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Improving Student Understanding and Motivation in Learning Heat Transfer by Visualizing Thermal Boundary Layers*

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The thermal boundary layer concept is an abstract topic due to the difficulty of direct observation. Three different approaches are used to allow students to visualize the thermal boundary layer for a geometry that is relevant to heat exchanger design. We focus on the case of a heated cylinder in cool water for both natural and forced convection. High-magnification videos of the boundary layer were made using a telecentric imaging system. Numerical simulations of the experimental system agree with observations. A set of ultra-low-cost desktop learning modules based on shadowgraphy were constructed to allow students to directly see aspects of natural and forced convection from a cylinder. Numerical simulations and telecentric imaging clearly show the initial diffusive growth of the boundary layer and subsequent onset of buoyant convection. When flow is initiated, both show a thinning of the boundary layer on the upstream side of the cylinder. The boundary layer itself may be impossible to see by eye for the low-cost experiment, however, the plume and disruption of the boundary layer by laminar cross flow can be seen. We implemented the thermal boundary layer visualization activities in a fluid mechanics and heat transfer course with 48 students. Numerical simulations and videos were shown after which the thermal boundary layer modules along with the worksheets were given to students. Statistical analysis of pre- and posttest results shows significant improvements for three out of five questions with moderate to very large effect sizes. Feedback is positive, with students finding the exercises interesting, helpful, informative, and well-explained. We believe that these visual representations aid learning and can actively engage students in the learning process.

Keywords: low-cost desktop learning module; thermal boundary layer visualization; shadowgraph; heat transfer simulations; hands-on learning

1. Introduction

Concepts related to thermal boundary layers (TBLs) are some of the more abstract concepts dealt with in heat transfer courses. One primary reason for this is that TBLs are normally invisible to us. Moreover, the solution of partial-differential equations describing heat transfer in stagnant or flowing fluids near solids is not practical without the help of computers except for special simple cases where similarity solutions exist, such as near the leading edge of a heated thin flat plate with parallel flow. For exterior flows, TBLs are often sketched in lectures as a curved line next to a flat plate representing the region whose temperature is affected by the boundary. In a study of student misconceptions in heat transfer based on student interviews, Jacobi et al. [1] found that students "have a vague physical picture of some of the mechanisms of heat transfer" and were "most certain about conduction" and "less certain about convection and radiation." Learning approaches that clarify the physical picture may be of help. One approach to tackle this issue is to visualize the TBLs. It has been shown in numerous studies that visualization is an efficient tool that actively engages students in the learning process and promotes student comprehension and assimilation of knowledge significantly [2, 3]. Past work in our institution with open channel flow hands-on learning equipment resulted in dramatic improvement in conceptual understanding of a number of directly observable flow phenomena such as the hydraulic jump [4]. The success in use of readily observable phenomena in repairing misconceptions has motivated us to develop a module to help students visualize the important concepts related to TBLs.

The work described here is part of a long-term effort to improve student problem solving abilities in the thermal fluids area by developing low-cost transparent miniaturized industrial equipment and associated learning materials [5–7]. A vacuum-formed shell and tube heat exchanger that allows students to see the flow configuration and measure temperature changes has been found to improve student understanding of how to properly select the control volume when applying energy conservation to find heat duty [5]. Although these cartridges are useful for helping with such systems-level concepts, they do not allow students to directly see the

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physical phenomena that govern heat exchanger performance. The first step in the current work was to develop and test a low-cost hands-on learning cartridge to allow students to observe some aspects of the convective heat transfer mechanism in a geometry relevant to shell and tube heat exchanger design.

The ultimate goal of the current effort is to improve problem solving ability in the area of heat exchanger analysis by developing students' conceptual understanding of some of the equations involved in this process. When experts solve physical problems in general, they are guided by conceptual reasoning in selecting the proper equations, in manipulating the equations, and in interpreting the results to see if they make physical sense [8]. Novices, on the other hand, typically try to find an equation with the right set of variables and then manipulate the equations mathematically without conceptual guidance. In the end, they may not know whether the answer makes sense physically [8–10]. Learning theory suggests that expert problem solvers are able to pull relevant pre-compiled knowledge structures from long-term memory into their working memory when solving a particular problem thus reducing the cognitive load relative to the novice who does not have such pre-compiled knowledge structures [9, 11–13]. In the context of multimedia learning of causal systems, the construction of mental models by learners is found to be enhanced when visual and verbal representations are held in working memory at the same time [14]. The synchronization of visual and verbal material minimizes the cognitive load required in the learning process itself [15]. In the analysis of shell-and-tube heat exchanger designs, it is necessary to predict the forced convection heat transfer coefficient for the shell side of the exchanger where liquid flows mostly perpendicular to tubes that carry a second fluid. The heat transfer coefficient is predicted from an appropriate correlation of the Nusselt number to the Reynolds and Prandtl numbers. In our experience, the process of selecting the proper correlation and combining it with the Nusselt number definition to solve for the heat transfer coefficient can be very abstract for the novice problem solver. It is hypothesized that a scaffolded approach that includes visualization will help students make the connection between the equations and the physical phenomena being modeled, that this will improve their conceptual reasoning in this area and finally lead to improved problem solving ability.

Many approaches have been used to assist learning through visualization. Videos have been produced for teaching complex subjects like fluid mechanics, e.g., a set of comprehensive, high-quality films were produced by the National Committee for Fluid Mechanics Films [16]. Similarly an interactive set of animations and videos was produced by Homsy (Multimedia Fluid Mechanics) which engages students with experimental and computational demonstrations [17]. Other Java-based interactive simulations and computational fluid dynamics simulations have also been used [18–22]. Interactive simulations facilitate learning by allowing students to reinspect the phenomena, e.g., by pausing and replaying the animation, zooming in on a specific part, controlling different parameters, etc. [23]. A meta-analysis of 76 pair-wise comparisons of dynamic and static visualizations, revealed that animations are better than static pictures in general [24]. A potential disadvantage of adding animation to a lecture is that it can induce the so-called "illusion of understanding" in some students [25]. Although the utility of videos and animations for learning a complex subject like fluid mechanics seems obvious, there has been little attempt to study the effects of viewing such materials on learning in this domain and there are still open questions about the effectiveness of direct observation of phenomena in real systems as well as combined simulation and direct observation.

