Low Cost Virtual Reality and its Application to Chemical Engineering - Part Two

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Introduction and Update from Part One

This article has been broken up into two parts, the first of which presented an introduction to virtual reality and some discussion of what low-cost hardware and software options are available[3]. This second part will cover some applications of virtual reality, including areas where VR is being or could be applied to chemical engineering, and in particular the work being done at the University of Michigan's department of Chemical Engineering to apply low-cost virtual reality to undergraduate education. First of all, however, it is necessary to address a few issues which have changed substantially since part one was written. The fact that so much has changed in just six months is typical of this rapidly developing field.

- **Sourceless trackers improving and gaining in popularity[15]:** Part one of this article discussed head trackers costing hundreds or thousands of dollars which utilize a transmitter and receiver combination, (either electromagnetic or ultrasonic), to track the position and orientation of a users head, and mentioned the existence of sourceless trackers. These latter devices, which incorporate gravimetric tilt sensors, compasses, gyroscopes, and other self-contained sensors are termed "sourceless" because they are entirely self contained, which eliminates some of the clutter of a VR setup, and avoids the interference problem when multiple sensors are used in close proximity. These sensors are much less expensive to produce, and have become quite popular, particularly as a 3 degree of freedom (rotation only) sensor for tracking head movements of a seated user, because the position of the head does not change appreciably in that environment.

- **HMDs available for $800 with built-in head tracker:** In the first part of this article a low-cost head mounted display was one which cost only a few thousand dollars, such as the CyberEye from General Reality Company, which then also required the separate purchase of a head tracking device of some kind. While that solution is still available, and is a good quality device, a new product has recently hit the market which has won many awards and much praise from the virtual reality industry. That product is the *i-Glasses*, from Virtual I/O inc., which weighs in at just 8 ounces and fits in your pocket for color

stereo viewing and built-in 3 DOF tracking for only $800. i-Glasses are the first product offered by this fledgling company, and other (e.g. VGA) products are expected within a year. Zwern[20] provides a good review of available head-mounted display devices.

- **New low-cost wired gloves available and others announced:** Part one discussed the Nintendo Powerglove, a discontinued toy accessory which some homebrew VR enthusiasts have wired into their computers, and also mentioned the existence of more advanced gloves costing thousands of dollars based on fiber optics technology. Two announcements have been made within the last month regarding the availability of new low-cost wired gloves. First of all, Arthur Zwern, of General Reality Company, announced the U.S. availability of a fiber-optic glove produced by Fifth Dimension, with an introductory price of $495, and a quality equivalent to the original fiber-optic gloves produced by the (now-defunct?) VPL corporation.

  The second announcement was by Chris Gentile, of Abrams/Gentile Entertainment, the manufacturers and patent holders of the discontinued Nintendo PowerGlove. AGE announced the development of a "PC PowerGlove", to be available in 1996 for less than $120, with much higher resolution and better features than the Nintendo PowerGlove, and pre-configured to connect to a PC serial port. Special options such as left-handed gloves, two glove packages, and tactile feedback will be available at slightly higher costs.

- **WTK: New product replaces SPEA solution:** WorldToolKit from Sense8 formerly had a Windows 3.1 version which ran on ordinary PCs, and a DOS version which required a special graphics board, the SPEA Fire graphics board (and a number of products running on higher-end platforms). The Windows 3.1 solution is still being sold, and is a popular product, but unfortunately the SPEA card is no longer available, which puts a damper (at least temporarily) on the DOS product. However, Sense8 now has an alternate product, using OpenGL and Windows NT. OpenGL is based upon the graphics language developed by Silicon Graphics for their high-end graphics supercomputers, and will be supported by the new Windows NT operating system. Because of the huge potential market for CAD applications and computer games, a number of companies have announced plans for OpenGL graphics accelerator cards, which will be initially expensive, but will rapidly drop in price as volume sales and competition develops. Some systems available now from InterGraph corporation rival high-performance SGI workstations in performance for a fraction of the cost, but the nice thing about it all is that Windows

NT will support OpenGL applications whether or not a graphics accelerator is present - they will just run faster with the special cards.

Current Applications of Virtual Reality, Including Possible Future Applications, and Their Extension to Chemical Engineering

Virtual reality has been applied to a wide variety of fields and problems, though very few specifically addressed at chemical engineering. Here are some of the current applications of virtual reality, with considerations of how they might be extended to chemical engineering where appropriate. The few applications where VR is already being applied to chemical engineering problems are also covered here, along with some ideas as to how this technology might be applied to chemical engineering in the future. (Note that this section includes, but is not restricted to, low-cost implementations.)

The first application of virtual reality was flight simulation conducted by NASA. This is still a major use of the technology, allowing potential pilots to "crash" million dollar simulators, with no real loss, rather than billion dollar aircraft with considerable loss. In addition, much of the technology developed for flight simulators is now used in actual aircraft cockpits, such as the head mounted display unit to show the pilot critical information without taking his/her attention away from the action in front of him/her. 3D sound cues also provide the pilot with important information, with the "location" of the sound adjusted for optimal effect.

