
[c] Included two engineers with high school education.
[d] Included one engineer with doctoral education.

3.1.2 Qualitative data collection

For the qualitative portion of the study, engineers were recruited through personal contacts of the research team and subsequent snowball sampling. Our qualitative sample is comprised of twenty-nine practicing civil engineers in the Pacific Northwest who self-identified as working in water resource engineering. Their experience and education levels were comparable to those in our quantitative sample.

Qualitative data was collected via clinical interview techniques [35]. Participants were presented, one at a time, with the four pressurized pipe flow problems diagrammed below. First, participants were asked first about what happened to velocity from point 1 to point 2, and then about pressure. After each response, participants were asked to explain why they thought velocity and pressure would change (or not change) in the way they predicted. The interviewer asked follow-up questions to elicit participants' conceptual understanding of the given problem and explore their deeper reasoning for their responses (e.g., could you explain what you mean when you say more water will have to "squeeze in" to the smaller section?). Interviews lasted between 20 and 40 minutes and were audio recorded. Audio recordings were transcribed and scrubbed of identifying information prior to analysis.

3.2 Data analysis

3.2.1 Quantitative analysis

For the present research, we focus on responses to a specific subset of FMCI problems. In particular, those which probe for understanding related to pressurized pipe flow. We focus on these problems for two key reasons. First, problems concerning flow in pipes are common across a range of fluid pumping and pipe flow systems. The underlying concepts that govern flow in pressurized pipes (i.e., conservation of mass, Bernoulli's principle) are ubiquitous across water resources engineering, and therefore engineers in this discipline should have some level of experience with and understanding of them. Second, these problems align with and build on existing research conducted in regards to student understanding of fluid mechanics concepts [3, 18]. By asking practicing engineers the same questions that have been used to explore student misconceptions, we can also begin to explore the persistence of particular kinds of misconceptions.

Quantitative analysis in the present study is limited to descriptive statistics for correct responses and distractors. Although researchers have used other concept inventories to assess overall understanding as well as understanding of specific subscores (e.g., [36], (Brown, Lutz, Perova-Melo, Ha, 2018, https://doi.org/10.1002/jee.20246)), such analyses were not possible with our current dataset. Both item and factor analyses conducted on the present dataset pointed to potential issues with particular items. Specifically, item analyses (e.g., difficulty and discrimination indices, point biserial correlations) suggested that many items might have been unsuitable for subsequent statistical analyses. Further, results from an exploratory factor analysis suggested that there were no coherent groups of problems that might be combined into concept subscores. Given these noted issues, we focus on a descriptive analysis of the four questions for which we have accompanying qualitative data.

3.2.2 Qualitative analysis

For qualitative analysis, we performed *a priori* coding based on prior research surrounding student misconceptions in fluid mechanics. In particular, we created a codebook based on findings from Brown, et al. [3] and Montfort, et al. [18]. We created four codes as shown below in Table 2. These codes were chosen because of their usefulness in describing students' understanding of fluid mechanics concepts, and so they represent a useful starting point

Table 2. A priori codebook developed from Montfort, et al. [18] and Brown, et al. [3]

Code	Definition	Example
Fluid Flow as a single idea	Conflating concepts of pressure, velocity, elevation, and depth into a single, higher order concept of "flow."	Incorrectly predicting that as velocity increases in a flow, pressure must also increase.
Physical features cause changes	Assuming that changes in velocity or pressure are directly caused by changes features of the pipe, while ignoring the dynamic balance between various system components.	Incorrectly attributing a contraction as the cause of increase in velocity of the fluid and ignoring components of upstream pressure.
Water is compressible	Treating water as if it has the properties of a compressible fluid and violating conservation of mass principles.	Describing water as "squeezing" into a tighter space. References to having to "push harder" through a smaller space. Same water in a smaller area.
Hydrostatics govern vertical pipes	Applying principles of hydrostatics to solve dynamic problems.	Describing sections lower in the pipe as having more "weight on them." Using depth alone to predict pressure changes in pipe flow.

from which to analyze our data. However, because our research involves practicing engineers, we also remained open to the possibility of additional emergent codes that might arise from our sample in particular.

