

Development of a VRML Application for Teaching Fluid Mechanics

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Abstract

Fluid mechanics is a core subject for Mechanical, Aerospace, Civil, and Chemical engineering disciplines. One of the main obstacles in teaching fluid mechanics to undergraduate students is the lack of visualization tools that enhance and improve learning process of the students. With the widespread availability of multi-media software and hardware tools, development and integration of 2- and 3-dimensional visualization tools to the undergraduate fluid curriculum becomes necessary. This paper discusses the development of a Virtual Reality Modeling Language (VRML) application to be used in an undergraduate fluid mechanics course at Lamar University. Simple fluid flow problems such as fully developed flow in a pipe are solved by an application written in Java programming language. The solutions obtained are displayed in a VRML application that also provides user interaction. Users can change certain parameters of each problem within a given range, and the VRML application provides the solution of the problem with new parameters.

Nomenclature

H	Half of the distance between plates (m)
L	Length of pipe (m)
R_0	Radius of pipe (m)
R_1	Radius of imaginary pipe (m)
T	Time (s)
T_0	Temperature of bottom plate or wall of pipe (K)
T_1	Temperature of top plate or center of pipe (K)
U	Velocity along x-axis (m/s)
U_1	Velocity of top plate (m/s)
U_2	Velocity of bottom plate (m/s)
Greek letters	
μ	Dynamic viscosity (kg/ms)
κ	Thermal conductivity (W/mK)

ν	Kinematic viscosity (m^2/s)
τ	Shear stress (N/m^2)
δ	Shear layer stress (N/m^2)

Subscripts

0	final or minimum value
1	maximum value
2	fixed

Introduction

Everyday, engineering applications involving fluid flows are encountered by engineers of many disciplines. As a result, fluid courses form a critical part of the undergraduate core courses in the mechanical, civil, chemical, aerospace, environmental, petroleum, and biomedical engineering curricula. Understanding fundamental principles of fluid flow and applying these principles to engineering applications are problematic for undergraduate engineering students for the following reasons: the subject involves advanced mathematics topics such as ordinary and partial differential equations and vector and tensor calculus. Solutions of fluid flow depend on many parameters, length and time scales, and the solutions are generally obtained by sophisticated experiments and computations that are difficult to explain. However, when the result of a fluid flow simulation is presented as a visualization of the calculated flow field, it becomes a powerful educational tool, giving students an idea of how the fluid behaves under many different conditions.

Although many Computational Fluid Dynamics (CFD) software packages such as CFX and Fluent are available in the market, their availability to undergraduate engineering curriculum has been limited due to the following reasons¹:

- The software is targeted towards industrial users and the cost tends to be high
- The users must have access to powerful, high speed computers to do the analysis
- It takes a very long time to get used to the software, i.e. the learning curve is steep

As the technology changes rapidly, the importance of educating and training students in fluid mechanics becomes more critical. Conventional teaching methods fall short of conveying the complex ideas needed to be mastered by students. There is a range of problems in this method of instruction and some of them experienced are²:

- Lack of teaching aids to explain the principles used in fluid mechanics
- Shortage of time to teach in details
- Inadequate visual learning environment
- High student to teacher ratio due to increasing number of students
- Inability to make the course interesting
- Difficulty in explaining students the link between theory and application of fluid mechanics
- Inability to include students who are unable to attend classes

Therefore, a variety of learning tools such as interactive texts, multimedia videos and CD-ROMs, computational and experimental tools, has been developed and used by many educators teaching fluid and thermodynamics courses in order to improve the learning process of students^{1, 3, 4, 5}. Moreover, with the advancements in information technology over the last few years, conventional teaching methods of having an individual lecture to a group have been supplemented, and in some cases, replaced by the rapid development and implementation of new distance learning methods. The development of the Internet, specifically World Wide Web (WWW), has led to unprecedented growth over the last decade in access to information. It offers many advantages: ease of use, quick access, low cost, available without the limitation of time or location, computer platform independent, and flexible in allowing students to control their learning pace. With the advent of JAVA programming language, which offers features such as platform independence, engineering applications can be easily developed for the web.

One example is CFDnet¹ that provides users with interactive Internet-based access to powerful server-side meshing, solving, and solution visualization routines for solving practical engineering problems in fluid flow. Registered users access CFDnet through their web browsers using a Java user interface. No software downloads or plug-ins are required. It is used in the undergraduate and graduate teaching of fluid mechanics, and can be used to obtain qualitative solutions to simple fluid mechanics problems. The driving force behind it is the creation of CFD software that is readily accessible and simple to use. This allows students, scientists, and engineers to learn some of the jargon, as well as the basic principles, behind a CFD solution. When used in conjunction with a fluid mechanics course, it can be used to teach some of the fundamentals of fluid flow analysis, and 'replace' some of the laboratory experiments used to teach these principles.

Similar examples include CALF (Computer Aided Learning in Fluid Dynamics)³, the NTNU Virtual Physics Laboratory⁶, Virtual Laboratory⁷, and Java Virtual Wind Tunnel⁵. CALF (Computer Aided Learning in Fluid Dynamics) is an interactive web-based course developed at the Universities of Glasgow and Paisley. It gives an introduction to CFD and covers subjects like CFD illustrations, turbulence modeling, parallel computing, and grid generation. The NTNU Virtual Physics Laboratory, a web site developed by Professor Fu-Kwun Hwang, Department of Physics, National Taiwan Normal University, lists applets for various topics in physics-mechanics, dynamics, waves, thermodynamics, electromagnetics, light/optics etc. Virtual Laboratory at John Hopkins University lists a collection of online experiments to enable students to learn more about experimentation, problem solving, data gathering, and scientific interpretation. The Java Virtual Wind Tunnel at MIT is an applet which uses computational fluid dynamics (CFD) methods to simulate the flow of air over a two dimensional object. The applet solves the equations of motion (the Euler equations) in real time and the simulation provides more information about the flow than one could easily access in any real wind tunnel. The Virtual Laboratory⁸, Department of Physics, University of Oregon, has an interesting collection of Java applets for use in physics, astronomy, or engineering science courses. It also offers Java based tools to assist students in making graphs, figures, spreadsheets, etc.

