A WEB-BASED VIRTUAL SUPERSONIC NOZZLE MODULE AS AN INTERACTIVE VISUALIZATION TOOL FOR TEACHING CONCEPTS RELATED TO ONE-DIMENSIONAL GAS DYNAMICS

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Abstract

A web-based virtual supersonic nozzle module has been developed for teaching students basic concepts related to one dimensional gas dynamics. This interactive visualization module uses a simulation program and a visualization software to help students understand variation of flow properties such as Mach number, density, pressure, speed of sound etc. in supersonic nozzles operating under isentropic (shock free) and non-isentropic (embedded normal shock) conditions. The module has been integrated in the thermodynamics course (ME 312) as a supplementary tool to conventional teaching. Four learning outcomes have been formulated and have been assessed to determine effectiveness of the module in enhancing student learning of basic concepts. Results indicate that there was significant improvement, as measured by class performance in test, in student learning for three of the four learning outcomes. The overall performance of students in the module enhanced class was substantially higher than the conventional class without the introduction of the module.

Introduction and Motivation for Present Study

Conventional classroom lecture is still the dominant mode for educating engineers. However, engineering education is currently undergoing major changes brought about by fast evolving computer and internet technologies. Reinforcing the need for a change is the fact that present day students unlike their counterparts a generation ago have unfettered access to computers and internet. There is also a growing realization among engineering educators that current students familiarity with interactive video and computer games presents opportunities for development of new pedagogies that are in sync with students interactive learning style. This is echoed in one academic leader's remarks [1], "I think it's the television and computer, and video-games – that they can play at home either on their television set or on their personal computer - I think the interactive nature of these games - the live action - I think, that's what has changed the way students learn. They are not nearly as passive as my peers were when I was a college student." Also driving changes in engineering education is the fact that increasingly, industry is relying on computer and internet technologies to eliminate expensive mock-up experiments to cut costs and stay competitive in a globalized market place. Two technologies namely simulation and visualization are emerging as the key players in both industrial and engineering education applications. Some industrial leaders, as well as educational leaders, have suggested that computer modeling and visualization be used in an interactive mode to provide students hands-on skills now being demanded by industry [1-3]. Visualization has always been a critical factor in a successful engineering program, largely through physical laboratory experiences. In fact, the ability to visualize a physical process is essential for engineers to work successfully in industry [4-7]. Rapid advances in computer and communication technologies in the past ten years have opened a new avenue for providing hands-on skills to students through visualization in the virtual domain. According to Kartemeyer and Bauer [8], “We are now on the threshold of the ability to use the emerging computing and communication technologies in education to mediate and augment interactions among teachers and learners.”

The present work, as the title indicates involves development of a web-based tool that is easily accessible to students and which will enable them to better understand phenomena related to high speed nozzle flows. Students, as our past experience suggests, face difficulty in comprehending property variations in the flow direction and they also lack clear understanding of delineation of flow regimes into shock-free (isentropic) and normal shock (non-isentropic) flows. Students also fail to make connections between real life phenomena that occur in high speed flows, and the underlying principles and equations that govern them. For example, nozzles are often shown in textbooks as a simple device with an area change. In reality, a high speed nozzle for rocket applications can be a very complex engineering system. With the advancement of computer and internet technologies it has become possible to develop web-based resources that can provide ample information about practical nozzle and diffuser configurations and flow regimes to a student population that has become increasingly web-savvy.

