Virtual Reality Tools for Enhancing Interactive Learning

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Abstract

Virtual reality (VR) technology is capable of constructing a user-centered, three-dimensional environment that is familiar to the student onto which abstract and complex information can be imposed. This virtual environment can stimulate interactive learning and comprehension, which are essential in engineering education. Despite these advantages, there are several barriers to the use of virtual reality in engineering education, including a lack of simple, easy-to-use, low cost software that can enable the instructor to build virtual environments for educational use. In this paper, we discuss our experiences in developing a virtual education program in biotechnology for Indian Hills Community College. This discussion includes the development of VE-Suite, an extensible, cross-platform, open source, freely downloadable library of tools that enable engineering education in a virtual environment. Using this software, a virtual fermentor was developed, which not only allows students to explore the inner workings of the fermentation tank, but also to be able to simulate the fermentation process so they can test-run the virtual fermentor by varying the operation parameters and observe the results instantly. Finally, a human factor experiment was conducted to study the effectiveness of different data visualization methods that should be used in the virtual fermentor at facilitating students' self-paced learning.

1. Education Enhancement Using Virtual Reality

The rapid advancement of technology requires that engineering students master an increasing amount of abstract knowledge to remain competitive in today's job market. However, in recent years, there has been an increasing concern that the current higher education system is not adapted to this pace of change. Many educators believe that traditional engineering education must be improved by using innovative educational materials and methods. Joseph Bordogna, Deputy Director and Chief Operating Officer of NSF, addressed the 2002 National Advances in Technological Education (ATE) Principal Investigators Conference, saying that the rapid pace and increasing complexity of technological change "has irreversibly altered how we prepare ourselves to understand, control, shape, and embrace and

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exploit" new knowledge. It has been pointed out that in the current engineering classroom, students are often taught using abstract symbolic and mathematical formulas "without a context, without an opportunity to interact with the course material or apply it through practice" [1].

Most engineering courses are designed to teach students real-world problem solving, but most of today's undergraduates lack real world experience and find it difficult to construct the "mental models of the course materials" [1]. Hence one of the challenges facing educators is to provide students with a visible and familiar context so they can internalize how things work. Additionally, some courses, such as computational fluid dynamics (CFD), are now taught almost exclusively using symbolic and mathematical formulation, while the complex and abstract information can be overwhelming to students. Hence, another challenge is to provide realistic and engaging learning experiences so that the students can easily understand the course materials. Furthermore, engineering faculty try to create practice-oriented courses, but students sometimes complain about the lack of experiential, interactive opportunities for learning and practicing. Therefore, it is a challenge to provide hands-on, interactive learning environments for students so that they can further explore and comprehend what is learned in the classroom. Educators also suggest that, especially in the engineering fields, the content and education methods must be reformulated to meet students' diverse learning styles. Some students learn well with verbal and written instruction and are comfortable with the traditional education methods, "while visual oriented students find it hard to capture the information without seeing the illustration of concepts" [2, 3]. Therefore, it is a challenge to provide versatile and integrated learning tools to support different learning styles and self-paced learning.

We believe virtual reality (VR) is an innovative platform that can greatly improve traditional engineering education. VR is defined as "immersive, interactive, multisensory, viewer-centered, three-dimensional computer generated environments and the combination of technologies required to build these environments" [4]. VR technology provides a user-centered, three-dimensional environment that is familiar to the student. Students can also explore and discover unexpected but critical details that are either inaccessible or hidden from view in the real world. Additionally, students can conduct multiple virtual experiments with immediate feedback and visual verification to suit their curiosity without incurring expense or damage to equipment. For example, the airflow in a pipe can be shown in a virtual environment, and streamlines, vectors, and contours can be used to provide the student with the opportunity to learn various abstract concepts. More importantly, students can alter the size and length of the pipe and observe the impact of their change in real time, following their individual learning styles. We believe that using VR in the classroom can stimulate interactive learning and comprehension, which are essential in engineering education. Therefore, if these challenges are solved, the learning experience will become more appealing.