However, these websites are mostly 2-dimensional based websites and do not involve much interaction. If the fluid mechanics theories are exemplified in a virtual reality environment, conceptual understanding of the students will be much more enhanced. Important advantages of virtual reality environment over other computer based design tools are that it enables the user to interact with the simulation to conceptualize relations that are not apparent from a less dynamic representation, and to visualize the models that are difficult to understand in other ways.

Objectives of the Study

The main objectives of the present work are

- (a) To develop a 3-D web-based VRML module for teaching fluid mechanics
- (b) To enhance learning process of students by providing an easy, interactive, and graphic learning tool
- (c) To provide educators and students free access to the module

Methodology

Three modules have been developed to illustrate 3-D web-based VRML applications. These modules use tools such as VRML (Virtual Reality Modeling Language) and JAVA for interactivity and full 3-D visualization. A virtual environment is a place where a 3D model exists, that is viewed over the internet using a browser with a VRML plug-in. The Internet has given rise to a myriad of new technologies and standards. One of the most promising for engineering has been the Virtual Reality Modeling Language (VRML), which was developed solely for viewing 3D graphics on the Web. It all started at the “Birds of a feather” sessions organized by Mark Pesce and Tony Parisi at the 1994 World Wide Web and SIGGRAPH conferences where many felt the need of a 3D graphics file format that followed a similar model to HTML, platform-independent, text based scene description language⁹. The first version of VRML (VRML 1.0) was developed and available on the Web in 1995. Although it was very successful as a file format for 3D objects, there was nothing interesting about it, it had two major limitations: lack of support for dynamic scene animation, and no traditional programming language constructs. After redefining the language and tackling these issues VRML 2.0 followed in 1996. This allowed objects to move in the world and allowed the user to interact with them. This version became an international standard (ISO/IEC 14772) in 1997 under the name VRML97. This study uses VRML 2.0. At present the Web3D Consortium, the organization responsible for the creation of open standards for Web3D, is working on X3D (Extensible 3D) as the successor of VRML 2.0.

The VRML file serves as a blueprint for building the virtual world. It is nothing but a textual description of the VRML world, it specifies and organizes the structure of the VRML world. It can be created with any text editor or word processor. VRML files are generally referred to as worlds and end with an extension .wrl. When a browser reads a VRML file, it builds the world described in the file and displays it as one moves around the browser. These files may also contain references to files in many other standard formats like JPEG, PNG, GIF, and MPEG. WAV and MIDI files may be used to specify sound. Files containing Java or JavaScript code may be referenced and used to implement programmed behavior for the objects in the VRML world. VRML files contain four main types of components:

- VRML header
- Prototypes
- Shapes, interpolators, sensors and scripts
- Routes

In addition to the above components, a VRML file also contains comments, nodes, fields, and field values. To present 3D VRML worlds, the browser needs special helper applications called plug-ins. Plug-ins are programs that enable the viewing of non-HTML content in the browser. To view VRML files, a VRML helper application or a plug-in is needed. For this study, a special kind of plug-in (ParallelGraphic's Cortona) was used to view the VRML files.

The programming language used to control the VRML file and perform the calculations requires seamless integration with the Internet and the web browser. These requirements are satisfied by the Java programming language developed by the Sun Microsystems. Java has become very popular because of the many features designed to make it operate on the Internet. With this language one can “write once and run anywhere”¹⁰. Developers can write full-fledged applications in Java, whose architecture is much like C and C++. It is freely available from the Sun Microsystems website (<http://java.sun.com/>). Java can be used to create two types of programs: applications and applets. An application is a program that runs on the computer, under the operating system of that computer. An application created using Java is more or less like C or C++. Java's ability to create applets is what makes it more important. An applet is an application designed to be transmitted over the Internet and executed by a Java-compatible Web browser. An applet is a tiny Java program; dynamically downloaded across the network, just like an image, sound file or video clip. In other words, an applet is an intelligent program that can react to user input and dynamically change. The interaction between Java and VRML can be described as shown in Fig. 1.

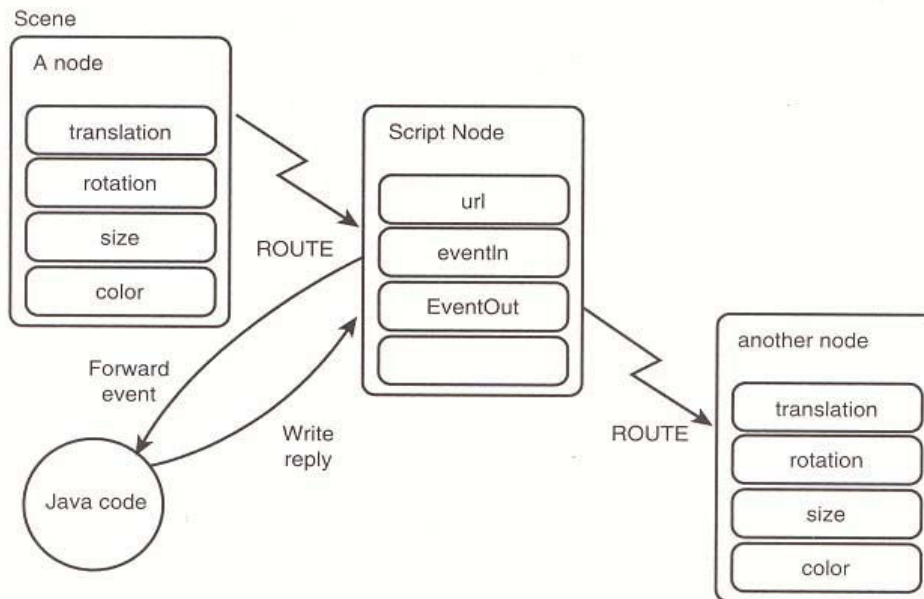


Fig. 1 Interaction between Java and VRML (Source: JAVA for 3D and VRML Worlds)

The Modules

This section gives the detailed description of the three modules for solving Couette, Hagen-Poiseuille, and Rayleigh flows.

