Work-in-Progress: Visualization and Simulation of the Thermal Boundary Layer around a Cylinder as a Classroom Demonstration

Negar Beheshti Pour, Washington State University

Negar Beheshti Pour received her B.S. in chemical Engineering at Tehran University where she also taught as a teacher assistant. She is currently working towards a Ph.D. in Chemical Engineering at Washington State University under the supervision of Dr. Van Wie and Dr. Thiessen. In addition to her chemical engineering research into phase separation in microgravity, Negar is interested in engineering education and new pedagogies. Now she is working on the low-cost version of desktop learning modules.

David B. Thiessen, Washington State University

David B.Thiessen received his Ph.D. in Chemical Engineering from the University of Colorado in 1992 and has been at Washington State University since 1994. His research interests include fluid physics, acoustics, and engineering education.

Prof. Bernard J. Van Wie, Washington State University

Prof. Bernard J. Van Wie received his B.S., M.S. and Ph.D., and did his postdoctoral work at the University of Oklahoma where he also taught as a visiting lecturer. He has been on the Washington State University (WSU) faculty for 34 years and for the past 20 years has focused on innovative pedagogy research and technical research in biotechnology. His 2007-2008 Fulbright exchange to Nigeria set the stage for him to receive the Marian Smith Award given annually to the most innovative teacher at Washington State University and in 2016 he received the inaugural WSU Teaching Innovation a Award.

Work-in-Progress: Visualization of the Thermal Boundary Layer around a Cylinder Using a Shadowgraph Technique as a Classroom Demonstration

Abstract

This paper presents the educational application of shadowgraphy in visualizing thermal boundary layers. The thermal boundary layer concept is an abstract topic due to the difficulty of direct observation. In this work, we use a collimated light beam for illumination and a camera with a telecentric lens to visualize the thermal boundary layer that forms around a heated copper tube placed in a tank containing cold still water. The video clearly shows the initial diffusive growth of the boundary layer and the subsequent onset of buoyant convection. Then when flow is initiated, a thinning of the boundary layer on the upstream side of the cylinder is clearly visible. After showing video clips in two sections of an Introduction to Transport Phenomena course, student feedback was very positive; they found it interesting and helpful. We believe this visual representation aids in learning and can actively engage students in the learning process.

1. Introduction

Concepts related to thermal boundary layers (TBLs) are some of the more abstract concepts dealt with in heat transfer courses. They are not only difficult for students to learn but also difficult for instructors to teach. One primary reason for this difficulty is that TBLs are normally invisible to us. Moreover, the solving of partial-differential equations describing heat transfer in stagnant or flowing fluids and illustrating solutions on two-dimensional surfaces is not practical without the help of computers except for special simple cases like a thin flat plate with parallel flow. Thermal boundary layers are often sketched in lecture as a curved line next to a flat plate representing the region whose temperature is affected by the boundary. Based on the authors' observations, many students even near graduation have not fully understood this concept and have some misconceptions about it. A study of student misconceptions in heat transfer based on student interviews found that they "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" [1].

One approach to tackle this issue is to visualize the TBL. 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 [2]. Many free, open-source Java-based interactive simulation tools have been developed to enhance student understanding of heat transfer [3-7]. Besides computer simulations, considerable work has been done to engage students in learning heat transfer through simple, portable and low-cost classroom hands-on activities [8-11]. However, none of these works specifically focus on the TBL concept. To the best of the authors' knowledge, no prior work is available that uses the shadowgraph method for visualizing the thermal boundary layer for in-class education purposes.

In this paper, we present a shadowgraph technique to visualize and create a video of the TBL that forms around a heated cylinder placed in water tank filled with cool water. The video shows the initial diffusive growth of the boundary layer, the formation of a buoyant plume, and finally the effect on the boundary layer of forced cross flow. We surmise that student conceptual understanding of the TBL will be enhanced with the help of this visual representation.

2. Methods

2.1. Shadowgraph

Shadowgraphy is a research method developed and used for decades by scientists for flow visualization [12] but there is no reason it cannot be applied as an effective learning tool in classroom teaching of heat transfer. The shadowgraph technique 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 a parallel beam of light changes its direction according to the refractive index gradient. When a collimated light beam passes through a flow field with a temperature distribution, it will be deflected as the non-uniform temperature distribution leads to a non-uniform refractive index within the fluid. Hence, refracted light rays cast a shadow with varying light intensity to produce the shadowgraph. After passing through the fluid, the light beam may be projected onto a screen or can be refocused by another lens or mirror and recorded by a CCD camera [12, 13].

