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# Comparison of CFD visualization techniques in virtual reality

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# Comparison of CFD visualization techniques in virtual reality

by

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Signatures have been redacted for privacy

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# ABSTRACT

Many analysis tools are available that can help provide students with a detailed understanding of engineering systems and equipment. This is particularly true when the output from these tools is displayed in a virtual environment (VE) enabling the students to see the results in a natural user-centered environment. To obtain the greatest teaching advantage, educators need to know which of the available formats students best understand. This thesis compares different techniques for visualizing computational fluid dynamics (CFD) data in a VE for the education of technicians and engineers. CFD data has both vector and scalar components, and two standards of visualization are compared for each component. The ability of students to analyze and interpret these types of three-dimensional data sets within a VE is measured. Vector fields are compared to streamlines for the visualization of vector data, and contour plots are compared to isosurfaces for the visualization of scalar data. These comparisons are made for two different groups of student volunteers, one composed of typical community college technical students and the other composed of juniors/seniors in mechanical engineering. The mechanical engineering group showed no preference between the vector field and streamlines methods when analyzing vector data, but the community college technical students showed a strong preference for the streamlines method. This indicates that students who have a formal fluid mechanics education understand each method equally, while those without one are able to understand CFD data better using streamlines. Both groups showed a strong preference for the contours method over the isosurfaces method when analyzing scalar data.

# 1. INTRODUCTION

When teaching students technical material, one of the most common questions is, "How does it work?" In the case of complex equipment, understanding this is often difficult because the student cannot take the device apart and see inside it. Virtual reality offers the opportunity to do this by allowing the student to make solid geometries transparent and view visual representations of the physical processes inside. In large part this process is data visualization because the visual representations are based on a solution given by a numerical analysis tool or perhaps experimental data being sent to the computer. The role of data visualization has become more important as better algorithms and the declining cost of computational resources have made high fidelity modeling (e.g., computational fluid dynamics [CFD]) more available to engineers and students. It is not uncommon for a modern CFD problem to contain millions of cells and be geometrically equivalent to the real, complex three-dimensional system being modeled.

In the past, the primary users of CFD data were analysts. Typically these analysts had master's or doctoral degrees in numerical analysis of fluid flow and were trained in viewing analysis results. Today, CFD results are used and viewed by production engineers, design engineers, students, and other non-CFD specialists. These non-CFD specialists need to have the CFD data presented in familiar and readily understandable formats. Virtual reality provides the solution to this need. However, there has been very little research done to determine what representations of CFD data are most appropriate for the non-CFD specialist. This thesis examines common visualization techniques for vector and scalar CFD data to determine which of the representations works best for non-CFD specialists.

## 1.1 Virtual Environments

Virtual reality (VR) is a computer simulation that uses three-dimensional graphics and devices to allow the user to interact with the simulation. Unlike the traditional desktop monitor, virtual environments (VEs) give the user the feeling of being immersed in the graphics she/he is looking at. The level of immersion that the user feels depends on the type of VE that he/she is using. Three common types of VEs are the desktop VE, the single wall VE, and the surround screen VE.

### 1.1.1 Desktop virtual environments

Figure 1.1 shows a desktop VE, which is very similar to the traditional computer. The difference is that these computers are equipped with stereo-enabled graphics cards that work in conjunction with liquid crystal shutter glasses to produce a three-dimensional image on the monitor. Also, the 3D mouse shown in Fig. 1.1 usually replaces the traditional mouse. The 3D mouse is convenient for navigating in virtual worlds and provides many buttons for providing input to the VR application. The desktop VE is the least immersive of the three types of VEs listed above, but is very popular because it provides the user with a three dimensional view of the graphics at a relatively low cost. For a higher level of immersion and a larger display, one may choose to use a single wall VE.

**Figure 1.1: A typical desktop virtual environment**

### 1.1.2 Single wall virtual environments

The single wall VE as shown in Fig. 1.2 is very common in visualization laboratories around the world. Single wall VEs have one screen that can vary in size significantly for different systems. A typical screen size is approximately three meters wide by three meters tall although they can be larger. The single wall VE differs from the desktop VE in that it provides a larger display and a more natural interface. For single wall VEs, the computer sends the graphics to a VR projector, which shines on the screen either from the front or from behind. The Indian Hills Community College single wall VE, the system used in this study and shown below, is a rear-projected system with a 2.7 meters wide by 2.1 meters tall screen. Also, the navigation for these VEs is usually accomplished using a tracked wand. A tracked wand is a handheld device with buttons for performing various functions in the VE. Since it is tracked, the position and orientation of the wand is always known allowing it be used as a pointer. For example, one may point the wand in the desired direction of travel and then push a button to move, or, the user might use it like a laser pointer with a button assigned for selecting whatever object the wand is currently pointed at. The large display and additional hardware make the single wall VE more immersive than the desktop VE, but at a substantially higher cost. The most immersive type of VE is the surround screen virtual environment.

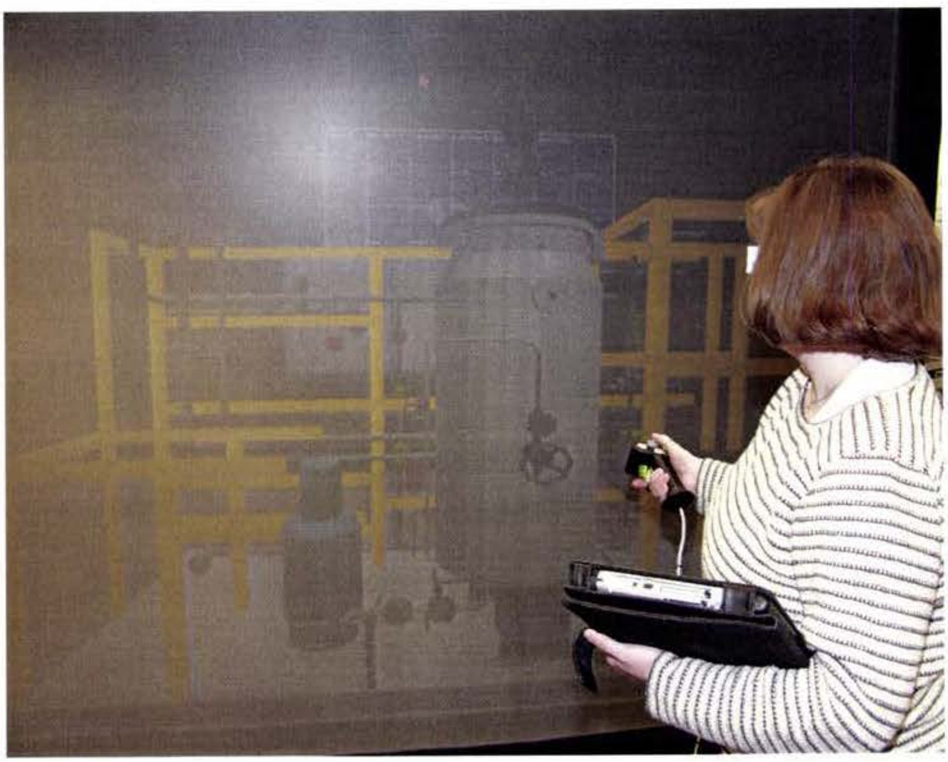


**Figure 1.2: The Indian Hills Community College single wall VE**

### 1.1.3 Surround screen virtual environments

Surround screen virtual environments (SSVEs) are the most immersive. These are configured with multiple walls "surrounding" the user. This type of VE is often called a CAVE$^{TM}$. Figure 1.3 shows Iowa State University's C4 SSVE. It is made up of four walls surrounding the user on every side except for above and behind. These systems use the same hardware as single wall systems, and differ only in the configuration and number of walls. The C4's sidewalls can also be swung open to make a large single wall as shown in Fig 1.4.

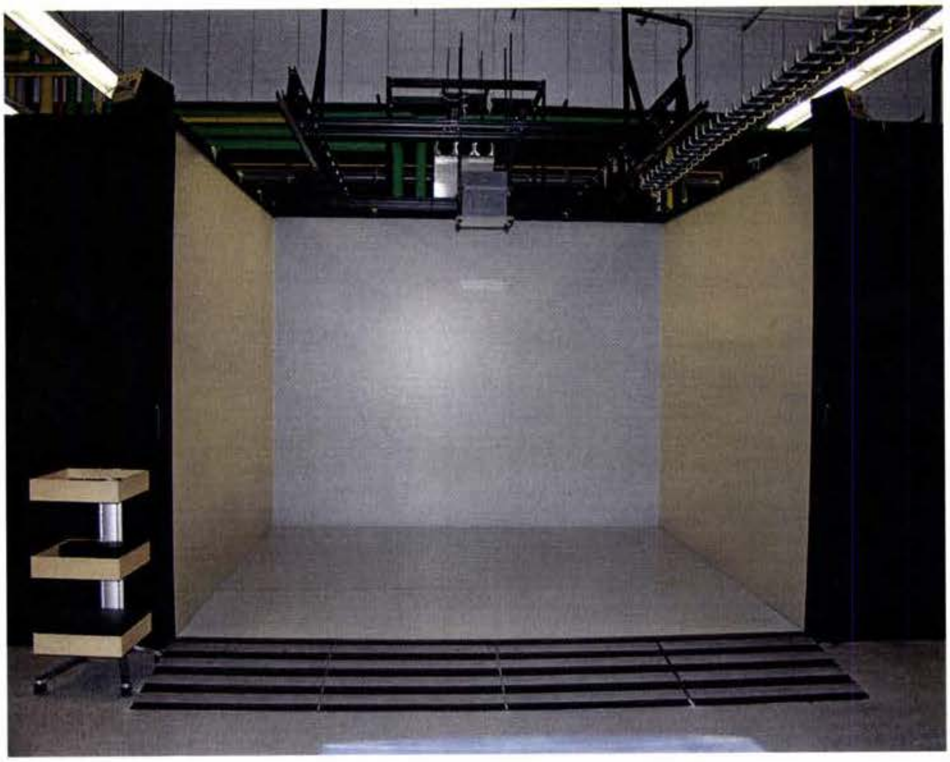


**Figure 1.3: Iowa State University's C4 surround screen VE**

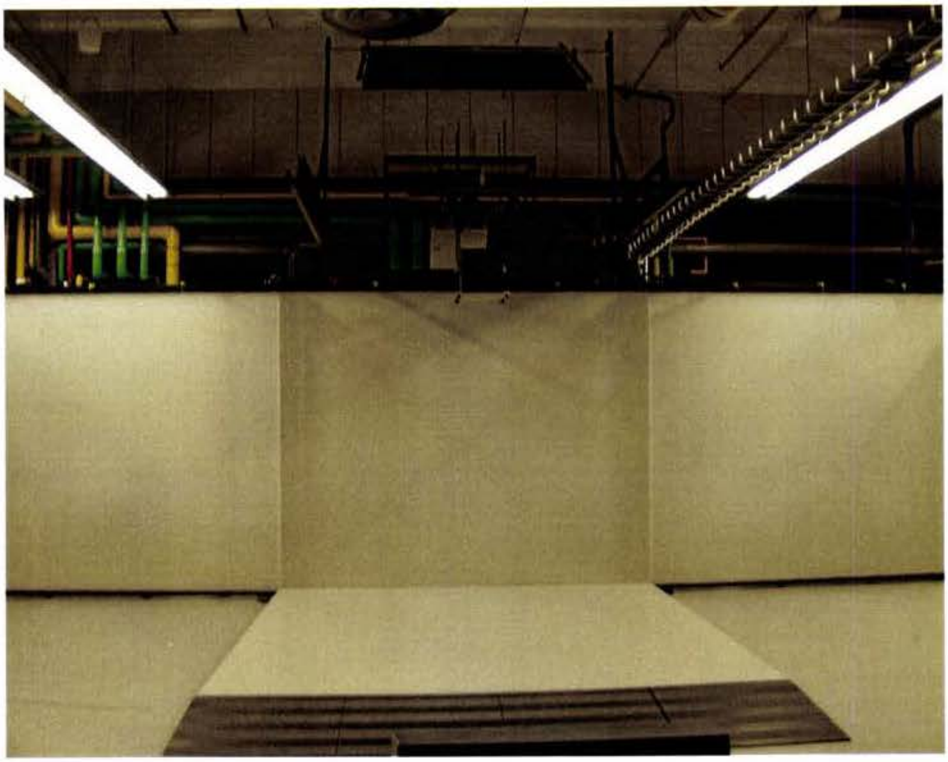


**Figure 1.4: The C4 in the open configuration**

## 1.2 Data Visualization Past and Present

CFD is used in education to provide detailed knowledge of a system, giving students a more detailed understanding than can be obtained by studying the bulk characteristics of the system alone. Virtual environments have significantly changed the way humans interact with CFD data. In the past, users would import CFD data into a separate visualization package to create visual representations of the data and then view the results on a desktop monitor. This is a good approach to summarizing the data in a useful way, but viewing the results on a two-dimensional monitor screen fails at giving the user a true sense of complex three-dimensional data. Users often end up viewing planes of data one at a time and trying to keep a mental inventory of all of the planes and how they interact to form the real three-dimensional solution.

Interfacing with VEs makes this process unnecessary. Three-dimensional visualization of the data gives a clear picture of the data at any point in space and from any angle. The user can get a feel for the entire three-dimensional solution with a single look. He/she can also look at specific areas of interest from the appropriate angles and get a real feel for the data there. Doing this on a 2-D monitor often results in a lack of clarity about what is being seen. This can result in important flow features being missed or incorrectly analyzed, resulting in poor decisions being made or misunderstandings about the system of study. Because of this, VEs can be very helpful for non-CFD experts who need to make decisions based on the data.

### 1.3 Data Visualization in Education

Visual representation of data is found everywhere in education. When an instructor wants to show students how a mathematical function changes with respect to time, a graph is drawn. Solving for the stresses in a structural member always begins by constructing a free body diagram, followed by plotting the forces and moments at different sections of the member. The ways in which visual representations of data are used in education are too numerous to mention. These methods are so popular because they take a difficult concept and summarize it in a clear and easily understandable format. Learning advanced concepts without visual aids would be very difficult for many students and impossible for others.

The ability to teach advanced concepts to students is limited by the ability to produce visual representations of them. In the past, this was not a significant problem in fluid mechanics education since analysis relied more heavily upon analyzing the bulk characteristics of a system and treated only general geometries that were easy to work with. The increasing availability of CFD and other sophisticated analysis tools on college campuses is changing the way problems are being solved. Now the impacts of local phenomena and exact geometry can be studied with the use of an average computer. However, effective visualization of the output from these analysis tools is essential if they are to be useful for the purpose of educating students.

Because of this, VR can be a powerful tool in engineering and technical education. A three-dimensional graphical interface is required to adequately represent data from complex geometries to students. Just as using two-dimensional visualization techniques does not give non-CFD experts a clear picture of the physical processes of a system, a two-dimensional visualization will impede the learning of a student relative to a three-dimensional graphical interface. Having a VE available in the classroom will give instructors the ability to teach many advanced concepts to students more easily.

# 2. RESEARCH OVERVIEW AND GOALS

While the potential benefits of VR in technical education are clear, which representations are best for enabling students to interact with and understand CFD data is not clear. Because the ability to view three-dimensional data in a clear and easily understandable manner is necessary to take advantage of modern analysis tools in education, answering the question of what representations of the data are most easily understood is essential.

This research project involves conducting a human factors experiment to determine which methods of CFD data visualization students most easily understand. A group of sixteen juniors and seniors from Iowa State University majoring in mechanical engineering and a group of sixteen first and second year students from Indian Hills Community College majoring in bioprocess technology participated in the study. Each of the thirty-two student volunteers was immersed in a single wall VE where they were shown graphical representations of real world systems involving fluid flow. They were then asked to answer technical questions about the data they were seeing. These questionnaires were scored and the results were used to make determinations about the effectiveness of various three-dimensional CFD visualization techniques.

CFD data can be broken down into two primary classifications, vector data and scalar data. Vector data has a magnitude and direction associated with it. An example of vector data is the wind blowing at ten miles an hour from north to south. Scalar data only has a magnitude associated with it. Some common examples of scalar data are pressure, temperature and chemical concentration. In this study, the effectiveness of two different visualization methods for each classified type of data were compared. That is, two methods of visualizing vector data are compared to one another, and independently, two methods of visualizing scalar data are compared to one another. These comparisons are made for the two independent groups of students discussed above. This is done because it is reasonable to assume that students with different educational goals may find different visualization methods to be most useful.

## 2.1 Background

Other human factors experiments that deal with the effectiveness of using virtual reality technology in engineering and educational applications have been performed. One study compared the effectiveness of using a single wall VE to a two-dimensional monitor, and a pinch™ glove to a standard mouse, in designing spherical mechanisms [1]. Another study carried out on a desktop VE compared the ability of students to estimate linear and angular distances of mechanisms in an automotive cabin with and without the use of a haptic device [2]. This study was later expanded to include a head mounted display (HMD) VE, and the data was combined to evaluate the effectiveness of the VE used as well as the presence or lack of a haptic device [3]. A fourth study dealt with safety hazards in a polyether polyol production facility [4]. Students were given a written description of the plant operations and material safety data sheet (MSDS). One group of students wrote a summary of potential hazards based on this knowledge alone, and their summaries were compared to that of another group who took a virtual tour of the chemical plant before writing the summary . There was also a scientific visualization experiment performed in which six different methods of visualization vector fields were compared to one another to determine the strengths and weaknesses of each method [5]. This study was limited to two-dimensional visualization.

# 3. SOFTWARE FOR DATA VISUALIZATION

Conducting this study required a software package that could create all of the desired graphical representations of CFD data, would run on the Indian Hills Community College single wall VE, would show solid geometry CAD models of the real world system as well as the associated CFD data, could store the three-dimensional scenes to be shown in the study, and could be interfaced with easily by a beginner. All of these features are found in VE-Suite. Because of this, VE-Suite, an open source, multifunctional, extensible virtual engineering software package, was used for the visualization of the CFD data for this experiment. This software is being developed by the Thermal Systems Virtual Engineering Group headed by Professor Mark Bryden at Iowa State University, with the purpose of performing thermal systems design and analysis in VEs. For this study, built-in functions intended for use in education were added. These features will be discussed later.

VE-Suite is an OpenGL Performer™ graphics application that is used to create virtual engineering models of real world systems. A virtual engineering model is made up of two primary components, geometry and data. 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 data to be displayed along with the geometry originates from a CFD package and is acted on by VTK to create the various graphical representations of it. VE-Suite uses VR Juggler to handle interfacing with VR hardware and three-dimensional graphics rendering.

