ACTIVE LEARNING IN FLUID MECHANICS: YOUTUBE TUBE FLOW AND PUZZLING FLUIDS QUESTIONS

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Active learning is an umbrella term for instructional methods used in the classroom in which students are actively engaged in the learning process, as opposed to a traditional lecture in which students play a passive role. Active learning can take many forms such as collaborative learning, cooperative learning, and problem-based learning.[1] Research has shown that such nontraditional methods may lead to improved academic achievement, retention, and student attitudes toward learning, depending on the method of active learning utilized.[1,2] Indeed, Felder, et al.,[3] have included active learning methods on their list of teaching methods that work. Courses on fluid mechanics are a particularly good match for active-learning techniques (see, for example, Reference 4), since everyday examples are ubiquitous.

In this paper, two active-learning modules targeted for use in an undergraduate fluid mechanics course are described. Materials for both have been designed and made available via the Internet (<http://hrenya.colorado.edu/Hrenya.php?page=teaching>) so that they can be incorporated by interested educators with little time investment. These modules involve several of the aforementioned forms of active learning, including both collaborative learning and cooperative learning.

The first activity involves a contest among small groups of students to correctly predict the outcome of tube-flow experiments using the mechanical energy balance. The students are first introduced to the experimental apparatus (gravity-driven flow from a tank), and then charged with predicting the outlet flow rates from various tubes. An announcement that prizes will be awarded to groups with predictions that best match the experimental data is also made at the start. The class culminates in the running of the experiments, and real-time identification of the "winners." This class period allows the students to put their knowledge into practice via active-learning, while also providing a high level of energy

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and enthusiasm due to the contest format. To facilitate use by other instructors, videos with an introduction to the apparatus and the collection of experimental data are available. A spreadsheet has also been developed in which group predictions and experimental data can be recorded, which is followed by an automated identification of the contest winners.

Unlike the tube-flow experiments which are best used just after the relevant material has been introduced in the course, the second activity is targeted at the final week of class. This week presents a challenge for instructors since any new material will not be assigned as homework and typically will not be covered on the final exam. As an alternative that involves active learning, creativity, and oral presentation skills, small groups of students are assigned a unique, puzzling question involving fluid mechanics and found in everyday life. These questions are assigned several weeks prior to the end of the semester, and each group presents its findings to the entire class during a short presentation (~6 minutes), often involving demonstrations, videos, etc. A current listing of these questions, which involve current events, sports, hobbies, and a bit of humor, is included below. Also available via the Internet are an example project description, signup sheet, and grading sheet.

Given below is a more detailed description of each of these activities and the corresponding course materials. Afterward, a student-based evaluation of both activities is summarized, followed by concluding remarks.

CONTEST: TUBE FLOW EXPERIMENTS ON YOUTUBE

Description. Knowing how to identify and solve fluid mechanical problems using the mechanical energy balance is an essential tool for engineers with a training in fluid mechanics. Typically, the basic equation, friction factor charts, and tables with loss coefficients for fittings, etc., are introduced in one lecture, with another lecture dedicated to example problems. The latter is justified given the different level of complexities that can be encountered—*e.g.*, a simple plug-and-chug solution when finding the pressure drop for laminar tube flow to a trial-and-error solution for sizing pipe diameters when the flow is turbulent.

In this class period, an alternative to the traditional lecture on example problems for the mechanical energy balance is given. Namely, a "contest" is set up for small groups to correctly predict the outcome of a tube flow experiment. The class takes three parts: (i) introduction of the tube flow experiment, including the specific measurements to be taken, (ii) small groups work to make predictions of the experimental outcome, and (iii) experiment is run, with small prizes given to groups with best predictions. The experimental apparatus, as shown in Figure 1, consists of gravity-driven flow from a tank, in which the height of the water in the tank is maintained constant. The water drains from the tank via three horizontal tubes located at the base of the tank, each with different lengths and diameters. Two of the tubes are flush with the wall of the tank, while the third protrudes into the tank. With the dimensions and the materials of the tank and tubes given, students are asked to predict the volumetric flow rate exiting from each tube. The mechanical energy balance forms the basis of this calculation[5]:

