Development of a Flow Visualization Apparatus for Fluid in a Rotating Cylinder

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This work is in two parts. In the first part we propose a flow visualization technique to observe the flow behavior in a closed system. Experiments of this nature require the flow visualization material be added at the beginning of the experiment and remain stable with the flow during the course of the experiment. We also attempted to satisfy the condition of neutral buoyancy with our flow visualization media. The second part constitutes the construction of a structure to rigidly support a platform and a drive mechanism to rotate a fluid confined to a right circular cylinder about a horizontal axis.

INTRODUCTION

Flow Visualization

This study was designed to observe the behavior of fluid confined to a rotating right circular cylinder in the instances of rotation about a vertical axis and horizontal axes. Both situations require the flow visualization material be added once to a fixed volume of fluid in the confining vessel.

We adopted a minimal number of conditions that we wished our flow visualization material to satisfy: (1) brightly colored for photographic, video, and visualization purposes, (2) immiscible in water (the bulk fluid) so it would not be absorbed, (3) neutrally buoyant so it would not exhibit any behavior influenced by density differences between the flow visualization material and the bulk fluid, and (4) emulate the behavior of a similar fluid element of the bulk fluid.

The first condition from the list above amounted to having a number of brightly colored immiscible fluid droplets in water. G. I Taylor (1932) did work that dealt with the stability and droplet size of oil droplets in water subjected to a shear stress. Our droplet idea had theoretical credibility based on his work.

We anticipated testing condition 4 from the list above by using the colored immiscible droplet in a known flow situation, such as the flow in a partially filled cylinder rotating abut a vertical axis of rotation, this is a well known flow situation. Aliphatic hydrocarbons are reasonably immiscible. Gasoline and water mixed together is an example; however, this fails in the neutrally buoyant part of the criteria. Halogen containing hydrocarbons, such as carbon tetrachloride, exceed the density of water, and if one could prepare the appropriate mixture of aliphatic hydrocarbon and halogen containing hydrocarbon one would have a neutrally buoyant immiscible fluid. The brightly colored part of the liquid could be formed by adding some agent that was soluble in the immiscible phase but not soluble in the aqueous or bulk fluid.

In the following section we illustrate some of the flow visualization agents employed along with experimental observations of some visualization methods for static and rotating fluid situations.

Support Framework for Drive Drivelines and Cell Assembly for Rotating Fluid about a Horizontal Axis of Rotation

We were advised by Dr. Evan Lemley in the Department of Physics and Engineering at the University of Central Oklahoma

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(personal communication, 2002) about structures and trusses built to withstand large loads under a variety of conditions. He recommended a truss structure from Hibbeler (1993), which we adopted as the base unit of our structure. The details are given in the Materials and Methods.

MATERIALS AND METHODS

Flow Visualization

We attempted flow visualization efforts with traditional items, such as dyes and food coloring. They have some inherent difficulties, including becoming diluted in the bulk fluid over time, which makes their integrity an issue. They are also more dense than water (Smits and Lim 2000) and must be diluted to become neutrally buoyant. We illustrate a couple of examples of our experiments in Figs. 1 and 2. The examples show qualitative features of the flow field apart from the density problem, but they are plagued by the physical phenomena of diffusion and were unsuitable for our purposes. Color photographs of the figures in this paper are given in a version of the paper posted on

Figure 1. Green food coloring employed as a flow visualization aid. The food coloring trace emulates the qualitative features of the fluid motion apart from the change of elevation of the dye.

Figure 2. Crystal Violet employed as a flow visualization aid. Stain shows some departure from actual fluid motion

the website www.physics.ucok.edu/~dmartin/ at the link Taylor Paper.

We resorted to our plan mentioned in the introduction. We wanted a fluid that was immiscible in water, neutrally buoyant, and brightly colored. We consulted with Dr. D. M. Hellwege an organic chemist in the Department of Chemistry, University of Central Oklahoma, who suggested (personal communication, 2003) a mixture of pentane and methylene chloride with solid iodine as a coloring agent. He suggested this mixture because it was the least toxic mixture that would satisfy our problem.