Scope of the Present Study

The present work represents a case study of information technology driven transformation of one of the courses in the mechanical engineering curriculum at Old Dominion University. This study is part on a broader on-going transformation in which we hope to demonstrate that pedagogical improvements in engineering education can be made as a result of assimilation of interactive simulation and visualization throughout the engineering curricula. The desired goal of the transformation is to allow students to achieve a deeper understanding of basic principles and engineering context of the phenomenon in consideration via a dynamic leaning process that involves simulation and visualization. The senior author (S. K. Chaturvedi) has recently received a grant from the National Science Foundation titled “Planning Grant: Simulation and Visualization Enhanced Engineering Education.” An important objective of the NSF grant is to develop, test and integrate a visualization module in the Thermodynamics II (ME 312) course that emphasizes application of thermodynamic laws to real-life problems. As a result of grant efforts a web-based module titled “Virtual Supersonic Nozzle as a Visualization Tool for Thermodynamics II Course” has been developed, tested and assessed. The web-based module (www.mem.odu.edu/shockwave) is built on the foundational support provided by the pedagogy of “learning by doing in virtual environments” [8]. The central thesis of the present work is that web-based interactive tools employing simulation and visualization will provide students opportunities to learn by interacting and manipulating virtual tools of the type discussed in this study. This student-centric mode of learning should result in better student understanding of concepts and physical principles, and this in turn will be reflected in improvement in students performance as gauged by tests. The module discussed in this work was integrated in the course during Summer 2004 and Spring 2005 semesters; learning objectives and outcomes were developed, and tests incorporating the learning outcomes were administered and analyzed to evaluate the effectiveness of the web-based module in enhancing students learning of concepts and physical principles related to high speed flows in nozzles and diffusers.

Simulation and Visualization of Flow Characteristics

A normal shock in the nozzle represents a sudden change of properties in a very thin region. This is illustrated in Fig. 1. The flow is

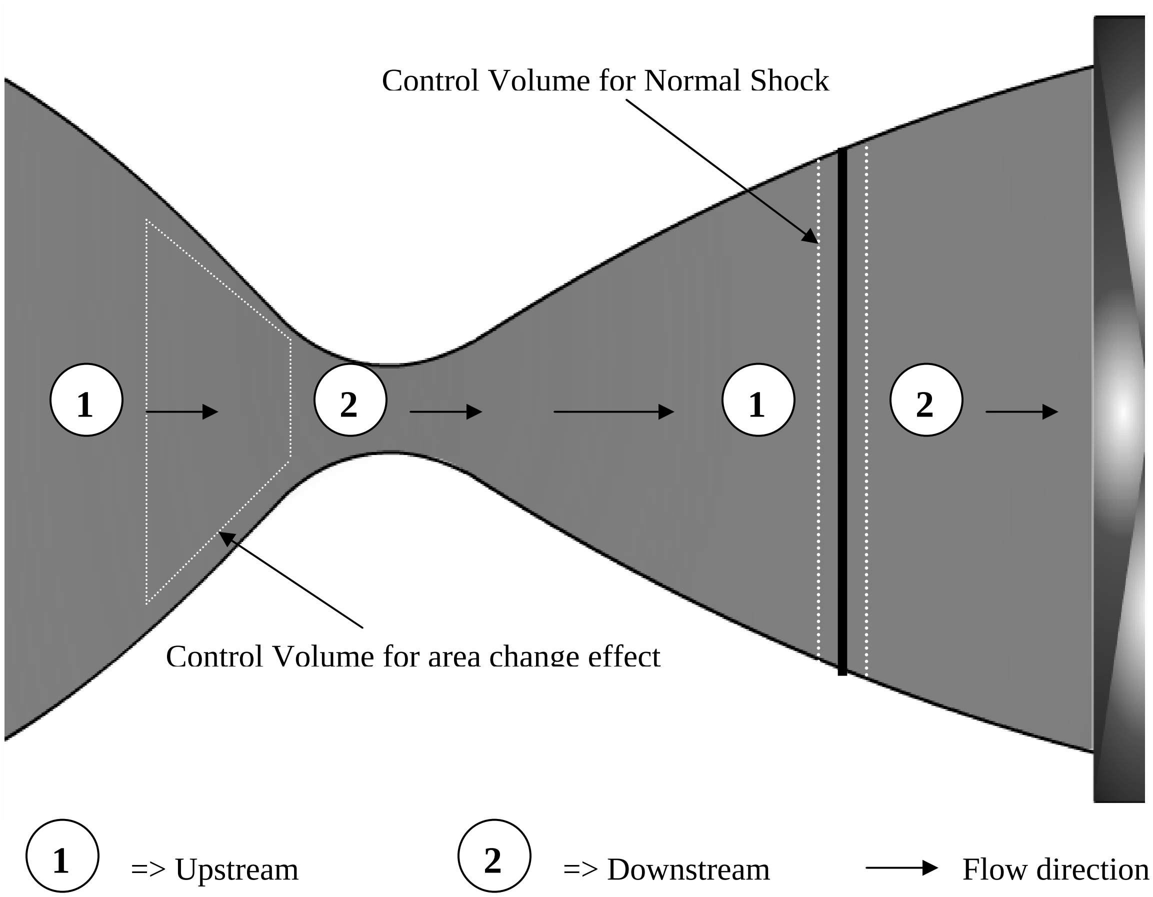

Fig. 1 Control Volumes for area change and normal shock effects.