Prior work on the classroom use of direct observation to teach heat transfer does not focus on TBL concepts specifically, and the experimental approaches tend to involve expensive equipment. Scientific imaging such as infrared thermography was introduced to science labs in schools as a useful tool to improve learning in heat transfer related subjects [26–28]. Xie [26] describes the use of infrared cameras by students to perform a set of experiments that cover conduction, convection, radiation, and heat capacity. Ambrosini et al. [29] provided a didactic description of holographic interferometry and schlieren imaging to introduce heat flow visualization into a laboratory course. They show good agreement between these two optical techniques for natural convection heat transfer in vertical smooth and rib-roughened channels. The current state of the art for visualizing convective heat transfer involves expensive equipment and a lower cost alternative is desirable.

We would like to study the effectiveness of the combination of simulation, video, and direct observation. In this paper, we present an educational application of shadowgraphy in visualizing TBLs. Two experimental approaches were developed for visualization of the TBL that forms around a heated cylinder submerged in cool water. Experiments involved a short hollow metal cylinder sealed between two parallel Plexiglas walls of a water tank to allow an end view of the cylinder submerged in cold water as hot water begins to flow through the cylinder. The apparatus also allows for the cold water to flow crosswise to the cylinder to see the effect of forced convection. One approach to visualization of the boundary layer in this kind of apparatus was to use a camera with a telecentric lens and collimated backlighting with the cylinder on the optical axis. This gives a detailed high-magnification view of the thin boundary layer during its initial diffusive growth and clearly shows the onset of buoyant convection and the effect of laminar forced convection. A low-cost version of this experiment was also developed that allows direct observation by eye of the buoyant plume formation and of the effect of weak cross flow. A finite element simulation of the experimental system was also used, both to confirm that the shadowgraphy images are correctly displaying the thermal boundary layer and as a way for students to see additional details. We present assessments of student learning, based on pre- and posttests, where we included questions related to student misconceptions about the TBL and its connection to heat transfer rate found during assessment of responses from a previous implementation. We surmise that student conceptual understanding of the TBL will continue to be enhanced with the help of these visual representations as we assess further implementations and promote dissemination of this pedagogical aid.

The shadowgraph technique is a research method developed and used for decades by scientists for flow visualization [30], but it can be applied as an effective learning tool in teaching heat transfer as well. Shadowgraphy is the least expensive and the simplest optical method that can be used for flow visualization in transparent media like air or water. It is similar but simpler than schlieren flow visualization. It works based on the fact that rays within a parallel beam of light are deflected by a transverse refractive index gradient. When a collimated beam of light passes through a flow field with a temperature distribution, it will be deflected as the non-uniform temperature distribution results in refractive index gradients. When the beam is projected onto a screen, an image called a shadowgraph is created from the varying light intensity. A typical experimental setup consists of a point light source, a parabolic mirror or lens to create a collimated beam, and a screen or camera for forming the image [30, 31]. Herein we describe two such systems, one more precise with higher contrast, but which uses more expensive equipment and a low-cost version that can be constructed by nearly anyone and yet be used to get across the major concepts.

2. Methods

2.1 Machine-vision camera videos

Figure 1 shows the schematic of the experimental setup used to take videos of the TBL that forms around a heated cylinder placed in a water tank filled with cool water. Rather than the traditional shadowgraph technique, we used a collimated light beam (LTCL36/G, Opto Engineering) directed along the cylinder axis and viewed this with a telecentric lens (TC2336, Opto Engineering) on a machine-vision camera (Scout, Basler). In principle, a telecentric lens allows only rays that are parallel to

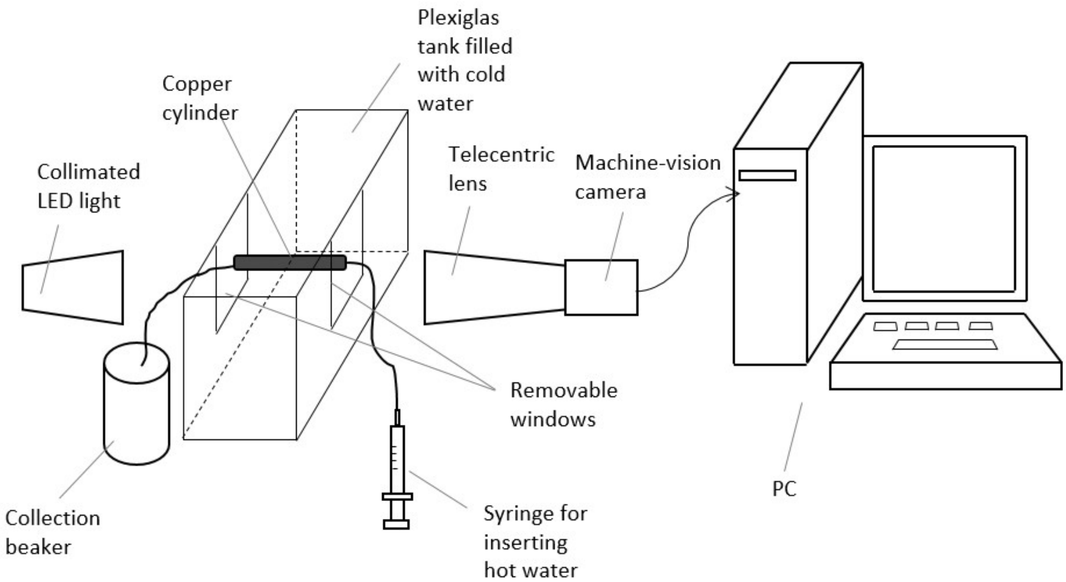

Fig. 1. Schematic of the system used for taking videos of the TBL, including the collimated light beam, telecentric lens, high-speed machine-vision camera, tank with removable windows, copper tube, syringe, collection beaker, pump, and computer.