Here, qualitative data was used to explain the findings in terms of why practicing engineers demonstrate particular levels of conceptual understanding [37]. While we will leverage participant quotes to explain our quantitative findings, we do not provide descriptive statistics regarding the percent correct and incorrect on qualitative questions. We believe the clinical interview format changes the context of participants' response in ways that make comparisons both challenging and analytically inappropriate. Participants in the qualitative portion of the study could ask (a limited range of) clarifying questions, think out loud, draw pictures, and change their answers multiple times. In contrast, respondents to the quantitative FMCI were provided a computer, but were not permitted to ask questions or prompted to explain their thinking during the task. Nonetheless, the reasoning used and rationale provided for responses to conceptual questions can illuminate important aspects of conceptual (mis)understanding demonstrated by engineers in both samples.

3.3 Limitations

Several limitations should guide the interpretation of this study. First, our data collection occurred via two independent samples. That is, the group of practicing engineers who provided the quantitative responses to the FMCI were not from the same group that participated in the clinical thinkaloud interviews. Therefore, any specific misconception in an interview cannot be explicitly linked to a misconception indicated by a distractor choice. Nonetheless, the population from which they were sampled (i.e., practicing civil engineers in the Pacific Northwest) is similar in ways that we believe allow qualitative explanations to provide elaboration for quantitative findings.

Second, the research focuses on a limited subset of the possible scope of the full FMCI. As noted, the full FMCI contains 30 questions and probes for a range of concepts that extend beyond laminar, fully developed, pressurized pipe flow problems. Therefore, our findings are limited to conceptions of pressurized pipe flow problems. However, the concepts that govern these particular problems (e.g., conservation of mass and Bernoulli's principle) span a variety of fluid mechanics problems, and so the findings from the present research might translate to other problems concerning the same concepts.

Finally, the wording of the problems deserves some scrutiny. While the horizontal pipe problems advised respondents to ignore gravitational effects, the vertical problems made a specific note that gravitational effects were "no longer negligible." While it is true that the answer would not change regardless whether one chose to consider or neglect gravitational effects (i.e., the pressure and velocity changes would be the same regardless), the fact that the problem mentioned that they were *not negligible* seemed to confuse participants. That is, the change in wording might have prompted participants to overestimate or focus on the influence of gravity in ways that negatively impacted their problem solving approach. Still, if one is assumed to understand the concept, we might reasonably assume they also understand the relatively small effect of gravity when compared to that resulting from the change in diameter of the pipe. And while these limitations should guide the interpretation of the study, they should not be interpreted as threats to the credibility or trustworthiness of our findings.

4. Results

Practicing engineers in our study expressed misconceptions described by our four *a priori* codes. Consistent with findings from research with engineering students, participants in this study demonstrated misconceptions regarding a number of fluids mechanics concepts. Participants often referred to *fluid flow as a single idea* or higher-order concept, thus conflating velocity and pressure. Participants also often made comments that implied a belief that *water was compressible*, and made predictions supported by that belief. They relied on physical features, equations, and other relationships that provided them with an *overly simplified causal model*. Finally, when participants were presented with vertical (as opposed to horizontal) pipes, concepts related to *hydrostatic pressure* became salient in their explanation of pressure and velocity changes through the pipe. Importantly, these codes were present in different ways in response to different questions. As a result, we present the results according to the individual questions that were asked both in interviews with participants (qualitative data) and on the FMCI (quantitative data). (When illustrating the presence of a particular code from Table 2, we will italicize the wording to clarify the reference.)