isentropic up to the shock front; the entropy as well as other flow properties jump across the shock, and from there onwards the flow remains isentropic. The flow properties in the nozzle change due to two reasons. The first one is due to the area change effect that induces changes in pressure, density and velocity. This is illustrated through the first control volume. The second control volume is for a normal shock which occurs as fluid adjust pressure suddenly across control volume to match the prevailing pressure boundary condition at the exit of the nozzle.

The isentropic and non-isentropic flows are governed by following equations:

a. Mass Conservation:

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2 \qquad (1)$$

where ρ is the fluid density, V is the fluid velocity, A is the cross sectional area and the subscripts 1, 2 denote the upstream and the downstream locations respectively.

b. First Law of Thermodynamics:

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2} \qquad (2)$$

where h is the enthalpy.

c. Equation of State for Ideal Gases:

$$\frac{P_1}{\rho_1 T_1} = \frac{P_2}{\rho_2 T_2} \qquad (3)$$

where P is pressure and T is the temperature.

d. Enthalpy –Temperature Relationship for Ideal Gases:

$$(h_2 - h_1) = C_{Po}(T_2 - T_1) \qquad (4)$$

where C_{Po} is the specific heat at constant pressure.

e. Second Law of Thermodynamics:

$$\int_{s1}^{s2} Tds = (h_2 - h_1) - \int_{P1}^{P2} vdP = 0 \qquad (5)$$

(For isentropic flows ds=0)

where v is the specific volume and s is the entropy.

f. x- Momentum Equation:

$$P_1 + \rho_1 V_1^2 = P_2 + \rho_2 V_2^2 \qquad (6)$$

Equations (1-5) govern the variations of pressure, density, velocity, temperature and enthalpy for isentropic flows. For given P_1,ρ_1,V_1,T_1,h_1,A_1 and A_2 (a new area section), properties (P_2,ρ_2,V_2,T_2 and h_2) at the new section can be determined from equations (1-5). For non-isentropic (normal shock embedded) flows, entropy increases across the shock (ds>0). For this case, equations (1-4) and equation (6) represent five equations to determine properties P_2,ρ_2,V_2,T_2 and h_2 for given values of properties P_1,ρ_1,V_1,T_1 and h_1 ahead of the shock.

A simulation program was written for air to predict the variation of properties in the flow direction for cases with or without normal shock in the nozzle. The program is general enough to accommodate other ideal gases or a medium consisting of combustion products. The purpose of this program is to simulate different flow conditions in the nozzle by changing back pressure conditions, and to provide numerical data to a visualization program that would display results on the computer screen. This is done by integrating the simulation program with the Macromedia Flash software for visualization [9]. The software Flash allows the integration of video, text, audio, and graphics into immersive, rich experiences that deliver superior results for interactive activities and presentations, e-learning, and application user interfaces.

Module Objectives and Leaning Outcomes

The supersonic nozzle visualization module (www.mem.odu.edu/shockwave) uses a simulation program and a visualization software to illustrate basic concepts and underlying principles governing one-dimensional flow phenomena. Students learn to apply the first and second laws of thermodynamic, the mass conservation law and Newton’s second law to analyze the variation of flow properties such as Mach number, density, temperature, pressure, speed of sound etc. in a supersonic nozzle operating under isentropic (shock free) and non-isentropic (embedded normal shock) conditions. The module is interactive, and this allows students to vary upstream and downstream pressure conditions to establish isentropic flows, normal shock embedded flows, and flows with oblique shocks (diamond shock) in the exhaust plume of the nozzle. The module has been used as a supplementary tool to conventional classroom teaching.