Figures 3.1 and 3.2 show a virtual engineering model of a fermentor that is used in the bio-processing industry for producing ethanol, citric acid, lysine, and alcohol. As a part of this study, this model was created for the Indian Hills Community College Bioprocess Training Center as a tool to help students learn to become equipment operators and technicians in a bio-processing plant. It is used to simulate the fermentation process so students can practice varying chemical and biological inputs and controlling process pH without the expense of doing this with real equipment. Figure 3.1 shows the fermentor from the point of view of a person who has just walked into the laboratory. This is a typical view of a scene when VE-Suite is initially loaded. It gives the user the impression of being in a laboratory and sets the stage for the simulation. As shown, this virtual engineering model shows features in the room such as a table, whiteboard, wall clock, and lights in addition to the fermentor. The visual detail that goes into these models is only limited by the imagination of the user. In this case, the room was made to look the same as it does at the

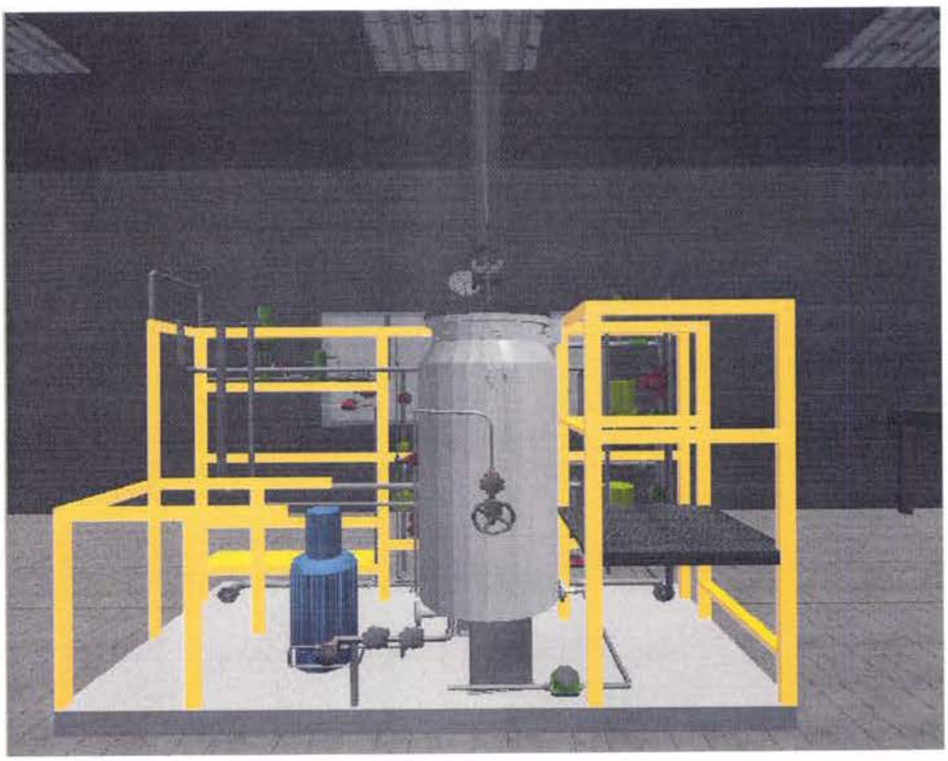


**Figure 3.1: The virtual fermentor in a laboratory**

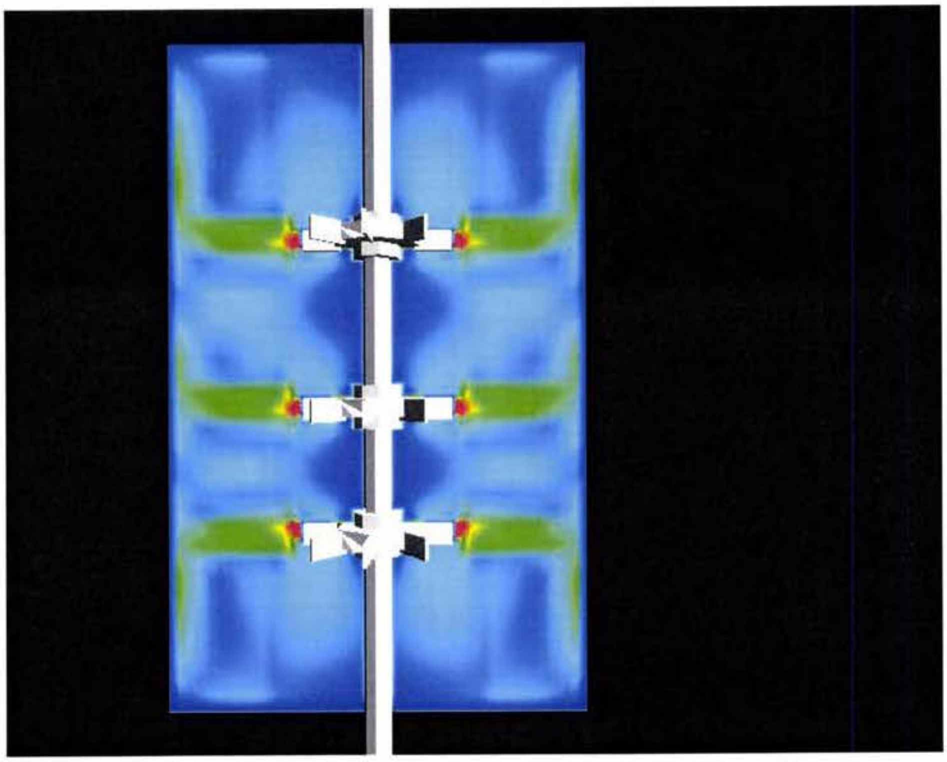


**Figure 3.2: A close-up view of the virtual fermentor with velocity magnitude contours**

real location. Figure 3.2 shows a close-up view of the fermentor. In this instance, the student has turned off the surrounding geometries and only a transparent version of the stainless steel fermentor remains. This is an option available to students to give an unobstructed view of the data. Figure 3.2 shows an individual velocity magnitude contour while the fermentor is operating at a steady speed of 60 rpm. This figure shows that the highest velocity in the fermentor can be found right at the tip of the impeller where there is red. Where the three impellers are, there are three "jets" of high velocity liquid (shown in red) leaving the tip of the impeller and colliding with the inside wall of the fermentor where it climbs or descends. The regions of dark blue near the impeller shaft and elsewhere indicate very slow speeds.

### 3.1 The VE-Suite User Interface

Since VE-Suite has many built in capabilities, for ease of use a graphical user interface (GUI) was created to allow the user to directly interact with the CFD solution. This interface is shown in Fig. 3.3 and is usually run on a PC tablet that communicates wirelessly with the host computer that is running the graphics application. The following operations can be performed on each tab of the GUI:

- **Visualization** This is the main screen for displaying steady state data in the scene and is shown in Fig. 3.3. The user selects one visualization method (contours, vectors, etc.) from the "category" section and chooses a direction to create planes in. The user can opt to show pre-computed data or to show data computed on the fly. The "record scene" button is used to save the tree structure currently displayed, and the "clear all" button resets the scene to its default. Figures 3.1 and 3.2 are examples of stored scenes.
- **Vectors** This screen allows the user to define how vector fields are being displayed. She/he can vary the size and sampling of the vectors. The sampling density defines how many data points there are for each vector drawn. This parameter can be adjusted to avoid "crowded" vector representations on fine meshes.
- **Streamlines** This screen is used for creating streamlines on the fly. 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. These seed points appear in the scene and the user positions them in the desired location by moving the wand. The seed points follow the movement of the wand.

- **Geometry** This screen 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 data of interest.
- **Data Set** This allows the user to select multiple data sets from which to view. Students who use the fermentor virtual engineering model might want to see data sets representing different speeds at which the fermentor impeller is spinning.
- **Scalars** This screen allows the user to select what the current scalar of interest is. Users of the fermentor model switch between looking at ethanol concentration and PH. Most real systems have many scalars of interest.
- **Teacher** Recall that the visualization tab has a button that allows the user to store the scene they are currently looking at. The teacher screen is used to load these stored scenes and is shown in Fig. 3.4. Each item in the list is a scene that can be loaded by selecting the button next to the name of the stored scene. When this is done, the current scene is erased and the stored scene appears just as it was when it was created.

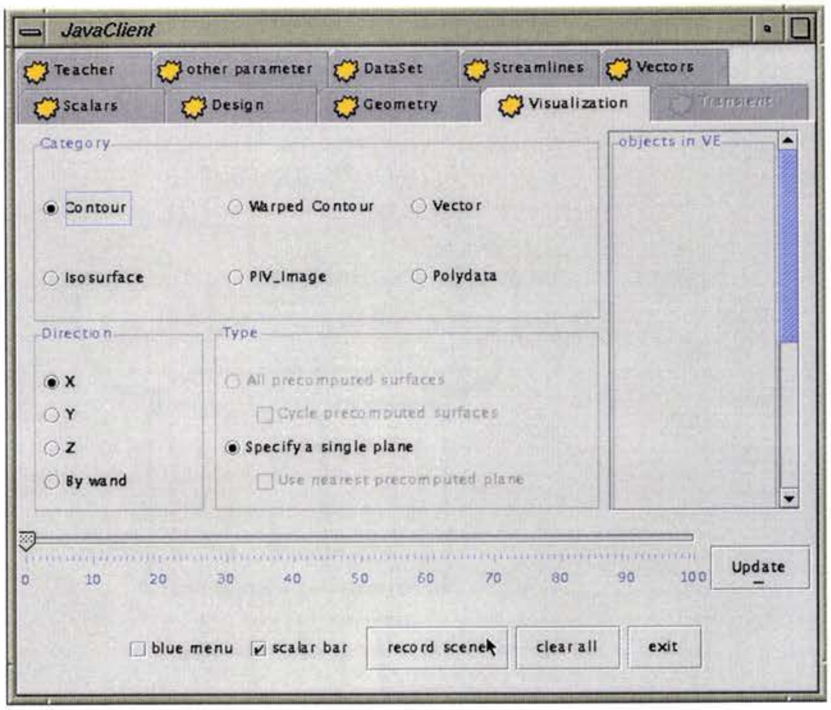



**Figure 3.3: VE-Suite GUI visualization tab**

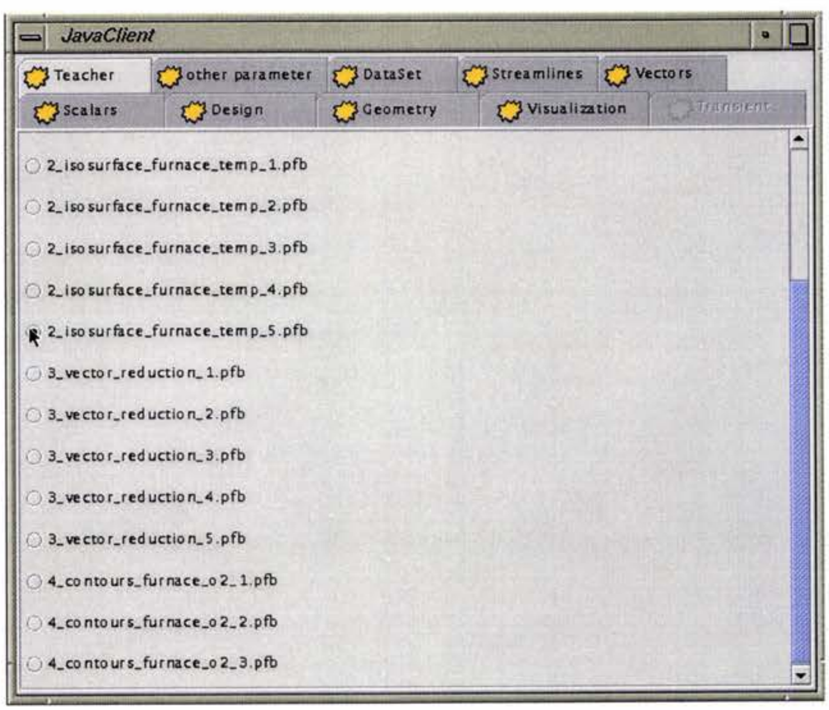



**Figure 3.4: VE-Suite GUI teacher tab**

### 3.2 VE-Suite's Built-in Capabilities for Education

As previously mentioned, additional capabilities for education were added to VE-Suite. Specifically, an instructor can develop a complete virtual engineering model, then use this to build specific training modules. In the training modules, the instructor can set up as much or as little of the virtual system 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 to select the desired combination of geometry and data. The instructor can then use the "store scene" button to save it for later use by students or in lectures. In addition, the instructor can provide written comments on the stored scenes for the students. This may include exercises, discussions, exams, or other needed teaching material.

After a scene is stored, it can be accessed by the students using the VE-Suite GUI "teacher tab." These functions enable educators to produce virtual educational rooms spanning as many data sets and modeled systems as needed. The stored virtual rooms 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. In addition, if a question arises that is not addressed by any of the stored scenes, the instructor can still use VE-Suite's other capabilities to display the necessary data on the fly. In this research project, the "record scene" feature was used to create the virtual rooms for the visualization experiment, and students used the "teacher tab" to access them.

# 4. DESCRIPTION OF THE EXPERIMENT

After the VE was built, a human factors experiment was performed in which students were shown graphical representations of CFD data and asked technical questions about the data. The purpose of the study was to determine which methods of CFD visualization, if any, are best suited for using VEs to instruct students. All four of the visualization methods and all four of the exercises used in the study are described in detail in the following sections.

## 4.1 Environments Studied

- Figure 4.1 shows airflow going around a corner in a rectangular heating and cooling duct. This is one of two exercises that will be used in the study for displaying vector data and will be referred to as Vector Data Exercise 1 (VX1). This figure shows the streamlines method for visualizing vector data, which will be referred to as Method S. Important features in this flow field include a separation and recirculation region on the left side of the lower portion of the vertical section, higher localized velocities in that same region, and a stagnant area in the lower right corner.
- Figure 4.2 shows airflow through a sudden neck in a circular heating and cooling duct. This is the other exercise used for displaying vector data and will be referred to as Vector Data Exercise 2 (VX2). This figure shows the vector representation for vector data, which will be referred to as Method V. Important features of this exercise include a stagnant region near the outside edge of the large duct where it ends, increased velocity in the small duct inversely proportional to the cross-sectional areas of the ducts, and a slightly higher localized velocity to the right of the neck caused by separation there.

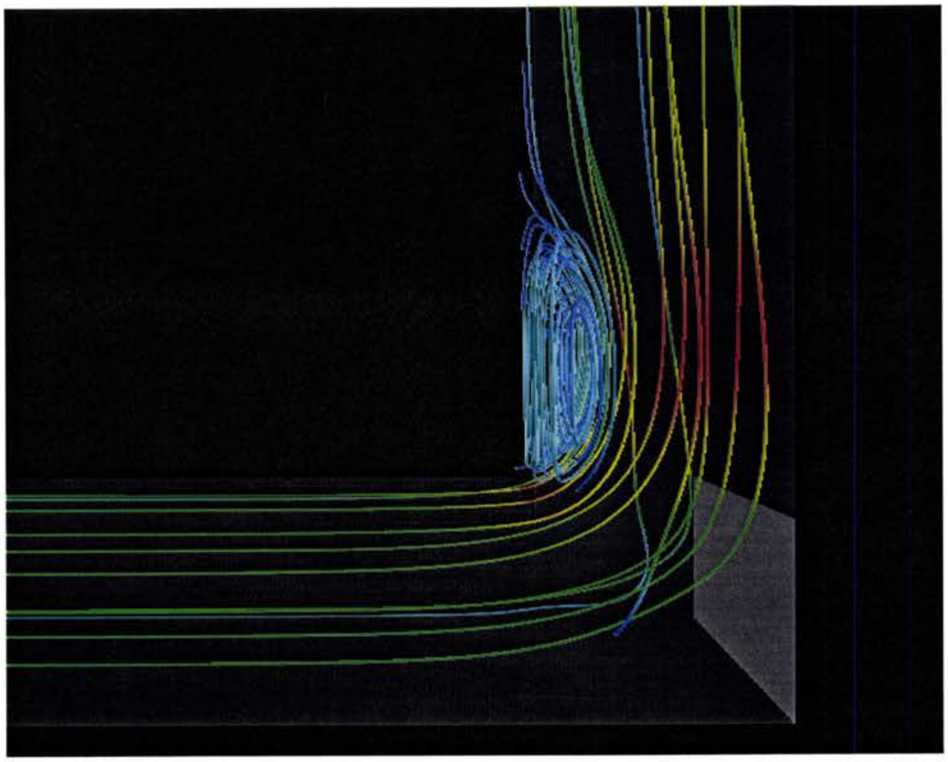


**Figure 4.1: Streamlines shown for VX1**

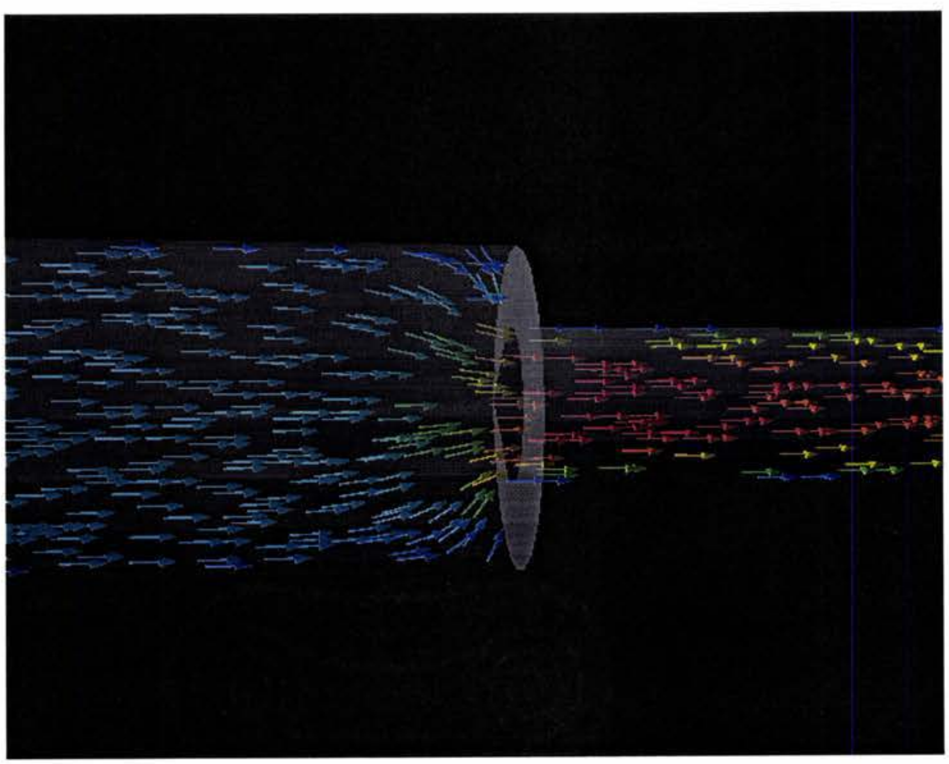


**Figure 4.2: A vector field shown for VX2**

- Figure 4.3 shows the concentration of oxygen inside a power plant furnace. This exercise is used for visualizing the oxygen concentration scalar and will be referred to as (SX1). Here, the contours method of visualizing scalar data is shown and will be referred to as Method C. Important features that can be seen here are that the highest oxygen concentration is found at the coal/air inlets, the concentration tends to be higher near the walls, and the concentration is non-zero at the exit indicating that excess air is used in the combustion process.
- Figure 4.4 shows the temperature inside the same power plant furnace mentioned above. This exercise is used for visualizing the temperature scalar and will be referred to as (SX2). Here, an isosurface of temperature, which will be referred to as Method I, is shown. Important features are difficult to show using a single isosurface. Toggling between several isosurfaces is required to get a feel for temperature variation in the furnace. This is what was done for the study.