the optical axis to reach the image plane of the camera. Thus, rays from the parallel beam that are refracted by the transverse refractive index gradient in the boundary layer are not received at the image plane, causing the boundary layer to appear dark in the images. The camera is connected to a computer where the digital videos are saved. A Plexiglas flow tank with inside dimensions of 2 inches wide, 24 inches long and 4 inches deep with special removable Plexiglas windows was designed in SolidWorks, cut out on a laser cutter, and cemented together. A hole is drilled in the window to insert a 2-inch long section of copper tubing with a 0.50-inch outside diameter and 0.25-inch inside diameter. This tank allows for end viewing of the TBL that forms around a heated/cooled cylinder placed in cold/hot water, respectively. The use of removable windows facilitates installation of the cylinder and would allow for different configurations such as multiple cylinders. Figure 2 shows the schematic of the window seal where several O-rings were used to seal the window hole. The ends of the copper tube were threaded for tube fittings. The tank is filled with cold tap water and hot water is caused to flow through the copper tube using a 60-mL plastic syringe connected to the copper tube by ¼-inch OD Tygon® tubing. The pump (Swiftech, MCP655-B) creates a flow in the tank perpendicular to the cylinder that allows for imaging the effect of forced convection on the boundary layer. The camera and the light are lined up and positioned at a distance that gives the best image resolution. Because of the high thermal conductivity of copper, a thermal boundary layer is observed to begin forming within only a few seconds of the start of hot water injection. The refractive index of the warm water around the heated cylinder is different from the cold water of the surroundings, so the parallel beam from the collimated LED beam bends according to the refractive index gradient and this results in the thermal boundary layer appearing dark when imaged with the telecentric lens. In the absence of forced flow in the tank, the imaging method described here clearly shows the initial diffusive growth of the boundary layer that lasts several seconds before significant buoyant flow develops. The effect of a low-speed forced cross flow on the boundary layer thickness is also clearly seen with this system.

2.2 Ultra-low-cost TBL module

The telecentric imaging system is expensive and generally not practical for classroom use because of a lack of portability and the delicate nature of optical alignments. The idea behind the ultra-low-cost TBL module is to make an affordable desktop learning apparatus that can be used to visualize TBLs. Figure 3 shows the schematic of the TBL learning module, consisting of a thin transparent water tank with an embedded metal cylinder, 60 mL syringe (Monoject), bright LED flashlight (Lux-Power), a piece of paper and a disposable 1-liter beaker. The Plexiglas tank has inside dimensions of 6” × 4” × 0.5” and is totally enclosed except for input/output ports on the ends. The tank parts were cut out with a laser cutter and cemented together with an acrylic solvent. A ½-inch long section of aluminum pipe with a 0.50-inch outside diameter and 0.25-inch inside diameter is glued with silicone between the walls of the tank. The aluminum pipe (McMaster-Carr) is an off-the-shelf part known as a spacer, so no machining was required. Holes in the tank walls were threaded for tube fittings to allow for hot water flow through the aluminum cylinder. Figure 4 shows the mechanical structure of the low-

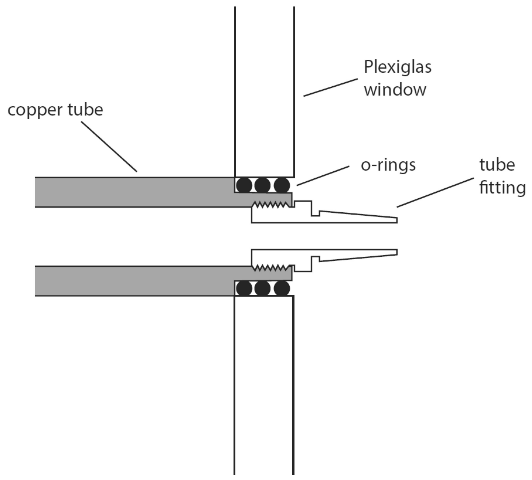

Fig. 2. Schematic of the mechanical structure of the window used in telecentric imaging experiment. O-rings were used to prevent water leakage from the ends.

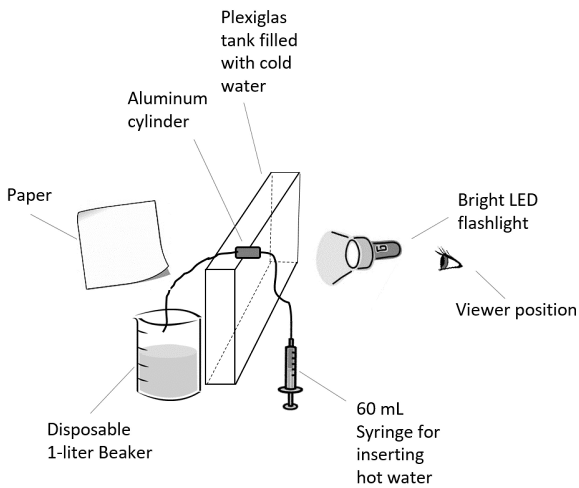

Fig. 3. The schematic of the ultra-low-cost TBL desktop learning module, including a flashlight, piece of paper, Plexiglas tank, aluminum tube, syringe, and the collection beaker.

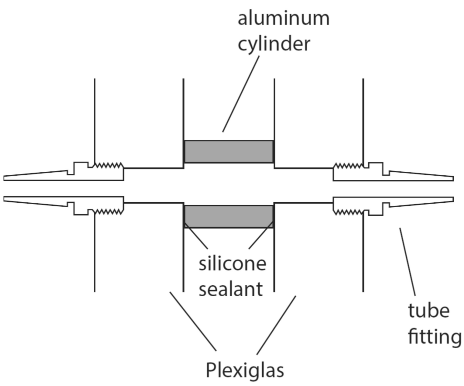

Fig. 4. Schematic drawing of mechanical structure of the low-cost TBL module.