Couette Flow

The flow was named in the honor of M. Couette¹¹ who performed experiments on the flow between a fixed and a moving concentric cylinders. Couette flow involves the laminar flow of an incompressible fluid of constant viscosity between parallel plates, where the bottom plate is fixed and the top plate travels with a particular velocity. If the fluid flows due to a moving surface and a pressure gradient, it is called Couette-Poiseuille flow. This flow finds its practical application in viscous screw pumps and fluid driven motors. Two cases are considered, one without pressure gradient (plane Couette flow) the other with pressure gradient (generalized plane Couette flow). Results are also presented for the temperatures calculated between the two plates in a plane Couette flow.

The flow considers both conservation of momentum and energy equations. In order to simplify these equations the fluid is assumed to be incompressible, i.e. the density of the fluid is constant. Furthermore, it is also assumed that the coefficients of viscosity and of heat conduction of the fluid are constant. The program allows the choice of fluids with different properties: air, water, glycerin, SAE30 oil or mercury. The user needs to provide necessary parameters such as velocity of the top plate, type of fluid, gap between the plates, and the pressure gradient. The results for this flow consist of a velocity profile and a temperature profile. With the velocity profile, results such as shear stress and the position of maximum velocity are also shown. In case of the temperature profile the user enters the temperatures of the top and bottom plates.

Eq. 1 gives the solution for the velocity profile of the Couette flow

$$u = -\frac{h^2}{2\mu} \frac{dp}{dx} \left(1 - \frac{y^2}{h^2}\right) + \frac{U_1 - U_2}{2} \frac{y}{h} + \frac{U_1 + U_2}{2} \quad (1)$$

where u is the velocity between the plates at a particular y , h is the half distance between the plates, U_1 velocity of the top plate, U_2 velocity of the bottom plate and $\frac{dp}{dx}$ is the pressure difference. Shear stress is calculated using the following equation

$$\tau = \frac{\mu U}{2h} = \text{constant} \quad (2)$$

and Eq. 3 determines the position of the maximum velocity.

$$y = \frac{(1+P)}{2P} h \quad (3)$$

where $P = \frac{-h^2}{2\mu U} \left(\frac{dp}{dx}\right)$. In the case of no pressure gradient, $\frac{dp}{dx} = 0$, and a stationary bottom plate, $U_2 = 0$, the velocity profile is given by

$$u = \frac{U}{2} \left(1 + \frac{y}{h} \right) \quad (4)$$

In this case, the velocity distribution is linear between the two plates. In the case with pressure gradient, $\frac{dp}{dx} > 0$, but a stationary bottom plate, $U_2 = 0$, the velocity profile is given by

$$u = -\frac{h^2}{2\mu} \frac{dp}{dx} \left(1 - \frac{y^2}{h^2} \right) + \frac{U_1}{2} \left(1 + \frac{y}{h} \right) \quad (5)$$

The velocity distribution is parabolic between the two plates. The VRML model for the Couette flow starts with the screen showing two parallel plates and a Java frame window to accept input from the user. The frame window asks for the following inputs: top plate velocity in m/s, type of fluid, which the user selects from a list, gap between plates in m and the pressure difference in Pa. The opening screen shot of the Couette flow problem is shown in Fig. 2.

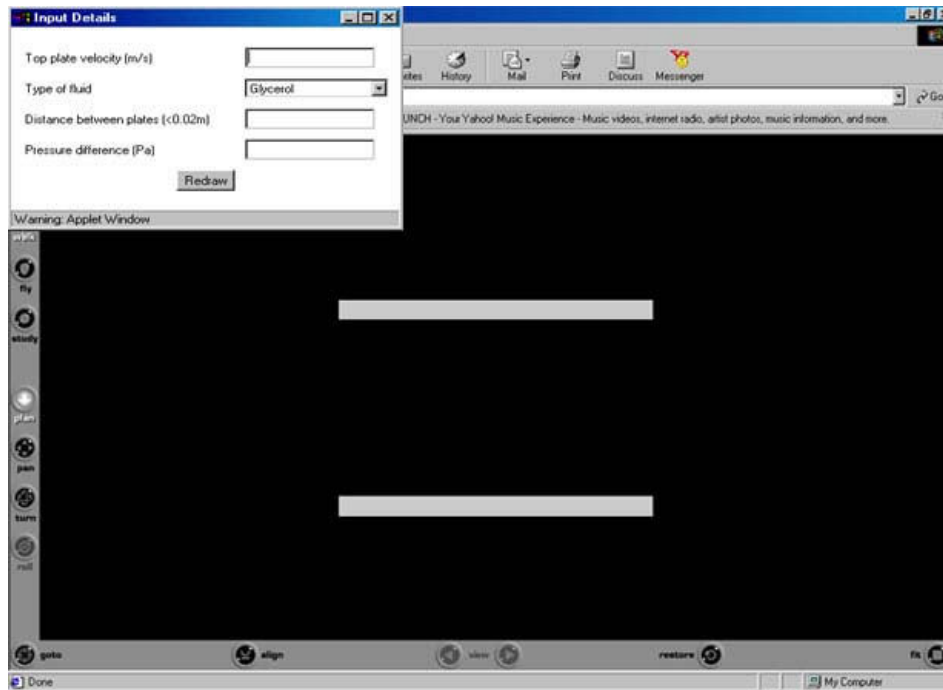


Fig. 2 An Opening Screen Shot of the Couette Flow Problem (Velocity)

The user enters the values and clicks the draw button. In the case of plane Couette flow, the pressure difference is zero. The result is shown with the layer of fluid with maximum velocity as a row of arrows in red color, the color changes till blue, which represents the minimum velocity. The magnitude of the velocity of the layer of fluid is known from the velocity legend. The profile obtained is of linear in nature as indicated by Eq. 4.