In an industrial setting, virtual reality has been applied to the training of assembly line personnel by Nina Adams and Art Paton at Motorola University[18]. In a carefully controlled study, they found that new employees trained using virtual reality were actually able to operate complicated machinery with fewer mistakes than similar employees who had been trained using the actual production equipment. Simulator training involving virtual reality is also used in several other fields, and could be applied in chemical engineering to the training of control room personnel in large, complicated chemical plants, or to other operating personnel where turning the wrong valve could lead to disaster. These simulators could also be used to develop operational procedures, practice emergency shutdowns, and for re-enacting events leading to accidents or alarm conditions.

By far the most well-known and well-developed application of VR to date is the entertainment industry. There are virtual reality gaming centers popping up all across the country, with the most popular game being "Dactyl Nightmare" played on the Virtuality system from W Industries. This game allows from one to four participants to enter together into a virtual environment, where they attempt to find and kill each other before being killed by their opponents or by roving pterodactyls. VR has appeared as the

main focus of a weekly TV game show in Great Britain, and has been idealized in several movies and television programs such as "Lawnmower Man" "VR5", and "Wild Palms", not to mention the Star Trek holodeck. The home gaming market has seen the introduction of home VR gaming equipment from Sega, Nintendo, and others, and can expect an explosion of new products and games within the next year. This application does not lend itself to practical engineering, but could be used to stir interest in the chemical engineering field if an appropriate chemical plant simulation game were to be developed.

The next biggest application is the architectural walk through (fly through.) Using a program such as WorldToolKit, it is a simple matter to import anything drawn by a 3D CAD program, such as AutoCAD, into a virtual environment. (Some advanced CAD programs allow interactive rendering of their 3D constructions directly, bypassing the need for a separate rendering engine.) This allows users to view buildings and other constructions before they have actually been built. If the user doesn't like the results, it is a simple matter to enlarge a window, move a wall, or change the coloring, often from within the virtual environment. In Japan, where land is scarce and large showrooms prohibitively expensive, housewives can use VR to preview their new kitchens prior to remodeling. One research group has hooked up a wheelchair to a virtual display system, in order to check designs for handicap accessibility.

Closer to our field, major construction engineering firms such as Bechtel, Fluor-Daniel, Parsons, Stone & Webster, and CADCentre have long used sophisticated CAD programs to keep track of large projects. As the years progressed, those programs have gone from 2D to 3D, have developed sophisticated rendering capabilities, and now allow dynamic viewpoint adjustment and interaction. Essentially the drafting programs have become VR engines, allowing engineers to walk through plants before they are constructed, to bring up project data on screen, and to discover problems and make modification before ground is broken or materials ordered. While not exclusively aimed at chemical engineering, this tool has been utilized in the construction of a number of chemical plants and refineries, such as ARCO's Cherry Point refinery, designed by the Ralph M. Parsons Company, using Intergraph's "Plant Design System".

Medical imaging is another big application for virtual reality. By using collected data, doctors are able to visualize and interact with a virtual patient. This is useful for training purposes, for long-distance consultancy, and for viewing the patient in ways that might not be otherwise possible. One application for this latter technique aids doctors in placing and aiming radiation sources so as to best affect cancerous tissue without affecting the neighboring healthy tissue. Prior to VR, most doctors used radiation

projected only along x, y, and z axes, since that was the easiest to visualize and calculate. By experimenting with a see-through patient in a virtual environment, doctors are able to better determine optimal, often oblique radiation angles, yielding less damage to healthy tissue and faster recovery times. Biochemical engineers might apply VR to observe the diffusion and breakdown of drug and other molecules in the body's circulatory system, and their accumulation rate in various organs.

One very interesting medical application being developed at UNC Chapel Hill, allows doctors to view unborn fetuses in-situ[1]. Ultrasound data is fed into a computer, which then produces a 3D image of the fetus, in real time. This image is then projected onto a half-silvered mirror located in front of the doctors eye. Because of the half-silvering, the doctor can see not only the computer generated image, but also the patient and the rest of the "real" world. The net effect, known as augmented reality, allows the doctor to view the fetus in-situ, rather than on a computer screen. Difficulties currently being worked out include the alignment of the projected image with the real world. Chemical engineers could incorporate temperature, pressure, and other real-time sensor measurements in a computer simulation to generate an image of the conditions inside of processing equipment.

Another application being developed at UNC is project GROPE[9], wherein pharmaceutical developers are using virtual reality and tactile feedback to determine docking sites for proposed drug molecules onto protein molecules. The researcher visualizes a room sized protein molecule, and holds the proposed drug molecule in his/her hand. When (s)he tries to dock the drug in an unfavorable location, a robotic arm resists his/her movements, in proportion to the intermolecular forces at work. This tactile feedback is greatly increasing the ability of these researchers to determine the correct docking sites, and thereby speeding up the drug development cycle. This is one of many examples of the application of VR to chemistry / molecular modelling, which has been a field of development for close to thirty years.