1.1 Related Work
VR has been successfully used in medical training, military training, and special education. However, it is not yet widely used in general engineering education due to the expensive equipment and the lack of simple, easy-to-use, low cost software that would enable the instructor to build a virtual environment for educational use. Recently, more and more successful experiences with using VR for education have been published or reported. Faculty at the University of Michigan use VR in the chemical engineering

classroom. Some of the VR modules addressing chemical reactions and plant safety issues are available for download [2, 3]. This VR system was later adapted and implemented at Lamar University. Researchers at Iowa State University use VR tools in manufacturing courses, which are then developed into VR machining [5]. At San Diego State University, a set of mechanical engineering courses are integrated using VR and successfully offered to students [1]. University of Kentucky is working to develop a VR system for a fluid mechanics course. In addition, faculty at the University of Wisconsin at Madison are presently teaching an undergraduate earth science course, SoilScience326, using VR, and MIT claims that many of its first-year physics courses are taught in VR. Besides this curriculum-related work, Salzman and colleagues present the ScienceSpace system to teach physics concepts in an immersive VR environment and evaluate students' understanding of complex concepts with the help of VR [6]. Bowman and colleagues develop an information rich virtual environment in which spatial and abstract information is combined to support more effective learning [7]. Stanney and coauthors present a thorough review of human factors issues in the virtual environment, most of which are closely related to education [8]. It is worth noting that we focus our introduction only on the research accomplished using the immersive VR systems. Some excellent educational materials that are developed using three-dimensional modeling tools and displayed only on computer monitors are not included, although most of them are also claimed to be VR systems, such as the manufacturing process simulation tools and a set of curricula developed at Wichita State University [9].

1.2 Bioprocess Training at Indian Hills Community College

In this paper, we discuss our experiences in developing a virtual education system for bioprocess training at Indian Hills Community College. Generally, the biotechnology industry in Iowa requires a qualified, well-trained workforce to sustain its development. The bioprocess training center at Indian Hills Community College has developed a curriculum to teach students to work in the manufacture of bio-products by operating fermentation equipment. It has been observed that students trained via traditional educational materials and methods are confronted on the job with situations requiring a quick, accurate, and sustained response; while being under-prepared for these situations can result in costly errors such as contamination or production interruption. The main reason for this situation is the complexity of the fermentation process. As the cornerstone of the biotechnology industry, fermentation is a complex process involving biochemistry reactions, fluid dynamics, and heat and mass transfer. However, the entire fermentation process happens within a stainless steel tank, or fermentor. The inside of a fermentor is hidden and not easily visualized by students from the descriptions and cutaway diagrams available. The dynamic nature of the process is not seen, and changing the process parameters and then determining the result is not easily achievable with traditional educational materials. Although repeat plant training can teach and strengthen these potential operators' essential skills, it is too expensive and time consuming, and the student cannot fully examine the transient conditions. Clearly, the ability to understand what is going on during a fermentation process in relation to the process parameters helps the students make quick, accurate responses to changing conditions. Familiarity with proper flow paths can lead to reduced operator error such as foam build-up that can lead to tank overflow and contamination, or plugging of pipes during purification by precipitated product. Hence, the fluid dynamics characteristics and the biochemistry reaction are abstract information that must be understood by the students.

In this case, an interactive virtual fermentor will provide students with a three-dimensional, immersive environment that will allow them to go places that are inaccessible and see things that are hidden from view in a fermentor. By combining the engineering models of the fermentation process with the virtual fermentor, a student can explore the parameter space rapidly, with no cost for fermentation media or equipment. Rather than simply informing the student of the optimum condition, as is usually done in traditional education, the student can explore what happens under all conditions and see what is happening inside the tanks. Moreover, the abstract information about the fluid flow inside the fermentor can be shown with certain data visualization methods. As introduced in [10], for vector data, there are at least two visualization methods, vector field and streamline. For scalar data, isosurface and contour surface are widely used methods. We can implement all these visualization methods in the virtual fermentor, but in a classroom, we must know which ones are best for enabling students to understand the fluid flow characteristics.

Our work in developing this virtual education system consisted of three steps. First, we developed an open-source, cross-platform VR software package named VE-Suite, which is capable of supporting CFD research and education in a virtual environment, Section 2. Second, a virtual fermentor was constructed to support the students' interaction and exploration, as introduced in Section 3. Finally in Section 4, we briefly introduce the results of a human factor experiment that was conducted to study the most preferred data visualization method for students.