Two learning objectives and four learning outcomes have been identified, and incorporated in the module. The learning objectives refer to broad goals that the module is designed to achieve. The learning outcomes refer to students ability to perform certain functions or activities, primarily related to concepts and problem solving, as a result of the module use. Table 1 shows the interrelationships between learning objectives and outcomes. The first objective relates to educating students about isentropic one-dimensional compressible flows in devices such as nozzles and diffusers. The second objective deals with non-isentropic (normal shock) phenomenon in one-dimensional flows. The outcome 1 requires students to demonstrate an understanding of relationships between

Table 1 Learning objectives and outcomes for ME -312 course module.

Objectives / Outcomes	Students are well prepared to analyze isentropic one dimensional compressible flows	Students understand and are capable of analyzing non isentropic (normal shocks) phenomenon in one dimensional compressible flows
Ability to use interrelationships between stagnation and static properties and isentropic gas tables, to delineate flow regimes using Mach number and speed of sound and identify geometric configuration to achieve these flow regimes and to analyze variation in flow properties in flow direction		
Ability to solve flow problems in converging nozzles or diverging diffusers for subsonic or critical (sonic) phenomenon regime, choking phenomenon		
Ability to solve problems involving isentropic flows in nozzles and diffusers and analyze effect of back pressure on nozzle flow		
Ability to use shock tables to analyze property changes across Normal Shock, and solve problems involving variation of back pressure in flows involving shocks in nozzles and diffusers.		

stagnation and static properties (isentropic gas tables) and delineation of flow regimes using Mach number. The second outcome relates to subsonic flow in nozzles and diffusers, and the choking phenomenon. For outcome 3, the students are expected to demonstrate their ability to analyze isentropic supersonic flows in converging-diverging nozzles and diffusers. The outcome 4 refers to students ability to predict the location of the normal shock and determine conditions under which a normal shock will occur in a nozzle and property variation across a normal shock.

Supersonic Nozzle Visualization Module Structure

The web-based visualization module as shown in Fig. 2 is organized into four parts namely "Analysis Module" for familiarizing students with governing equations and problem solving; "Physical Module" for providing physical configurations and engineering context to one-dimensional compressible flows; "Simulation Module" for detailed property variations from a Computational Fluid Dynamics (CFD) code, and "Interactive Module" for conducting virtual experiments by changing nozzle operating conditions. The module has been developed with the objective of enhancing active learning through the interactivity feature included in the module. Students learning has been facilitated by incorporating subject materials at three different levels that provide knowledge, comprehension and exploration as per Bloom's Taxonomy of Education Objectives [10]. The knowledge part of module covers governing laws, equations and practical examples to give students information about physical processes. This part is included in the analysis and physical module sections. The comprehension part (included in the "Analysis" section) includes several example problems illustrating how underlying principles and governing equations