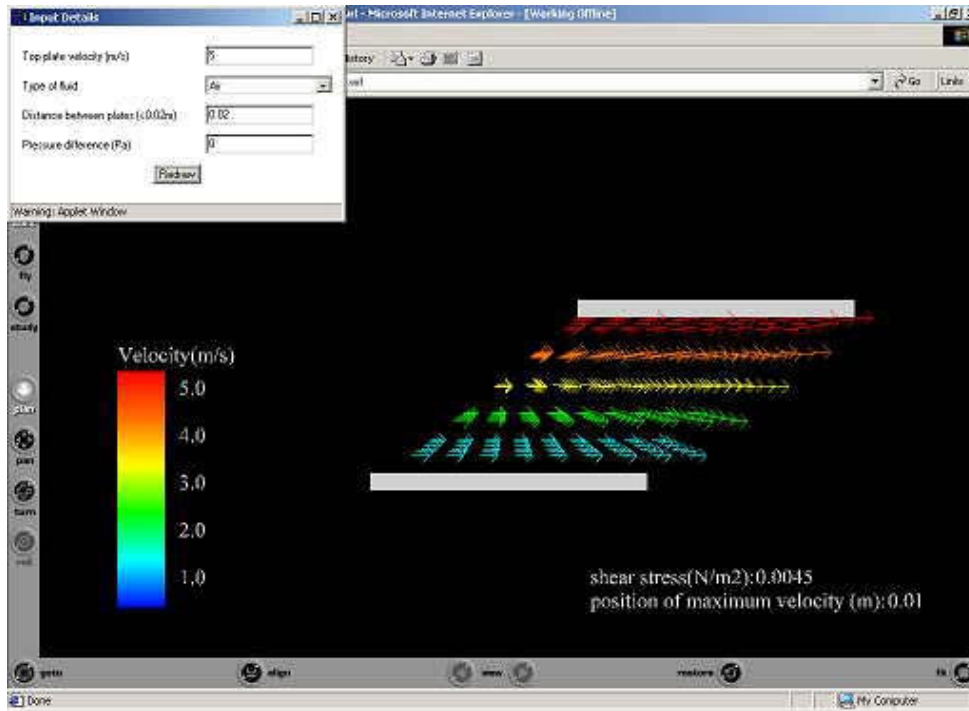


Fig. 3 The Velocity Profile of the Plane Couette Flow

In the case of the flow with pressure gradient, a positive or negative value is entered at the pressure difference field. The velocity profile has a parabolic profile.

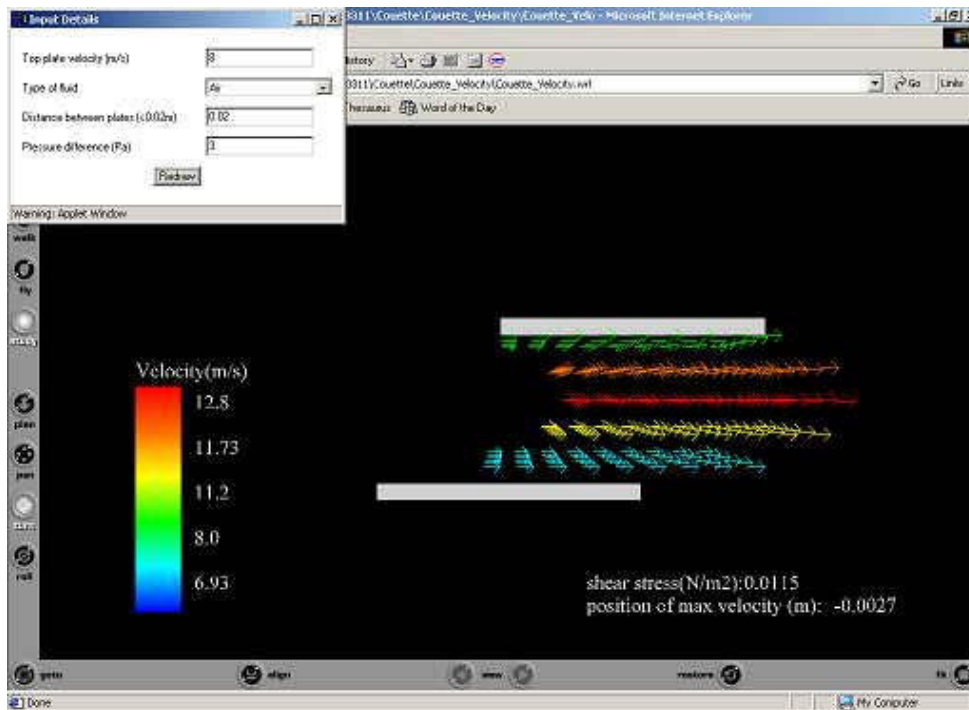


Fig. 4 Velocity Profile of the Couette Flow with Pressure Gradient

The solution of the temperature profile for a plane couette flow involving a laminar flow of an incompressible fluid between two parallel plates is given by

$$T = \left[\frac{T_1 + T_0}{2} + \frac{T_1 - T_0}{2} \frac{y}{h} \right] + \frac{\mu U^2}{8k} \left(1 - \frac{y^2}{h^2} \right) \quad (6)$$

The term inside the square brackets represents the straight-line distribution, which would arise due to pure conduction in the fluid. The second (parabolic) term is the temperature rise due to viscous dissipation in the fluid. The ultimate temperature profile is linear with the fluid near the top plate having the highest temperature and the temperature slowly decreases till the bottom plate. The opening screen shot of the Couette flow problem (temperature) is given in Fig. 5. The user interface asks for the temperature of the top and bottom plates in Kelvin, and the type of fluid. The resulting temperature profile is shown in Fig. 6. The temperature profile between the plates is shown with the values in the legend. The red and blue colors respectively represent the highest and the lowest temperatures of the flow.