We solved the neutral buoyancy problem with Archimedes's principle. The solution is $V_1/V_2 = (1 - \rho_2)/(\rho_1 - 1)$, where V_1 is the volume of the high density component, V_2 is the volume of the low density component, ρ_2 is the density of the low density component, and ρ_1 is the density of the high density component. The high density component used was methylene chloride, and the low density component was pentane. We have assumed an average density of the mix of 1.00 g/cm^3, and the total volume of the mix was the sum of the original volumes. We obtained our stock methylene chloride, pentane, and solid iodine from the Department of Chemistry at the University of Central Oklahoma. We employed burettes to prepare our mixture to the appropriate volume ratios. We then added solid iodine to the mixture until we decided we had a bright enough red color suitable for video and photography. We added the immiscible droplets in a number of ways, including the use of Pasteur's pipettes, medicine droppers, and burettes both above and below the water level

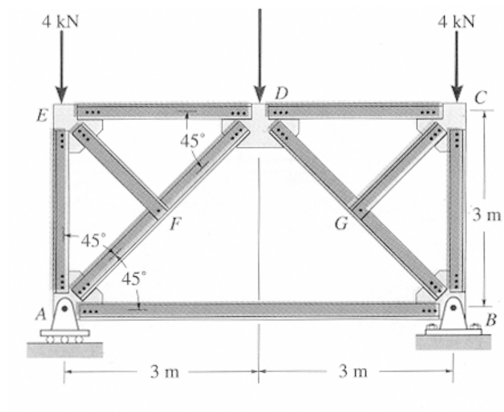

Figure 3. Single truss element for bearing large loads from Hibbeler (1993).

Construction of the framework for the horizontal rotation assembly

The unit structure suggested by Dr. Lemley from Hibbeler (1993) is shown in Fig. 3. Our design required that we concatenate three unit structures parallel to the rotational axis and one unit structure across the end perpendicular to the axis of rotation. The side and end views of our structure are shown in Fig. 4. We employed 5.08 x 5.08 x 0.64 cm L-shaped aluminum for construction of the base and top of the structure as well as the vertical struts that connected the top and bottom. The cross members that made up the individual unit structures were made up of 5.08 x 0.32 cm flat aluminum. The top cross members that supported the motor drive lines and cell supports were 5.08 x 2.54 x 0.32 cm channel aluminum. The top and bottom were assembled first and bolted together. The individual flat cross members were assembled in place on the base structure; holes were drilled and the flat alumi-

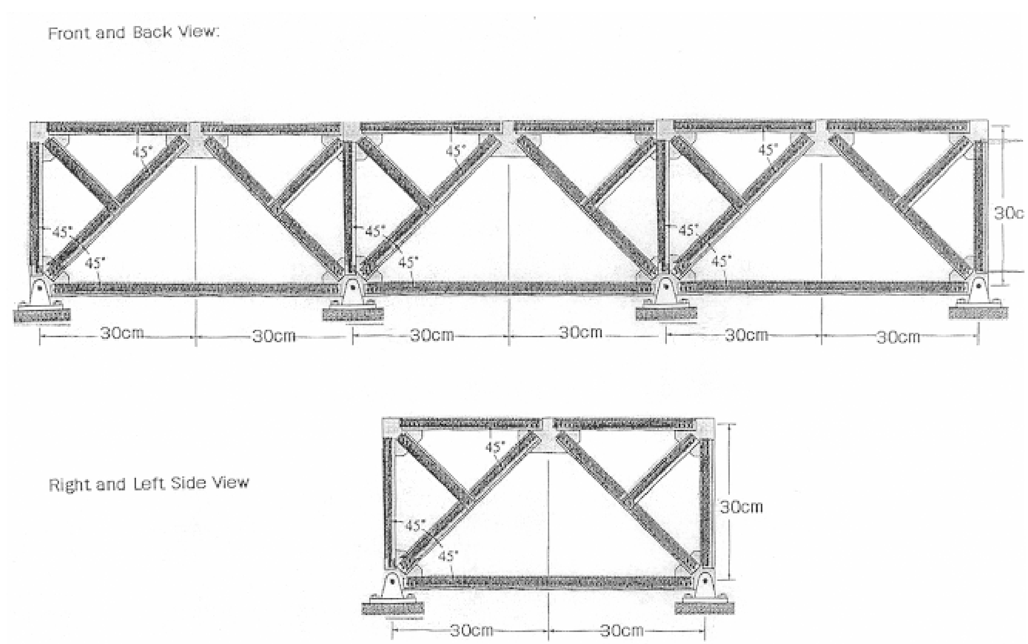

Figure 4. Long side of assembly with dimensions and angles to be employed as support framework for drive motor and cylinder for rotation of partially filled cylinder about a horizontal axis. Top parallel to the axis of rotation. Bottom figure is the end view.

num parts of the assembly were bolted in place.