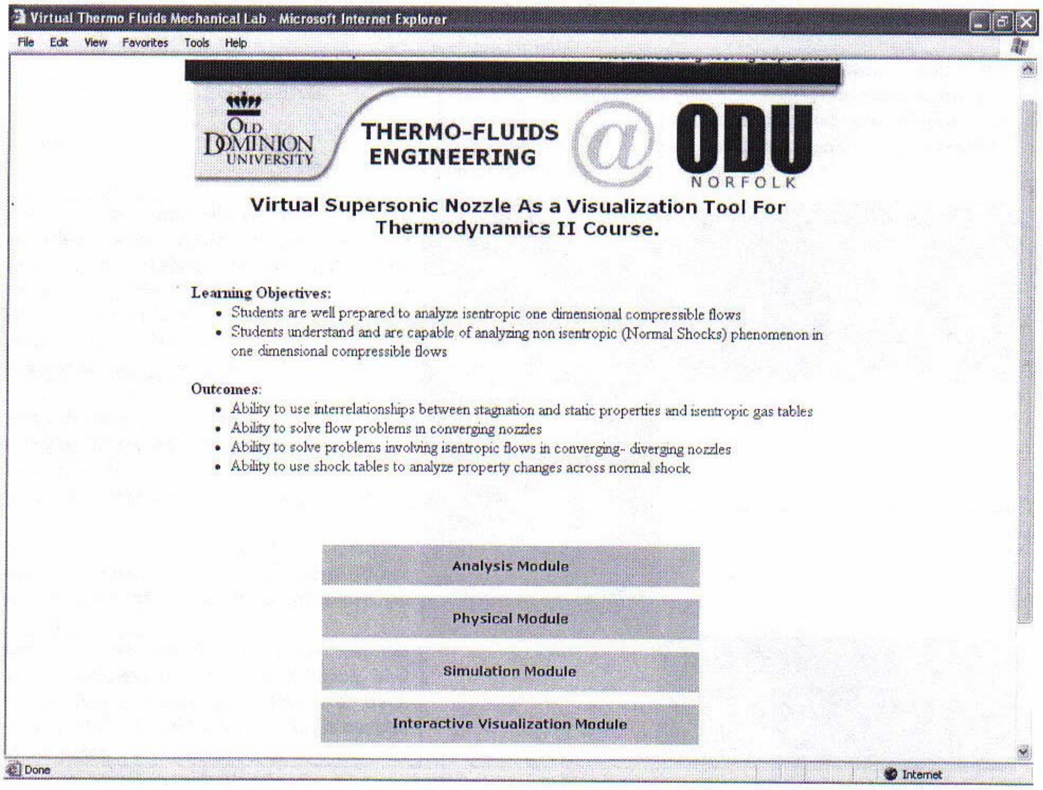

Figure 2 Structure of the web-based module.

can be used to solve a variety of problems arising from changed operating scenarios. The exploration part embedded in the "Interactive Visualization Module" allows learners to vary operating parameters (upstream and downstream pressures) to observe different flow regimes and flow property variations. For example, using an embedded simulation software, developed to predict the location and strength of normal shockwave, students can observe changing normal shock location and strength in real-time as the nozzle exhaust pressure is varied. Students can also vary the properties of flow medium (molecular weight and specific heat ratio) to evaluate effects of the medium properties on parameters such as shock location and nozzle thrust.

The "Interactive Visualization Module" is shown in Fig. 3. Students, using the slider bar can specify upstream (stagnation) and downstream (back) pressures as well as upstream stagnation temperature, molecular weight of the medium and ratio of specific heats. Air is the default medium. In order to help students visualize flow property variations in the nozzle, the clicking action of the computer mouse is used. The clicking action at a given point in the flow field creates a window that displays flow properties of interest such as stagnation pressure and temperature, static temperature and pressure, Mach number, flow velocity, density, speed of sound etc. This is shown in Fig. 4 for an operational scenario in which a normal shockwave occurs in the diverging section of the nozzle.

Assessment Results

The pilot supersonic nozzle module was integrated into the ME 312 (Thermodynamics II) course during the Spring 2005 semester. The course instructor used the module to enhance the conventionally taught lecture format. A quiz covering all four learning outcomes (Table 2) was administered after the complete coverage of the module. Assessment results from the