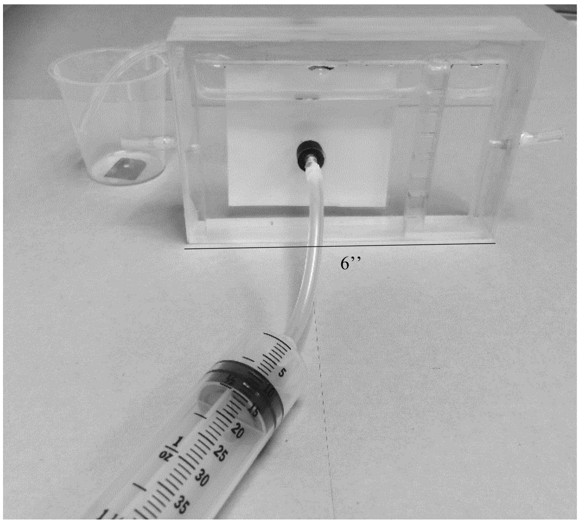

Fig. 5. The ultra-low-cost TBL module.

cost TBL module. The tank is filled with degassed, nano-pure water and about 0.5 inches of space at the top is allowed for sloshing the tank water back and forth to represent forced convection. A shadowgraph of the cylinder and the convection process is projected onto a piece of white paper taped to one side of the tank using the LED flashlight for direct viewing by the students. The light from the LED is collimated enough to eliminate the need of mirrors or lenses to make the light parallel. This makes the system much simpler than normal shadowgraph setups. Hot water is forced to flow through the pipe using the 60-mL syringe. Heat transfers from the hot water inside the pipe to the surrounding cold water and the resulting buoyant plume formation is easily visible on the illuminated sheet of paper. By sloshing the water in the tank, one can create an oscillating cross flow without a pump. A small battery-powered pump or gravity flow may be used to create steady forced convection if desired. In addition to allowing for visualization of the heat transfer process, the experimental configuration mimics the geometry of a baffled shell-and-tube heat exchanger. Visualization of the TBL and how its thickness changes with velocity in such a system can facilitate a discussion of heat exchanger design issues such as the role of baffles in shell and tube heat exchangers to increase fluid velocity and decrease TBL thickness which enhances the heat transfer rate. Figure 5 is a photo of the actual ultra-low-cost TBL module.

2.3 Two-dimensional COMSOL simulation

In order to test that the visualized boundary layer in the experiments correctly represents the boundary layer and as an additional pedagogical tool, we performed a two-dimensional finite element simulation using COMSOL Multiphysics. By coupling of heat transfer and laminar flow modules in a time-dependent study, we were able to simulate pure diffusion, and free and forced convection heat transfer from a heated cylinder surrounded initially by cold water. Heat transfer was modeled both in the solid cylinder wall and in the water surrounding the tube. On the inner tube wall, bulk temperature and a heat transfer coefficient were defined. We adjusted the model by changing the heat transfer coefficient to match the experimental conditions. The no-slip condition was enforced on the cylinder surface and at the tank wall as well. The container boundaries were all insulated. The model was run for the case of free convection and then for forced convection by adding a low-speed cross flow. The simulation results for free and forced convection at the experimental conditions are very similar to the videos and this comparison was shown to students to highlight the ability to model such complex physical phenomena. The model was also run for the case of zero gravity and a quiescent outer fluid to show what happens to the thickness of the heated layer around the cylinder in the absence of all convection (pure conduction).

3. Classroom implementation and assessment of learning

Six TBL desktop learning modules (DLMs) were implemented in a junior-level chemical engineering fluid mechanics and heat transfer course at Washington State University (WSU) during the spring 2017 semester. Units were used by groups of three or four students at a time in a class of 48 students meeting in their regular classroom with fixed tablet-arm seating. The six units were set up on tablet-arm desks along the aisles of the room, and two different groups took turns using each unit. The instructor gave a 15-minute lecture from PowerPoint where he reviewed the connection between TBLs and heat transfer coefficients and how this

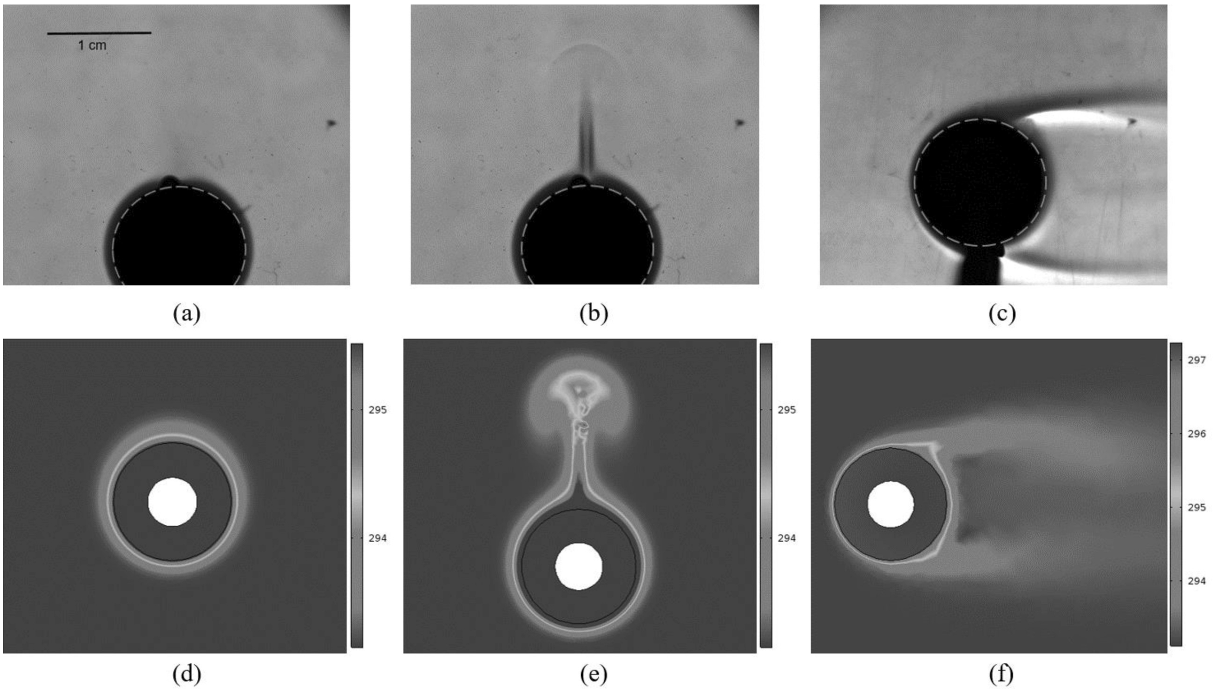

Fig. 6. (a)–(c) show one frame of each video taken by the machine-vision camera for pure diffusion (a), natural convection (b), and forced convection (c). Figures (d)–(f) represents one frame of COMSOL animation for each respective case. The dashed circle represents the actual diameter of the copper tube. Temperatures are in Kelvin in (d)–(f).

relates to shell-and-tube heat exchanger design issues. The thermal boundary layer videos, COMSOL simulation animations, and part of a short YouTube video [32] about flow visualization were embedded in PowerPoint slides as well.