4.1 Question 2

Question 2 is a contraction from left to right as shown in Fig.1(a). The question asks about pressure and velocity of water as it flows from the larger diameter section to the smaller one. In this case, the pressure will decrease and the velocity will increase

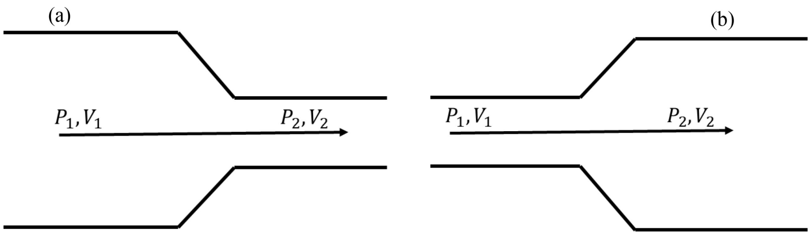

Fig. 1. (a) Schematic of Question 2 on the FMCI. Shown here, the pressure will decrease and velocity will increase through the contraction. (b) Schematic of Question 15 on the FMCI. This problem is reverse of #2, and the pressure will increase while the velocity will decrease through the expansion.

as the fluid moves from left to right. Shown in Table 3, about one third of engineers in our survey responded correctly, but a larger proportion selected response D, which suggests both pressure and velocity would increase through the contraction. Such responses are consistent with the conflation of pressure and velocity into a *higher order concept of "flow."*

Interview findings offered elaboration on engineers' responses. The following quote illustrates a participant *conflating the concepts of pressure and velocity* and combining them into some higher order concept of overall flow.

Respondent: The pressure's gonna increase in the smaller pipe.

Interviewer: Okay. And why is that?

Respondent: Because I'm having a velocity increase I'm gonna have a pressure increase. [Participant 126]

In the above passage, the participant directly relates the increase in velocity to a corresponding increase in pressure. Because the two factors are conflated, an increase in one implies an increase in the other, rather than the inverse relationship expressed by the different energy terms in Bernoulli's equation.

Participants also predicted increases in both pressure and velocity for reasons consistent with implicit beliefs that *water is compressible*. They often described the water as being "squeezed" into a tighter space or compressed so it can fit through the contraction. The following participant described why they believed both pressure and velocity would increase through the contraction.

Respondent: Velocity increases moving left to right.

Interviewer: And why is that?

Respondent: The cross-sectional area is reduced from the current and since we're talking about educational, you know . . . when you, it's just a ratio of the material.

Interviewer: Now what about pressure? What happens to pressure as flow goes through the pipe?

Respondent: The pressure will increase slightly.

Mark: And why is that?

Respondent: Because you've got more of an incompressible fluid, water in an area.

[. . .]

Respondent: These are still factors that come into play. As velocity increases, you have greater head losses but then you still have, you know, the pressure, you're trying to still push the same amount of water into the same . . . into a smaller area so the pressures do increase. [Participant 120]

Here the participant simultaneously notes that water is incompressible while describing the pressure increase that would result from "trying to still push the same amount of water." Such findings are especially interesting because even though the respondent stated that water is an incompressible fluid, the reasoning that followed would seem to run counter that assertion.

4.2 Question 15

Question 15 probes the same concepts as Question 2, but reverses the process. Shown in Fig. 1(b), water flows from left to right through an expansion, and the question asks respondents once again to predict the change in both pressure and velocity from one point to another. In this problem, pressure increases and velocity decreases as water flows from left to right through the expansion. Shown in Table 4, 21 engineers (21.9%) chose the correct response. At the same time, 64 respondents (66.7%) chose option A,

Table 3. Responses from practitioner survey on Question 2 of the FMCI

Answer Choice	Pressure	Velocity	Number	Percent
A	Decrease	Decrease	0	0%
B*	Decrease	Increase	33	34.4%
C	Increase	Decrease	6	6.3%
D	Increase	Increase	57	59.4%

Table 4. Practitioner responses to question 15 from the FMCI

Answer Choice	Pressure	Velocity	Number	Percent
A	Decrease	Decrease	64	66.7%
B	Decrease	Increase	7	7.3%
C*	Increase	Decrease	21	21.9%
D	Increase	Increase	4	4.2%

which suggests that both pressure and velocity will decrease through the contraction. Similar to Question 2, selecting response choice A is again potentially indicative of *conflating velocity and pressure* in to a higher order concept. Thus, while most engineers correctly understood how velocity would change throughout the pipe, they incorrectly predicted the change in pressure.