2. VE-Suite

VE-Suite is a C++ object-oriented, open source virtual engineering software package being developed by the Thermal Systems Virtual Engineering Group at Iowa State University, with the purpose of performing thermal systems design and analysis in virtual environments. Virtual engineering involves the integration of geometric models and related engineering analysis and simulation tools within a VR environment that facilitates product design and realization. Thus, a virtual engineering model is made up of two primary components, geometry files and engineering data. Currently, VE-Suite can load geometry files of virtually any graphics format to be placed in a scene. These models are usually colored and textured to give a realistic appearance. The engineering data originates from a CFD package and is acted on by VTK to create the various graphical representations of it. VE-Suite uses VRJuggler^{TM} to handle interfacing with VR hardware and three-dimensional graphics rendering. Using VRJuggler^{TM} allows the software to be run with any type of virtual environment and any combination of VR hardware.

2.1 Software Architecture of VE-Suite
The architecture of VE-Suite is shown as Figure 1. Only the most important modules and information flows are shown in this figure. The core modules of VE-Suite are VE-Builder and VE-Xplorer. VE-Builder is the toolkit developed on the VTK library that performs all the preparatory work to build a virtual engineering model. All the resource data, including the geometry files and engineering data, are transformed into a VTK data set. The data files can be CFD results from many types of software, e.g., Fluent ^{TM}, Star-CD ^{TM}, Fire ^{TM}, FEA analysis result, as well as empirical and experimental data. Other

functions such as scaling, transforming, and pre-computing specific visualization data are also included in VE-Builder. The VTK data set (with correct location and orientation) is then transferred to VE-Xplorer, which is a graphical engine built on VRJuggler[TM] and OpenGL performer [TM], for visualizing these data in the virtual environment. Since the pre-computed data do not cover every point in the geometry model, VE-Xplorer automatically carries out interpolation so that smooth isosurfaces, streamlines, etc., are displayed.
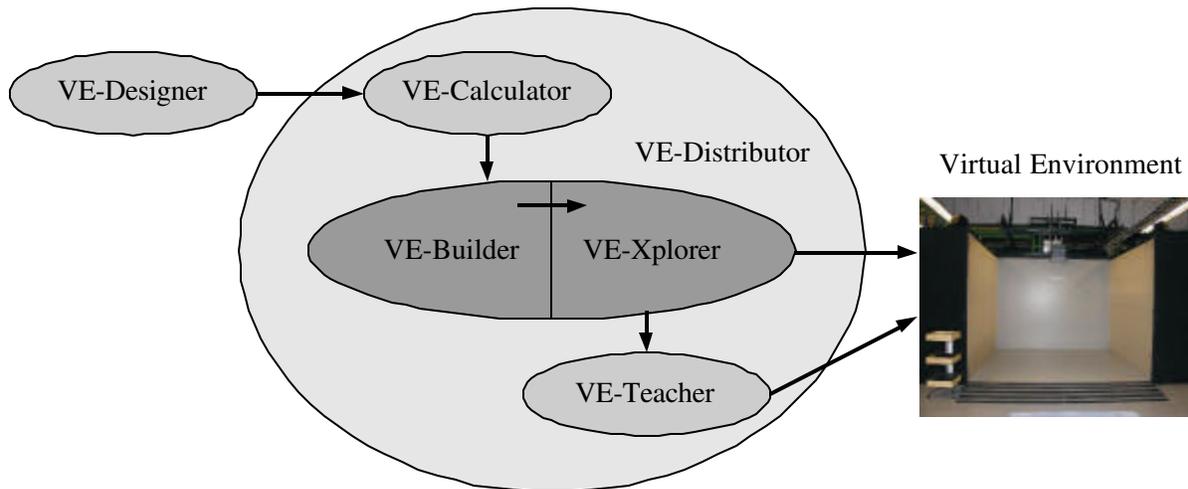

Figure 1. Software Architecture of VE-Suite

As mentioned above, engineering models must be included in the virtual engineering model to support the user interactions. That is, the user can modify design parameters and observe the results in a virtual environment. This function is sustained by a computing engine, VE-Calculator. Within the virtual fermentor introduced in the next section, students practice varying the operation parameters, e.g., chemical and biological inputs, blending speed, temperature, etc. The resulting product (ethanol) concentration, pH value in the fermentor, etc., are calculated from the biochemistry models. Then the resulting data are sent to the core modules for preprocessing and display, as shown in Figure 1. VE-Designer is a module that allows the user to modify the parameters and observe the result in a virtual environment.