Four video clips and three animations were shown to students. The first video showed a few seconds of the formation and growth of the diffusive layer around the copper cylinder before the plume forms. In the second video clip, students were shown both the diffusive growth of the thermal boundary layer and the subsequent convective plume. The third video was trimmed to only show students the forced convective plume. Corresponding COMSOL animations for each case were shown right after each of the video clips to allow students to see that there is good agreement between the experiment and simulations. The last video clip was a longer video showing the initial diffusive growth of the boundary layer, the subsequent onset of buoyant convection, and the thinning of the boundary layer when a pump is turned on. The simulations are in good qualitative and quantitative agreement with the experimental results. The formation and growth of the diffusive TBL lasts about 10 seconds before natural convection becomes significant. Then the buoyant plume forms and a vortex pair rises to one cylinder diameter above the copper cylinder in 3 seconds. The velocity of the buoyant flow was measured to be about 2 mm/sec by monitoring the movement of small dust fibers in the water from the video frames. The average thickness of the diffusive thermal boundary layer before the start of buoyant convection was about 1 mm and when pump flow was set to a velocity of $\sim$1 cm/sec, the TBL decreased to 0.5 mm on the upstream facing side of the cylinder.

To give readers an idea of what the plume looks like in the student TBL module, we took a series of photos using a macro lens, Fig. 7, showing the sequence of formation and growth of the convective plume.

There were 11 groups present in the class and

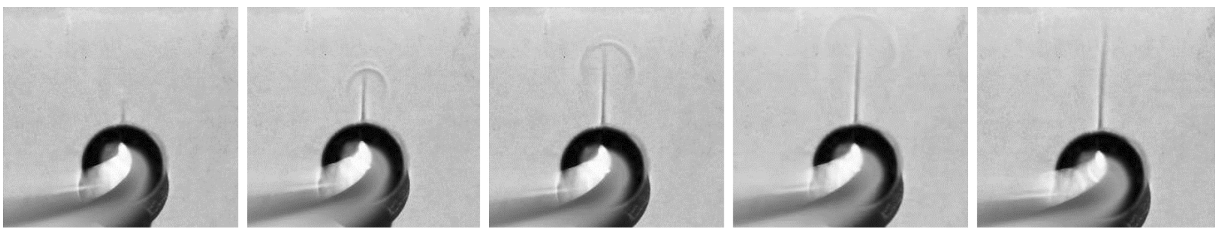

Fig. 7. Initial plume formation using the ultra-low-cost TBL student module illustrating roughly what is visible with the naked eye.

three professors and a graduate student available to circulate and interact with groups. Six groups started with DLMs observations while the other five started on other worksheet questions. Two worksheets were used, one for those groups starting with the observations and the second for those that did not start with the experimental units (see Appendix). However, the material and discussion activities were the same. The four instructors circulated amongst the groups that were making observations to help guide them through the activity and make sure they were able to see the natural and forced convective phenomena. Groups were able to make their observations within 5 minutes. During this time, room lights were turned off for better observation. All groups were finished with 23-25 minutes left in the class. Then they were asked to discuss the worksheet questions. Students were asked to describe and sketch the shadowgraph image they saw when the hot water flowed through the aluminum pipe, and on the same diagram to draw streamlines to show how they think the water surrounding the cylinder is flowing. Following the observation part, we had a reflection section with four questions to guide students in making the connection between the physical phenomena and practical aspects of heat exchanger design. In the first question, we asked students to explain what they would expect to see if they had injected cold water through the cylinder and the tank contained hot water. This type of question makes students think more deeply about the TBL, its origin and formation. The next three questions focused on forced convection and were designed to help students make the connection between factors that directly influence the heat transfer rate and heat exchanger design choices. One question was used to ask them to explain what would happen to the heat transfer rate if they started flowing cold water horizontally through the tank past the cylinder. We then asked them to consider what would happen to the heat flux from the cylinder if the tank width was cut in half while maintaining the same flow rate and tank height. In a final question, they were asked whether they see any relevance of these issues to the use of baffles in shell-and-tube heat exchangers.

For assessing the learning outcomes, we designed a short test using the online survey tool Qualtrics that focused on the connection between TBL and heat transfer coefficients and how this relates to shell-and-tube heat exchanger design issues. Students completed this online test during the session before the implementation and were asked to complete the same online test again immediately following the hands-on session when there were 5 minutes left in the class. The test consisted of five questions as outlined in Table 1. To design the questions for the pre/posttest, we used student misconceptions found and categorized in our previous implementation. We had previously implemented the TBL videos and COMSOL simulations in an introduction to transport processes course. This preliminary study helped us to find some of the student misconceptions about heat transfer mechanisms and TBLs. The first three questions in Table 1 are true or false questions targeting misconceptions observed from past student responses in three areas: the relation between the TBL thickness and heat transfer rate, the difference between temperature difference and temperature gradient and their relation to the TBL and heat transfer rate. Open-ended Question 4 is designed to see if students can think about the TBL concept in real applications. The fifth and final question was to test our hypothesis that a better physical picture of the heat transfer process would

Table 1. Description of pre- and posttest questions

Question	Description
Question 1	The thicker the thermal boundary layer is, the higher the heat transfer rate would be. (True/False)
Question 2	The thicker the thermal boundary layer is, the higher the temperature difference through the layer would be. (True/False)
Question 3	The thicker the thermal boundary layer is, the lower the temperature gradient would be. (True/False)
Question 4	One of the places where the thermal boundary layer plays an important role is in a shell and tube heat exchanger. Based on the thermal boundary layer concept, can you explain why baffles are favorable for heat transfer in shell and tube heat exchangers?
Question 5	Which one is the definition of the Nusselt number, Nu? (a) $Nu = 0.023\ Re_D^{0.8}\ Pr^{0.4}$ (b) $Nu = 0.027\ Re_D^{0.8}\ Pr^{0.3}(\frac{\mu}{\mu_s})$ (c) $Nu = \frac{hD}{K_f}$ (d) $Nu = 0.023\ Re_D^{0.8}\ Pr^{0.3}$