The cell was a blend of acrylic pipe and Plexiglas; this gave us the capability to construct a number of different sized containers inexpensively compared to other clear materials such as glass. The cell was a modification of a design we originally employed in some of our experiments with fluids rotating about a vertical axis of rotation. Our initial cell design was made from stock acrylic of 16.51 cm inner diameter and 0.64 cm wall thickness. The cell was open ended and had a length of 17.78 cm. One of the ends was centered and glued to a 30.48 x 30.48 cm Plexiglas square that was 0.64 cm thick. The lid was a 3.81 cm ring cut from the stock acrylic pipe mentioned above that was split down its length and spread so that the acrylic pipe fit tightly inside. The split ring was centered in another 30.48 x 30.48 cm square of Plexiglas and glued; the acrylic pipe could be removed after a certain cure time for the cement. Four aligned 0.64 cm holes were drilled in each Plexiglas square. A 16.51 cm inner diameter O-ring was inserted into the lid and the container was filled to the desired fill volume and bolted together with 0.64 cm x 22.86 cm long carriage bolts with felt washers on the cell side and flat washers on the outside of the felt to compress the felt for a tight fit. A proto-type of our cell is shown in Fig. 5. Our leak testing consisted of bolting the assembly together snugly and turning the entire assembly horizontal. The procedure was repeated until no leaks were observed.

Thoroddsen and Mahadevan (1997) cited a number of variables associated with the coating flows for fluids confined to a horizontally rotating right circular cylinder. One of these variables is the aspect ratio, A, which is descriptive of the cylinder geometry. A is given by $A = L/R$, where L is the length of the cylinder and R is the cylinder radius. Our cell radius and aspect ratio were 8.25 cm and 2.15, respectively. The cell Thoroddsen and Mahadevan used most in their work was R = 6.25 cm and A = 7.8.

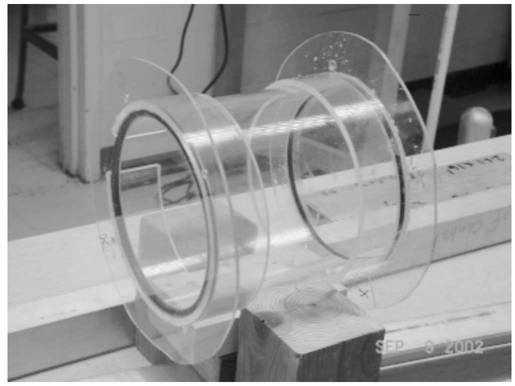

Figure 5. Cell constructed of 16.5 cm I. D. acrylic pipe Plexiglas ends and O-rings for seals.

Other cells Thoroddsen and Mahadevan worked with had the following radius and aspect ratios: R = 2.35 cm, A = 16.0, R = 3.8 cm, A = 15.4, R = 7.1 cm, A = 8.2 and R = 14.6 cm, A = 5.9, respectively. A comparison shows that our cell radius is about half of their largest and slightly larger than the one they used. The aspect ratios employed in their work were considerably larger than ours.

RESULTS

Flow Visualization

We prepared our mixtures with burettes. This gave us the capability to prepare our mixtures to the nearest 0.01 ml. The iodine was added and gave a reasonably bright red color. A photograph of our mixture suspended in water is shown in Fig. 6. We were careful in preparing our mixtures and made about 100 ml so that adherence to the neutral buoyancy condition should be fairly close. Based on our tolerances, our precision should be two parts volume in ten thousand.

We had a number of experimental difficulties. We encountered problems with the fluid adhering to the tip of the Pasteur pipette and the burette. We usually had to shake the droplet loose or deliver a larger volume and hope the volume of fluid would break up into usable droplet sizes, which it sometimes did. We tried adding droplets

Figure 6. Droplet suspension of immiscible droplets in water

above the level of the fluid; however, these droplets had a downward vertical component of velocity. Droplets introduced in this fashion would head to the bottom of the vessel and would continuously rebound from the bottom to the top, changing composition as this rebounding process continued. The neutral buoyancy condition was lost quickly and our immiscible fluid was rendered useless as a flow visualization aid. Usually at the end of a sequence of bounces all of the immiscible fluid would settle on the bottom of the vessel. Our usual vessel was a glued acrylic and Plexiglas assembly. Our immiscible mixture of methylene chloride-pentane-iodine had a disastrous effect on our vessel. The methylene chloride-iodine-pentane mixture dissolved the bottom of the vessel and rendered it useless.