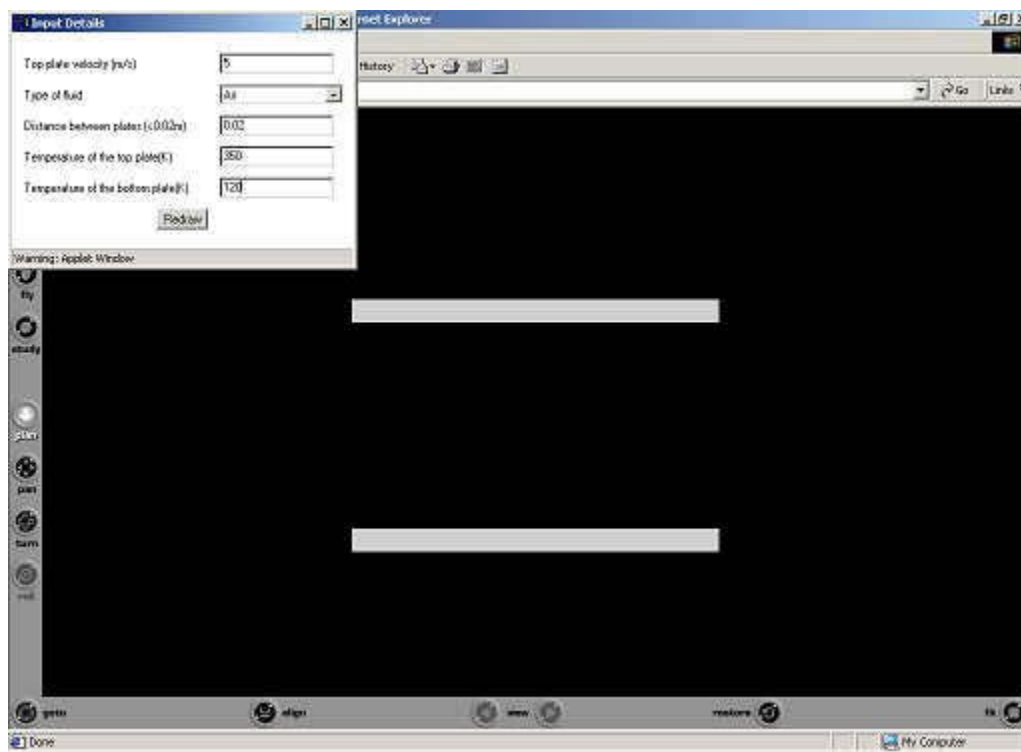


Fig. 5 An Opening Screen Shot of the Couette Flow Problem (Temperature)

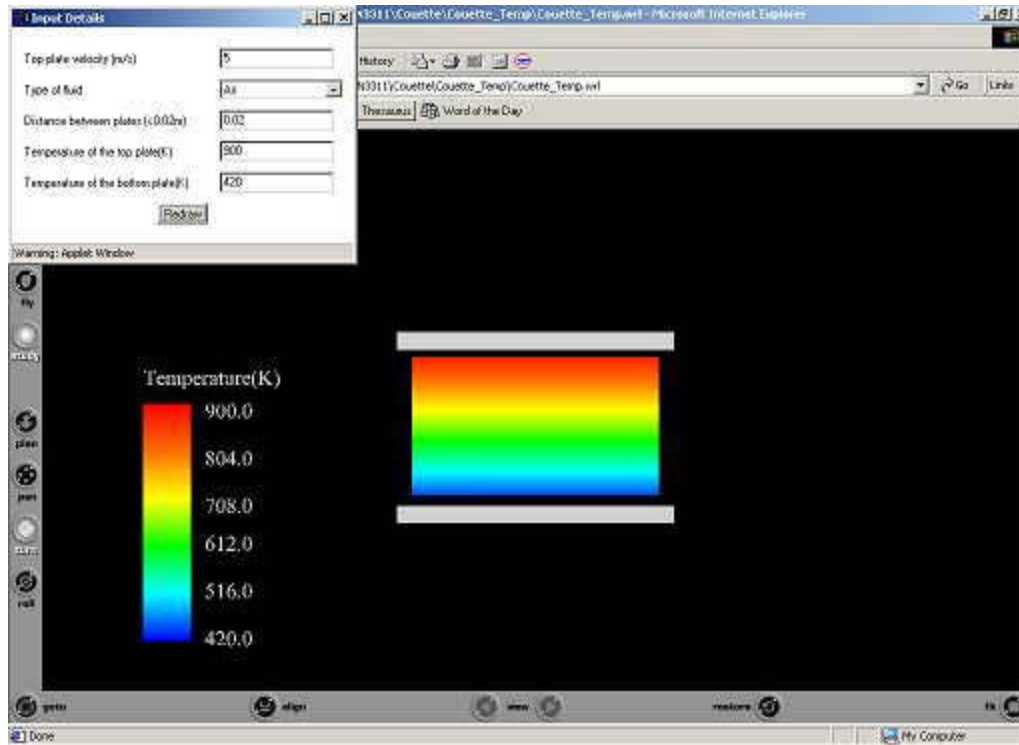


Fig. 6 The Temperature Profile of the Couette Flow Problem

Hagen-Poiseuille Flow

Hagen-Poiseuille flow, named after Hagen and Poiseuille, is the flow of an incompressible viscous fluid through a circular pipe. The assumptions for the Hagen-Poiseuille flow are similar to the assumptions for the Couette flow considering both conservation of momentum and energy equations. The solution of the velocity profile for the Hagen-Poiseuille flow is given by Eq. 7:

$$u = \frac{p_1 - p_2}{L} \frac{r_0^2}{4\mu} \left(1 - \frac{r^2}{r_0^2} \right) \quad (7)$$

where u is the velocity at a particular radius r , r_0 is the radius of the pipe, $\frac{(p_1 - p_2)}{L}$ is the pressure difference and μ is dynamic viscosity of the fluid used. The above equation shows that the velocity distribution is parabolic and the maximum velocity is at the center. As soon as the model is loaded into the browser, it shows a section of the pipe and an input window (Fig. 7). For the velocity profile, the user enters the values for the pressure at the inlet and outlet, the type of fluid, the length and the radius of the pipe. The user is again given the choice of selecting the fluid: air, water, glycerin, SAE30 oil or mercury. In the case of temperature profile, the temperatures at the center and the walls of the pipe and the radius of the pipe are required as input.