Table 2. Survey questions

1. How would you rate your experience with this demonstration (PowerPoint slides and hands-on activity)?					
Helpful	not at all true of me	2	3	4	very true of me
Interesting	not at all true of me	2	3	4	very true of me
Well-explained	not at all true of me	2	3	4	very true of me
Informative	not at all true of me	2	3	4	very true of me
2. What was the most interesting point of this demonstration for you?					
3. What was the muddiest point of this demonstration for you? (the point you did not like)					
4. What changes would you like to see in the way the thermal boundary layer demonstration is used to help students learn better in future classes.					
5. In one sentence explain the most important concept you learned about thermal boundary layers from this demonstration (PowerPoint slides and hands-on activity).					

repair the common student error of mixing up the definition of a dimensionless transport coefficient, such as the Nusselt number, with correlations for that coefficient.

For assessing the educational learning outcome, we did a question-by-question statistical analysis using a paired t-test of the scores. Our goals were to see if there were any differences in student answers between the pre- and posttest and to determine if improvements were significant for each particular question. For the open-ended Question 4 we developed a rubric, and three raters normed on a 25% sample when this question was used in a previous implementation. For the current implementation one of the normed raters rated all papers.

A short online survey was designed in Qualtrics to collect student feedback on the TBL implementation as summarized in Table 2. We were particularly interested to learn how students felt about the effectiveness of the TBL implementation for their learning. In the first question students were asked to rate their experience in four areas on a 5-point Likert scale, the next two questions were based on the minute paper technique (Questions #2 & 3) [13], the fourth question was used to ask for suggestions for improving subsequent implementations, and the final question was about the most important concept they learned from the implementation.

4. Results and discussion

4.1 Assessment results

Based on our observations in a previous implementation, many students had a vague understanding of TBLs. They did not have a good feeling of what the TBL is exactly, how it forms, and how it affects heat transfer rate. In questions related to the convective heat transfer mechanism, out of 78 students, only 20 made the correct connection to boundary layer thickness. There were 30 students who did not answer at all, implying they had little or no understanding of the concepts. Of those who did answer, but incorrectly, five said that a thicker TBL provides a more favorable heat transfer rate. One of these persons when asked to compare the heat transfer coefficient between pure diffusion, free convection, and forced convection said: "Diffusion has a higher heat transfer coefficient because the boundary layer is larger (thicker) around the surface."

Past students also were confused about temperature difference versus temperature gradient. Only 5% of reported answers showed proper understanding that it is the temperature gradient that affects heat transfer rate. Many answers revealed misconceptions or a lack of depth of understanding. For example, one student in response to the question of why on a snowy and windy day, we feel much colder than on a just snowy day, said that "wind causes a thinner thermal boundary layer $\rightarrow$ higher ΔT $\rightarrow$ you feel colder". In this example, ΔT, which is the temperature difference between the surface and bulk air, can be assumed constant, while the temperature gradient increases as the boundary layer becomes thinner resulting in a higher heat transfer rate. Our premise has been that these misconceptions can be repaired with improved teaching and learning strategies.

In the current implementation, a question by question paired t-test analysis of pre-/posttest results shows significant improvements for Questions 3, 4, and 5 (p-values less than 0.05). In Question 3, where we are targeting student misconception about the relation between TBL thickness and heat transfer rate, we observed an increase in average score (out of 1) from 0.31 to 0.58 with $p = 0.003$. For Question 4, which was focused on the TBL concept in real applications like a shell-and-tube heat exchanger, the average score increased markedly from 0.26 to 0.73 ($p = 0.000$). Question 5, used to test a student's ability to differentiate between the definition of and correlations for the Nusselt number, showed an increase from 0.56 to 0.73 ($p = 0.019$). The average scores on Questions 1 and 2, centering on the relation of heat transfer rate

Table 3. Data analysis of pre-test and posttest

Question	Shows Significant Improvement?	Means (Std. Deviation) Pre-test	Means (Std. Deviation) Posttest	t	P-value	Effect size (Cohen's d)
1	No	0.688 (0.478)	0.854 (0.357)	–1.94	0.059	0.282
2	No	0.291 (0.459)	0.396 (0.494)	–1.22	0.229	0.176
3	Yes	0.313 (0.468)	0.583 (0.498)	–3.08	0.003	0.444 (Medium)
4	Yes	0.255 (0.498)	0.734 (0.245)	–10.1	0.000	1.49 (Very large)
5	Yes	0.563 (0.501)	0.729 (0.449)	–2.42	0.019	0.351 (Medium)

with temperature gradient and temperature difference also show increases, although they are not statistically significant.

Effect size is a factor that is not affected by sample size and is used to quantify the magnitude of the difference between the averages of different populations. It tells us how well the intervention worked by emphasizing the size of the effect rather than its statistical significance. A Cohen's d around 0.2 would be interpreted as a small effect size, around 0.5 a moderate effect size, and around 0.8 a large effect size. Effect sizes larger than 1.0 would be interpreted as very large effect sizes [33]. Based on these categories, Questions 3 and 5 have medium effect sizes (~0.5) while Question 4 has a very large effect size (~1.5).

In summary, the statistical analysis shows a statistically significant difference for three questions out of five. Two of these questions are associated with a medium effect size and the other a large effect size. It is interesting to note that the question with the largest effect size was a question at a higher Bloom's level (applying and analyzing) compared to the other four questions (remembering and understanding). This is consistent with the findings of Burgher et al. [34] when miniature hands-on equipment is combined with interactive discussion environments. She reported higher learning gains for the experimental versus a control lecture-based group, and medium to large effect sizes at the higher levels of Bloom's taxonomy, such as the analyze, create or evaluate levels where for example students need to defend a solution based on evidence. This was attributed to the reduction of cognitive load, via visual and physical scaffolding. However, for learning at the lower levels of Bloom's taxonomy, conceptual gains were not statistically different with or without the hands-on experience.