Interview responses from practicing engineers echo these findings, illustrated in the following quote:

> *Respondent: Velocities will go down [. . .] because we've doubled the areas, well I guess it doesn't say we've doubled the areas but it's a function of ah discharge and the area and so the velocities have to go down.*
>
> *Interviewer: What happens to pressure?*
>
> *Respondent: In this one here they're probably going to go down a little bit.*
>
> *Interviewer: What makes you say that about pressure?*
>
> *Respondent: I'm just trying to think that uh we've got a larger pipe and therefore well. I think the pressures are going to be about the same to tell you the truth.* [Participant 110]

The participant correctly predicts the change in velocity through the expansion, but similar to Question 2, they express confusion regarding changes in pressure. The participant initially stated that pressure would "go down a little bit" but changed their answer to say that pressure would stay the same. Neglecting gravitational effects (as instructed) in this problem would simplify the calculations for conservation of energy to include only two terms on either side—i.e., pressure and velocity. Therefore, to satisfy the necessary conditions for conservation of energy, a decrease in velocity must necessarily be accompanied by an increase in pressure.

In addition to conflating pressure and velocity, participants also responded in ways that suggested *inappropriate causal attribution*.

> *Respondent: Well, again the velocity will decrease as the flow diameter or the pipe diameter increases.*
>
> *Interviewer: Okay. And what happens to pressure then?*
>
> *Respondent: I'd say there'd be a slight decrease in pressure.* [Participant 126]

Here, the participant relates the change in velocity to a change in pipe diameter, which is correct. However, if the velocity goes down the pressure must increase, according to the conservation of energy. While participants seemed to understand that an increase in diameter was related to a decrease in velocity, they also used this reasoning to describe pressure changes—suggesting evidence for the use of overly simplified models in addition to conflating pressure and velocity.

4.3 Question 21

Shown below in Fig. 2(a) is Question 21, in which water flows vertically down through a pipe and enters a rapid expansion. The problem is conceptually similar to question 15, but rotated 90 degrees. While the question prompt noted that gravitational effects are not negligible, the changes in diameter will have much more influence on the pressure compared to elevation, assuming that there is more than minimal velocity. For example, if D2 is 3 × D1 then V2 would be V1/9 and this change in velocity would have a far greater effect on pressure than elevation.

However, for Question 21, participant responses shifted from those concerning the horizontal version of the same problem. Shown in Table 5, 30 participants selected the correct answer. And while the group of 30 is the largest single group of respondents, over half of respondents still selected an answer in which the change in pressure is incorrect (i.e., that pressure would increase as the fluid flowed from top to bottom). Although the orientation alone may be sufficient to change the way individuals think about similar phenomena, the notion that pressure decreases through an expansion, as shown by the preponderance of respondents who selected such responses, appears to transcend that change.

Response choice E would seem consistent with *conflating pressure and velocity*, and selecting B

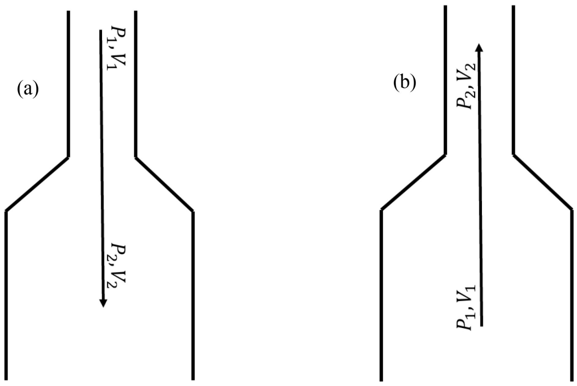

Fig. 2. (a) Schematic of Question 21 on the FMCI. Shown here, the pressure will decrease and velocity will increase through the contraction. (b) Schematic of Question 25 on the FMCI. Here, pressure will increase while the velocity will decrease through the expansion.