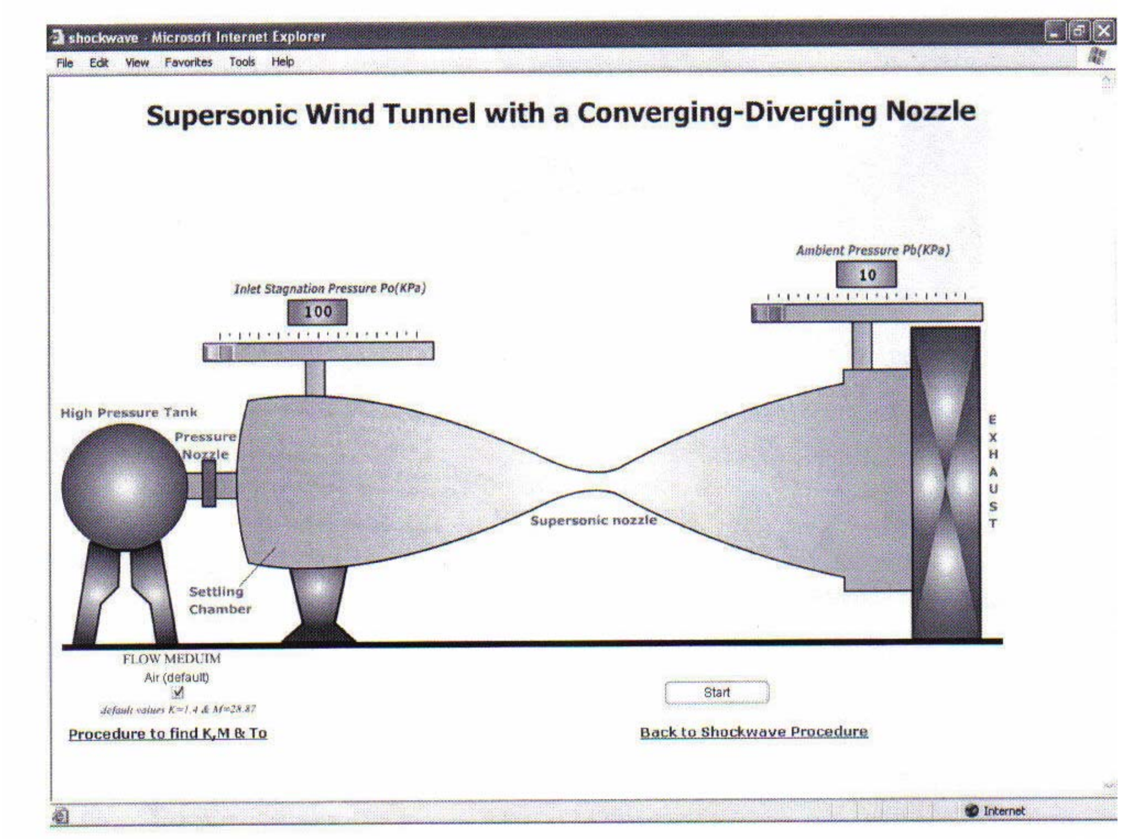

Figure 3 The interactive visualization module.

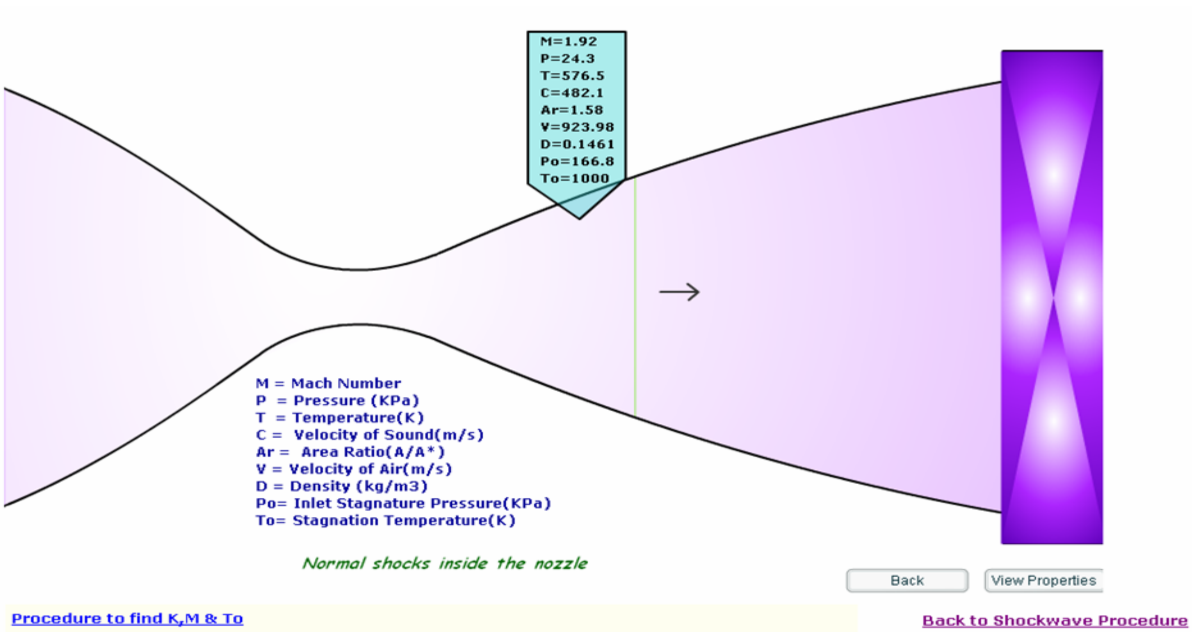

Figure 4 Visualization of shock location and flow properties.