4.2 *Student feedback*

Figure 8 shows student responses to the Likert-scale questions. These questions had 5 levels: level 1 if the statement is not at all true of the students; level 5 if it is very true of them and a number between 1 and 5

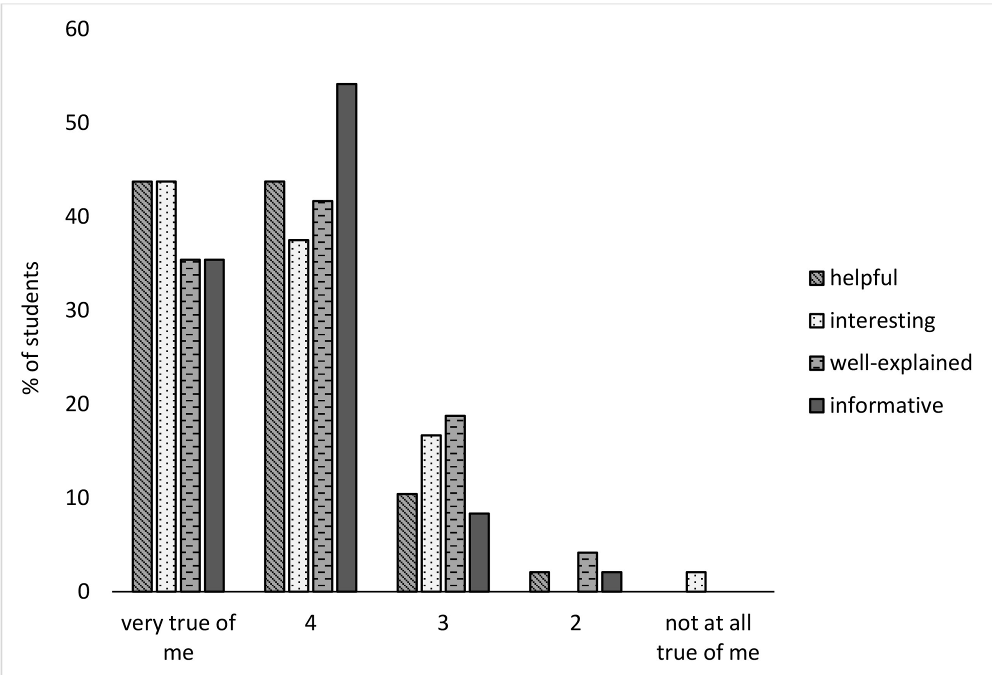

Fig. 8. Student responses to the Likert scale questions (n = 48). Most of the students rated the demonstration highly with an average of 84% selecting responses in the more favorable 4 – 5, true or very true of me, range.

that best describes them if the statement is more or less true of them. Most of the students rated the implementation highly. Looking at student ratings in Fig. 8, 88 % of them found the TBL implementation helpful or very helpful (level 4 and 5), 81 % rated it interesting or very interesting, 77 % believed it was well-explained or very-well explained, and 90 % of students think it was informative or very informative.

In Questions 2 and 3 of the survey, we asked students about the most interesting and the muddiest points of the demonstration, respectively. In total 94% pointed to the visual nature of being able to see the concepts in action with comments like:

- "It was interesting getting to see the experimental setup and apply what we have been learning in class, as well as actually getting to observe the thermal boundary layer. The COMSOL models were cool because they helped reinforce the concepts and showed different ways of obtaining the effects of the boundary layer."
- "Being able to see how this textbook stuff looks in real life. It is really hard to picture the boundary layer, so seeing it was great."
- "The most interesting part was being able to physically see the convection plume."
- "Actually being able to visualize the boundary layer, as well as seeing how accurately it could be modeled in COMSOL."
- "Actually being able to see it with a simple setup."
- "The most interesting point was how the boundary layer got thinner on the sides of the tube when sloshing was taking place."
- "Seeing the concepts in real life."

Student feedback was quite positive, with 63% of the class writing that they enjoyed the implementation and there were no unclear or muddy points about the TBL module. However, there were a few students who complained about the small size of the module.

In Question 4 we asked for suggestions for future implementations. In total 67% of the 48 respondents said that they do not have any suggestions by writing, e.g., "None. It made many things a lot clearer.", or "Nothing, I thought it was very effective", "Nothing really, pretty straight forward". We received good suggestions from students as well which indicate they were engaged with the TBL module. For example, some students suggested doing the reverse case as well with cold water in the tube and hot water in the tank. A few students suggested that a little more time would be helpful. One student suggested trying different shaped cylinders. Another suggested having enough setups for all the groups to do the experiment at once. It was also mentioned that lab space or a classroom with big desks would be better than tablet arm desks.

We agree with the students' perspectives. Although the student TBL modules were very compact and easy to use, implementation in a classroom with fixed tablet-arm seating was a challenge. Implementation in a room with tables would have made it easier for students to operate the experiment and make their observations. Having more units would have given students more time to work with the apparatus but requires more time for setup and takedown. The very low cost of these units makes it feasible in future implementations to give each student a module to take home to perform the experiments individually without time limits.

In the last question of the survey, we asked students to explain in one sentence, the most important concept they learned through the TBL implementation. Of the 48 responses, 10 students mentioned the relation between the TBL thickness and heat transfer rate; nine mentioned the beneficial impact of including more baffles on decreasing the area for cross flow to increase the velocity past the tube and thinning of the boundary layer; eight the relation between the velocity and the TBL thickness; seven said visualization that leads them to understand the heat transfer mechanisms; and seven just mentioned they learned the purpose of baffles in shell-and-tube heat exchanger design.