Construction of the Framework for the Horizontal Rotation Assembly

We began construction of the assembly as indicated in Fig. 4. We started with the various types of structural aluminum described in the Materials and Methods. The top was identical to the bottom and was bolted onto the uprights. Fig. 7 shows the entire framework assembly completed. The motor, cell assembly, and drive lines have yet to be mounted on the framework. Johnson (1988) constructed an apparatus to effect the horizontal rotation of fluids. A device similar to his was used in the work of Thoroddsen and Mahadevan (1997). The finished version of our framework for rotating a fluid about a horizontal axis with drive lines, motor and cell assembly included is shown in Fig. 8. The system at this stage is still is in need of testing. The first spin with a partially filled cell was with pure water shown in Fig. 9. At this time we had difficulty determining the speed of rotation and can provide only estimates. We were still addressing the determination of rotation speed. The cell shown in Fig. 9 was approximately 1/4 full and rotating at an estimated speed of 3-5 rotations per second.

Figure 7. Fully assembled framework for rotating a partially filled right circular cylinder about a horizontal axis of rotation

DISCUSSION

Flow Visualization

We concede to having difficulty in controlling droplet size, stability, and location in

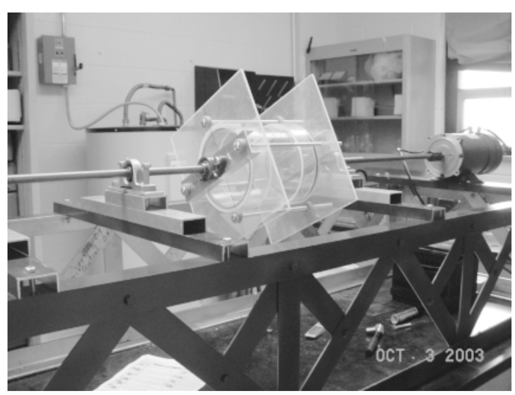

Figure 8. Apparatus fully assembled with motor, drive lines and cell. The apparatus is ready for testing.

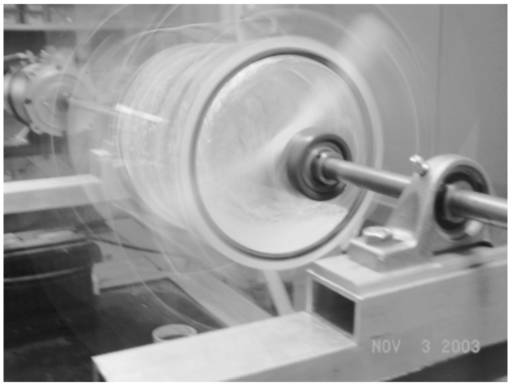

Figure 9. First spin of cylinder partially filled with fluid. The cylinder was about 1/4 full. The cell rotational speed was about 5 rotations per second.

the vessel. A successful dispersion is shown in Fig. 6. One needs to be careful when putting organic mixes in polymer based vessels. Plexiglas-acrylic vessels have a great deal of appeal, such as the cost of materials and ease of fabrication of a particular cell design. However, we were not able to control droplet size or placement within the bulk fluid. The very act of attempted droplet placement introduced a vertical velocity component to the droplet so we had no control over position. Any contact of the mixture with the surface of the vessel for any length of time would completely render the vessel useless. We did the majority of our work with the immiscible organic materials with glass vessels.

We believe the immiscible mixture droplet idea has merit, but we encountered some problems. The experiment assumed a neutrally buoyant mixture had been prepared. A method should be developed to deliver an immiscible stationary droplet at any depth in the fluid. The immiscible fluid mix needs to be stable in the aqueous environment. Ours was stable for short durations, but after time, the instabilities would cause our droplet to settle on the bottom of the vessel rendering the vessel useless.

We only had time to attempt one mix. Other mix possibilities should be attempted and tested for reproducibility. Our approach to the immiscible droplet problem was based on toxicity of the reagents used. A more appropriate procedure would be to conduct the study based on the physical properties of the mix pair. One would hope to keep this as simple as possible and use only binary mixes. The problem has enough variables without introducing additional ones. We would recommend staying away from anything as complex as a ternary mix. The immiscible droplet problem should be a study in design, physical properties, and chemical equilibrium. The most obvious variables to be addressed would be interfacial surface tension, viscosity, and stability of the mix in the bulk fluid. The components of the mix should be more soluble in one another than in the bulk fluid, a question that still needs to be addressed.

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