Table2: Student Survey of Shockwave Visualization Module In Spring Semester January 2005

	Questions	Score
1	The visualization module was helpful in understanding fundamental concepts	4.31
2	The visualization module has improved my problem solving skills	3.78
3	The visualization module exposed me to information not readily available in textbooks or lectures	3.62
4	The visual images in the module will helped me understand interrelationships between various flow properties	4.16
5	The visual images in the module will help me retain concepts and other related information for a longer period of time	3.97
6	The visualization module provided a real life context through practical examples that made concepts easier to comprehend	4.09
7	The time allocated for studying the visualization module was adequate	4.19
8	It is recommended to use this visualization module in future class	4.56
9	The visualization module was user friendly	4.06
10	More visualization modules of the type presented here should be developed for other topical areas.	4.38

Legend: 5 » Strongly Agree,
4 » Agree
3 » Neutral
2 » Disagree
1 » Strongly Disagree

enhanced course were compared with results from the same course taught conventionally (without module enhancement) in Summer 2004 semester, using the same quiz. Results shown in Fig. 5 indicate that the average quiz score increased from 59 % (for traditionally taught course) to 74 % (for the visualization enhanced course). Furthermore, results for Outcomes 2 to 4 were substantially better for the enhanced course compared to the conventionally taught course. For instance, results for Outcome 4 dealing with normal shock phenomena, a difficult topic to grasp, showed significant improvement in student learning, attributable directly to the Virtual Interactive Sub-Module for visualizing normal shocks in supersonic nozzles.

A survey was also conducted during the Spring 2005 semester to have student feedback

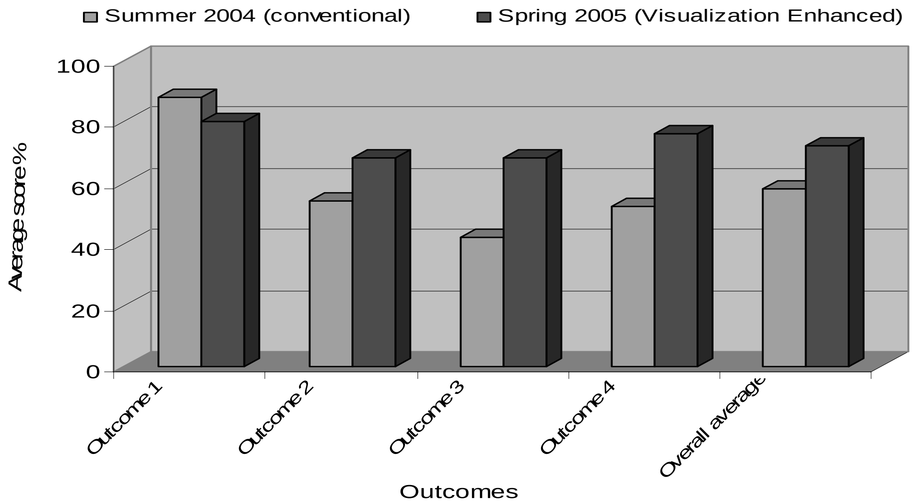

Figure 5 Comparison of enhanced course conventionally taught course (ME 312).

to this newly developed module. A questionnaire, on a scale of 1 (strongly disagree) to 5 (strongly agree), having ten questions related to the supersonic visualization module was developed. The confidential survey was conducted after student took a test, covering all four learning outcomes of the module. The results from the survey are summarized in Table 2. Results in Table 2 indicate the positive tone of students responses. For example, they enthusiastically endorse the idea of developing more visualization modules for other topical areas (Question 10). They also felt that the visualization module was helpful in understanding fundamental concepts (Question 1) and the engineering context of the problem (Question 6). Lower than expected responses to questions 2 and 3 was primarily due to the fact that many students did not have enough time during the 3 week session on this topical area to fully explore the module and utilize its full potential. Based on this finding, we would try in future a more structured introduction to the module with lesson plans that would require a fuller use of the module.

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