$$\frac{P_{out}}{\gamma}+\frac{\alpha_{out}\bar{V}_{out}^2}{2g}+z_{out}=\frac{P_{in}}{\gamma}+\frac{\alpha_{in}\bar{V}_{in}^2}{2g}+z_{in}-h_L \qquad (1)$$

where p refers to pressure, γ refers to specific weight, α is the kinetic energy coefficient (α =1 for uniform velocity profile and α =2 for laminar flow), g is gravity, z refers to vertical height, and h_L refers to the overall head loss:

$$h_L=h_{L,major}+h_{L,minor}=f\frac{\ell}{D}\frac{\bar{V}^2}{2g}+K_L\frac{\bar{V}^2}{2g} \qquad (2)$$

where major losses refer to frictional losses over straight piping of length ℓ, and minor losses refer to frictional losses associated with additional components (valves, bends, etc.); f is the friction coefficient, D is the pipe diameter, and the loss coefficient K_L is available from graphs and tables specific to component type.

To solve for the flow rate using the mechanical energy balance, students need to find a value for friction coefficient f, which depends on the Reynolds number Re, and hence on flow

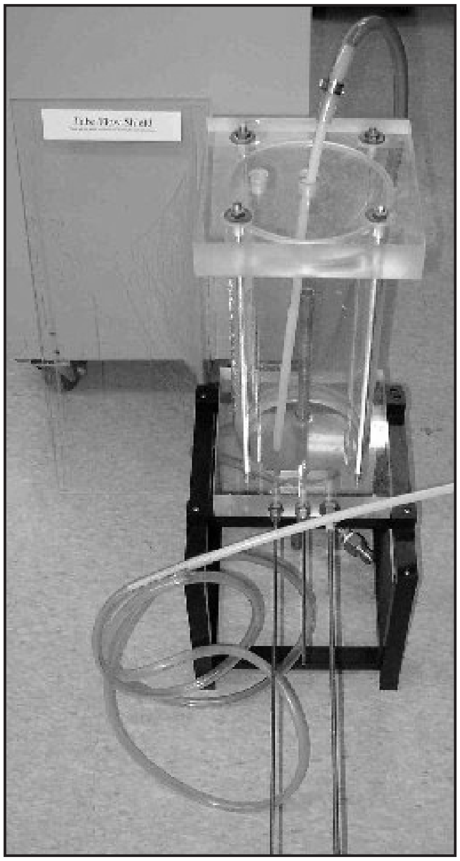

Figure 1. *Tube flow apparatus. The tank is open to the atmosphere and the water level is maintained at a constant height by means of a pump. Three horizontal tubes of different diameters, length, and entrance types (*i.e.*, flush vs. inserted) are located near the tank bottom. The flow rates emanating from each of these tubes are measured by means of a graduated cylinder and stopwatch.*

rate (for which they are solving). An analytical expression for f in terms of Re is only possible for laminar flow; otherwise, it must be determined using the Moody diagram and thus a trial-and-error solution for the flow rate is required. The tubes are designed such that flow rate from each is different, but all are near the transitional region. Accordingly, the student calculations should involve a combination of analytical and trial-and-error approaches, along with the checking of their initial assumptions (laminar vs. turbulent).

This exercise can be adapted easily to classes of different durations. In our experience, asking the students to predict flow rates from all three tubes is doable in a 1.25-hour period: 10 minutes to form groups and introduce experiment, 50 minutes for group calculations, and 15 minutes for tallying of predictions, running of experiments, and identification of contest winners. In the last few minutes, the general problem solution is also outlined, with detailed calculations given as handouts at the end of class. For a 50-minute class period, a reasonable variation would be to ask students to predict the flow rate from only one of the tubes. Either way, one may consider alerting students one class period beforehand to an upcoming "contest," in order to motivate their review of the material ahead of time.