2.2. Experimental apparatus

The shadowgraph visualization setup is simple, including a point light source, a couple of mirrors or lenses, a screen or a CCD camera to capture the images [12]. Instead of a point light source along with a mirror or lens to make a parallel beam of light, we use a collimated LED light source, and a machine-vision camera with a telecentric lens, that only receives light rays parallel to the optical axis, is used instead of a screen and a lens or mirror to refocus the image. Fig. 1 shows the schematic of the set up. The camera views the cylinder from the end and the light beam is parallel to the cylinder. The collimated light passes through the non-uniform test section and the captured images recorded by the camera are saved on the computer.

A Plexiglas flow tank with inside dimensions of 5 cm wide, 30 cm long and 10 cm deep with special removable windows was designed in SolidWorks, cut out with a laser cutter, and cemented together. A hole is drilled in the Plexiglas window to insert a 0.5-inch diameter copper tube. This tank allows us for end viewing of the TBL that forms around a heated or cooled cylinder placed in cold or hot still water, respectively. For the forced convection experiment, water is pumped through holes embedded in the tank wall. Having removable windows enables us to use the tank for different experiments (different tube sizes, numbers and materials) and allows us to save time and materials as we just need to make a new set of windows rather than requiring an entire new tank.

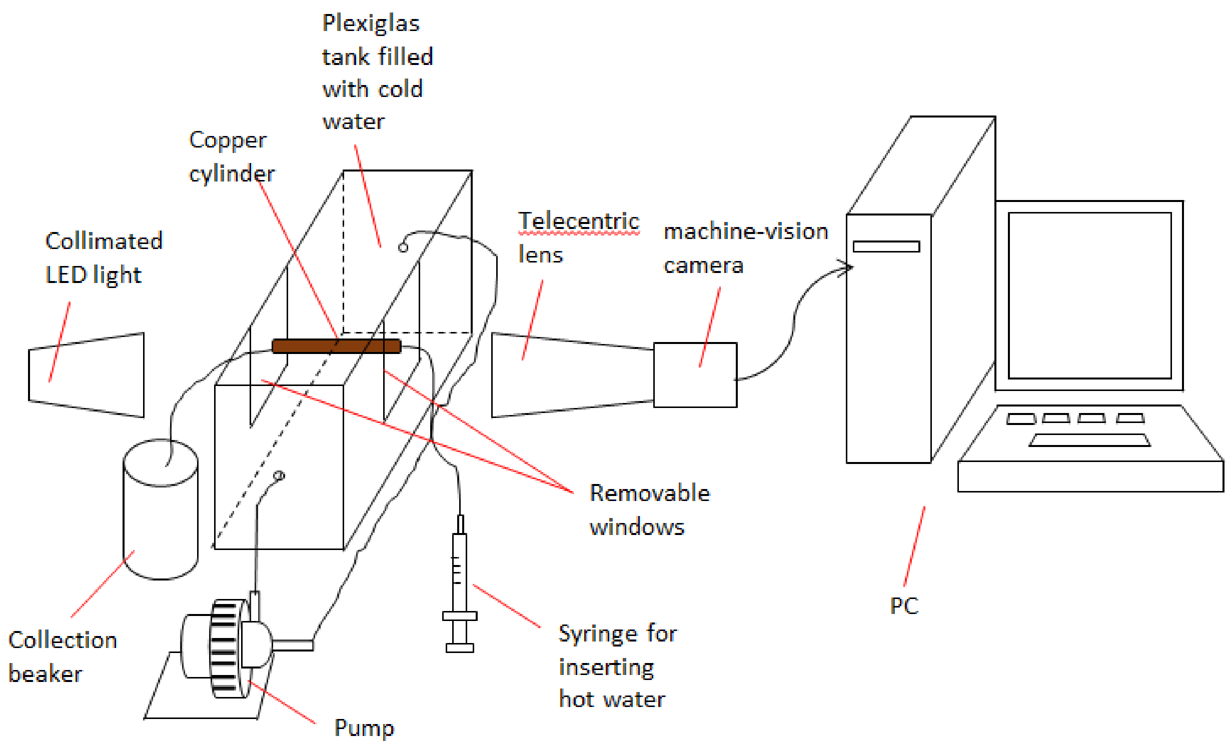

Fig.1. The schematic of the system, including the collimated beam of light, telecentric lens, machine-vision camera, tank with removable windows, copper tube, syringe, collection beaker, pump and the computer.