VE-Teacher is a simplified version of VE-Xplorer that enables storing the entire virtual engineering model and later exporting it to the virtual environment for educational purpose. The stored model is called a "scene". VE-Distributor distributes the computational workload between available computing resources. For instance, VE-Distributor may allow a graphics workstation to perform rendering and displaying while sending the calculation task to a different computer. This eases the computational burden on the graphics workstation and makes the display faster and more realistic. VE-Suite also has a graphical user interface (GUI), which is a command center that allows the user to interact with and manipulate all of these components. Some functions of the GUI are introduced in the following section.

2.2 Graphic User Interface of VE-Suite

As shown in Figure 2, the VE-Suite GUI is usually run on a tablet PC that communicates wirelessly with the host computer that is running the graphics application. Some typical operations can be performed on each tab of the GUI:
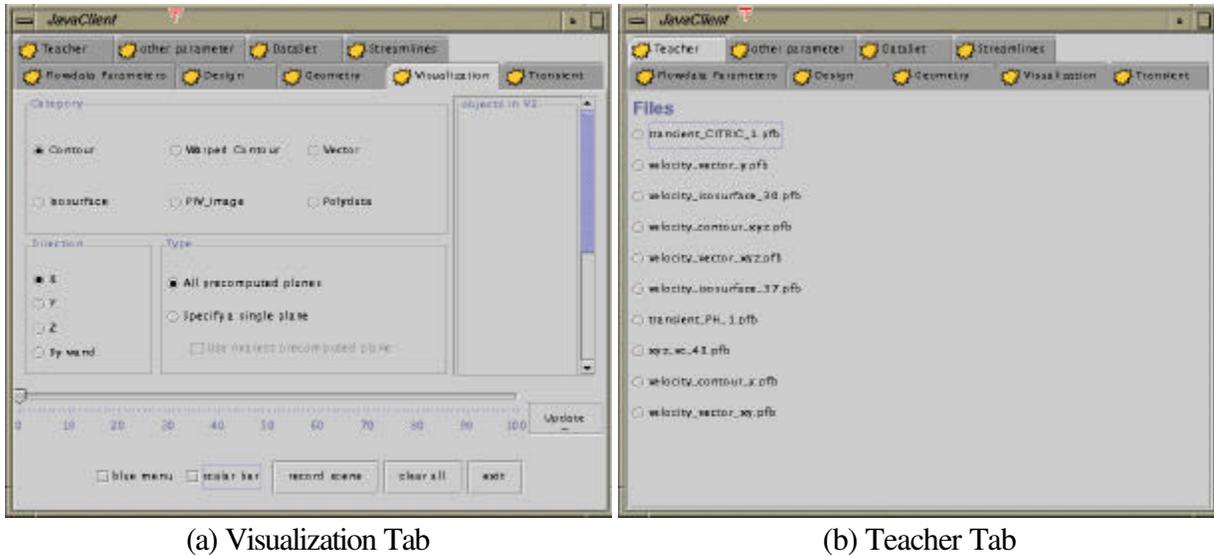
| (a) Visualization Tab | (b) Teacher Tab |

Figure 2. VE-Suite GUI Visualization and Teacher Tab

The Visualization Tab, Figure 2 (a), is the main screen for displaying steady state data; the controls of transient data that show the changing nature of a flow field are in the Transient Tab. The user selects one visualization method (contour surface, vectors field, etc.) from the "category" section and chooses the location he/she is interested in using with the sliding bar. The user can opt to show pre-computed data or to show data computed on the fly, as shown in the "type" section. The "record scene" button is used to save the virtual engineering model currently displayed, and the "clear all" button clears the current display. Therefore, an instructor can develop a complete virtual engineering model, then use it to develop a specific training program. In the training program, the instructor can set up as much or as little of the virtual engineering model as needed to be accessible to the students. For example, in an initial exercise a student may only be able to walk around the equipment, observe the gauges, and understand the layout. In later exercises, the student may be able to operate equipment and conduct virtual experiments. The instructor can also specify a starting viewpoint and use the VE-Suite GUI, Figure 2 (a), to select the desired combination of geometry and engineering data. Students are free to load and explore any model at their own learning pace. As mentioned before, after a scene is stored, it can be accessed by the students using the VE-Suite GUI's Teacher Tab, Figure 2 (b). These functions enable instructors to produce virtual educational rooms spanning as many data sets and modeled systems as needed. The stored scenes are not fixed in space. Once displayed, the student can still navigate and perform all of the tasks permitted by the instructor in VE-Suite.