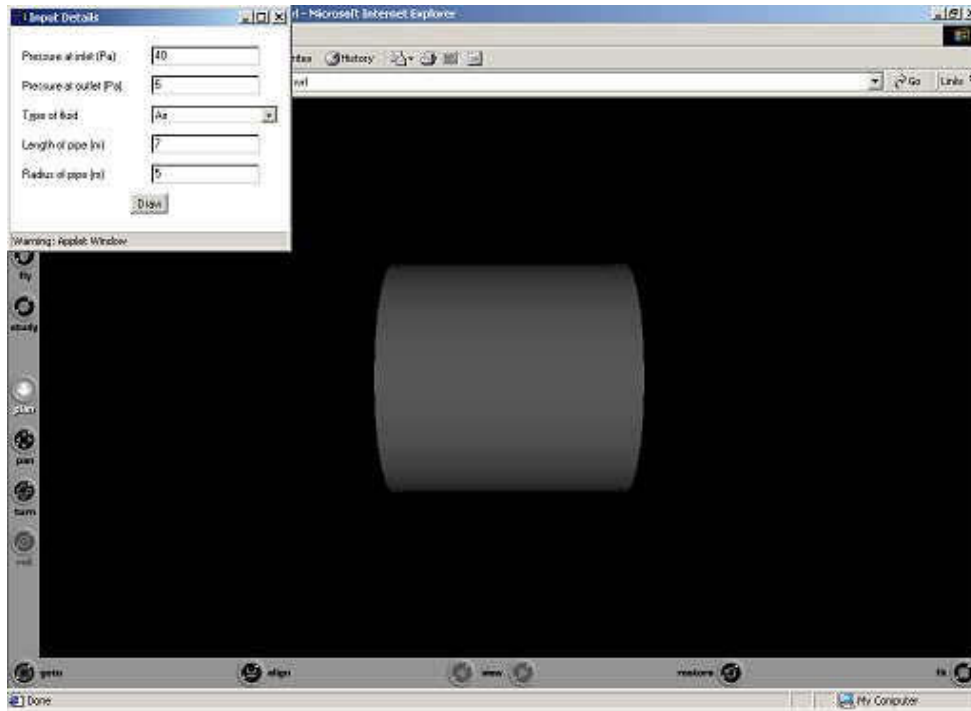


Fig. 7 An Opening Screen hot of the Hagen-Poiseuille Flow Problem (Velocity)

Once the user enters these values and clicks the draw button the results are shown as in Fig. 8.

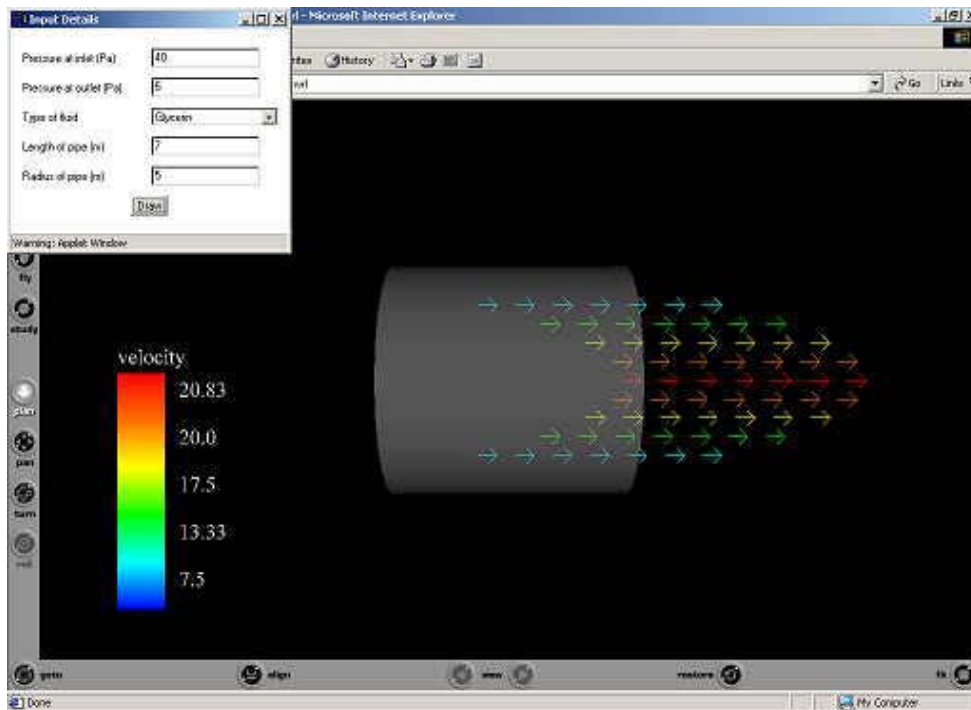


Fig. 8 The Velocity Profile of the Hagen-Poiseuille Problem

The velocity profile is of parabolic shape with the maximum velocity at the center. The result is shown with the layer of fluid with maximum velocity as a row of arrows in red color, the color changes till blue, which represents the minimum velocity. The velocity legend gives the velocity values of the regions shown. The temperature profile of the flow is based on the assumption that the temperature of the wall is constant. The equation for finding the temperature distribution of a laminar flow in a pipe is given by Eq. 8:

$$T = T_0 + (T_1 - T_0) \left(1 - \frac{r^4}{r_0^4} \right) \quad (8)$$

Figures 9 and 10 respectively show the opening screen and the temperature profile of the Hagen-Poiseuille flow. The highest temperature is found at the center of the pipe and the temperature reduces to the minimum at the wall. As before, the red color represents the highest temperature and the blue color the smallest temperature.