**Table 4.1: Summary of exercises and visualization methods**

| **Exercises** | | **Visualization Methods** | |
|---|---|---|---|
| *exercise* | *abbreviation* | *visualization method* | *abbreviation* |
| Flow around a corner in rectangular air duct | VX1 | Streamlines | S |
| Flow through a sudden neck in a circular air duct | VX2 | Vectors | V |
| Oxygen concentration in a furnace | SX1 | Contours | C |
| Temperature in a furnace | SX2 | Isosurfaces | I |

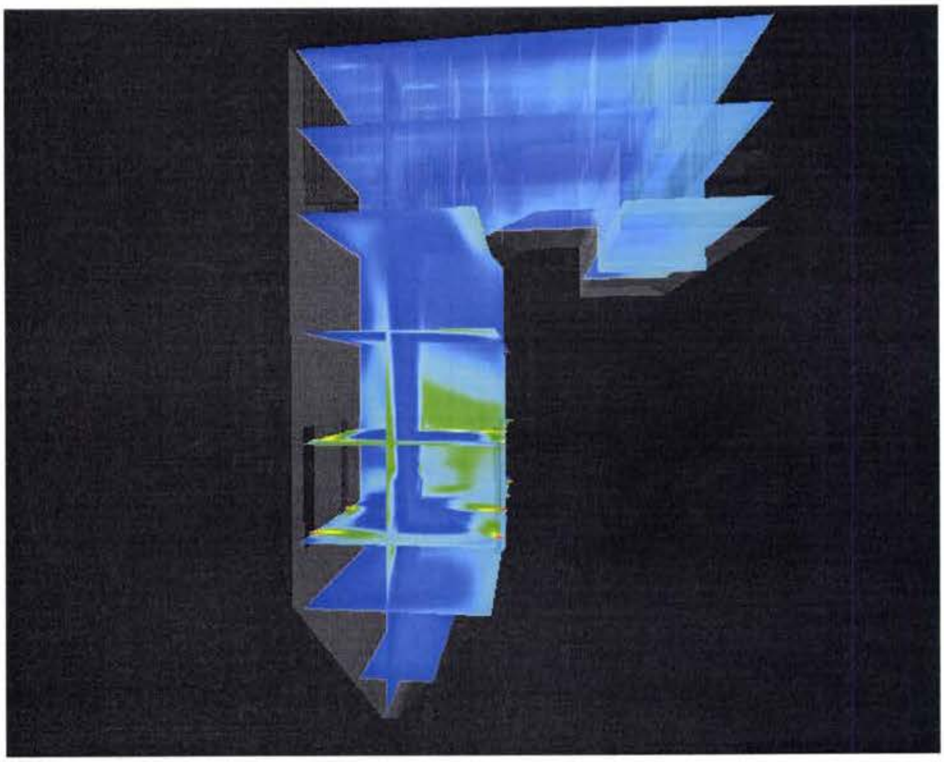


**Figure 4.3: Contours shown for SX1.**

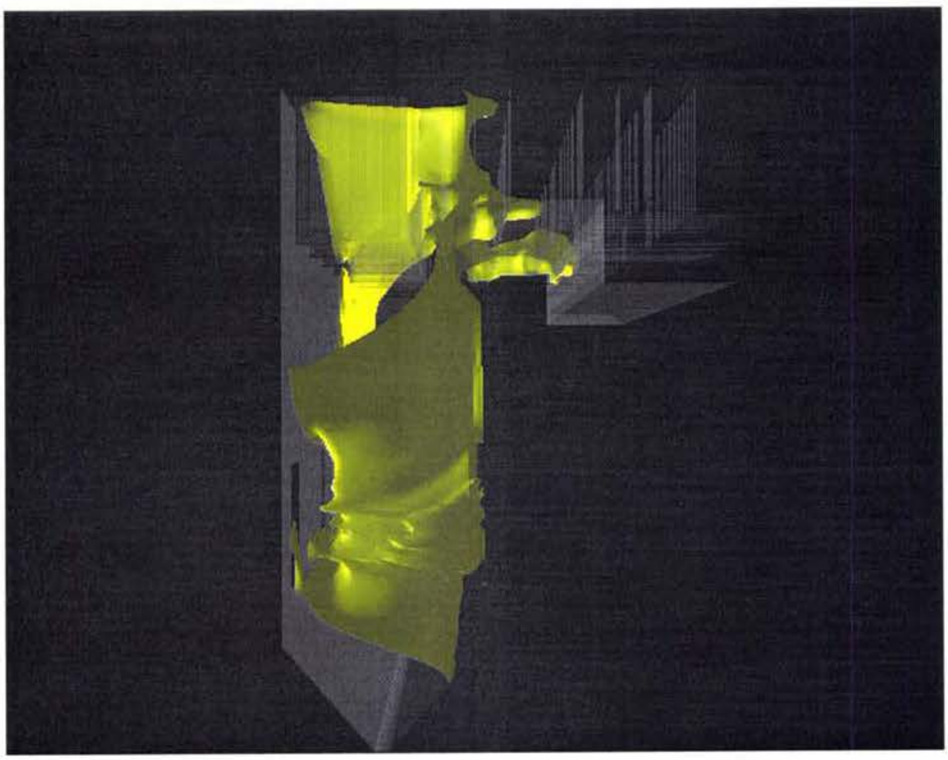


**Figure 4.4: An isosurface shown for SX2.**

## 4.2 Visualization Methods Studied

Four of the most commonly used CFD visualization methods were studied in this experiment. For vector data, the streamlines method is compared to the vector field method. For scalar data, the contours method is compared to the isosurfaces method. A qualitative comparison of the vector data visualization methods and scalar data visualization methods will be made in subsequent sections.

### 4.2.1 Vector data visualization methods

Figures 4.5 and 4.6 show the vector field and streamlines methods of vector data visualization respectively. When using the vector field representation, one specifies geometric planes in which the vectors should be drawn, how many vectors should be drawn in each of the planes, and how large the vectors should be. In Fig. 4.5, a single plane located halfway between the front and back of the duct was specified. When using the streamlines representation, one places a specified number of seed points into the flow at specified locations. Then a line is computed and drawn at a specified thickness, that represents the path that a mass less particle would travel if it were placed into the flow where the seed point is. Both methods use color to show velocity magnitude.

The strengths and weaknesses of these methods are application dependent. The vector field method gives the user the ability to specify a region of interest and see the solution there, but does not clearly trace out a path. The streamlines method shows a clear path of travel, but leaves larger gaps in the flow field where no information is displayed. With either method, some trial and error is required to clearly capture the important features of the flow.

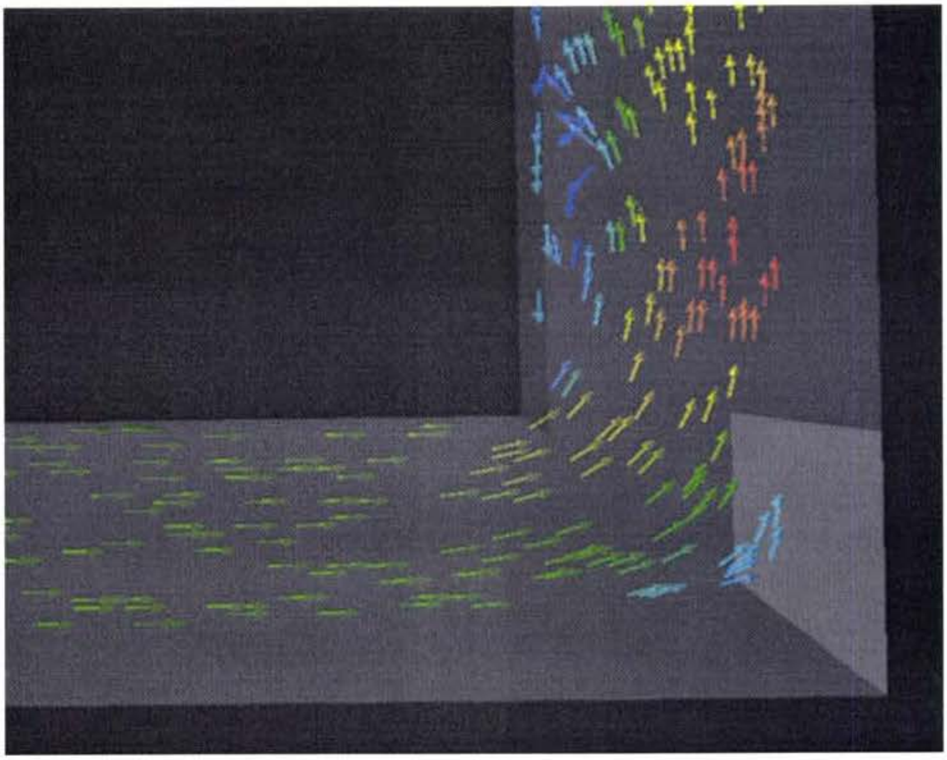


**Figure 4.5: Vector representation of flow through a duct**

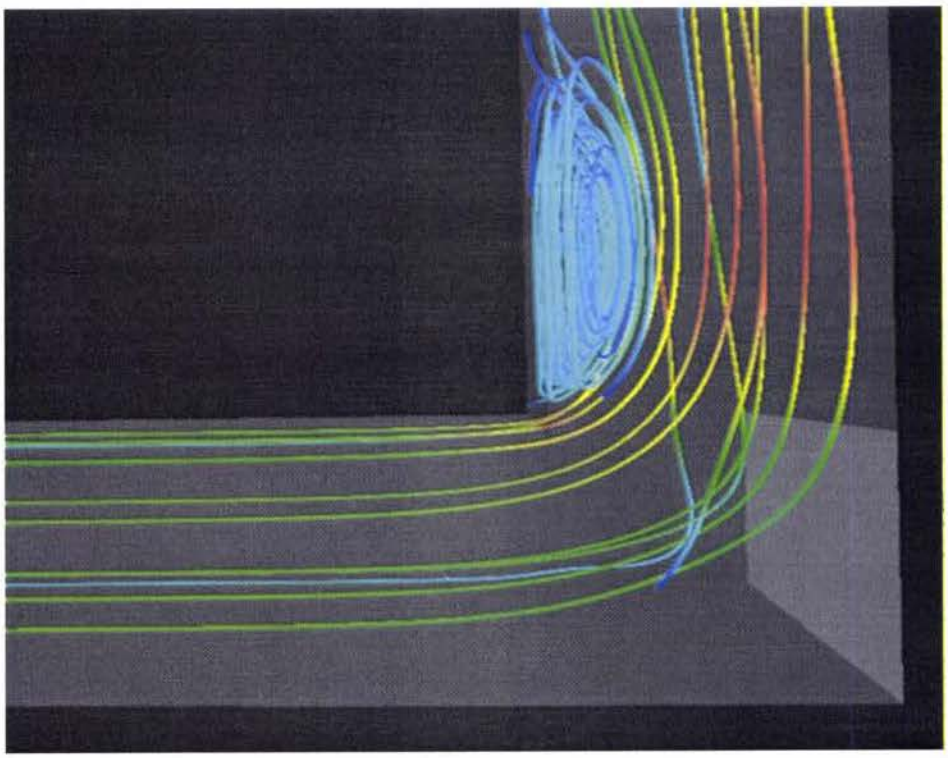


**Figure 4.6: Streamlines representation of flow through a duct**

### 4.2.2 Scalar data visualization methods

Figures 4.7 and 4.8 show the contours and isosurfaces methods of scalar data visualization respectively. Figures 4.9 through 4.12 show more isosurfaces from the same data set. These figures show the temperature distribution in a power plant furnace. To create contours, one specifies geometric planes in which to show data. The student can look at color change to see the temperature distribution on each plane. To create an isosurface, one would specify a temperature, and then a point is drawn at every location in the furnace where the temperature is the same as what was specified. The locus of these points form surfaces of constant value colored to show the magnitude of each surface.

Like the vector data visualization methods, the strengths and weaknesses are application dependent. Generally speaking, the contours method shows users the gradient of values at a specified location while the isosurfaces method shows constant value surfaces at locations that are not defined. Again, some trial and error must be used to create appropriate virtual images that are useful for showing students important features of the system being studied.

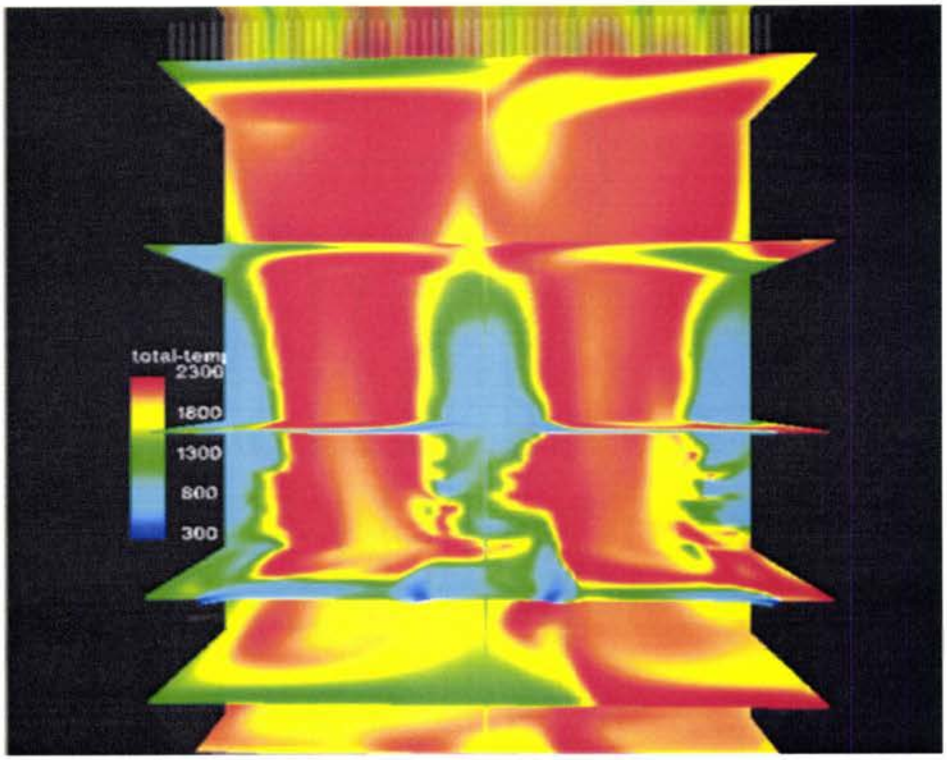



**Figure 4.7: Contours of temperature in a furnace**

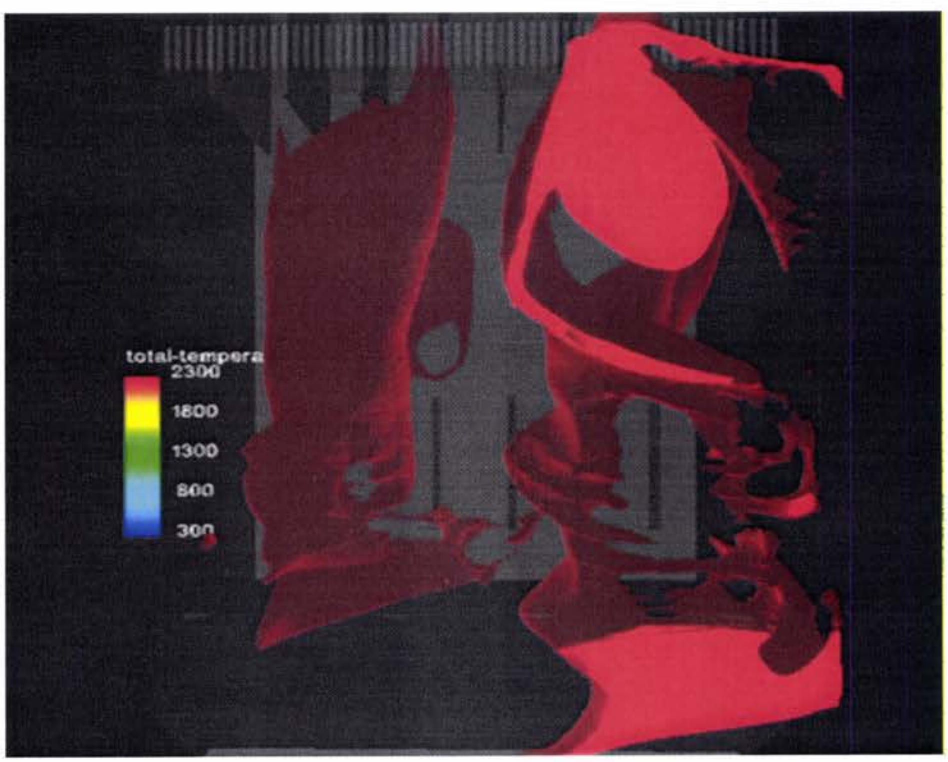



**Figure 4.8: 2280°K temperature isosurface in a furnace**

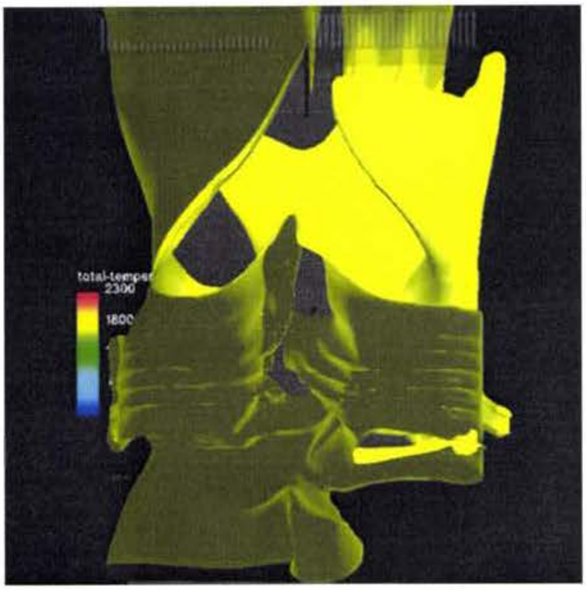


Figure 4.9: 1700°K isosurface

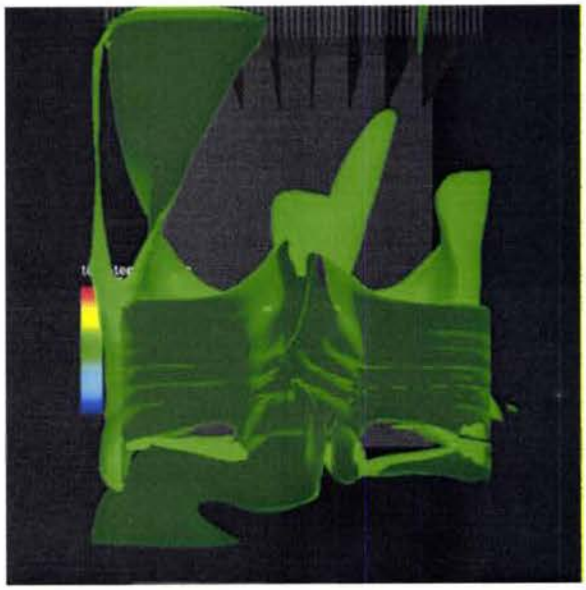


Figure 4.10: 1200°K isosurface

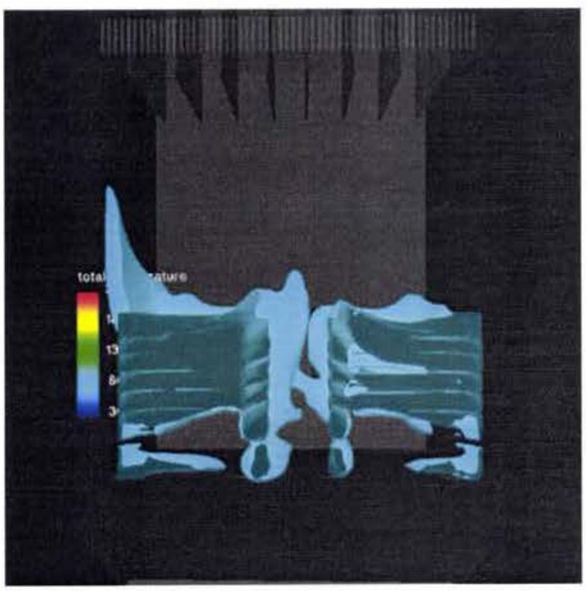


Figure 4.11: 600°K isosurface

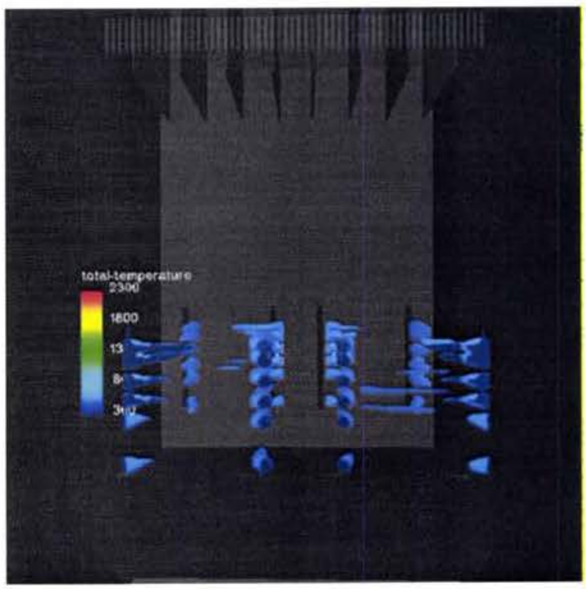



Figure 4.12: 320°K isosurface

### 4.3 Description of the Participants

There are two primary groups of students who participated in this study. The first group consists of sixteen student volunteers who were enrolled in an undergraduate mechanical engineering fluid dynamics course (ME 335) at Iowa State University. They range in age from 20 to 23 years old with an average age of 21.4 years old. There were 14 male students and 2 female students. These students can be characterized as juniors/seniors in mechanical engineering.

The other group consists of 16 students from the Indian Hills Community College bioprocess training program. They range in age from 18 to 49 years old with an average age of 27.4 years old. There were 9 male students and 7 female students. This group can be further broken down into a group of nine traditional students (younger than 27 years old) and seven non-traditional students. The traditional students range in age from 18 to 22 years old with an average age of 19.9 years old and the non-traditional students range in age from 30 to 49 years old with an average age of 37.1 years old. This division within the Indian Hills group was not expected prior to the beginning of experiments and they will be treated as one group unless stated otherwise. There will be an informal comparison between the traditional and non-traditional students. The Indian Hills group could be characterized as typical students enrolled in a two-year technical education major program.

### 4.4 Description of the VE

The same VR system was used by both the Iowa State and Indian Hills groups. The system is owned by Indian Hills Community College and is a 2.7 meters wide by 2.1 meters tall single wall, rear-projected system driven by a SGI Octane 2™. It is a passive stereo system that utilizes a Christie-Digital Mirage 2000™ projector with a Stereo Graphics projector Z-screen™. The wand is tracked by an Ascension flock-of-birds™ with an extended range transmitter and has four buttons for digital input. The digital button input is handled by an Immersion interface box (IBox). Navigating is accomplished by pointing the wand in the desired direction of motion and holding down one of the buttons. Of the remaining buttons, two were used for clockwise and counter clockwise rotation of the model about the vertical axis and one was not used. The VE-Suite GUI was run on a tablet PC so the students had freedom to walk around with it. A picture of this system is shown in Fig. 4.13.