Additionally, the Streamlines Tab is used for creating streamlines to show a flow field. The user selects how many seed points he/she wants to use and what orientation they will be in. There will be one streamline computed for each seed point. The Geometry Tab is used for toggling geometry off and on

and making geometries transparent. This allows the user to see only the desired level of detail in the virtual engineering model. It is common to remove some geometries and make others transparent while taking a careful look at the area of interest. The Data Set Tab allows the user to select multiple data sets to view. For instance, students who use the virtual fermentor might want to compare data sets representing different blending speeds. Also, students might want to observe another set of FEA analysis data after viewing the CFD one. The Scalars Tab allows the user to select from a set of different scalar data because real systems usually have many scalars of interest. For instance, the user of the virtual fermentor can switch between the scalar data representing product (ethanol) concentration and pH value in the tank.

VE-Suite is now undergoing constant updates and modification. Although still a prototype system, the current functions can well sustain educational usages. Instructors may still have to use the tools in VE-Suite to construct course materials, but the students only use the GUI for navigation and interaction, which makes VE-Suite a suitable tool for educational and training purposes.

3. Virtual Fermentor at Indian Hills Community College

The virtual fermentor consists of geometric files of the fermentor, CFD data sets representing the fluid flow, and engineering models of biochemistry reaction within the fermentor. The CFD data sets are scalar data that represent temperature distribution, product (ethanol) concentration, pH distribution, and vector data that represent the flow speed and direction in the tank. Engineering models include the product concentration and pH values with respect to the chemical and biological inputs, initial temperature, and the spinning speed of the impeller. Again, the engineering models simulate the fermentation process so students can practice varying chemical and biological inputs and controlling process parameters without the expense of doing so with real equipment.

The VR environment used at the Indian Hills Community College is a 2.7 meters wide by 2.1 meters tall single-wall, rear-projected system driven by an SGI Octane 2^{TM}, Figure 3 (a). It is a passive stereo system that utilizes a Christie-Digital Mirage 2000^{TM} projector with a Stereo Graphics projector Z-screen^{TM}. The navigation for these VR environments is accomplished using a tracking wand, so the position and orientation of the wand is always known, allowing it be used as a pointer, Figure 3 (b). In this VR environment, the wand is tracked by an Ascension flock-of-birds^{TM} with an extended range transmitter and has four buttons for digital input. The digital button input of the wand is handled with an Immersion interface box (IBox). The VE-Suite GUI is run on a tablet PC that has a cable connecting it with the host computer that the VR application is running on, so the students have the freedom to walk around and operate the GUI at the same time. Generally, the large display screen and additional peripherals make the single wall VR environment more immersive than a desktop one, but less immersive than a Surround Screen VR environment such as the CAVE^{TM}.