Benefits. The benefits of this exercise include: (i) active learning with an ad hoc group of peers, (ii) in-class collection of data (via video) provides experimental verification of the mechanical energy balance, (iii) high level of motivation instilled due to contest format, and (iv) complexity of example problems not sacrificed, as the three-part experiment provides a range of straightforward to complex calculations.

Course Materials. Below is a listing of the course content for use by educators in their own classes:

1) *a YouTube video introducing the experiment to the class: <http://www.youtube.com/watch?v=cwcVnEMyCNU>;*
2) *an Excel spreadsheet that can be used to record the predictions of each group, record the experimental results [as obtained from video, see item (3) below], and then automatically determine contest winners: <http://hrenya.colorado.edu/Hrenya.php?page=teaching>;*
3) *a separate video showing the experiment being run and a "solutions" document with detailed calculations from the mechanical energy balance; interested educators should e-mail hrenya@colorado.edu with a request for this video from their university e-mail address.*

END-OF-SEMESTER PROJECT: PUZZLING QUESTIONS IN EVERYDAY FLUIDS

Description. The last week of the semester is typically reserved for course review, since the introduction of new material the week prior to final exams is challenging at best. In this variation on that theme, small groups of students answer unique questions related to a puzzling fluid mechanical phenomena seen in everyday life, the answers to which draw on the course content throughout the semester: buoyancy, turbulence, drag force, hydrostatics, surface tension, mechanical energy balance, dimensionless numbers, surface forces, etc. The questions are assigned several weeks prior to the end of the semester. During the final week of class, each group turns in a short report on their findings, and gives a 6-10 minute presentation to the entire class, in which illustrative calculations, demonstrations, and videos are encouraged.

Table 1 contains a listing of the project questions, along with the general topic area. Before the questions are revealed to the class, a sheet is passed around for students to sign up in self-selected groups, with each group having a unique group number. The project questions assigned to each group are then read aloud, generating a considerable amount of enthusiasm given the perplexing and often humorous nature of the questions. Because an aim of the presentation is to "teach" the class a variety of topics, students are asked to relate their content to the material presented previously during the course. Also, because of the varying degree of difficulty associated with the project questions, students are asked to make their own decision as to whether a full analysis with example calculations is possible, or whether the bulk of the material will be presented in a qualitative manner. Finally, students are encouraged to be creative in their presentations, using videos and in-class demonstrations where appropriate.

The presentations are intentionally brief. First, practical time constraints exist. Most recently, this project has been used with a class of 100 students forming 18 groups (five to six students / group). This breakdown allowed for 6-minute presentations (1 minute per student) and two additional minutes for questions and transition, which consume nearly the entire 150 minutes (for a three-credit course) during the last week of class. Because keeping to the schedule is critical, students are asked to treat this like a timed conference presentation and are encouraged to rehearse ahead of time. To further aid in keeping to the schedule, (i) the instructor stands with a minute left on the clock, (ii) an alarm goes off at the end of the allotted time, and (iii) a portion of the grade goes toward keeping under the time limit. Second, and perhaps more importantly, since fluid mechanics is typically required early in the chemical engineering curriculum (sophomore year), many students have not yet had an opportunity to orally present technical results to their peers. As such, nerves can be high, so keeping the presentations short and the environment both encouraging and informal helps to build confidence for future presentations.

The short report by each group on the puzzling question allows for more detailed technical feedback on the approach and corresponding calculations. Because these questions are intentionally open-ended and do not take the form of a typical homework problem where there is a single correct numerical answer (since different assumptions may be made in the analysis), students are encouraged to come to office hours to discuss their topic well in advance. As a result, the reported findings are generally scientifically sound, but regardless the instructor has the opportunity to give feedback at this stage.