Table 5. Overview of practitioner responses to Question 21

Answer Choice	Pressure	Velocity	Number	Percent
A	No change	No change	9	9.4%
B	Increase	Increase	7	7.3%
C*	Increase	Decrease	30	31.3%
D	Decrease	Increase	21	21.9%
E	Decrease	Decrease	29	30.2%

might suggest the influence of *hydrostatic principles*, but it is less clear from quantitative data alone what might influence respondents to choose response D. The following quote demonstrates an engineers' thought processes as they work through the vertical pipe problem.

> *Respondent: [Velocity]'s going to it's going let's see. How important is gravity? Velocity is going to have to increase.*
>
> *Interviewer: Why is that?*
>
> *Respondent: Uh [sic] due to gravity.*
>
> *Interviewer: What happens to Pressure as water flows from top to bottom?*
>
> *Respondent: So the pressure is the pressure is. Oh man I should have reviewed my fluid mechanics before this. I feel like I need about a 15-minute refresher to get my thoughts straight to make sure but I mean just go with the I mean intuitively the pressure should decrease.*
>
> *Interviewer: And why is that?*
>
> *Respondent: Because the velocity is increasing*. [Participant 113]

This participant used a *simplified causal relationship* (velocity increases due to gravity, pressure decreases due to velocity) to incorrectly explain the behavior of the fluid in the pipe without accounting for the dynamic balance of different forms of energy.

Other times, participants reasoned that pressure would indeed increase as fluid moved through the expansion (i.e., got the answer correct), but attributed the increase to the wrong aspects of the problem.

> *Respondent: [Pressure will increase] because there is more material above when you are going down like a particle of water in the larger diameter section has more material above it than the particle of water in the smaller diameter section so the pressure would be higher. Just like more stuff above it pushing down on it. Maybe but yeah not really confident on that*. [Participant 103]
>
> [. . .]
>
> *Respondent: For pressure uh I'm struggling to draw the complete system of I mean if you're measuring if this is a static water column then water pressure would be more but if it's moving and you've got other things downstream because that's the governing pressure. So I guess I'm changing my answer pressure would increase. Now you can get my logic with that. Pressure should increase.* [Participant 102]

Here, notions of *hydrostatic pressure* come into play for participants, even though they are shown a problem in which the fluid is in dynamic equilibrium. And while it is true that a particle of water will face more pressure than another slightly above it, the changes in pressure due to the expansion of the pipe outweigh any gravitational effects related to height differential within the section. Even though the same concepts—and indeed, governing equations—apply in Question 21 as in Question 15, the fact that the water is flowing vertically seems to change the way participants reason through the problem. When the pipe was horizontal and gravity was negligible (as in Questions 2 and 15), participants were more confident in their responses, but introducing a vertical or gravitational element to the problem shifted their reasoning. Even though hydrostatic pressure changes would be too small to change the answer in this problem, participants were unsure how to account for an additional term and often incorrectly predicted the change in pressure.

4.4 Question 25

Finally, Question 25 is a 90-degree rotation of Question 2, in which water flows from bottom to top through a pipe contraction. Here, as in Question 2, the velocity of the fluid will increase and the pressure will decrease as it moves upward through the contraction. Shown in Table 6, similar to Question 21, while the largest single group of respondents did answer correctly, more than half selected responses suggesting that pressure would *increase* as water flowed upward. This finding is interesting because it runs counter to the notion that *hydrostatics* governs the behavior of vertical flow and instead seems to rely on *water as compressible.*

As the following quote demonstrates, the vertical orientation once again was a source of confusion for participants.