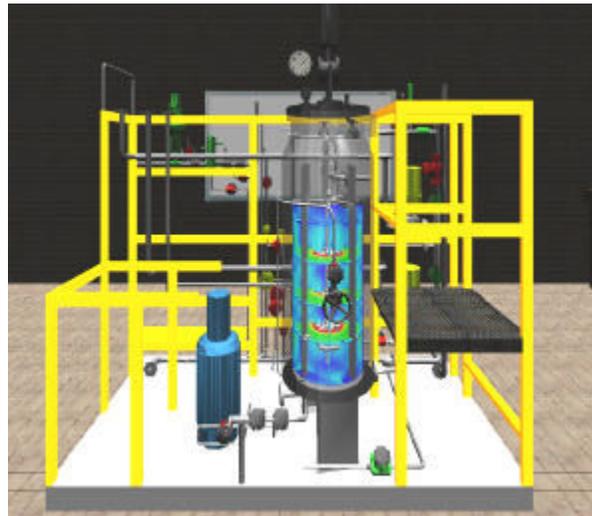(a) VR Environment   (b) Peripherals

Figure 3. Virtual Reality Environment at Indian Hills Community Collage

(a) Actual Picture of the Fermentor   (b) Virtual Fermentor

Figure 4. The Virtual Fermentor at Indian Hills Community College

Figure 4 shows a stainless fermentation tank (fermentor) and its virtual engineering model created for Indian Hills Community College. The room, including table, whiteboard, wall clock, lights, etc. was made to look the same as it does at the real location. Hence, the virtual fermentor gives the student the impression of being in a laboratory and sets the stage for the simulation within this familiar context. The virtual engineering model is capable of demonstrating the inner workings of the fermentor, allowing students to navigate the entire virtual bio-processing plant and investigating the details of the fermentation parameters including the vector and scalar data mentioned before. Hence, the virtual fermentor provides the students with a realistic and engaging learning experience that help them understand the course material. Additionally, running in VE-Suite, the virtual fermentor is used to simulate the fermentation process so students can try any combination of process parameters and see the result instantly. This hands-on, interactive learning environment helps students comprehend what is learned in the classroom. It is shown in Figure 4 (b) that a transparent fermentor tank is loaded, with a

set of velocity data represented using contour surfaces while the impeller in the tank is rotating at a steady speed of 60 rpm. For instance, with closer observation of the virtual fermentor, the student can find that the highest velocity in the fermentor is right at the tip of the impeller where there is red, and the regions of dark blue near the impeller shaft and elsewhere indicate very slow speeds. Students can operate the virtual fermentor using the wand and tablet, based on their own learning styles and paces.

Figure 5 shows two close-up views inside the tank with the surrounding geometries turned off. Figure 5 (a) shows the same velocity magnitude contour as Figure 4 (b); white arrows show the flow directions. In this case, the fluid flow characteristics are shown with a set of transient data, which is controlled using the Transient Tab on the VE-Suite GUI, Figure 2. Students can stop, fast forward, fast backward at any time, or select any particular moment using a slide bar. Figure 5 (b) shows a view when pH = 6 within the tank; the color changes with respect to different input from students and time to simulate the change of pH value in an actual fermentation process. Please note that on this picture a transparent version of the tank remains.
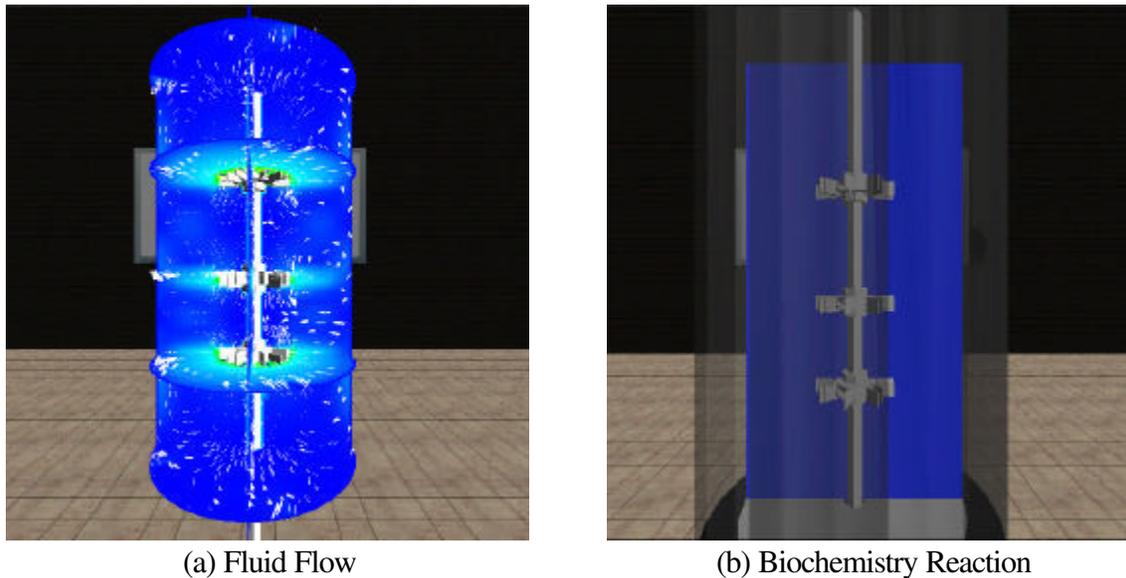

| (a) Fluid Flow | (b) Biochemistry Reaction |

Figure 5. Close-Up Views in the Virtual Fermentor

4. A Human Factor Experiment Using VE-Suite

As mentioned early, the abstract information about the fluid dynamics is shown with different data visualization methods: vector fields and streamlines for vector data; isosurfaces and contour surfaces for scalar data. As part of this research effort, we conducted an experiment to test which data visualization method is preferred by students. We chose the direct-by-carry-over model of Balaam's design for two treatments [11], which is a two treatment, two period, four sequence cross-over design. This means that four different groups (or sequences) are used to compare two different visualization methods (or treatments) by seeing them in two different periods. Kershner and Federer introduce the benefits and disadvantages of many two-treatment cross-over designs [12], and the criteria for selecting experiment design is introduced by Laska and coauthors [13].