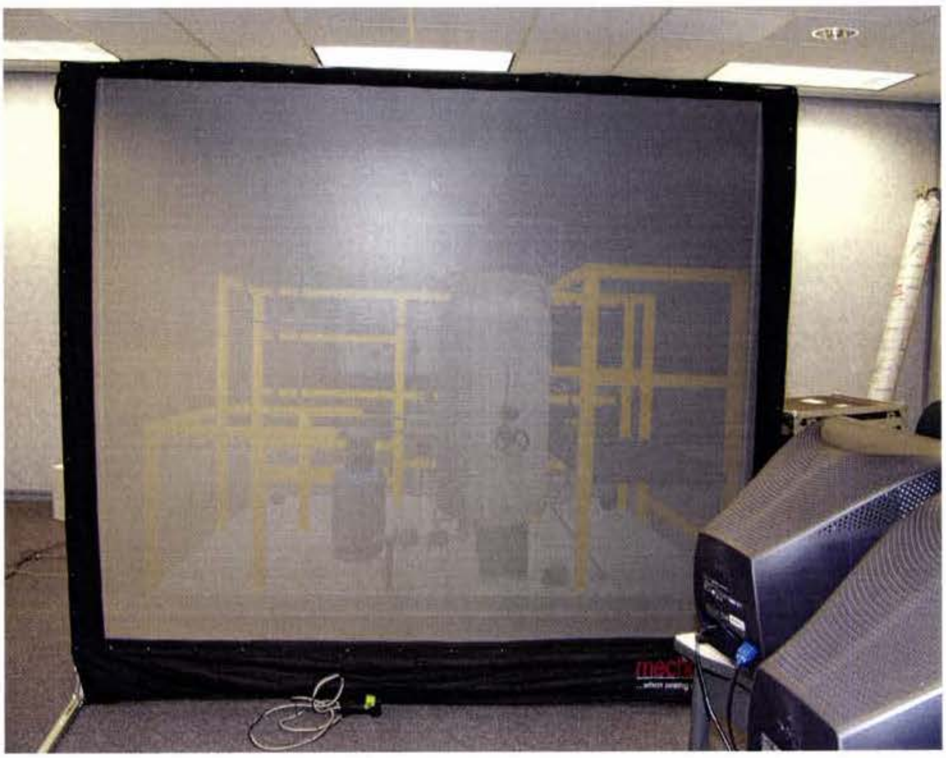


**Figure 4.13: The VE used for this study**

### 4.5 Conducting the Experiment

All thirty-two participants performed this study individually, and were in the room alone with the graduate student conducting the study. The average time needed to complete the study was I hour, and there was no time limit. There was a table set up to the left of the VE's screen that the student could use to write on. This table was also used to rest the tablet PC on, and had a lamp sitting on it to give the student light since the room lights were turned off during the experiment. The students were seated on a chair with rollers so they could easily move between a straight-on view of the screen and the table without having to continually leave the chair and then seat themselves again. The graduate student was in the room for the entire duration of the experiment, and was available to answer questions that the students had, or assist with any difficulties in navigating or working with the GUI. Each student answered four sets of questions that were stapled together in one packet. They were stapled in the order required by the design of the experiment (Table 4.2), and the student was not permitted to go back once they had moved on to the next set of questions. At the beginning of each set, the graduate student described the system that was about to be shown in enough detail for the student to answer the questions. There were no scheduled breaks during the experiment, but the student could take one if they wished. Each set of questions was graded on a scale of 0 to 100, and the graduate student was unaware of which methods were used when grading the questionnaire.

When the students first arrived at the testing location, they were given an informed consent document to read and sign (Appendix D). This document explains their rights as volunteers in the study and provides them with contact information for university officials in case they have any concerns. Next, the graduate student who conducted the study introduced the student volunteers to the virtual reality hardware they were going to use. After the student was familiar with navigating and using the teacher tab of the VE-Suite GUI, the graduate student worked through a tutorial with him/her that is similar to the exercises that were performed for the study. Sample pictures and the questionnaire for this tutorial can be found in Appendix B. When the graduate student was satisfied that the volunteer understood all of the visualization methods that would be used, the study began.

For each 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. Table 4.2 shows the assignment of visualization methods and exercises to each participant. A detailed discussion of why the students were assigned as they were is given in Section 4.6. For example, Subject 9 is a member of group AB. He/she begins the study in Period 1 by seeing vectors inside the bend and answers four questions. In Period 2, she/he sees contours to answer four questions about the oxygen concentration in a furnace. In Period 3, the student sees streamlines to answer four questions about air flow in the reduction. Finally, the student sees temperature isosurfaces to answer four questions about the temperature distribution in the furnace in Period 4.

**Table 4.2: Assignment of participants to groups**

| | | Vector Data | | Scalar Data | | Vector Data | | Scalar Data | |
|---|---|---|---|---|---|---|---|---|---|
| *subject* | *group* | *period 1* | | *period 1* | | *period 2* | | *period 2* | |
| | | method | exercise | method | exercise | method | exercise | method | exercise |
| 1 | AA | V | VX1 | C | SX1 | V | VX2 | C | SX2 |
| 2 | - | V | VX1 | C | SX1 | V | VX2 | C | SX2 |
| 3 | - | V | VX2 | C | SX2 | V | VX1 | C | SX1 |
| 4 | - | V | VX2 | C | SX2 | V | VX1 | C | SX1 |
| 5 | BB | S | VX1 | I | SX1 | S | VX2 | I | SX2 |
| 6 | - | S | VX1 | I | SX1 | S | VX2 | I | SX2 |
| 7 | - | S | VX2 | I | SX2 | S | VX1 | I | SX1 |
| 8 | - | S | VX2 | I | SX2 | S | VX1 | I | SX1 |
| 9 | AB | V | VX1 | C | SX1 | S | VX2 | I | SX2 |
| 10 | - | V | VX1 | C | SX1 | S | VX2 | I | SX2 |
| 11 | - | V | VX2 | C | SX2 | S | VX1 | I | SX1 |
| 12 | - | V | VX2 | C | SX2 | S | VX1 | I | SX1 |
| 13 | BA | S | VX1 | I | SX1 | V | VX2 | C | SX2 |
| 14 | - | S | VX1 | I | SX1 | V | VX2 | C | SX2 |
| 15 | - | S | VX2 | I | SX2 | V | VX1 | C | SX1 |
| 16 | - | S | VX2 | I | SX2 | V | VX1 | C | SX1 |

The students were able to see more than just one stored scene for each set of questions. There were several stored scenes prepared ahead of time for each visualization method. There were seven stored scenes of isosurfaces, three stored scenes of contours, five stored scenes of vectors, and five stored scenes of streamlines. Each one is slightly different and focuses on a different important feature of the system being studied. 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. These were carefully prepared to ensure that the student was able to see clear representations of all of the important characteristics of the various exercises.

There are two different exercises for both vector data and scalar data out of necessity. It would not make sense to show Subject 9 vectors in the bend during the first period followed by streamlines in the bend for the third period. This would be asking him/her to answer the same set of questions he/she did shortly before. It should be noted that the furnace is used for both scalar periods, but the exercises are not the same. In one period, oxygen concentration is shown while temperature is shown for the other making them different and non-similar exercises.

At this point, some organizational details and notation need to be discussed. The results from this study are actually broken down into four independent 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.

This means that each student is actually part of two independent studies. Returning to the Subject 9 example (from Table 4.2) and assuming this person is an Iowa State student, Period 1 and Period 3, which are gray, are actually Period 1 and Period 2 of the Iowa State vector data study. Period 2 and Period 4 are actually Period 1 and Period 2 of the Iowa State scalar data study. Notice that Table 4.2 has already adopted this notation, which will be used form here on. It should also be noted that Table 4.2 shows 16 students who are all from Iowa

State. An identical table with 16 students from Indian Hills would also exist. Both tables containing the raw data for the study are given in Appendix C.

### 4.6 Design of the Experiment

The structure chosen for this experiment is the direct-by-carry-over model of Balaam's design for two treatments [6]. This 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. In two period cross-over trials, each participant receives a treatment in Period 1 and then crosses over to the other treatment in Period 2. There are two primary advantages to using cross-over designs as opposed to the traditional parallel group design. The most important difference is that cross-over designs require fewer participants than the parallel group design since two observations are taken from each participant instead of just one. Secondly, a difference in groups is of minimal concern since crossing over would offset any differences.

As can be expected, there is a price to pay for the economy that is enjoyed when using the cross-over design. By using multiple periods and crossing over to different treatments, several effects are introduced that must be accounted for. Direct treatment, period, and carry-over are the three fundamental effects that are important in all cross-over trials and are denoted by $\tau$, $\pi$, and $\lambda$ respectively. The period effect, $\pi$, is significant when the performance of the participant is dependent on what period he/she receives a given treatment. This could happen if a participant became tired and rushed to finish the questionnaire in Period 2, or if a person became more comfortable with being in the VE as time passed, leading to better performance in the second period. Another consequence of the cross-over design is the potential for carry-over, which is denoted by $\lambda$. This occurs if the effect of the treatment in Period 1 is still present in Period 2. An example would be if a participant had a bad experience while working on the visualization method shown in the first period and carried a negative attitude into working on the second method in Period 2. The carry-over can only be present in Period 2 and differs from the period effect in that it is a function of the previous treatment and not a function of physical time. If the carry-over effect is also dependent on what the visualization method in the second period is, this is called direct-by-carry-over interaction denoted by $(\tau\lambda)$. More discussion of direct-by-carry-over interaction follows in the description of the linear model for this design.

### 4.6.1 A linear model for Balaam's design

This design has four groups with two means in each group, so there are four degrees of freedom for within-group comparison. This means that four effects of the design can be accounted for in a linear model and therefore, the four most important effects should be chosen to be represented in the model and one must hope that the other effects that cannot be accounted for are insignificant. The four effects mentioned above were chosen and a linear model of the design is represented in Table 4.3. In this table, the use of A and B is generic. For the vector data study, A is replaced by V and B is replaced by S. For the scalar data study, A is replaced C and B is replaced by I. Section 6.2.1 presents a discussion and some recommendations for designing cross-over experiments.

**Table 4.3: Linear model for each participant's score**

| *Group* | *Period 1* | *Period 2* |
|---|---|---|
| 1 (AA) | $\mu + \pi_1 + \tau_1 + \xi + \in$ | $\mu + \pi_2 + \tau_1 + \lambda_1 + (\tau\lambda)_{11} + \xi + \in$ |
| 2 (BB) | $\mu + \pi_1 + \tau_2 + \xi + \in$ | $\mu + \pi_2 + \tau_2 + \lambda_2 + (\tau\lambda)_{22} + \xi + \in$ |
| 3 (AB) | $\mu + \pi_1 + \tau_1 + \xi + \in$ | $\mu + \pi_2 + \tau_2 + \lambda_1 + (\tau\lambda)_{12} + \xi + \in$ |
| 4 (BA) | $\mu + \pi_1 + \tau_2 + \xi + \in$ | $\mu + \pi_2 + \tau_1 + \lambda_2 + (\tau\lambda)_{21} + \xi + \in$ |

The group names are indicative of what order each volunteer sees the various visualization methods in. For example, the participants in Group 1 (AA) see Method A in Period 1 and Method A again in Period 2 while Group 4 (BA) participants see Method B in Period 1 followed Method A in Period 2.

In Table 4.3, $\tau$, $\lambda$, $\pi$, and $\tau\lambda$ have already been defined. The parameter $\mu$ is the overall mean, $\xi$ is the effect of the individual participant, and $\in$ is a random error effect. $\xi$ is assumed to be normally distributed with mean 0 and variance $\sigma_s^2$ and $\in$ is also assumed to be normally distributed with mean 0 and variance $\sigma_e^2$.

For analysis, it is convenient to define the parameters as follows:

$$\tau = \left|\frac{\tau_1 - \tau_2}{2}\right|$$

$$\lambda = \left|\frac{\lambda_1 - \lambda_2}{2}\right|$$

$$\pi = \left|\frac{\pi_1 - \pi_2}{2}\right|$$

Doing this introduces the following constraints:

$$\tau_1 = -\tau_2 = -\tau$$

$$\pi_1 = -\pi_2 = -\pi$$

$$\lambda_1 = -\lambda_2 = -\lambda$$

$$(\tau\lambda)_{11} = (\tau\lambda)_{22} = (\tau\lambda)$$

$$(\tau\lambda)_{12} = (\tau\lambda)_{21} = -(\tau\lambda)$$

Table 4.4 summarizes the expected values of all eight group means. Recall that the expected value of the subject and random error effects is zero, and thus these effects are not represented in the table and only the fixed effects remain.

**Table 4.4: Expected values for the group means**

| *Group* | *Period 1* | *Period 2* |
|---|---|---|
| 1 (AA) | $\mu - \pi - \tau$ | $\mu + \pi - \tau - \lambda + (\tau\lambda)$ |
| 2 (BB) | $\mu - \pi + \tau$ | $\mu + \pi + \tau + \lambda + (\tau\lambda)$ |
| 3 (AB) | $\mu - \pi - \tau$ | $\mu + \pi + \tau - \lambda - (\tau\lambda)$ |
| 4 (BA) | $\mu - \pi + \tau$ | $\mu + \pi - \tau + \lambda - (\tau\lambda)$ |

If desired, the parameters above can be estimated.

$$(\tau\lambda) = \frac{1}{4}\left(-\bar{y}_{11} + \bar{y}_{12} - \bar{y}_{21} + \bar{y}_{22} + \bar{y}_{31} - \bar{y}_{32} + \bar{y}_{41} - \bar{y}_{42}\right)$$

If the direct-by-carry-over interaction is not significant, the period and carry-over effects can be estimated as follows:

$$\lambda = \frac{1}{2}\left(\bar{y}_{11} - \bar{y}_{22} - \bar{y}_{21} + \bar{y}_{22}\right)$$

$$\tau = \frac{1}{4}\left(\bar{y}_{11} - \bar{y}_{12} - \bar{y}_{21} + \bar{y}_{22} - \bar{y}_{31} + \bar{y}_{32} + \bar{y}_{41} - \bar{y}_{42}\right)$$

If the carry-over effect is not significant, the direct treatment effect is estimated as below.

$$\tau = \frac{1}{4}\left(-\bar{y}_{31} + \bar{y}_{32} + \bar{y}_{41} - \bar{y}_{42}\right)$$

Now that the effects introduced by using a cross-over design are adequately modeled, formal statistical analysis can be performed to determine which visualization methods are better for the two student groups. This is done in Chapter 5.

# 5. ANALYSIS OF THE DATA

Table 5.1 shows the mean value for each visualization method applied to each group. Inspection of this table shows that the Iowa State group has no preference between the vector field and streamlines methods for visualizing vector data, but they do have a strong preference for seeing contours over isosurfaces when analyzing scalar data. The Indian Hills group shows some preference for the streamlines method of visualizing vector data and a strong preference for the contours method of seeing scalar data. The right hand side of this table shows the Indian Hills group when divided into traditional and non-traditional students. While there are differences in the means, there is no clear indication that either of these groups is more capable than the other in their ability to analyze data.

In general, comparing group means gives some indication about the difference between visualization methods, but does not provide any formal measure of whether or not the difference in means is significant. For example, if two groups are made up of only one participant each, then a difference in means does not indicate anything about the associated visualization methods. A formal comparison of methods must account for group size and variance for it to have any meaning.

**Table 5.1: Average scores for the visualization methods**

| | **Iowa State** | **Indian Hills** | **Traditional (IHCC)** | **Non-traditional (IHCC)** |
|---|---|---|---|---|
| *Vectors* | 59.19 | 44.56 | 44 | 45.3 |
| *Streamlines* | 59.68 | 52.13 | 53.9 | 49.9 |
| *Contours* | 67.52 | 48.1 | 50 | 45.7 |
| *Isosurfaces* | 54.88 | 33.7 | 36 | 33.7 |

There is a type of formal statistical inference that is used for making comparisons between two means called significance testing. A significance test has two possible outcomes:

1. Acceptance of the null hypothesis.
2. Rejection of the null hypothesis in favor of the alternative hypothesis.

The null hypothesis ($H_o$) states that the two visualization methods being compared are equal. For this study, the alternative hypothesis (Ha) is that the method with the higher mean score is superior to the other method. It is important to keep in mind that the means we calculated in this study are based on a sample of sixteen students. If sixteen different students were tested, the means would likely be different. Therefore, these "sample" means are random variables that hold a range of values depending on which sixteen students are tested. This range of values can be thought of as a distribution that forms the bell-shaped normal distribution. The center of the distribution is the "population" mean, which is the average score of all the students in the world. The means obtained in this study are sample means and fall somewhere on the distribution. This is why it is not a good idea to simply compare the sample means of the two visualization methods being compared to one another. For example, the population mean of Method A may be the same as the population mean of Method B, but the sample mean of Method A may be higher than the sample mean of Method B because of the particular sixteen student samples. This is known as type I error. In the context of significance testing, a type I error is deciding in favor of the alternative hypothesis when in fact the null hypothesis is true. The probability of making a type I error is known as the p-value. A p-value of ($< 0.05$) is accepted as being statistically significant. That is, if a significance test yields a p-value of ($<0.05$), then the null hypothesis of equal methods will be rejected in favor of the alternative hypothesis of one method being superior to the other. P-values can be computed many ways depending on the type of study. This study will use the type 1 general linear method analysis of variance (ANOVA) F-test to compute the p-values.

The F-statistic is a ratio of the between-sample variance to the within-sample variance. So, small values of F indicate that the variance between samples is similar to the within-sample variance, resulting in overlapping distributions. This is the case when two methods are close to identical. Large values of F indicate that there is far more variance between samples than within samples resulting in non-overlapping distributions. In this case, the centers of the sample means are far enough apart that it is not likely that the population distributions are similar. Thus, one of the methods is superior. For this study, the ANOVA was performed using SAS 8.2, a statistical computer program. An ANOVA table, like that in Table 5.2, was constructed for each of the four independent studies for the purpose of significance testing.

Another useful and sometimes very insightful way of analyzing data in cross-over trials is to look at subject profile plots and group-by-periods plots. Subject profile plots show the within-subject change of each participant between periods. This can provide information about period effects, carry-over effects, and direct treatment effects. Similar inferences can be made by looking at a group-by-periods plot, which gives an overview of the direct treatment effect. Figures 5.1 through 5.4 are the subject profiles plots for the Iowa State vector data group, and Fig. 5.5 is its group-by-periods plot. These plots along with the ANOVA will be presented for each of the four independent studies along with discussion in subsequent sections.

## 5.1 Analysis of the Iowa Sate Vector Data

Analysis of this data is carried out by inspection of the ANOVA table followed by analysis of the subject profiles plots and the group-by-periods plot. The following observations can be made.

- The ANOVA shown in Table 5.2 has each factor of the design listed on the left-hand side. Recall that the p-values of less than 0.05 indicate that a factor is statistically significant. Exercises, periods, carry-over, and direct-by-carry-over interaction are secondary factors, but must be checked if one wishes to validate the parameter estimates made in Chapter 4. Each of these factors has (p-value < 0.05) and so the effects of exercise, periods, carry-over, and direct-by-carry-over interaction are equal and thus the estimators for the parameters are valid. The factor of primary interest, direct treatments, has (p-value > 0.5), so Method V is equal to Method S for this group.

**Table 5.2: ANOVA for Iowa State vector data**

| *Source* | *d.f.* | *SS* | *MS* | *F* | *p-value* |
|---|---|---|---|---|---|
| Between subjects: | 15 | 407.88 | 40.51 | | |
| Within subjects: | | | | | |
| Exercises | 1 | 3.13 | 3.13 | 0.35 | 0.56 |
| Periods | 1 | 2.00 | 2.00 | 0.23 | 0.64 |
| **Direct treatments** | **1** | **0.56** | **0.56** | **0.06** | **0.81** |
| Carry-over | 1 | 3.06 | 3.06 | 0.35 | 0.57 |
| Direct-by-carry-over | 1 | 10.125 | 10.13 | 1.15 | 0.31 |
| Residual | 11 | 97.13 | 8.83 | | |
| Total | 31 | 523.88 | | | |

- The AA subject profiles plot shown in Fig. 5.1 does not show any significant effect. A sharp increase or decline in score from Period 1 to Period 2 would indicate significant period or carry-over effects.
- The BB subject profiles plot in Fig. 5.2 does not show any significant trends. Like the AA subject profiles plot, the average score between period for this group is approximately the same.
- The AB subject profiles plot in Fig. 5.3 shows a slight increase in scores when the participants crossover from V to S indicating a possible preference for Method S or possibly an A to B carry-over effect.
- The BA subject profiles plot in Fig. 5.4 shows a slight increase in score when the participants cross-over from S to V. This nullifies the previous assertion that method S might be preferred, but still leaves open the possibility that there are both A to B and B to A carry-over effects that are approximately equal.
- The group-by-periods plot in Fig. 5.5 shows no pattern of one method scoring consistently higher than the other. The average values of each method appear to be about the same as would be supported by the ANOVA.