5. Conclusions and future directions

In this paper, we introduce and validate the use of shadowgraphy in combination with simulation and videos as an effective learning tool in teaching how the TBL affects heat transfer rates. First, we find that a simple bright, partially collimated, LED flashlight-based apparatus can be constructed that allows direct visualization and can replace a more expensive telecentric imaging system and is in sharp contrast to the more elaborate and expensive units used in research labs or commercially available educational equipment dependent on particle image velocimetry. In addition, this novel and inexpensive system provides TBL imaging that corresponds qualitatively and quantitatively to simulated plume formation in natural convection and TBL thinning in a flow field. While learning measures show statistical improvements between pre- and posttests with encouraging effect sizes, it will be helpful in future work to compare results with a control group. Furthermore, it will be important to differentiate gains based on the simulations, videos and hands-on experiences to see which are more important or if the combination itself is essential. The findings that greater improvements at the higher Bloom's levels are intriguing and in agreement with our previous work, however, a broader controlled study with multiple questions at each Bloom's level will be helpful to determine if the combined simulation, video and hands-on learning indeed proves better uniformly at the higher Bloom's levels. Again, it will be important to separate out the different learning elements in a controlled set of studies to determine which learning elements are most essential. Future work will also focus on whether knowledge gains from this type of activity transfer to problem solving skill in heat exchanger analysis. Student feedback and satisfaction rate is encouraging and opens the door for a fuller in-depth motivational and situated learning study. Finally, there are a host of other hands-on visualization studies that can be performed with this basic set up, such as use in different geometries, e.g., plates, fin-tubes, multiple parallel tubes, different media such as convective current above a flame, etc. and turbulent mixing by injecting fluid directly into the outer tank past a submersed object. Studies related to other transport phenomena such as mass transfer may also be possible. In summary, this low cost, yet robust technique and its impact on learning offers promise for teaching and student understanding of some of the more difficult mass transfer concepts.

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Appendix

Thermal Boundary Layer Worksheet

Group 1

Apparatus: A ½-inch long section of aluminum pipe with 0.50-inch outside diameter and 0.25-inch inside diameter is sealed between two parallel transparent walls of a small tank that is filled with cold water. A piece of white paper is taped to one of the walls of the tank for making shadowgraphs of the thermal convection process in the cold water. Hot water can be flowed through the pipe using a syringe. Heat will transfer from the hot water inside the pipe to the surrounding cold water.

Procedure:

1. Fill the syringe with the hot water.
2. Connect the syringe to the tubing that goes to the cylinder and place a beaker to collect the hot water coming out the other side.
3. Hold the flashlight at a distance of several feet from the tank, center the beam on the cylinder and try to align the beam with the cylinder such that you see a clear circular shadow of the cylinder on the paper.
4. Inject the hot water into the cylinder with the syringe at a slow steady rate (emptying the syringe in about 10 seconds).
5. Carefully observe the shadowgraph image formed on the white paper. You may need to get fairly close to see the fine details of the process.
6. Repeat this process and take turns amongst your group members making the observations.

Observations:

1. Describe and draw a sketch of the shadowgraph image you saw when the hot water flowed through the aluminum pipe. On the same diagram, sketch streamlines of how you think the water surrounding the cylinder is flowing. You can also try taking a still image or video with your cell phone.
2. If you gently shake the tank back and forth in the long direction to slosh the water in the tank during the injection of hot water what do you observe on the shadowgraph?

Reflection Questions:

1. What would you expect to see if you had injected cold water through the cylinder and the tank contained hot water? Draw a sketch and explain your reasoning.
2. What do you think would happen to the heat transfer rate if we started pumping cold water through the tank past the cylinder? Explain.
3. Imagine that we are pumping cold water at a volumetric flow rate of 10.0 mL/s through the tank. How would the velocity of fluid flow past the cylinder change if we reduced the width of the tank from ½ inch to ¼ inch while keeping the height constant? What would you expect this to do to the rate of heat transfer per unit surface area of the aluminum pipe?
4. Do you see any relevance of your observations to the design of shell and tube heat exchangers? Explain.

Group 2

Apparatus: A ½-inch long section of aluminum pipe with 0.50-inch outside diameter and 0.25-inch inside diameter is sealed between two parallel transparent walls of a small tank that is filled with cold water. A piece of white paper is taped to one of the walls of the tank for making shadowgraphs of the thermal convection process in the cold water. Hot water can be flowed through the pipe using a syringe. Heat will transfer from the hot water inside the pipe to the surrounding cold water.

Pre-Activity Questions:

1. Imagine that a cold horizontal cylinder is placed in a tank of hot water. How would the water surrounding

the cylinder move and how would the temperature of the water near the cylinder be affected? Draw a sketch and explain your reasoning.

2. For the apparatus described above, what do you think would happen to the heat transfer rate if we started pumping cold water through the tank past the cylinder compared to the case without pumping? Explain.
3. Imagine that we are pumping cold water at a volumetric flow rate of 10.0 mL/s through the tank. How would the velocity of fluid flow past the cylinder change if we reduced the width of the tank from ½ inch to ¼ inch while keeping the height constant? What would you expect this to do to the rate of heat transfer per unit surface area of the aluminum pipe?
4. Do you see any relevance of your observations to the design of shell and tube heat exchangers? Explain. (You should revisit this question after making observations.)

Experiment Procedure:

1. Fill the syringe with the hot water.
2. Connect the syringe to the tubing that goes to the cylinder and place a beaker to collect the hot water coming out the other side.
3. Hold the flashlight at a distance of several feet from the tank, center the beam on the cylinder and try to align the beam with the cylinder such that you see a clear circular shadow of the cylinder on the paper.
4. Inject the hot water into the cylinder with the syringe at a slow steady rate (emptying the syringe in about 10 seconds).
5. Carefully observe the shadowgraph image formed on the white paper. You may need to get fairly close to see the fine details of the process.
6. Repeat this process and take turns amongst your group members making the observations.

Observations:

1. Describe and draw a sketch of the shadowgraph image you saw when the hot water flowed through the aluminum pipe. On the same diagram, sketch streamlines of how you think the water surrounding the cylinder is flowing. You can also try taking a still image or video with your cell phone.
2. If you gently shake the tank back and forth in the long direction to slosh the water in the tank during the injection of hot water what do you observe on the shadowgraph?

Negar Beheshti Pour received her BS in Polymer Engineering at Tehran University and her MS in Chemical Engineering at Washington State University (WSU) where she also served as a teacher assistant. She is currently working towards a PhD in Chemical Engineering at WSU. In addition to her chemical engineering research in phase separation in microgravity, Negar is interested in engineering education and new pedagogies. Now she is working on low-cost versions of desktop learning modules.

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