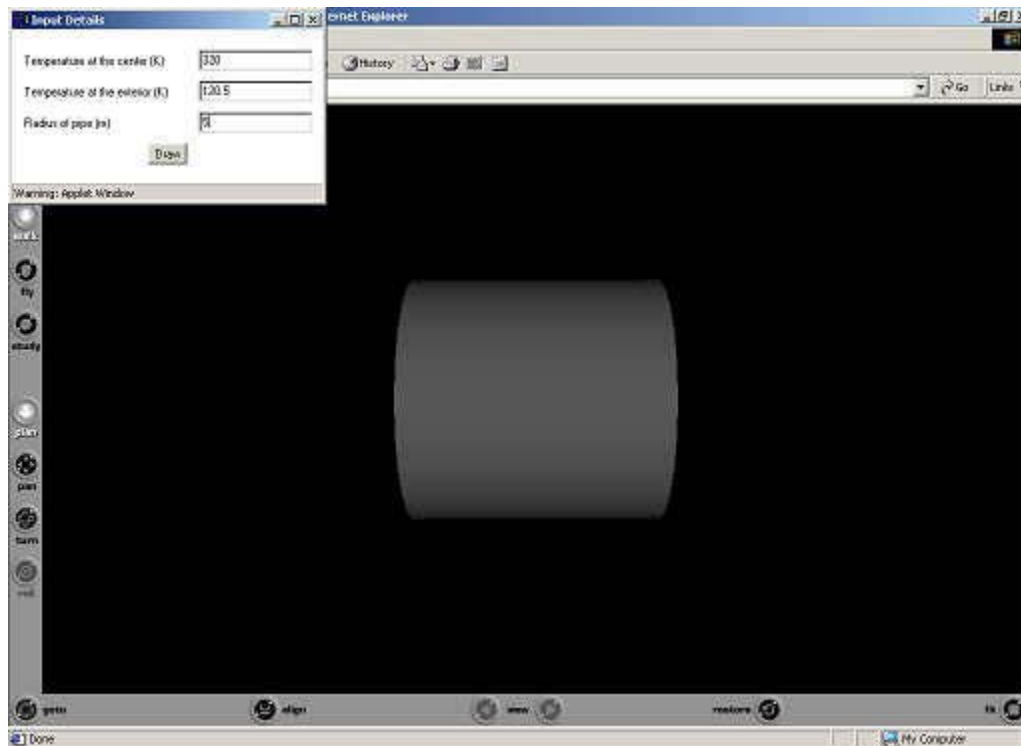


Fig. 9 An Opening Screen Shot of the Hagen-Poiseuille Problem (Temperature)

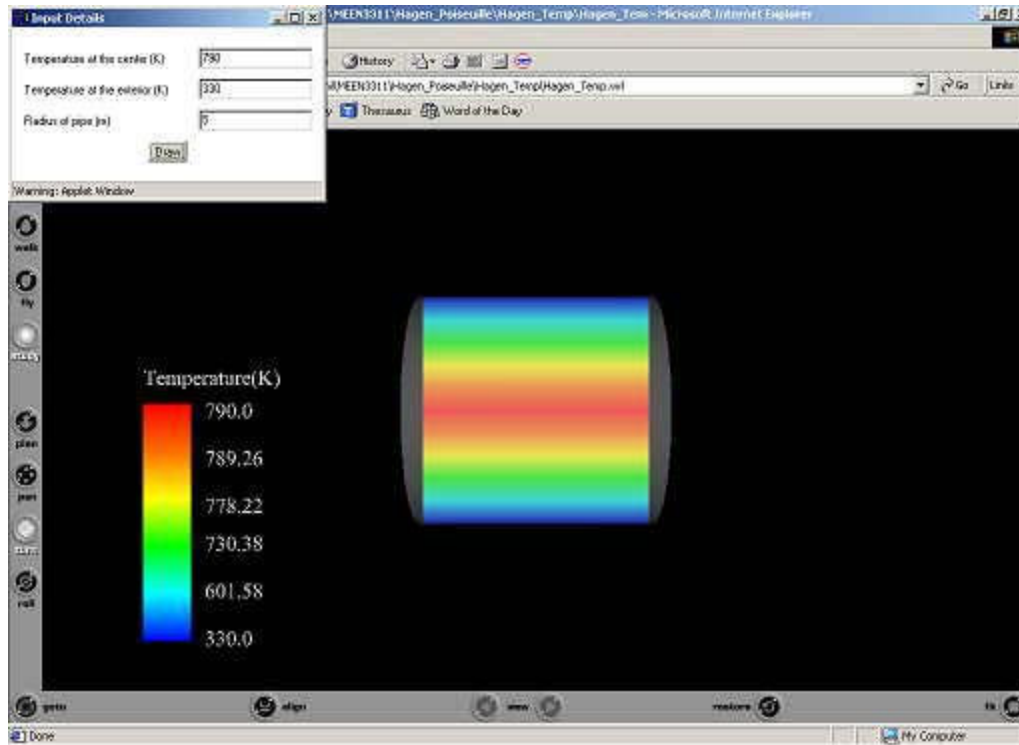


Fig. 10 The Temperature Profile of the Hagen-Poiseuille Problem

Raleigh Flow

Investigated by Lord Rayleigh, this problem deals with the solution of the impulsive motion of an infinite plate¹². Raleigh problem deals with the movement of an incompressible viscous fluid over a suddenly moving flat plate with a particular velocity. This problem also solves the conservation of energy and momentum equations. Assumptions are made that the fluid is incompressible, i.e. the density is constant and that the coefficients of viscosity and heat conduction of the fluid are constant. This problem involves the sudden movement of a plate in its own plane with a constant velocity U . Equation 9 below gives the solution of the Raleigh flow problem:

$$u = U(1 - \text{erf}(\eta)) \quad (9)$$

where $\eta = \frac{y}{2\sqrt{\nu t}}$, y is the distance in the y -direction, ν is kinematic viscosity and t is the time. The shear layer thickness is calculated using Eq. 10.

$$\delta = 3.64\sqrt{\nu t} \quad (10)$$

A screen shot of the Raleigh problem interface is given in Fig. 11. The model is a flat plate with a frame to input the plate velocity in m/s and the type of fluid used. The user is again given the choice of selecting the fluid: air, water, glycerin, SAE30 oil or mercury.