On a final note, past students have more than risen to the occasion with a plethora of entertaining and effective demonstrations, like watching an egg sink in tap water but float in salt water to demonstrate the principles behind floating in the Dead Sea, making hourglasses of both sand and water to demonstrate the linear nature of timekeeping by the former but not the latter, etc. Furthermore, students are encouraged to add to the list of puzzling questions for use in future courses, and indeed several of the questions appearing in Table 1 have been put forth by former students. Additional suggestions are welcome (send to hrenya@colorado.edu), and will be shared with the community via inclusion on the website indicated below (see course materials).

TABLE 1
Puzzling Fluids Questions for End-of-Semester Project

#	Question	Topic Area
1	Why is sand used in an hourglass instead of a liquid?	Hydrostatics
2	Why does a golf ball have dimples?	Drag force
3	Why does a knuckleball appear to "dance"?	Drag force
4	If a graduate of this class was hired by the police in 2009 to determine whether Falcon Heene (a.k.a. "Balloon Boy") could be supported by his parents' homemade contraption, would he/she have recommended to continue the all-day, costly chase or search for the boy on the ground?*	Buoyancy
5	Why can a sailboat travel faster than the wind?	Drag force
6	Why can a water bug walk on water when I can't, and how big could the bug be?	Surface tension
7	Why is it easy to float in the Dead Sea and not in the ocean?	Buoyancy
8	When deep sea diving, why can't a really long snorkel be used for breathing?	Hydrostatics
9	Prior to 2002, the Colorado Rockies had difficulties recruiting pitchers due to the large number of home runs hit in Coors Field, and thus high ERA's. In 2002, the Rockies started storing their baseballs in humidors, leading to a dramatic decrease in home runs. Why was the number of home runs in Denver so high prior to 2002? What caused the reduction?	Fluid properties (density) / drag force
10	Why is it that I get more snow on my windshield when my car is stopped at a light than when it's moving, but I get more rain on my windshield when it's moving than when it's stopped?	Dimensionless numbers (Stokes)
11	How is body fat measured via the immersion method?	Buoyancy
12	How do water rockets work?	Force balance
13	In 2003, Denver taxpayers justified spending $165 million to build the longest runway in the United States (~3miles) to ensure the airport's competitiveness in attracting wide and heavy aircraft. Why are Denver's runways longer than those of most other airports? Why does this new runway see relatively more use during summer months?	Fluid properties (density)
14	What basic techniques should a swimmer use to maximize her efficiency?	Drag force
15	Why do cyclists draft one another? How much does it help / hurt the leader and the followers?	Drag force
16	Why is the aerofoil (wing) shape mounted upside down in race cars relative to its mounting in planes?	Lift force
17	The Falkirk wheel is a rotating boat lift in Scotland with a capacity of nearly 200,000 gallons. Why does the weight of the wheel remain the same when boats enter or exit? Why does it consume so little power given the huge weight being moved?	Buoyancy
18	What are the effects of some "dirty tricks" in baseball: (i) lubrication of ball and (ii) roughening/polishing ball surface?	Surface forces
19	How does a hot air balloon work?	Buoyancy
20	What is the "magic" behind the trick in which a piece of cardboard is put on top a glass of water, and then the cardboard/water stays in place when the glass is flipped?	Surface tension
21	Why does a curve ball curve?	Surface forces
22	Does the distance a discus is thrown depend more on drag or lift or both?	Surface forces
23	How do self-righting and self-bailing boats work?	Buoyancy / stability
24	Why does a boomerang return to the thrower?	Force balance

*Some useful assumptions: (i) balloon was constructed with tarps (typically made from HDPE) and duct tape and then filled with helium, (ii) authorities said the silver balloon, 20 feet long and 5 feet high, at times reached 7,000 feet above the ground while adrift (<http://www.cnn.com/2009/US/10/15/colorado.boy.balloon/index.html>), and (iii) balloon can be estimated to be an oblate spheroid.