2.3. Procedures

To run an experiment, the tank is filled with cold tap water and hot tap water is injected into the copper tube through the connecting tubing with a syringe. The camera and the light are lined up and positioned at a distance that gives the best image resolution. As the hot water flows through the copper tube, the water around the heated tube warms up rapidly due to the high thermal conductivity of the copper. The refractive index of the warm water around the heated cylinder is different from that of the surrounding cold water, so the parallel beam coming out of the collimated LED light source bends according to the refractive index gradient and casts a shadow. The telecentric lens further enhances the contrast since it discriminates against rays that are not parallel to the optical axis of the lens.

2.4. Classroom demonstration

The recorded videos of the TBL were shown to two sections of the Washington State University ChE 310, Introduction to Transport Phenomena course within a PowerPoint presentation. The setup was first explained to the students and a very short YouTube video was used to demonstrate for students how the optical system works. One section with 25 students (control section) was taught the TBL concept through traditional lecture and the other section with 53 students (experimental section) had the traditional lecture along with the video. We did not use a pretest in this implementation as the TBL concept is quite new to ChE 310 transport students and one can assume they initially know very little about it, rather the semester-average quiz grade of each section before the implementation will be used as a reference instead of a pretest. Both groups took the same posttest where students were asked about the TBL effect on the heat transfer rate. The control section saw the video after the posttest, and both groups were asked to complete a short survey about this demonstration.

3. Results and Discussion

Figure 2 is one frame of the recorded TBL video for diffusion heat transfer, taken approximately 2 sec after the start of hot water flow. The dashed line represents the actual diameter of the copper tube. There is no significant natural convection until approximately 10 sec after the start of hot water flow; the effects of diffusion are clearly seen as the boundary layer forms uniformly around the cylinder heated with hot water from the inside. At this point, the posttest analysis has not been finished, but preliminary results show that there are some misconceptions among the students about the TBL concept, e.g., some students believe that pure diffusion has the highest heat transfer coefficient because, e.g. “molecules are closely packed” or “the boundary layer is larger (thicker) around the surface”. Hence, one of the benefits of this implementation is to find out student misconceptions and design appropriate questions that address these misconceptions for future implementations. The assessment results will be reported in the conference. Based on the student answers to the survey, they found this demonstration very helpful. For example, when asked about the interesting points of the implementation, the students made the following comments:

- "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."
- "It was interesting getting to see the experimental set up and apply what we have been learning in class, as well as actually getting to observe the thermal boundary layer…”

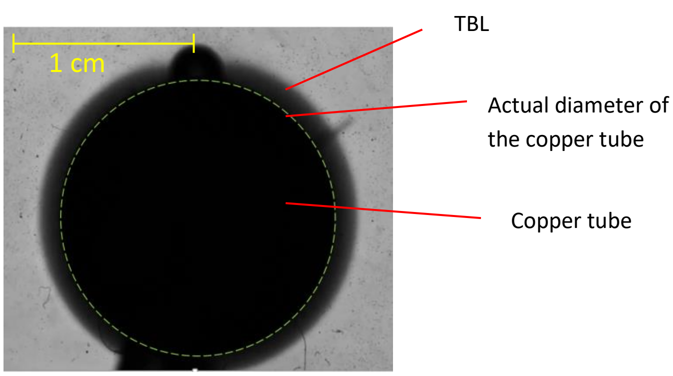

Fig. 2. Image from the video during the first few seconds following the start of hot water flow through the cylinder showing the diffusive growth of the boundary layer before buoyant convection became significant.

4. Future work

For future work, it is desired to enhance the video presentation to emphasize why thicker boundary layers increase the resistance to heat transfer, and to highlight why natural and forced convection scenarios enhance heat transfer. We will also show videos of the TBL under various conditions of free and forced convection as well as COMSOL finite element model animations of the same cases for comparison in an applied fluid mechanics and heat transfer class. We will develop in-class interactive small team exercises that help students translate what they see in the videos to practical heat exchangers. From an assessment point of view, lingering student misconceptions associated with the TBL from the transport class will hopefully be repaired. However, where misconceptions persist or new ones are revealed through posttest assessments we will modify videos, simulations and in-class activities as necessary and re-test the approach in subsequent course offerings.

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