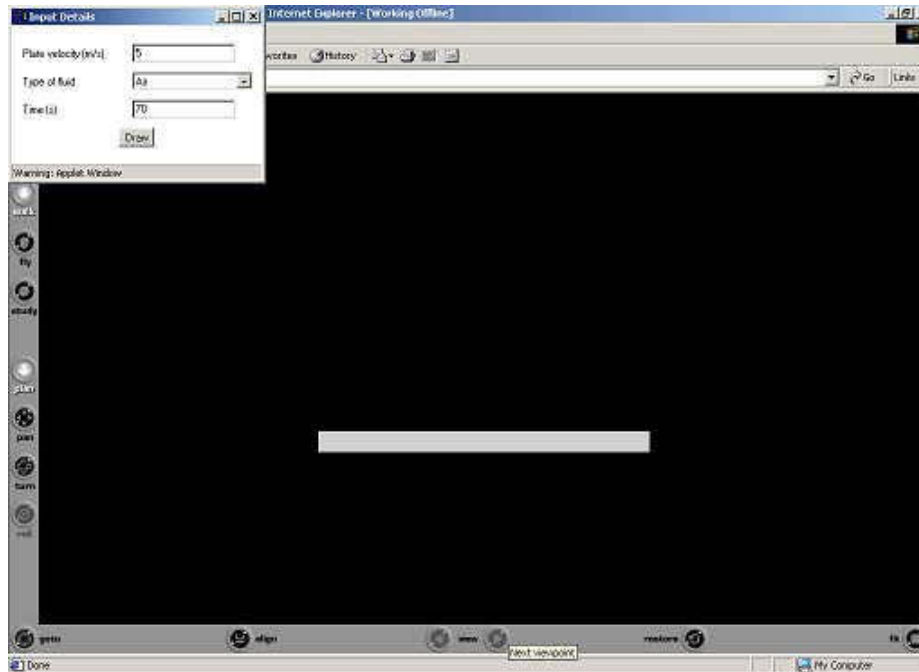


Fig. 11 An Opening Screen Shot of the Raleigh Problem

Once the user enters these values, the direction of movement of the plate is shown along with the velocity profile. The velocity values calculated at different points along the y-axis are shown on the legend. Results for the velocity profile at a particular time are calculated and shown.

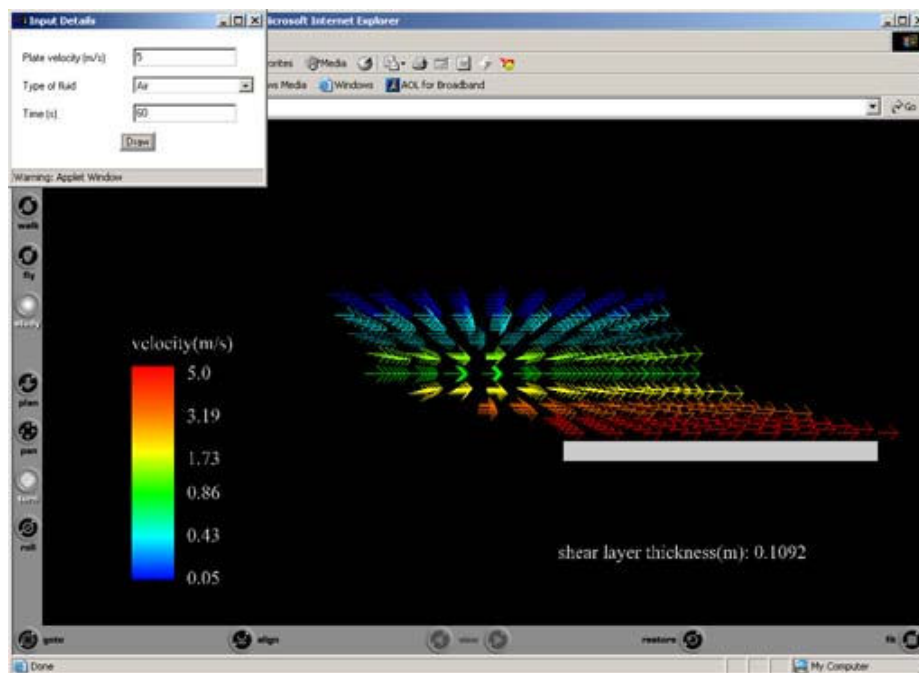


Fig. 12 Velocity Profile of the Raleigh Problem

Currently, these modules are in beta testing phase for the course MEEN 3311 Fluid Mechanics in the Department of Mechanical Engineering at Lamar University. Effectiveness of these tools on enhanced learning will be measured by conducting survey of students taking the class. All these modules will be made available in a dedicated website of the Department of Mechanical Engineering at Lamar University.

Conclusions

This paper described the development of a VRML application for web-based visualizations of common fluid flow problems, in order to aid in the teaching of fluid mechanics to undergraduate students. The three viscous flow problems, Couette flow, Hagen-Poiseuille flow, and the Raleigh problem, were programmed in Java language and the solutions of these flows were presented in VRML for visualization. The results included the velocity and temperature profiles.

The major conclusions of the present study are as follows:

- (a) A VRML application consisting of three modules of simple fluid flow problems has been successfully developed.
- (b) The VRML application shows the power and suitability of Java and VRML languages for developing interactive web-based 3-D visualization tools.
- (c) The VRML application significantly improve visualizations of simple fluid flow problems.
- (d) The VRML tool provide interaction and 3-dimensional visualization enhancing the learning process of students.

Future Work

At present, the VRML application developed works only for simple flow models. The future work includes developing powerful web server based visualization for Computational Fluid Mechanics (CFD) and more complex fluid flow problems. CFD involves solving an extensive number of equations to obtain solutions for a wide range of problems in fluid mechanics and heat transfer. Sets of partial differential equations, which require a powerful, or a network of computers to solve them, govern these phenomena. The web server accepts inputs from the user using a Java based user interface. This is then transmitted back to the web server, which solves the problem with the help of the network of computers. The results obtained are then converted back to a VRML model using VRML modeler software, which is then sent to the user to be viewed in a browser with a plug-in to view VRML files. A VRML modeler converts the model data from a standard file format to a VRML file format. Instant feedback of the results and visualizations of complex flow problems will significantly benefit the students' understanding of fluid mechanics.

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Biography

SUNIL APPANABOYINA is a pre-candidate for the Doctor of Engineering in the Department of Mechanical Engineering at James Mason University. This paper was his Masters thesis work under the supervision of Dr. Kendrick Aung (Co-author of this paper) when he was with the Department of Mechanical Engineering at Lamar University.

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