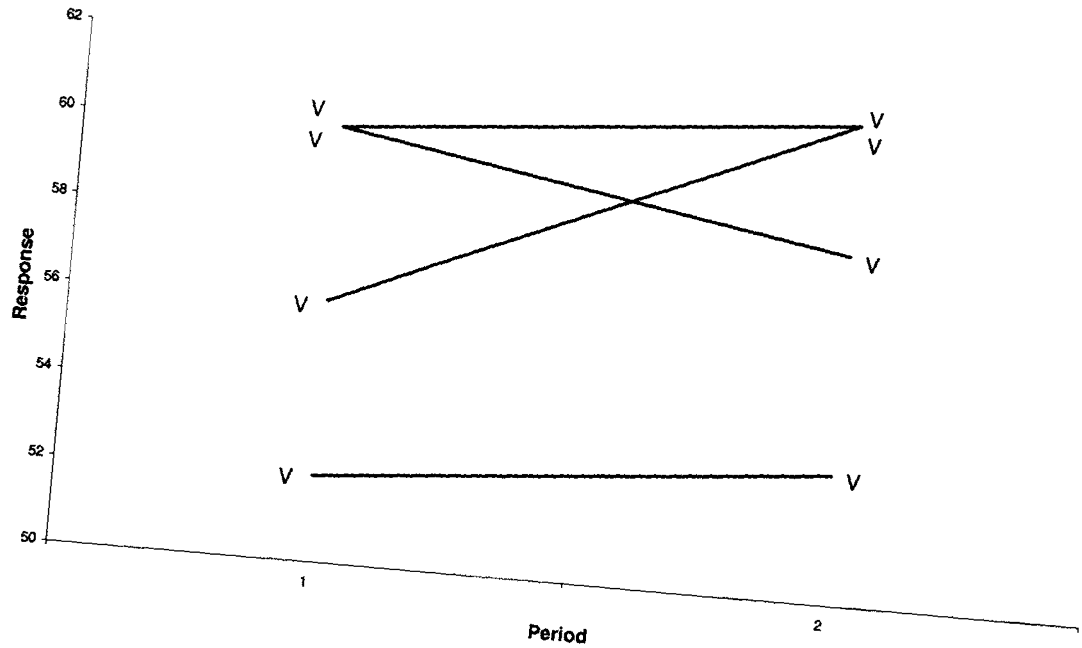



Figure 5.1: ISU vector group AA subject profiles

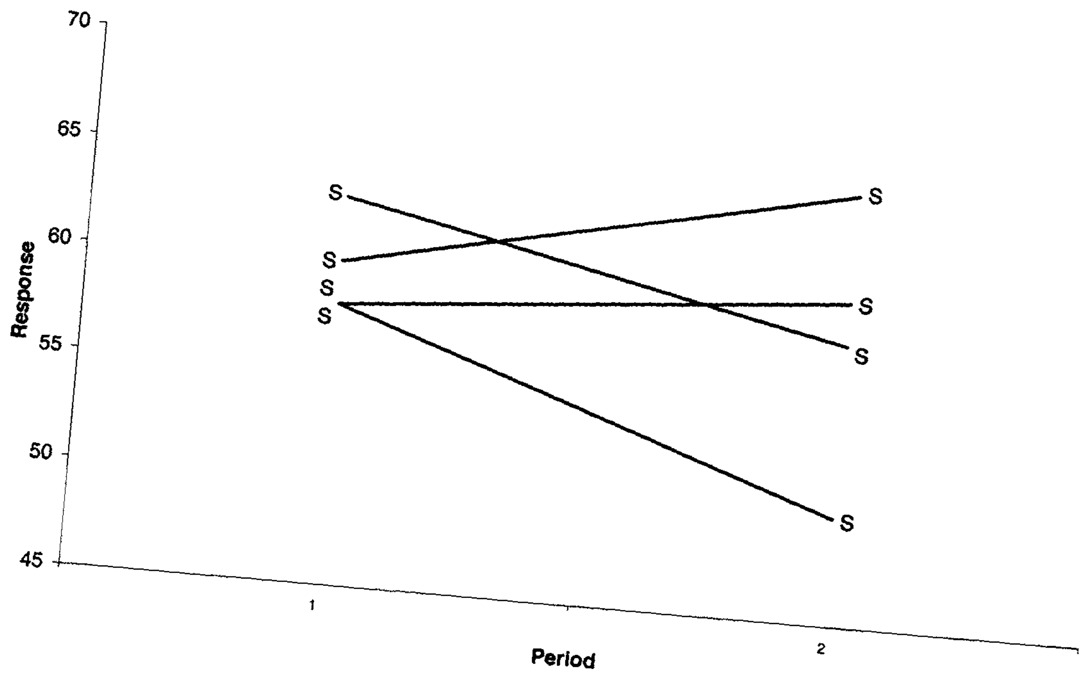



Figure 5.2: ISU vector group BB subject profiles

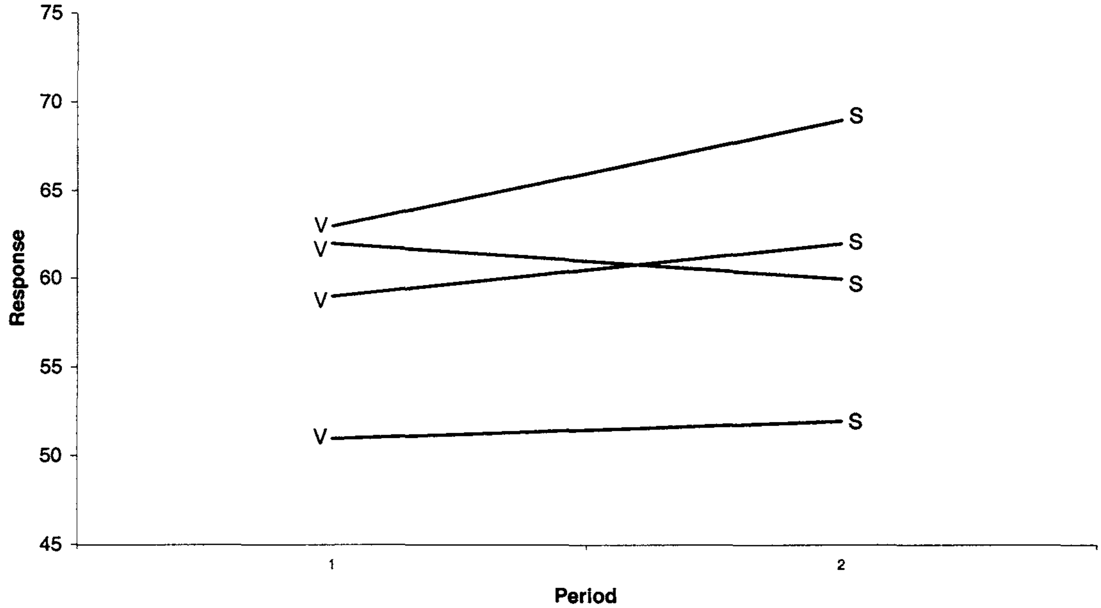



**Figure 5.3: ISU vector group AB subject profiles**

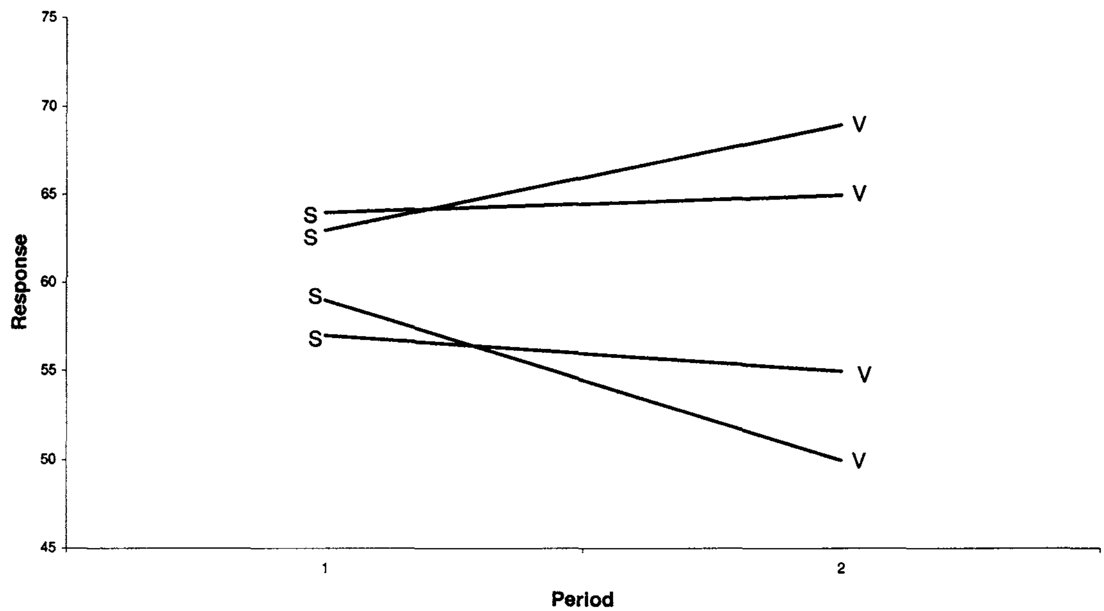



**Figure 5.4: ISU vector group BA subject profiles**

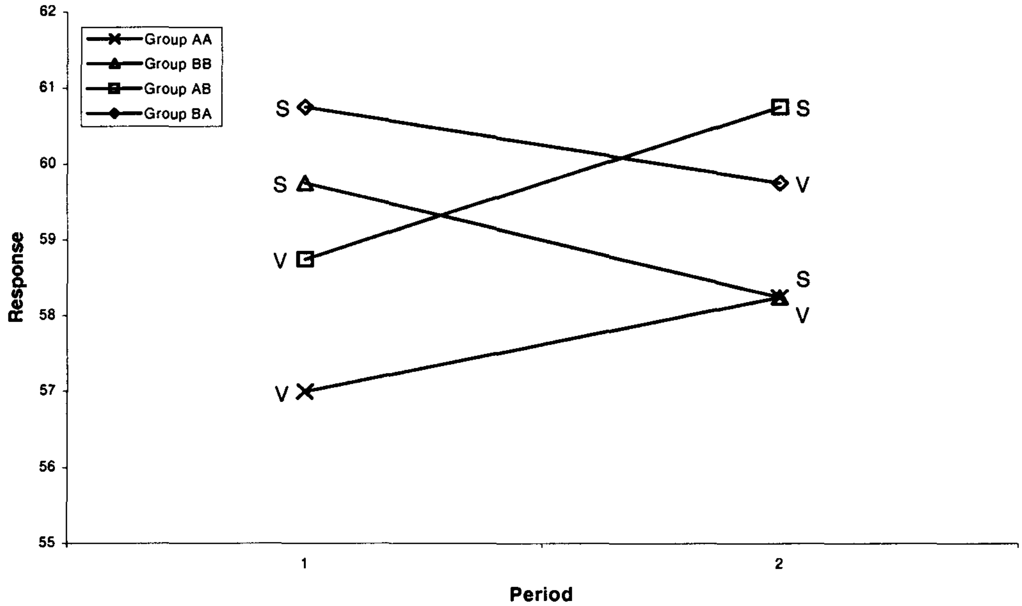



**Figure 5.5: ISU vector group-by-periods plot**

### 5.2 Analysis of the Indian Hills Vector Data

Analysis of this data is carried out by inspection of the ANOVA table followed by analysis of the subject profiles plots and the group-by-periods plot. The following observations can be made.

- The ANOVA shown in Table 5.3 has each factor of the design listed on the left-hand side. Recall that the p-values of less than 0.05 indicate that a factor is statistically significant. Exercises, periods, carry-over and direct-by-carry-over interaction are secondary factors, but must be checked if one wishes to validate the parameter estimates made in Chapter 4. Each of these factors has (p-value < 0.05) and so the effects of exercise, periods, carry-over and direct-by-carry-over interaction are equal. Thus the estimators for the parameters are valid. The factor of primary interest, direct treatments, has (p-value < 0.5) and so Method S is better than Method V for this group.

**Table 5.3: ANOVA for Indian Hills vector data**

| *Source* | *d.f.* | *SS* | *MS* | *F* | *p-value* |
|---|---|---|---|---|---|
| Between subjects: | 15 | 1094.71 | 40.51 | | |
| | | | | | |
| Within subjects: | | | | | |
| Exercises | 1 | 3.78 | 3.78 | 0.23 | 0.64 |
| Periods | 1 | 3.78 | 3.78 | 0.23 | 0.64 |
| **Direct treatments** | **1** | **138.06** | **138.06** | **8.34** | **0.01** |
| Carry-over | 1 | 36.00 | 36.00 | 2.17 | 0.17 |
| Direct-by-carry-over | 1 | 0.78 | 0.78 | 0.05 | 0.83 |
| Residual | 11 | 182.09 | 16.55 | | |
| | | | | | |
| Total | 31 | 1459.22 | | | |

- The AA subject profiles plot shown in Fig. 5.6 does not show any significant effect. A sharp increase or decline in score from Period 1 to Period 2 would indicate significant period or carry-over effects.
- The BB subject profiles plot in Fig. 5.7 does not show any significant trends. Like the AA subject profiles plot, the average score between periods for this group is approximately the same.
- The AB subject profiles plot in Fig. 5.8 shows a sharp increase when the participants cross-over from method V to method S, indicating a possible preference for Method S.
- The BA subject profiles plot in Fig. 5.9 shows a sharp decrease in scores when the students crossover from S to V. This is consistent with the AB plot in showing a preference for Method S. It is also supported by the ANOVA with (p-value $< 0.05$) for direct treatments.
- The group-by-periods plot in Fig. 5.10 clearly shows that Method S is preferred by this group. In fact, the lowest score for Method S is higher than the highest score for Method V.