Benefits. The benefits of this project include: (i) course material presented throughout semester is reinforced via peer instruction, including creative, student-generated demonstrations; (ii) students are exposed to a wide range of everyday applications of fluid mechanics, including current news stories; (iii) students work in self-selected group on question with open-ended nature; and (iv) students gain early experience in written and oral communication, with feedback from the instructor.

Course Materials. All materials listed below are available at the website <http://hrenya.colorado.edu/Hrenya.php?page=teaching>:

1) *list of puzzling questions, including those in Table 1 and to be updated with future suggestions;*
2) *sample signup sheet;*
3) *sample project description; and*
4) *sample grading sheet with point breakdown.*

EVALUATION

An anonymous, voluntary (online) survey was given at the end of the semester to get feedback from the students on their experiences with these active-learning exercises. Of the 97 students enrolled in the class, 46 students responded to the survey (~50%). The items surveyed are listed in Table 2, with results displayed in Figure 2a for the tube flow experiment and in Figure 2b for project on puzzling fluids questions. Overall, the student responses are quite positive, highlighting the learning value of these exercises relative to the traditional (non-active-learning) format and the added benefits of gaining experience with group work and the oral communication of technical material.

The survey also contained a section for open-ended comments addressing the best and worst aspects of each activity. Representative comments are included below.

Tube Flow Experiments—Best Aspects

- "Cannot overstate the benefit of actually observing how the equations we learn in class can be used in a real-time experiment."
- "the fact that we were able to see how the simplifying assumptions we made in class in order to solve the mechanical energy equation, as well as others (*e.g.*, Navier-Stokes), are actually applicable and pertinent, and not just things we do to make the problems easier."
- "allowed the student to become engaged in the solution, fusing academia with enthusiasm and a competitive spirit that promoted comprehension of the subject."

Tube Flow Experiments—Worst Aspects

- "I wish that we had been informed there would be a (competition) because I would have read and known better how to do the problem."
- "too little time"
- "slightly random nature of the answers—because the results were taken experimentally, somebody could have done the calculations exactly correct and yet not "won" the prize.

Puzzling Fluids Questions—Best Aspects

- "learning of how fluid mechanics affects our everyday lives without even knowing it"
- "It was great putting engineering minds together, and