There are two primary groups of students who participated in this study. The first group consists of 16 students who are enrolled in an undergraduate mechanical engineering fluid dynamics course (ME 335) at Iowa State University. These students can be characterized as juniors/seniors in mechanical engineering who have some background in fluid dynamics. The other group consists of 16 students from the Indian Hills Community College Bioprocess training program. The Indian Hills group can be characterized as typical students enrolled in a two-year technical education major program, who do not have a background in fluid dynamics. For each participating student, the experiment consisted of four periods. The first and third periods involved analyzing vector data, and the second and fourth periods involved analyzing scalar data. Within each period the students were required to explore a different set of CFD data and to answer a set of questionnaires, also called an exercise.

All thirty-two students performed this study individually. When the students first arrived at the testing location, an investigator introduced them to the virtual reality hardware they were going to use. After each student was familiar with navigating and using the Teacher Tab of the VE-Suite GUI, the investigator worked through a tutorial with him/her that is similar to the exercises that were performed for the study. The study began after the students understood all of the visualization methods that would be used. At the beginning of each exercise, the investigator described the system that was about to be shown in enough detail for the student to answer the questions. It should be noted that the students were able to see more than just one stored scene for each exercise. There were several stored scenes prepared ahead of time for each visualization method; each one was slightly different and focused on a different important feature of the data being studied. Moreover, these scenes were selected to ensure that the student was able to see clear representations of all of the important characteristics of the various exercises. The students could cycle back and forth between the stored scenes quickly and freely during the study by selecting the various scenes on the GUI, as shown on Figure 2 (b). Each student answered four sets of questions, each of which was graded on a 100 point scale. The grader was unaware of which visualization method was used when the student answered the questions.

The results from this study are actually broken down into four studies. Vector data results are treated separately from scalar data results, and the Iowa State group is treated separately from the Indian Hills group. So the four independent studies are:
- the Iowa State vector data study
- the Indian Hills vector data study
- the Iowa State scalar data study
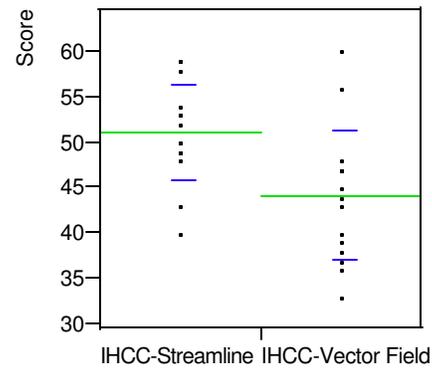- the Indian Hills scalar data study.

The mean value for each visualization method applied to each group is shown in Table 1. This table shows that the Iowa State group had no preference between the vector field and streamlines methods for visualizing vector data, but they did have a strong preference for seeing contour surfaces over isosurfaces when analyzing scalar data. The Indian Hills group showed some preference for the streamlines method of visualizing vector data and a strong preference for the contour surface method of seeing scalar data. Based on the students' scores, formal analysis of variance (ANOVA) was performed using a statistical package, SAS 8.2.
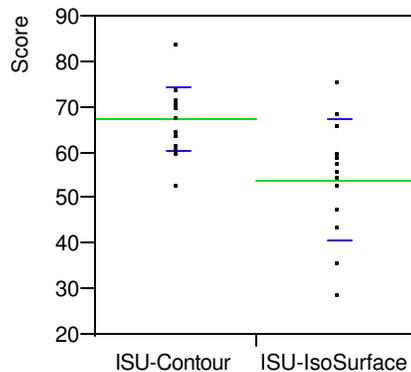
Table 1. Average Scores for the Visualization Methods