> *Respondent: Uh I think velocity would slow down uh yeah since it's working against the gravity it's getting more constrained the pressure would go up and then the velocity would decrease.* [Participant 106]

Now that the flow is moving in the opposite direction of gravitational forces, the influence of gravity altered the way participants reasoned about the changes in different components of energy within the flow (e.g., "since it's working against gravity. . ."). And again similar to Question 21, the orientation of the problem introduced aspects which participants perceived to dominate the behavior of the flow—even when effects would have been small relative to the other changes. The following participant quote demonstrates the significant influence of the direction of the flow relative to a gravity

Table 6. Overview of practitioner responses to Question 25

Answer Choice	Pressure	Velocity	Number	Percent
A	No change	No change	6	6.3%
B	Increase	Increase	35	36.5%
C	Increase	Decrease	15	15.6%
D*	Decrease	Increase	36	37.5%
E	Decrease	Decrease	4	4.2%

vector, indicative of a potentially *oversimplified causal model*.

> *Respondent: [T]he velocity decreases because it's going against gravity. I mean it could be going velocity 1 is going against gravity and velocity 2 is going to be less even though it's going into a smaller pipe* [Participant 113]

Again, the fact that the fluid is "going against gravity" implies the velocity will decrease over time. Height differences and *hydrostatic pressure* also became a common mechanism to explain changes in pressure on Question 25. In the following quote, the same participant correctly anticipates the change in pressure, but does so for the wrong reasons, leveraging hydrostatics alone to explain pressure rather than the fuller, scientifically viable explanation related to conservation of energy.

> *Respondent: [Pressure is] going to go down. Same reason as before. The velocity is flowing into an area where the pressure is less and it's flowing in there and it's accelerating so I'm going to say that pressure is less as it flows up.* [Participant 113]

Instead of considering the various aspects of the system in dynamic equilibrium, engineers in this study often relied on *overly simplified causal models* to explain the behavior of the fluid in the various pipe scenarios. And while it is technically true that, in a sufficiently long section of pipe, velocity would indeed decrease as fluid traveled further upward (converting kinetic energy into potential), similar to question 21, the contraction will result in changes much larger than those resulting from elevation changes in the same section.

4.5 Results summary

Engineers in both samples almost always correctly identified the direction of change in velocity, but often struggled to determine the correct changes in pressure in the same problem. Even though participants would identify water as an incompressible fluid, the misconception regarding pressure changes seems to arise from an inability to conceptualize the problem using principles of incompressibility. Participants often relied on overly simplified models to determine changes in pressure, and those models typically described a relationship between the physical features of the system and the flow itself. This misconception concerning pressure change seems to transcend both horizontal and vertical pipes, albeit in different ways. When solving horizontal pipe problems, participants discussed water in terms of compressible fluid dynamics. But when solving vertical pipe problems, concepts related to hydrostatics to determine changes in pressure along a "water column". Quantitative results indicate that while most participants can reasonably predict changes in velocity—for sometimes incorrect reasons—they tend to struggle with accompanying change in pressure. Qualitative results echoed these findings and added elaboration to the quantitative findings.

5. Discussion

The ways in which participant's conceptualized pressurized pipe flow problems seemed to remain relatively consistent across groups. Practicing engineers from both samples provided responses indicative of misconceptions related to the misapplication of principles of compressibility; relevance of hydrostatic pressure; use of overly simplified cause and effect relationships; and conflation of pressure and velocity into some higher order construct. Further, these findings add to a growing body of literature surrounding conceptual understanding and provide evidence for the robustness of particular fluid mechanics misconceptions. Our findings therefore echo existing research and extend the literature in ways that point to important questions about the way educators might articulate, teach for, and importantly, assess conceptual understanding of fundamental engineering concepts.

5.1 (Mis)Conceptions in practitioners

Interviews with practicing engineers revealed misconceptions in ways that aligned with our *a priori* codebook. That is, practicing engineers in our study articulated misconceptions related to four overarching concepts in fluid mechanics: (1) fluid flow is a single idea; (2) physical features of the pipe cause changes to the flow; (3) water is compressible; and (4) hydrostatics principles govern flow in vertical pipe problems. To situate our findings, we turn to related literature concerning student understanding in fluids (e.g., [18, 29, 30, 33, 38]) and discuss the ways our results extend prior research in conceptual understanding in terms of the four codes identified in our results.