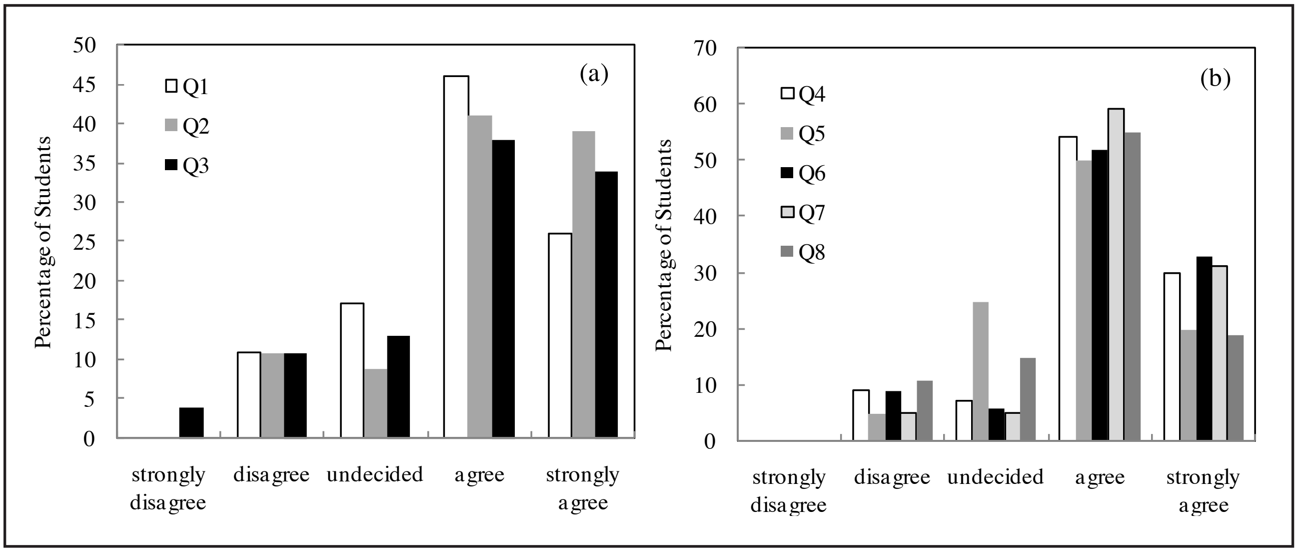

Figure 2. *Student survey results for (a) tube flow experiments and (b) puzzling questions in fluid mechanics. See Table 2 for listing of items surveyed.*

hearing each person's strong points about the particular problem. Groups can have a great deal of creativity with a cumulative effect from each individual."

- "learning about not only our project but other projects"
- "The projects were just plain fun."

Puzzling Fluids Questions—Worst Aspects

- "trying to get everyone to agree on ideas."
- "difficult to try to explain the concept and for everyone to talk and still keep it under 6 minutes"
- "having to talk in front of our peers (it was scary!)"
- "not all of the groups had applied fluids equations in an understandable manner"

TABLE 2

Items Used in Student Survey

See Figure 2 for responses.

#	Item
Tube Flow Demonstration	
Q1	This class period was a more valuable learning experience than a lecture with example problems.
Q2	The contest format (*i.e.*, prizes for winners) provided more focus and energy on the task than would have been present otherwise.
Q3	This class period was the most fun of the semester.
Puzzling Questions in Fluid Mechanics	
Q4	Attending these presentations and working on my own project illustrated the everyday relevance of fluid mechanics better than other means used during the semester (examples during lecture, homework problems, etc.).
Q5	Attending these presentations strengthened my understanding of basic fluid mechanical principles.
Q6	This project provided a good learning experience about working in teams.
Q7	This project provided a good learning experience for the oral communication of scientific ideas to peers.
Q8	This project provided a good learning experience in written communication of scientific ideas.

CONCLUDING REMARKS

In this work, two active-learning exercises appropriate for an undergraduate course in fluid mechanics are presented. Based on firsthand experience using these exercises with hundreds of students, it is found that the exercises effectively promote student interaction, give rise to thoughtful student questions, serve as good learning tools, and last but not least, add quite a bit of enjoyment to the class period for all involved.

ACKNOWLEDGMENTS

The author would like to express thanks to Will Brewer, who prepared the sample calculations and YouTube video. The author is also indebted to the students, teaching assistants, and colleagues who have contributed to the list of puzzling fluid-mechanics questions over the years. Funding support for this work was provided by the National Science Foundation (CBET-0658903).

REFERENCES

1. Prince, M., "Does Active Learning Work? A Review of the Research," *J. Eng. Ed.*, **93**, 223-231 (2004)
2. Smith, K.A., S.D. Sheppard, D. W. Johnson, and R.T. Johnson, "Pedagogies of Engagement: Classroom-Based Practices," *J. Eng. Ed.*, **94**, 87-101 (2005)
3. Felder, R., D. Woods, J. Stice, and A. Rugarcia, "The Future of Engineering Education: II. Teaching Methods That Work," *Chem. Eng. Ed.*, **34**, 26-39 (2000)
4. Ford, L.P. , "Water Day: An Experiential Lecture for Fluid Mechanics," *Chem. Eng. Ed.*, **37**, (2003)
5. Munson, B.R., D.F. Young, T.H. Okiishi, and W.W. Huebsch, *Fundamentals of Fluid Mechanics*, Wiley, New York (2009) ❒