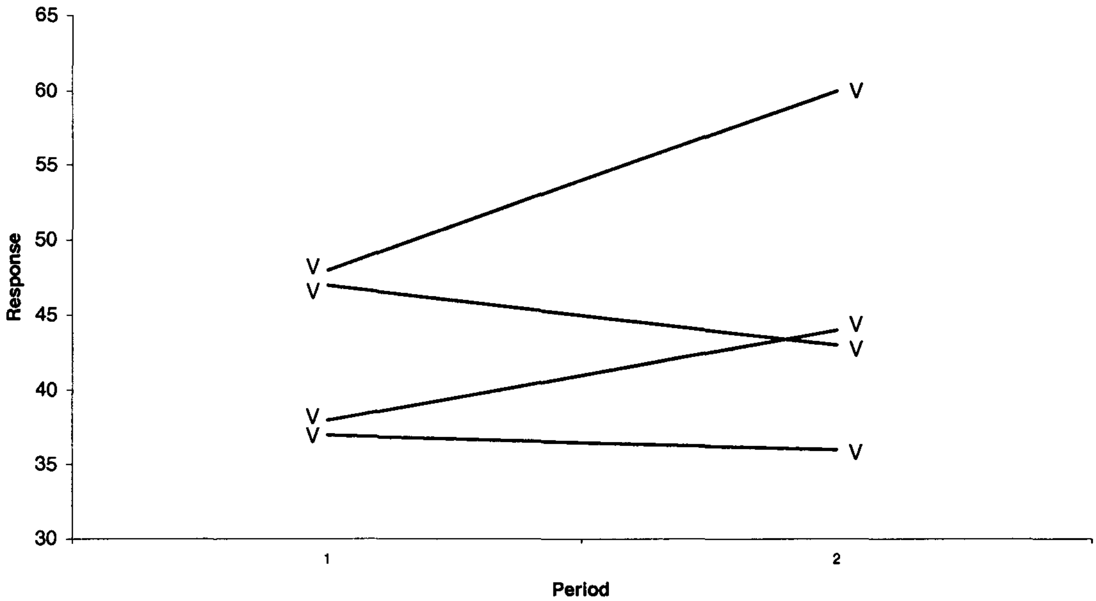



**Figure 5.6: IHCC vector group AA subject profiles**

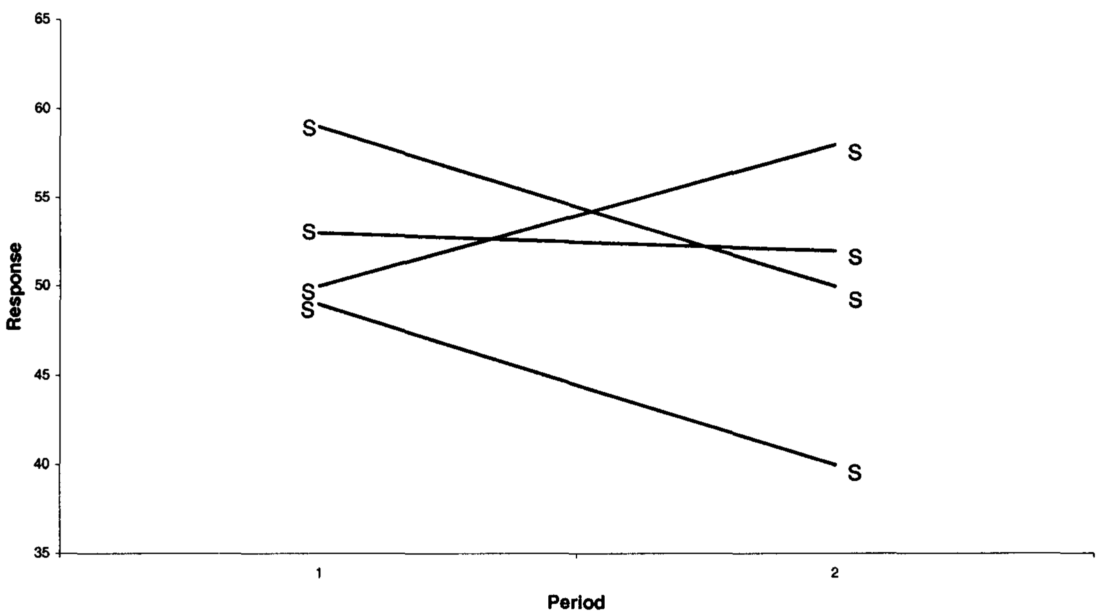



**Figure 5.7: IHCC vector group BB subject profiles**

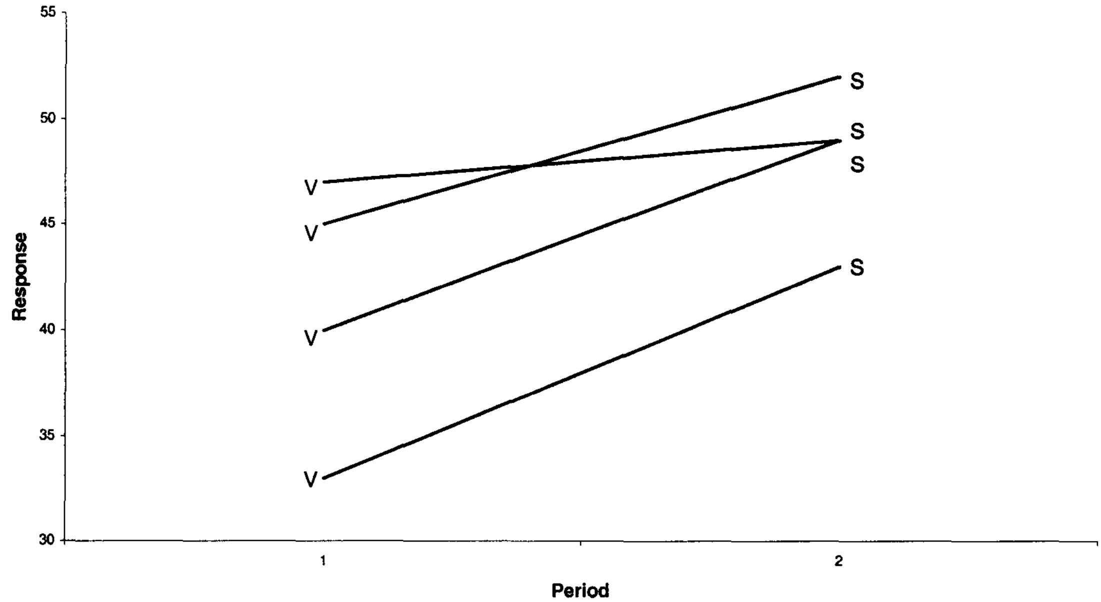



**Figure 5.8: IHCC vector group AB subject profiles**

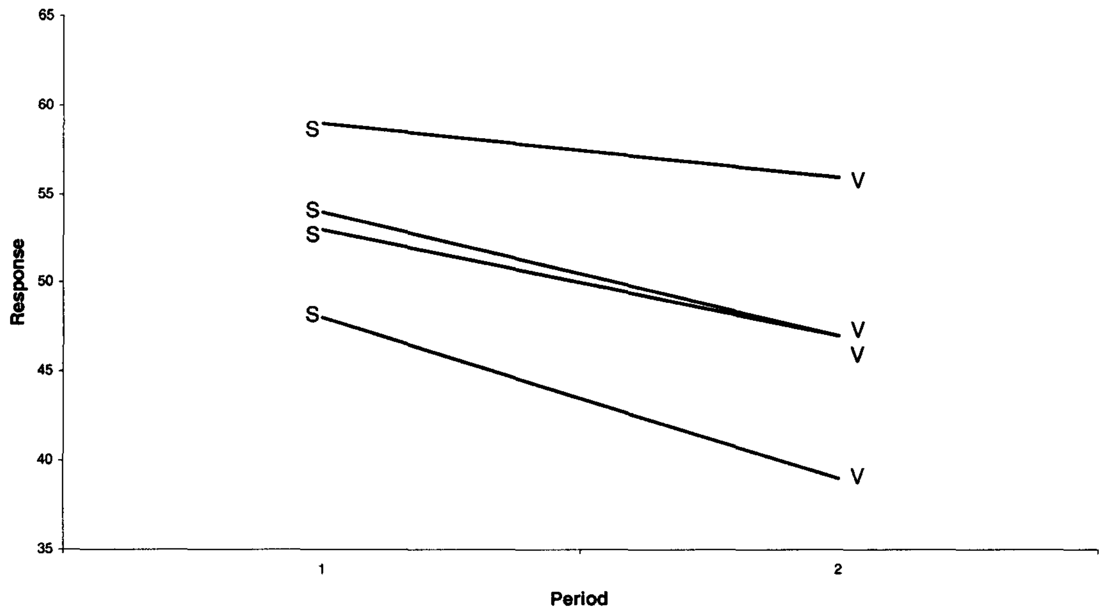



**Figure 5.9: IHCC vector group BA subject profiles**

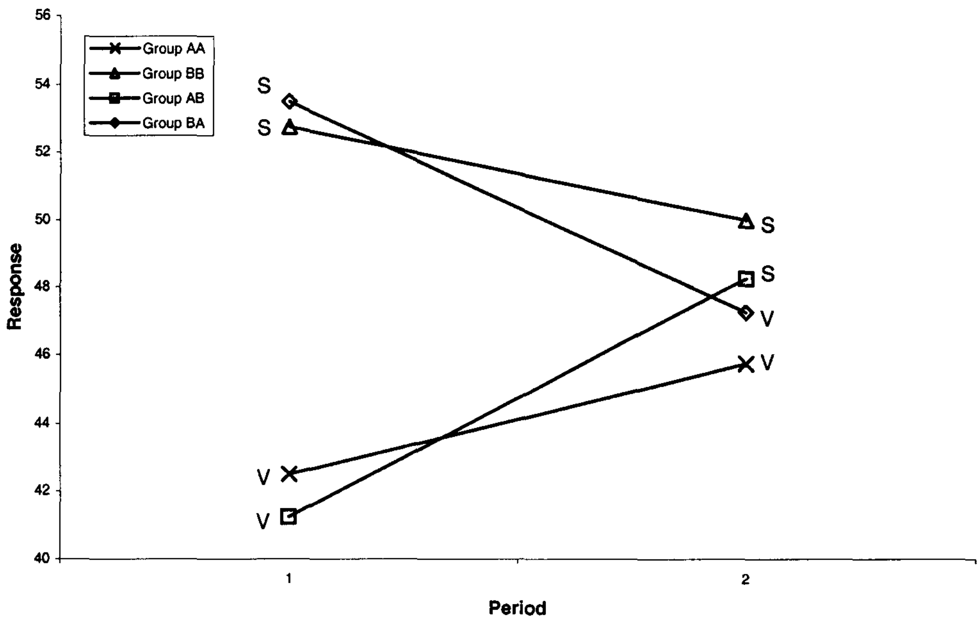



**Figure 5.10: IHCC vector group-by-periods plot**

### 5.3 Analysis of the Iowa State Scalar Data

Analysis of this data is carried out by inspection of the ANOVA table followed by analysis of the subject profiles plots and the group-by-periods plot. The following observations can be made.

- The ANOVA shown in Table 5.4 has each factor of the design listed on the left-hand side. Recall that the p-values of less than 0.05 indicate that a factor is statistically significant. Exercises, periods, carry-over and direct-by-carry-over interaction are secondary factors, but must be checked if one wishes to validate the parameter estimates made in Chapter 4. Each of these factors has (p-value < 0.05), so the effects of exercise, periods, carry-over, and direct-by-carry-over interaction are equal and thus the estimators for the parameters are valid. The factor of primary interest, direct treatments, has (p-value < 0.5), so Method C is better than Method I for this group.

**Table 5.4: ANOVA for Iowa State scalar data**

| *Source* | *d.f.* | *SS* | *MS* | *F* | *p-value* |
|---|---|---|---|---|---|
| Between subjects: | 15 | 2663.97 | 40.51 | | |
| Within subjects: | | | | | |
| Exercises | 1 | 75.03 | 75.03 | 1.18 | 0.30 |
| Periods | 1 | 26.28 | 26.28 | 0.41 | 0.53 |
| **Direct treatments** | **1** | **870.25** | **870.25** | **13.7** | **0.003** |
| Carry-over | 1 | 36.00 | 36.00 | 0.01 | 0.93 |
| Direct-by-carry-over | 1 | 0.56 | 0.56 | 0.01 | 0.92 |
| Residual | 11 | 698.59 | 63.5 | | |
| Total | 31 | 4335.47 | | | |

- The AA subject profiles plot shown in Fig. 5.11 does not show any significant effect. A sharp increase or decline in score from Period 1 to Period 2 would indicate significant period or carry-over effects.
- The BB subject profiles plot in Fig. 5.12 does not show any significant trends. Like the AA subject profiles plot, the average score between period for this group is approximately the same.
- The AB subject profiles plot in Fig. 5.13 shows a significant decrease in scores when the participants crossover from Method C to Method I.
- The BA subject profiles plot in Fig. 5.14 shows a sharp increase in scores when the participants crossover from Method I to Method C. The AB and BA plots indicate a preference for Method C.
- The group-by-periods plot in Fig. 5.15 verifies what is shown in the AB and BA plots as well as what is reported in the ANOVA table. This group has a statistically significant preference for Method C over Method I.

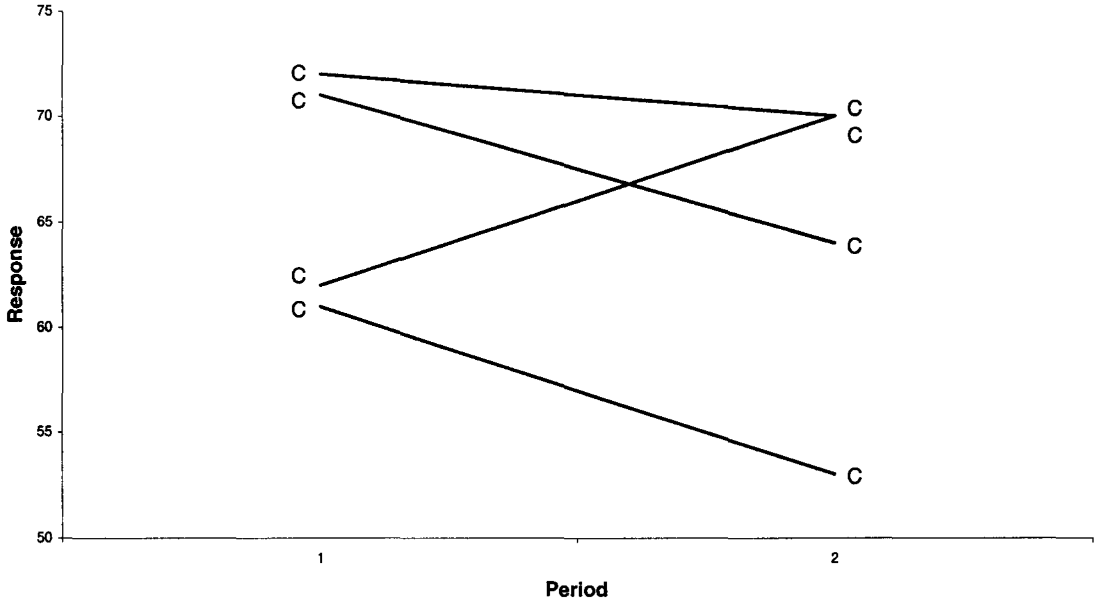



Figure 5.11: ISU scalar group AA subject profiles

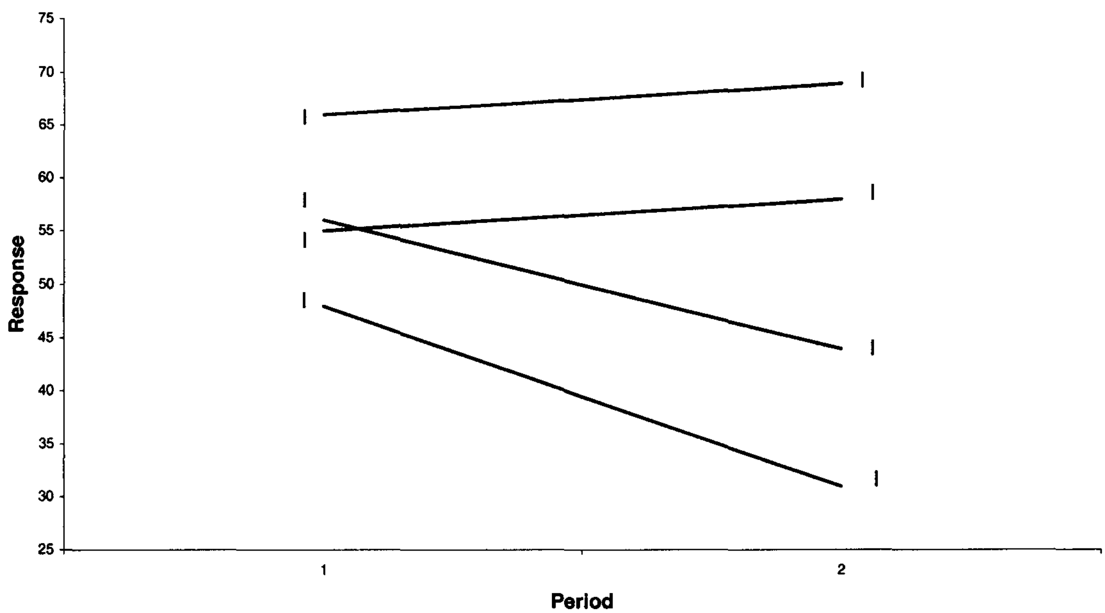



Figure 5.12: ISU scalar group BB subject profiles

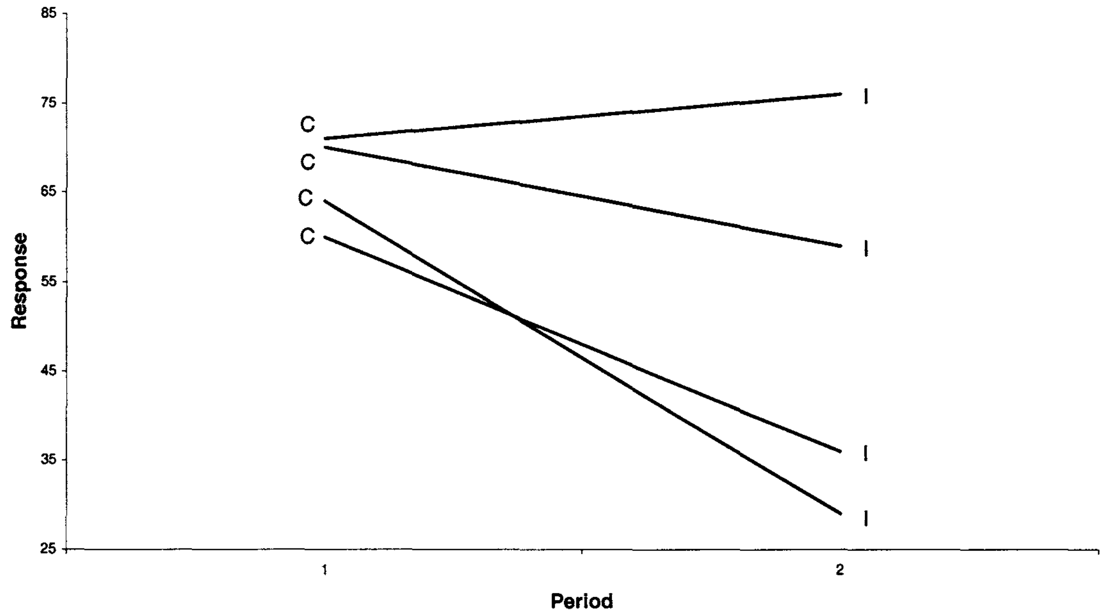



**Figure 5.13: ISU scalar group AB subject profiles**

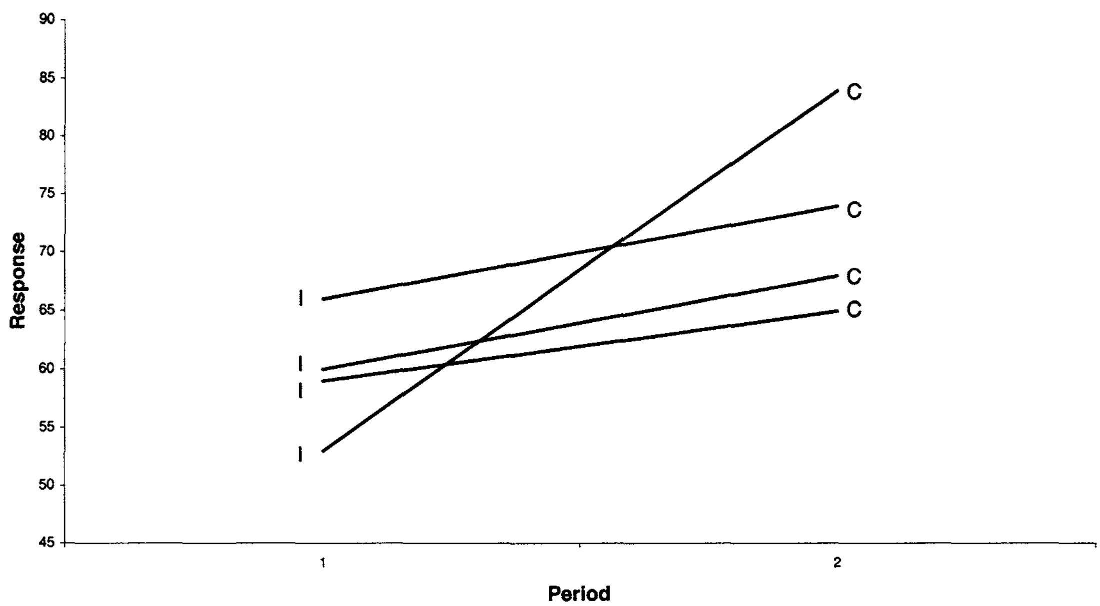



**Figure 5.14: ISU scalar group BA subject profiles**

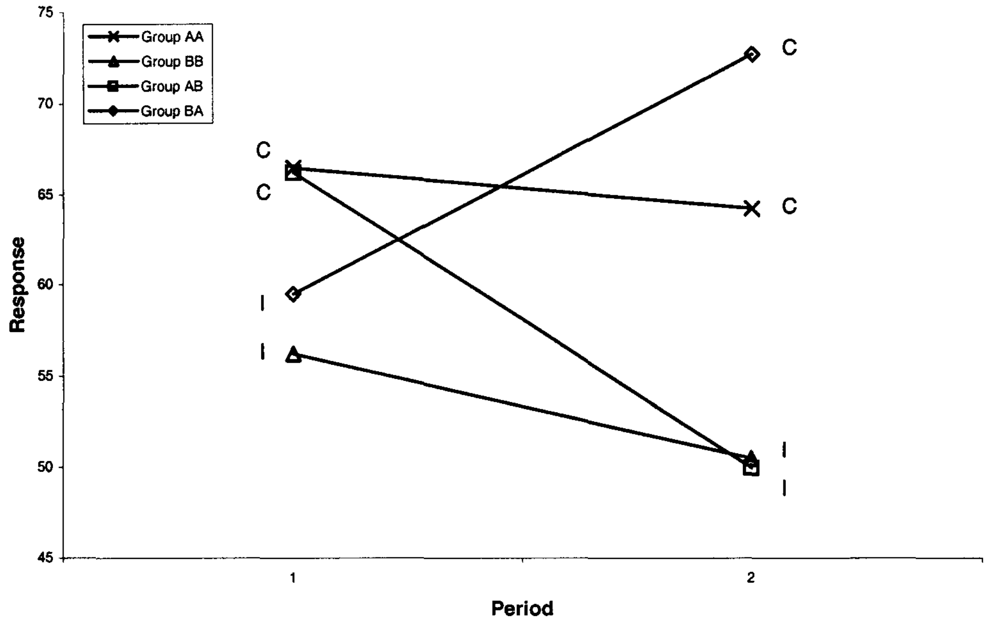



**Figure 5.15: ISU scalar group-by-periods plot**

### 5.4 Analysis of the Indian Hills Scalar Data

Analysis of this data is carried out by inspection of the ANOVA table followed by analysis of the subject profiles plots and the group-by-periods plot. The following observations can be made.

- The ANOVA shown in Table 5.5 has each factor of the design listed on the left-hand side. Recall that the p-values of less than 0.05 indicate that a factor is statistically significant. Exercises, periods, carry-over and direct-by-carry-over interaction are secondary factors, but must be checked if one wishes to validate the parameter estimates made in Chapter 4. Each of these factors has (p-value < 0.05), so the effects of exercise, periods, carry-over and direct-by-carry-over interaction are equal. Thus the estimators for the parameters are valid. The factor of primary interest, direct treatments, has (p-value < 0.5), so Method C is better than Method I for this group.

**Table 5.5: ANOVA for Indian Hills scalar data**

| *Source* | *d.f.* | *SS* | *MS* | *F* | *p-value* |
|---|---|---|---|---|---|
| Between subjects: | 15 | 2292.5 | 152.8 | | |
| | | | | | |
| Within subjects: | | | | | |
| Exercises | 1 | 10.13 | 10.13 | 0.18 | 0.68 |
| Periods | 1 | 2.0 | 2.0 | 0.04 | 0.85 |
| **Direct treatments** | **1** | **625.0** | **625.0** | **11.01** | **0.007** |
| Carry-over | 1 | 25.0 | 25.0 | 0.44 | 0.52 |
| Direct-by-carry-over | 1 | 4.5 | 4.5 | 0.08 | 0.78 |
| Residual | 11 | 624.375 | | | |
| | | | | | |
| Total | 31 | 3583.5 | | | |

- The AA subject profiles plot shown in Fig. 5.16 does not show any significant effect. A sharp increase or decrease in score from Period 1 to Period 2 would indicate significant period or carry-over effects.
- The BB subject profiles plot in Fig. 5.17 does not show any significant trends. Like the AA subject profiles plot, the average score between period for this group is approximately the same.
- The AB subject profiles plot in Fig. 5.18 shows a significant decrease in scores when the participants crossover from Method C to Method I.
- The BA subject profiles plot in Fig. 5.19 shows a sharp increase in scores when the participants crossover from Method I to Method C. The AB and BA plots indicate a preference for Method C.
- The group-by-periods plot in Fig. 5.20 verifies what is shown in the AB and BA plots as well as what is reported in the ANOVA table. This group has a statistically significant preference for Method C over Method I.