First, the notion that fluid flow is a single concept comprised of pressure and velocity (among others) is evident in prior work investigating students' conceptual understanding in fluid mechanics. For example, Montfort, et al. [18] demonstrated the persistence of student misconceptions related to conflation of different components of Bernoulli's principle. Students hold beliefs about the behavior of the flow based on intuition, which ultimately prove incorrect for solving pipe flow problems [39]. Indeed, participants in our study frequently provided both quantitative and qualitative responses that would suggest a misconception related to the conflation of different concepts into some higher order amalgam of "flow." Many participants explained their responses by stating that because velocity would increase, pressure would also "have to increase."

Second, concerning the oversimplification of causal relationships, participants often used these simple relationships to make predictions about the change in the flow that were mathematically correct, but nevertheless overlooked many other aspects of the relevant principles (e.g., an increase in area will *cause* a decrease in velocity). Montfort, et al. [18] also demonstrated this effect in engineering students, who often assumed that "changes to any variable in the equation will cause corresponding changes to the other variable." And while there are *relationships* among variables in Bernoulli's principle, they are not necessarily able to be deconstructed into simple cause-and-effect sequences.

Third, participants in this study frequently articulated misconceptions regarding the treatment of water as an incompressible fluid. In some cases, participants would even declare the fluid as incompressible only to imply the opposite in the next sentence. This phenomenon has been illustrated in other research related to student understanding in fluid mechanics. For example, Brown, et al. [3] conducted a thematic analysis on interviews with engineering students and found that they treated water as if it were compressible. Results in the current study show participants describing the water as *squeezing* or *condensing* and a number of variations that all seem to imply a belief that water functions like a compressible fluid. Both Fraser, et al. [33] and Recktenwald, et al. [39] have documented student misconceptions surrounding pipe flow with changing diameters, and the present findings would seem to reinforce the fact that such fundamental misconceptions are persistent throughout school and work.

Finally, although all four problems examined in the present work are thought to be conceptually similar (i.e., they all require the same set of equations to solve and the behavior of the flow is qualitatively similar and consistent across all four scenarios), participants in our study seemed to employ fundamentally different problem-solving approaches when asked about vertical pipes versus horizontal. Rather than relying on Bernoulli's principle or the conservation of mass to predict pressure and velocity changes in vertical pipes, hydrostatic concepts suddenly became salient. Brown, et al. [3] also demonstrated this phenomenon with students who had received fluid mechanics instruction, but whom nonetheless relied on the inappropriate concepts to predict the behavior of the flow. Addressing and clarifying misunderstanding related to hydrostatic pressure remains a challenge based on inappropriate connections between mass, weight, and pressure [30]. Such evidence was echoed in the present work through participant descriptions related to "water columns" and points lower in the pipe having "more pushing on it" than those above.

The similarities in reasoning between practicing engineers and undergraduate engineering students point to the robustness of misconceptions. Montfort et. al (2009) argued that many of these misconceptions are resistant to change and remain even after completing relevant courses. Similarly, findings from this study show that engineers with practical experience with these concepts make predictions based on incorrect intuitive models and naïve reasoning patterns. That is, after practical experience with fluid mechanics concepts, engineers still seem to harbor misconceptions similar to those found in students. Though a discussion of the specific mechanisms of conceptual change are beyond the scope of this paper, future research should build on this work using such theories to unpack the concepts themselves. (e.g., ontological categorization [40], framework theory [5], or p-prims [41]). For instance, Brown, et al. [34] used a framework theory to explore the specific nuances of student misconceptions in mechanics of materials. Given the apparent persistence of these fluid mechanics misconceptions, it seems important to gain a deeper understanding of how individuals develop their understanding in ways that can more closely align them with a scientifically valid way of knowing.