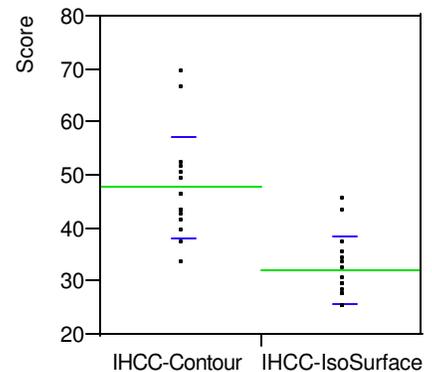|	Iowa State	Indian Hills
Vector Fields	59.19	44.56
Streamlines	59.68	52.13
Contour Surfaces	67.52	48.1
Isosurfaces	54.88	33.7
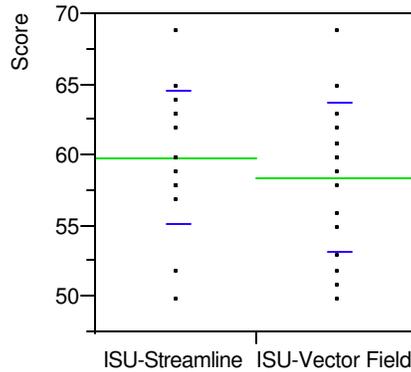
(a) ANOVA for Iowa State & Vector Data

(b) ANOVA for Indian Hills & Vector Data

(c) ANOVA for Iowa State & Scalar Data

(d) ANOVA for Indian Hills & Scalar Data

Figure 6. ANOVA for Different Groups v.s. Data Visualization Methods

The ANOVA of the students' scores is shown in Figure 6. Figure 6 (a) shows the distribution of the score of the ISU group exploring vector data. Dots in the graph represent the individual scores. The longer lines show the mean value of the scores corresponding to different visualization methods, while shorter lines mark the range of standard deviation. Clearly from the graph, the results of these two methods are too close to show any statistical difference. Also, the ANOVA result shows p-value > 0.05. Based on this, the vector field method is equal to the streamline method for this group. Figure 6 (b) is the result of the Indian Hills group interpreting vector data. ANOVA p-value < 0.05, so the streamline method is preferred to the vector field method for this group. Figure 6 (c) is the result of the Iowa State group interpreting scalar data. For this group, the contour surface method is preferred to the isosurface method for interpreting scalar data. Figure 6 (d) is the result of the Indian Hills group interpreting scalar data. It is clear that the contour surface method is preferred to the isosurface method for this group.

Therefore, for interpreting a set of vector data, the ISU group (mechanical engineering juniors/seniors) did not have a preference between vector field or streamlines while the Indian Hills group had a strong preference for using streamlines to analyze the CFD data. This indicates that streamlines are conceptually easier for students without a formal background in fluid dynamics to understand and thus are better to use when presenting data to this type of group. For interpreting scalar data, both groups of students showed a very strong preference for the contour surface method over the isosurface method. Many students commented that they understood what an isosurface was, but had a hard time keeping a mental inventory of several of them at a time in order to get a feel for the scalar value in the entire system. Perhaps isosurfaces are a good method to use for performing specific types of analysis, but they are not well suited for giving students a feel for what is going on in an entire system.

5. Closure

In this paper, we introduce our work experience in developing a virtual education system for bioprocess training. First, we developed VE-Suite, which is capable of supporting CFD research and education in a virtual environment. A virtual fermentor was constructed to support the students' interaction and exploration. A human factor experiment was conducted accounting for the different educational backgrounds and learning styles of the students in order to achieve the highest learning effectiveness. We suggest that students without a background in CDF prefer using streamlines to vector field to display vector data such as flow speed. For scalar data such as product concentration, students prefer using isosurfaces to contour surfaces.

There are some concerns to be addressed in the future work:
- The engineering models are an essential part for the virtual reality model to reflect the actual fermentation process, as well as the plant process. It is necessary to work closely with the industry to ensure that the controls and responses of the virtual fermentor accurately model those of the real plant.
- There are other methods available for the visualization of CFD data than those studied here. One example is the warped contours method, which uses color and warpage to indicate the velocity magnitude in the direction normal to a specified plane. The following human factor experiments in our research are to compare the preferred methods in this study to the other available ones.
- Text explanations are also important for enhancing student learning. We are working on inserting text into the virtual environment so students can read the text explanations while exploring the virtual environment.

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Biographical Information

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