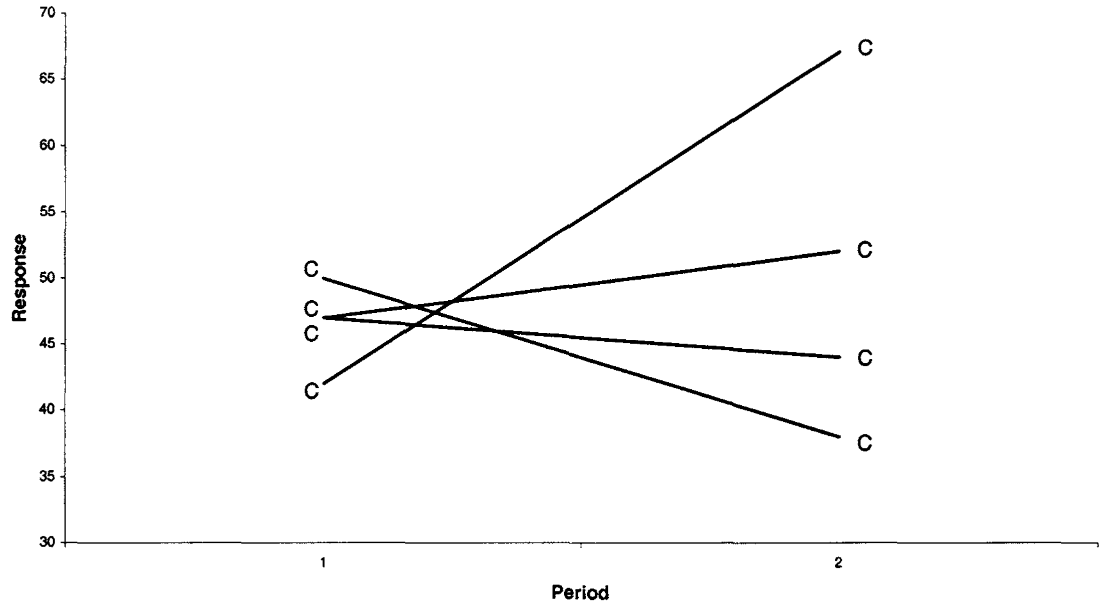



Figure 5.16: IHCC scalar group AA subject profiles

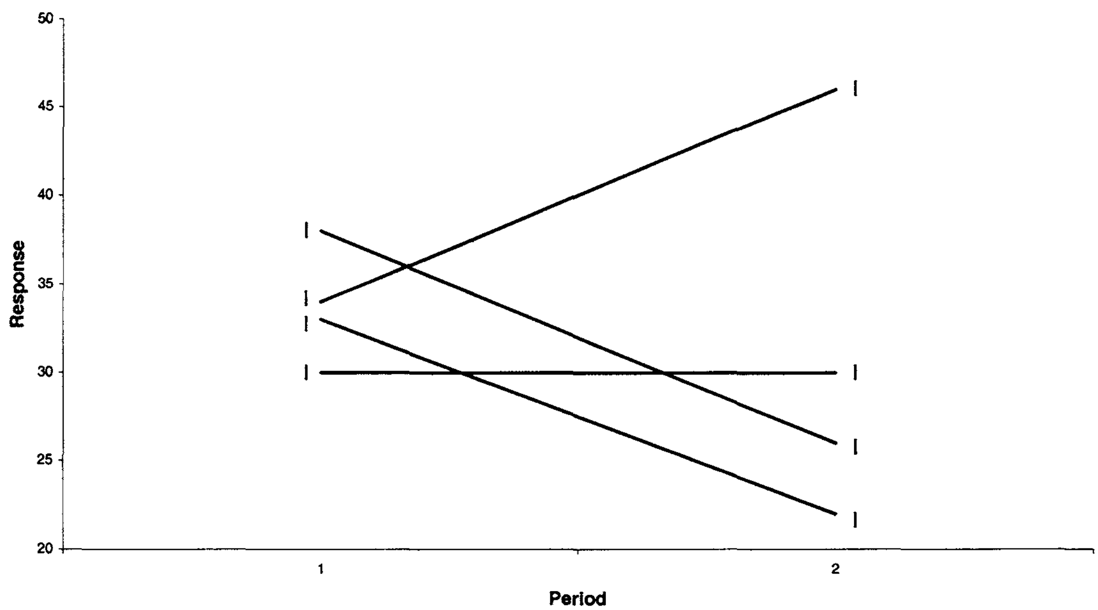



Figure 5.17: IHCC scalar group BB subject profiles

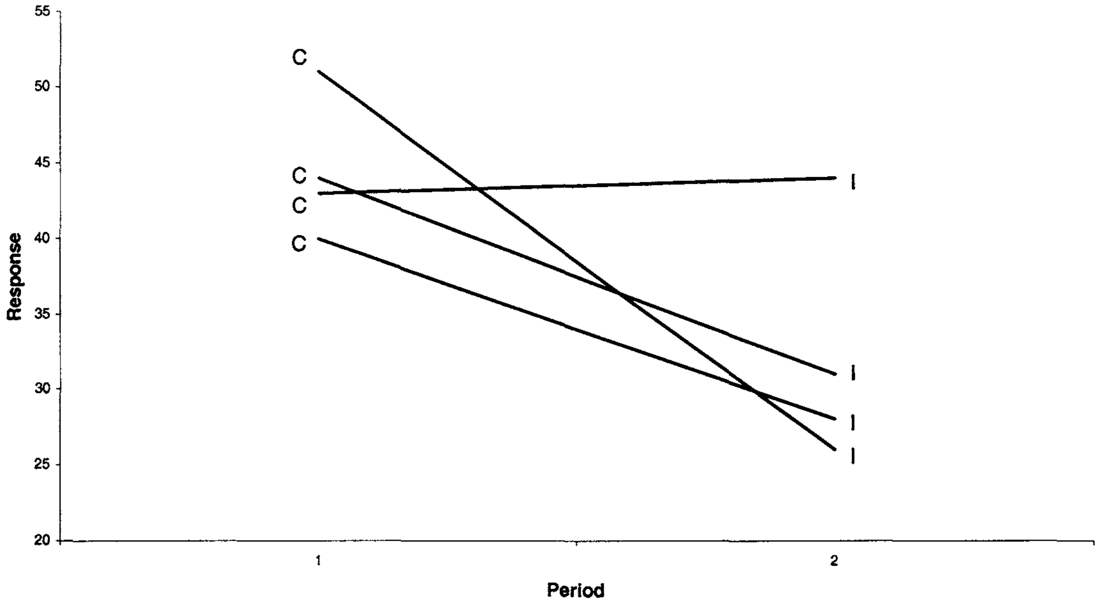



**Figure 5.18: IHCC scalar group AB subject profiles**

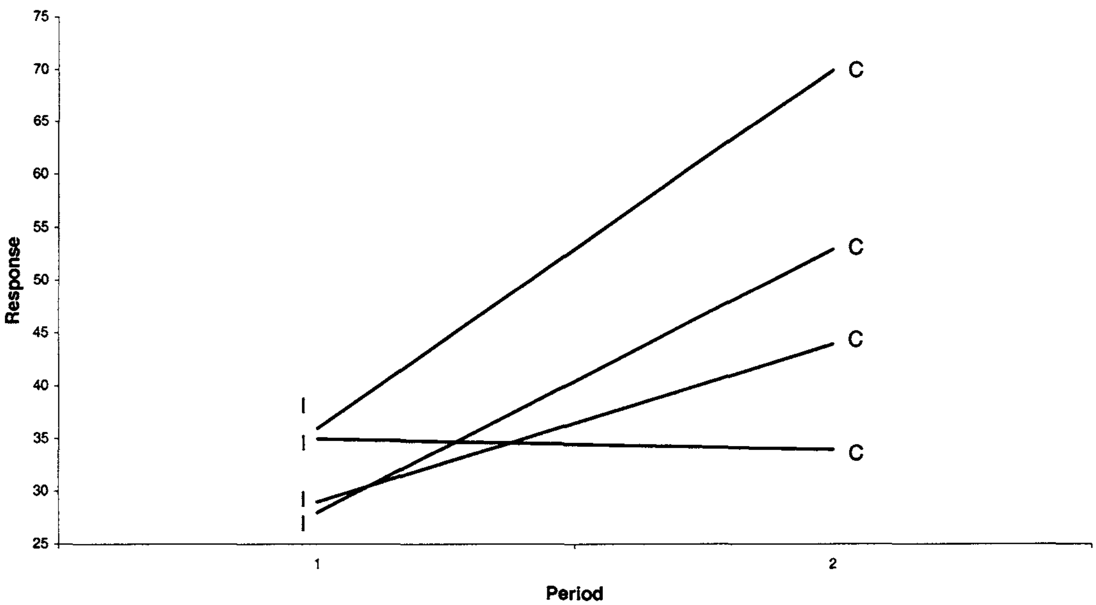



**Figure 5.19: IHCC scalar group BA subject profiles**

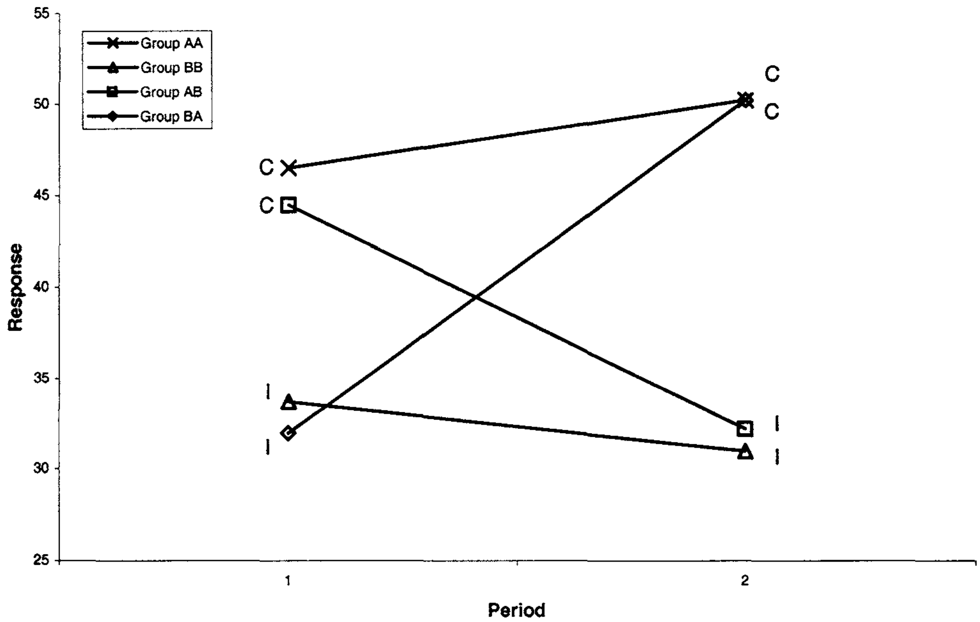



**Figure 5.20: IHCC scalar group-by-periods plot**

# 6. CONCLUSIONS AND FUTURE WORK

The ever-increasing use of CFD among engineers and in education has highlighted the need for an experiment to determine which methods of CFD visualization are most easily understood by people who have varying levels of experience. Recall that exercise, carry-over, period, and direct-by-carry-over interaction were not significant in any of the trials, which leaves the method of visualization as the only statistically significant factor observed.

## 6.1 Conclusions

For interpreting a velocity field, the mechanical engineering juniors/seniors did not have a preference between vectors or streamlines while the Indian Hills students had a strong preference for using streamlines to analyze the CFD data. This probably indicates that streamlines are conceptually easier for students and individuals without a formal background in fluid mechanics 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 contours method over the isosurfaces 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.

## 6.2 Future Work

There are many methods available for visualizing vector data that should be studied. One example is called the warped contours method (Figure 6.1) which was not used in this study due to time constraints. This method uses color and warpage to indicate the velocity magnitude in the direction normal to a specified plane. Inspection of Fig. 6.1 shows that the flow in the horizontal part of the duct is symmetrical, but the vertical section has a higher velocity on the right hand side and a region of negative velocity on the left hand side close to the corner.

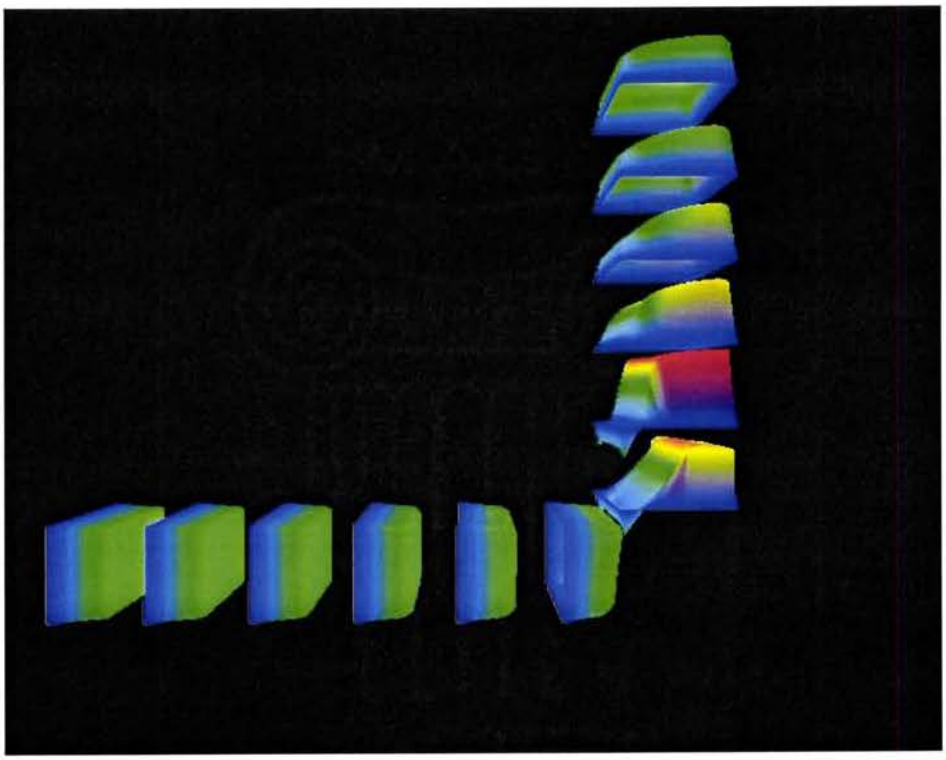


**Figure 6.1: Warped contours in a bend**

In addition to looking at other visualization methods, it would be beneficial to gain knowledge about what impact using different interfaces has on a student's ability to analyze CFD data. This would answer questions about how beneficial VR is compared to the traditional desktop monitor interface, and would indicate how human performance varies with how immersive an environment is.

### 6.2.1 Recommendations for designing cross-over experiments

The primary benefit of using cross-over designs is to minimize the number of subjects required to conduct an experiment. However, these designs introduce the undesirable effects that were discussed previously. For the case of two treatments, using higher order designs (more than 2 periods) can eliminate, or at least account for these effects. Kershner and Federer present the benefits and disadvantages of many two-treatment cross-over designs [7]. Time constraints did not allow for higher order designs to be considered for this experiment, so the two designs available were the standard two-period cross-over design and Balaam's design which was ultimately selected.

The standard two-period cross-over design is made up of two groups who receive the treatments in the AB and BA orders which is the same as groups 3 and 4 of Balaam's design. The designs are equivalent when used for performing the ANOVA to determine whether or not there is a statistically significant difference in students' ability to understand the various visualization methods, but they offer different strengths and weaknesses for estimating the direct treatment effect.

An optimal design is one that provides a minimum variance estimator for the direct treatment effect. Optimal cross-over designs are presented by Laska, Meisner, and Kushner

[8]. If the carry-over effect is shown to be statistically insignificant, the standard two-period cross-over design is optimal, and gives the minimum variance estimate for the direct treatment effect. However, if the carry-over effect is significant, then there is no valid estimator for the direct treatment effect using this design. In the event of significant carry-over effects, Balaam's design is optimal and can provide a valid estimate for the direct treatment effect.

This means that Balaam's design is the more conservative of the two designs, and should be used if the investigator is in doubt of whether or not the carry-over effects will be statistically significant. That is why this design was selected for this study. If the investigator is confident that carry-over effects will not be significant, the standard two-period design is optimal and will provide a better estimate of the direct treatment effect. Higher order designs should always be selected if the constraints of the study permit their use.

# REFERENCES

[1] P.T. Evans, J.M. Vance, V.J. Dark, Assessing the Effectiveness of Traditional and Virtual Reality Interfaces in Spherical Mechanism Design, *Journal of Mechanical Design* 121(1999), 507-514.

[2] S.A. Volkov, J.M. Vance, Effectiveness of Haptic Sensation for the Evaluation of Virtual Prototypes, *ASME Journal of Computing and Information Sciences in Engineering* 1(2001), 123-128.

[3] M.C. O'Leary, Effectiveness of Haptic Feedback Coupled With the Use of Head-Mounted Display for the Evaluation of Virtual Mechanisms, Masters thesis, Iowa State University, 2002.

[4] J.T. Bell, H.S. Fogler, A Virtual Reality Safety and Hazard Analysis Simulation, *Proceedings of the American Society for Engineering Education* 1996, 1-6.

[5] D.H. Laidlaw, R.M. Kirby, J.S. Davidson, T.S. Miller, M. Silva, W.H. Warren, M. Tarr, Quantitative Comparative Evaluation of 2D Vector Field Visualization Methods, *Proceedings of the IEEE Visualization Conference* 2001, 143-150.

[6] B. Jones, M.G. Kenward, *Design and Analysis of Cross-Over Trials*, Chapman and Hall, 1989.

[7] R.P. Kershner, W.T. Federer, Two-Treatment Crossover Designs for Estimating a Variety of Effects, *Biometrics* 76(1981), 612-619.

[8] E. Laska, M. Meisner, H.B. Kushner, Optimal Crossover Designs in the Presence of Carryover Effects, *Biometrics* 39(1983), 1087-1091.

[9] S.B. Vardeman, *Statistics for Engineering Problem Solving*, PWS Publishing Company, 1994.

[10] R.G. Marks, *Designing a Research Project*, Van Nostrand Reinhold Company, 1982.

[11] J.K. Lindsey, *Applying Generalized Linear Models*, Springer, 1997.

[12] H. Toutenburg, *Statistical Analysis of Designed Experiments*, Springer, 2002.

[13] J.H. Stapleton, *Linear Statistical Models*, John Wiley & Sons, 1995.

[14] J.T. Bell, S. Fogler, Ten Steps to Developing Virtual Reality Applications for Engineering Education, *ASEE Annual Conference Proceedings* 1997, 1-8.

[15] J.T. Bell, S. Fogler, Virtual reality in the Chemical Engineering Classroom, *ASEE Annual Conference Proceedings* 1998, 1-11.

[16] J.T. Bell, S. Fogler, Vicher: A Virtual Reality Based Educational Module for Chemical Reaction Engineering, *Computer Applications in Engineering Education* 4(1998), 285-296.

[17] V.S. Pantelidis, Virtual Reality and Engineering Education, *Computer Applications in Engineering Education* 5(1997), 3-12.

[18] J.T. Bell, S. Fogler, Undergraduate Research Experiences Developing Virtual Reality Based Educational Models, *ASEE Annual Conference Proceedings* 1997, 1-10.

[19] A. Van Dam, D.H. Laidlaw, R.M. Simpson, Experiments in Immersive Virtual Reality for Scientific Visualization, *Computers & Graphics* 26(2002), 535-555.

[20] G. Taxen, A. Naeve, A System For Exploring Open Issues in VR-Based Education, *Computers & Graphics* 26(2002), 593-698.

[21] B.W. Brown, The Crossover Experiment for Clinical Trials, *Biometrics* 36(1980), 69-79.

[22] L.N. Balaam, A Two-Period Design with $t^2$ Experimental Units, *Biometrics* 24(1968), 61-73.

[23] J.E. Grizzle, The Two-Period Chang-Over Design and Its Use in Clinical Trials, *Biometrics* 21(1966), 467-480.

[24] J.E. Grizzle, Corrections: The Two-Period Change-Over Design and Its Use in Clinical Trials, *Biometrics* 30(1974), 727.

[25] A.P. Grieve, The Two-Period Changeover Design in Clinical Trials, *Biometrics* 38(1982), 517.