5.1.1 Water resources in practice

A potential explanation for the practitioners' misconceptions is the relevance of the concept in this particular application to their day-to-day work. To be sure pressure and velocity are certainly important considerations for the design of piping systems. Pressure is important because of limitations of piping systems to withstand pressures and potential concerns with Net Positive Suction Head. Engineers may normally consider pressure on a larger scale in a system to make sure it is less than the design pressure of the piping materials. At the same time, however, they are less likely to consider pressure changes through fittings, because there is minimal practical relevance to knowing this.

Similarly, velocity is important because it relates to energy loss and scouring in some applications. For instance, understanding flow velocity is critical for thrust blocks applications (or concrete placed in pipe bends to guard against damage to the pipe and fittings) which alter the momentum of the flow. It may also be considered for fittings to match available diameters in pumps and other devices such as flow measurement. However, it is unlikely that engineers are concerned about change in velocity in an expansion or contraction. A similar example is "smooth" pipes and friction. In practice there is no such thing as a frictionless pipe, and virtually unheard of to not consider headloss due to friction in a piping system. Therefore, an engineer may interpret "smooth" as low friction, but likely not as no friction. In summary, the concepts as presented in these applications (i.e., the FMCI) may not be considered by our engineering participants, and water resources engineers in general.

This assertion could be examined by developing new conceptual questions that are more relevant to engineering practice and evaluating engineers' performance on these questions. One could also compare performance of these questions between practitioners and students. Doing so would begin to explain the role of contextual differences in concepts and conceptual understanding, and help improve the preparation of engineers for work.

6. Implications

Although our results seem to point to misconceptions, we think they also point to critical differences in the way concepts are understood at work when compared to school. That is, it is probably unfair to assume that because engineers provided incorrect answers that they do not understand the behavior of water flowing through a pipe. On the contrary, the manner in which engineers understand concepts such as conservation of mass or Bernoulli's principle or hydrostatic pressure might be qualitatively different. Indeed, the situations in which such principles apply might differ in critical ways and differences in context drive differences in knowing and understanding. It therefore seems important that future research explore the nature and use of concepts as they traverse contexts across school and work.

Our implications point to the potential to use this insight (i.e., practicing engineers' conceptual understanding) to guide curricular development and to further unpack the ways in which concepts might differ across these contexts. If researchers can more fully unpack ways of knowing that are important to practice, educators can more effectively integrate learning opportunities that can help cultivate that knowledge. Our research shows that practicing engineers struggle with basic fluid mechanics problems, but that struggle may be the result of working to eliminate factors that otherwise should be present. For instance, our problems instructed participants to ignore friction in the pipe, but friction can almost never be ignored in any practical application. (In fact, many practical problems concerning fluid flow in pipes center on calculating losses due to friction!) The fact that in practice concepts rarely exist in isolation is likely to influence the way a practitioner understands any one concept or group of relevant concepts. Future research should more deeply explore the ways in which practicing engineers employ fundamental engineering concepts as well as if or how those concepts—and their understanding of them—evolve over time.

7. Conclusion

Concepts and conceptual understanding are vital to the success of engineering education and practice. We rely on concepts to help us understand and describe the world we experience and, importantly, to make predictions about what will happen in the future. To gain a more complete depiction of fluid mechanics concepts, we investigated the problem solving approaches of practicing civil engineers. Using problems from the FMCI, we combined quantitative survey responses with qualitative clinical interviews to explore practitioner understanding of pressurized pipe flow problems. Similar to students, engineers in our study articulated misconceptions that led to both the incorrect application of principles and oversimplification of complex, dynamic relationships. Given that practitioners exhibit misconceptions in ways similar to those shown by students, educators should consider how to develop interventions that address and correct these persistent beliefs. By addressing fluid mechanics misconceptions in ways that target the core of the belief, instructors and other educational stakeholders can enhance learning and problem solving skills—skills that are crucial to effective engineering.

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