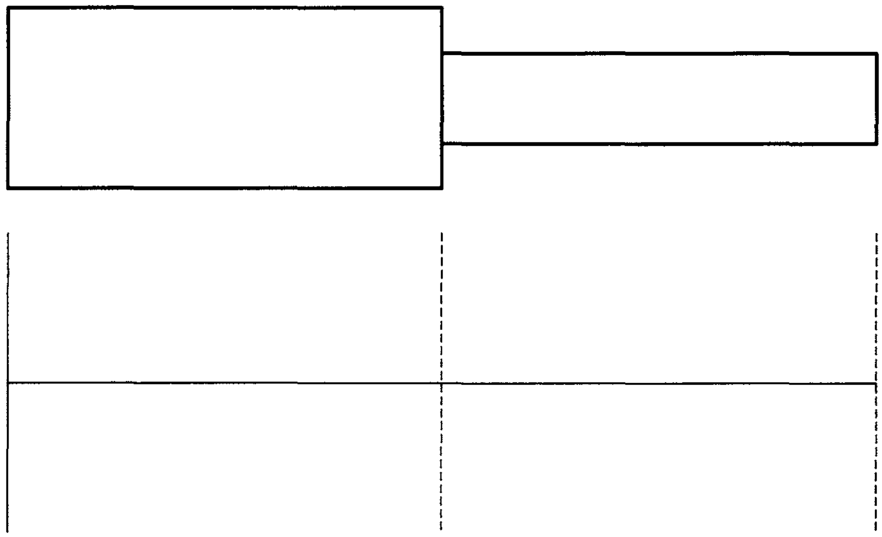
[26] A.R. Willan, J.L. Pater, Carryover and the Two-Period Crossover Clinical Trial, *Biometrics* 42(1986), 593-599.

[27] A.P. Grieve, S. Senn, A Comment on Interim Analysis in Crossover Trials, *Biometrics* 52(1996), 1515-1520.

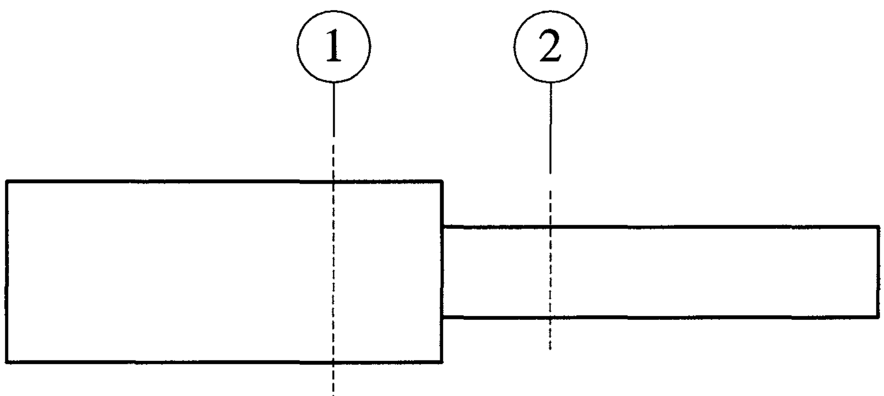
# APPENDIX A. QUESTIONNAIRE

## REDUCTION FLOW CASE

1. Plot the centerline speed of the flow beginning at the inlet and ending at the outlet.



2. Describe how the speed and direction of the flow change between section 1 and section 2.

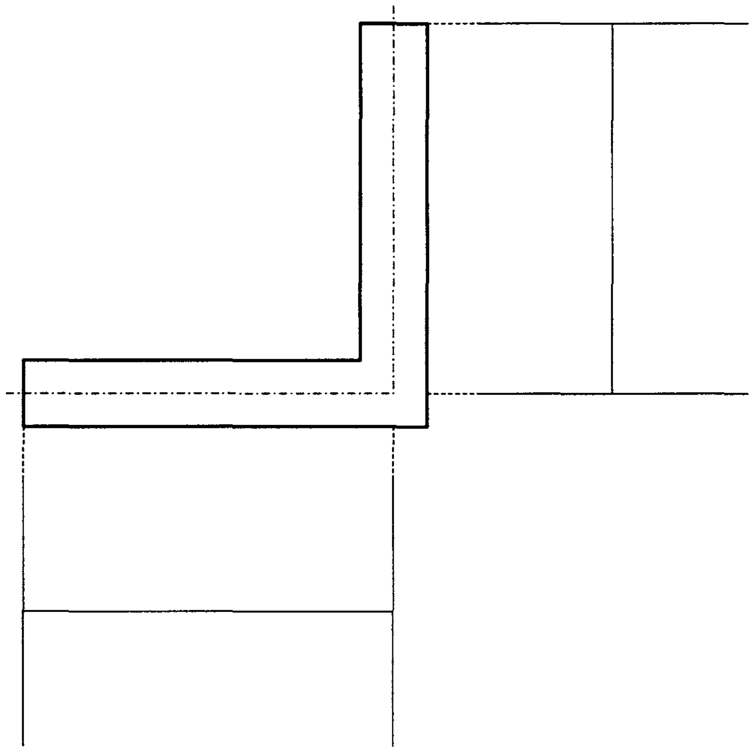


3. Describe how the speed of the flow changes between the centerline and outside wall of the duct.

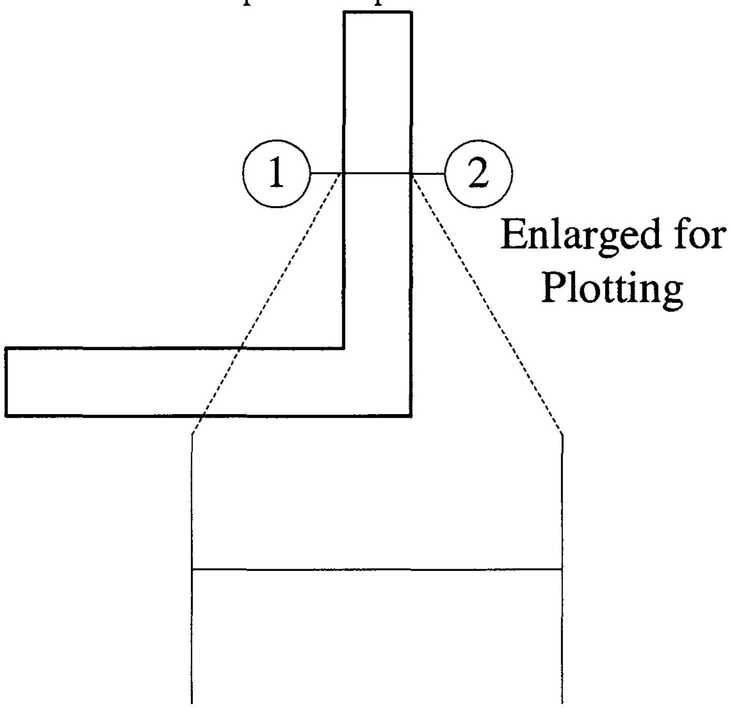
4. Describe the air flow through the duct. Please refer to the characteristics of the flow at different regions and comment on any differences between the wide and narrow sections of duct.

BEND FLOW CASE

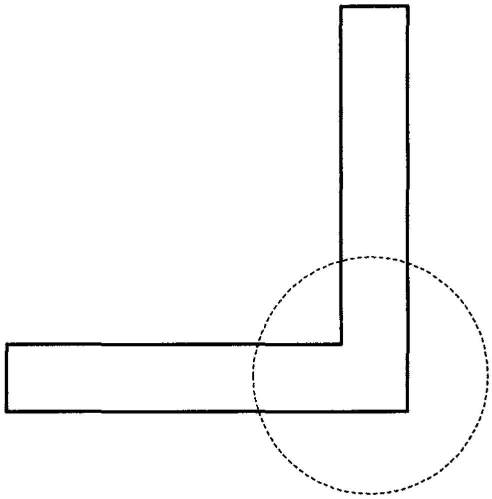
1. Plot the centerline speed of the flow from the inlet to the outlet.



2. Plot the speed distribution from point 1 to point 2.



3. Describe how the speed and direction of the flow change in this region.



4. Describe the airflow from the inlet to the outlet. Please comment on any important characteristics.

## FURNACE – TEMPERATURE

1. Approximate the temperature at the coal/air inlets.

2. Describe the temperature change in the furnace between the coal inlets and the outlet. In general, is the furnace getting hotter or colder along the way?

3. Describe where the fireball exists inside the furnace.

4. Describe the temperature distribution inside the entire furnace and how it relates to the working processes of the furnace.

## FURNACE – OXYGEN CONCENTRATION

1. Approximate the oxygen concentration at the coal inlets.

2. Describe the oxygen concentration change in the furnace between the coal inlets and the outlet. In general, is the concentration increasing or decreasing along the way?

3. Describe which general region of the furnace has relatively high oxygen concentration and whether it is higher near the walls or at the center of the furnace.

4. Describe the oxygen distribution inside the entire furnace and how it relates to the working processes of the furnace.

# APPENDIX B. TUTORIAL

Tutorial

1. Describe how the flow around the obstruction differs from the flow before or after it. Please make reference to the difference in magnitude and direction.

2. Describe how the propane concentration varies at different areas of the duct and relate this to your knowledge of the system as explained by the investigator.

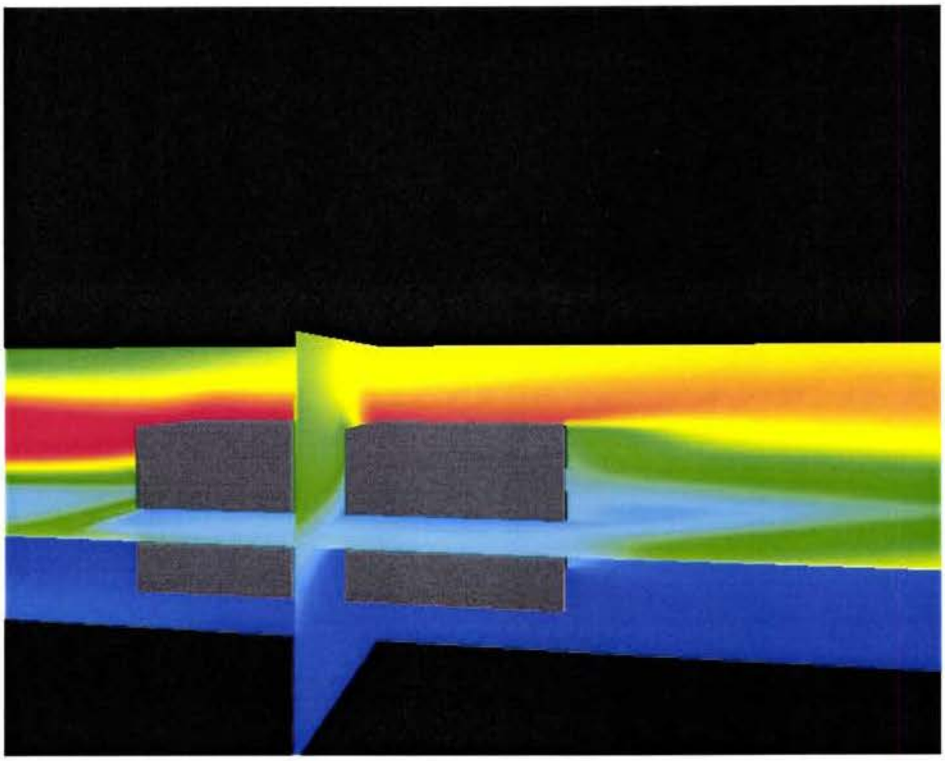


**Figure B.1: Propane concentration contours**

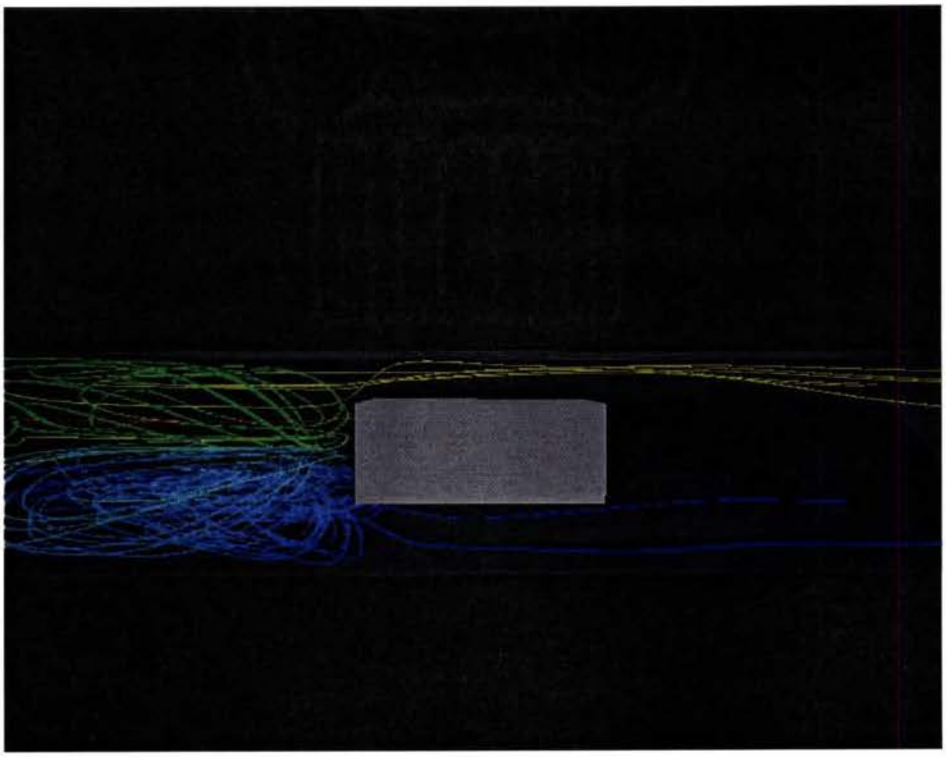


**Figure B.2: Streamlines flowing around an obstruction**

# APPENDIX C. RAW DATA

## Table C.1: Iowa State raw data

| | Velocity Data | | Scalar Data | |
|---|---|---|---|---|
| *Group* | *Period 1* | *Period 2* | *Period 1* | *Period 2* |
| 1 AA | 62 | 58 | 72 | 70 |
| | 60 | 62 | 71 | 64 |
| | 55 | 53 | 62 | 68 |
| | 56 | 61 | 61 | 57 |
| 2 BB | 58 | 50 | 55 | 52 |
| | 60 | 65 | 66 | 69 |
| | 58 | 60 | 48 | 36 |
| | 63 | 58 | 56 | 58 |
| 3 AB | 63 | 69 | 64 | 29 |
| | 62 | 60 | 70 | 59 |
| | 51 | 52 | 71 | 76 |
| | 59 | 62 | 60 | 36 |
| 4 BA | 63 | 62 | 66 | 74 |
| | 59 | 60 | 60 | 68 |
| | 57 | 59 | 59 | 65 |
| | 61 | 64 | 53 | 84 |

## Table C.2: Indian Hills raw data

| | Velocity Data | | Scalar Data | |
|---|---|---|---|---|
| *Group* | *Period 1* | *Period 2* | *Period 1* | *Period 2* |
| 1 AA | 48 | 55 | 47 | 45 |
| | 47 | 43 | 42 | 57 |
| | 38 | 44 | 52 | 53 |
| | 37 | 36 | 50 | 45 |
| 2 BB | 51 | 41 | 30 | 30 |
| | 61 | 51 | 38 | 26 |
| | 55 | 52 | 33 | 22 |
| | 52 | 59 | 34 | 46 |
| 3 AB | 40 | 50 | 43 | 44 |
| | 45 | 53 | 51 | 26 |
| | 47 | 47 | 40 | 28 |
| | 40 | 44 | 44 | 35 |
| 4 BA | 60 | 56 | 29 | 44 |
| | 55 | 47 | 32 | 53 |
| | 54 | 51 | 50 | 70 |
| | 49 | 39 | 35 | 34 |

# APPENDIX D. INFORMED CONSENT DOCUMENT

INFORMED CONSENT DOCUMENT

**Title of Study: Evaluation of CFD Visualization Techniques In Virtual Reality.**
**Investigators: Craig Riedel (B.S. in Mechanical Engineering, 2001)**
**criedel@iastate.edu**
**(515) 294-5289**

This is a research study. Please take your time in deciding if you would like to participate. Please feel free to ask questions at any time.

## INTRODUCTION

The purpose of this study is to determine which CFD visualization techniques are most useful for teaching students about systems that involve fluid flows. The information obtained will be used to determine how visual flow information should be represented in teaching materials and virtual training simulations. You are being invited to participate in this study because you are currently enrolled in an introductory Biology or Chemistry course, and are at least 18 years of age. This education level is representative of the audience that we will be designing educational materials and virtual training simulations for.

## DESCRIPTION OF PROCEDURES

If you agree to participate in this study, your participation will last for approximately 1 hour. During the study you may expect the following study procedures to be followed. Upon arrival, I verify that you are at least 18 years old by asking for identification, and will then introduce you to the equipment that will be used for this study. After showing you the equipment and allowing you to become familiar with it, the study will begin. You will be shown the flow fields for various systems, and then you will answer questions about the flow. Based on the answers of all of the participants, statistical methods will be used to determine what the best representation is for different flow variables. The purpose is not to evaluate your abilities, but rather to evaluate the abilities of different flow representations to meet the needs of teaching students. You will be given a copy of the consent form signed by you, and an investigator statement signed by me.

There will be no audio or visual recordings of you performing the study.

## RISKS

While participating in this study you may experience the following risks:

1) There is a very small chance you will feel nauseous.

## BENEFITS

If you decide to participate in this study there will be no direct benefit to you. It is hoped that the information gained in this study will benefit society by providing information about how to represent flows in a way that students can best understand, to people charged with the responsibility of designing educational materials and simulations.

## COSTS AND COMPENSATION

You will not have any costs from participating in this study. You will not be compensated for participating in this study.

PARTICIPANT RIGHTS

**Your participation in this study is completely voluntary and you may refuse to participate or leave the study at any time. If you decide to not participate in the study or leave the study early, it will not result in any penalty or loss of benefits to which you are otherwise entitled.**

RESEARCH INJURY

Emergency treatment of any injuries that may occur as a direct result of participation in this research is available at the Iowa State University Thomas B. Thielen Student Health Center, and/or referred to Mary Greeley Medical Center or another physician or medical facility at the location of the research activity. Compensation for any injuries will be paid if it is determined under the Iowa Tort Claims Act, Chapter 669 Iowa Code. Claims for compensation should be submitted on approved forms to the State Appeals Board and are available from the Iowa State University Office of Risk Management and Insurance.

CONFIDENTIALITY

Records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available. However, federal government regulatory agencies and the Institutional Review Board (a committee that reviews and approves human subject research studies) may inspect and/or copy your records for quality assurance and data analysis. These records may contain private information.

To ensure confidentiality to the extent permitted by law, the following measures will be taken:

1) An identification number will be used in place of your name for keeping raw data.
2) Your name will only be present on the consent form, which by rule must be kept for 3 years. These consent forms will be kept in a locked cabinet in a locked room, and only the principal investigator will have access to them except when the Iowa State University Institutional Review Board is inspecting records for quality assurance as stated above.

If the results are published, your identity will remain confidential.

**QUESTIONS OR PROBLEMS**

You are encouraged to ask questions at any time during this study. For further information about the study, Indian Hills Community College students should contact Dr. David Brigham, dbrigham@ihcc.cc.ia.us, 17601 Monroe-Wapello Road, Eddyville, IA 52553 and Iowa State University students should contact Dr. Mark Bryden, kmbryden@iastate.edu, VRAC, 2274 Howe Hall, Ames, IA 50011. If you have any questions about the rights of research subjects or research-related injury, please contact the Human Subjects Research Office, 2810 Beardshear Hall, (515) 294-4566; meldrem@iastate.edu or the Research Compliance Officer, Office of Research Compliance, 2810 Beardshear Hall, (515) 294-3115; dament@iastate.edu

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**SUBJECT SIGNATURE**

Your signature indicates that you voluntarily agree to participate in this study, that the study has been explained to you, that you have been given the time to read the document and that your questions have been satisfactorily answered. You will receive a copy of the signed and dated written informed consent prior to your participation in the study.

Subject's Name (printed) ______________________________________________

______________________________________________ ____________________________

(Subject's Signature) (Date)

**INVESTIGATOR STATEMENT**

I certify that the participant has been given adequate time to read and learn about the study and all of their questions have been answered. It is my opinion that the participant understands the purpose, risks, benefits and the procedures that will be followed in this study and has voluntarily agreed to participate.

______________________________________________ ____________________________

(Signature of Person Obtaining (Date)
Informed Consent)