Archaeologists are using virtual reality to model important historical sites. Their interests are many-fold. First is to present how important ancient cities looked during the height of their cultures' civilization, thereby allowing researchers and students to "travel" to ancient times. Secondly, by modeling sites under current excavation, they can formulate better hypotheses of how the ancient buildings were laid out, thereby directing their digging efforts towards the most promising areas. Third is to allow wide access to archeological sites which are off limits to the general public due to the frailty of the artifacts[8]. Extensions to chemical engineering would include the reconstruction of destroyed chemical plants, in order to aid in accident investigations, courtroom litigations, and as an educational example for future plant designers and operating personnel.

The aircraft industry has embraced virtual reality in several applications. Boeing conducted all of the design, development, and testing of its new 777 airplane using virtual reality, and produced the first production plane directly from the plans, with no prototypes or physical mock-ups. (The automotive and other design industries are also using virtual reality extensively to reduce prototyping costs.) McDonnell Douglas used virtual reality to test mechanics ability to change engines on the F18 before it was constructed, and to make design changes so that the engine could be replaced in 30 minutes or less. Another proposed application is to allow airline mechanics to view schematic drawings and maintenance manuals using a see-through head mounted display while performing maintenance operations. Extensions to the chemical engineering industry include the design and maintenance of chemical processing equipment.

There are several applications of virtual reality to database exploration, wherein the large amounts of data present and the complex relationships between different data items makes assimilation by human operators difficult. An example of this is the stock market, where analysts must keep track of thousands of stocks whose values are constantly changing, and where any competitive edge can be worth millions of dollars. Chemical engineering also has many large complex databases, which could be explored more intuitively if the appropriate VR implementation were developed.

Similar to this is the field of scientific visualization. Computer scientists working in the area of computer graphics have long been active in the visualization of complex scientific calculations, such as computational fluid dynamics. These applications have typically required tens or hundreds of hours of super computer time just to generate the underlying data, and almost as much effort to produce each beautiful 2D image of the results. As computer graphics capabilities have grown, these researchers have begun to develop VR based representations of scientific data. Two examples related to chemical engineering are NASA's virtual windtunnel[10,19], and an example problem regarding secondary oil recovery via chemical flooding developed at Lawrence Berkeley Laboratories in California[5].

The former application allows NASA scientists to walk around a model of the space shuttle in a virtual windtunnel, and to view the flow patterns without disturbing the surrounding air. Another implementation of VR to display CFD results has been developed by the Matshusta Electric Works, a home heating and air conditioning firm in Japan, to illustrate to potential clients the flow patters of heat and fumes through their new kitchens. (The CFD calculations still require many hours of supercomputer time; It is only the visualization of the results which is implemented using VR.)

The main focus of the Berkeley group is scientific visualization in general. They happen to have chosen a chemical example to illustrate their methods, which allows petroleum engineers to move oil recovery and flooding wells by hand and view the resulting changes in the subterranean flow fields. Note that none of the scientific visualization applications mentioned above are being performed on low-cost hardware, but they give some indication of what may be possible in the future, or even today at a lower performance standard. Virtual reality also shows great promise for visualizing phenomena of dimensionality higher than three.

Teleconferencing is another useful application of virtual reality. This centers around the ability to have several participants simultaneously present in the same virtual world. These participants see the same environment, including each other, and can interact with each other as well. Since the actual participants can be physically located thousands of miles apart, teleconferencing provides a unique mechanism for group interaction. (One assumes the group members would take advantage of the opportunity more constructively than in Dactyl Nightmare!) In chemical engineering this technique would allow engineers from distant locations to meet in a virtual chemical plant to discuss a common problem. Even if only a single engineer was involved, telepresence could yield tremendous savings in the travel time and expense involved in "visiting" a remote chemical plant. And if the plant has already been rendered in the construction phase, then the use of the model after the plant is completed represents little additional cost.

Similar in name but not in function is telepresence. This is really more in the realm of robotics / remote manipulation than virtual reality. Telepresence involves the use of a remote mechanical device, including a camera and controllable hardware, connected to a user wearing goggles and utilizing a controller. The user sees what the camera sees, just as if (s)he were there, and the user's motions are transferred to the remote device. Examples would be exploring the bottom of the ocean, the surface of the moon, or the inside of a nuclear containment vessel.

Process synthesis is an area where an abstract virtual environment could prove useful to chemical engineers. There are an almost limitless number of production routes available for producing most chemicals, involving different combinations of raw materials, equipment, by-products, hazards, wastes, and chemical pathways. The "optimal" production route for any given chemical is a complicated trade-off involving considerations of cost, feedstock availability, safety, flexibility, investment capital costs, labor requirements, energy consumption, environmental impact, and many other concerns. An abstract virtual environment could be constructed which would allow the chemical engineer to explore different combinations of chemicals and

processes, to see the impact of each different combination, and to develop new processes which are significantly better than other alternatives.

Process visualization can also be useful during developmental design phases, after the general process layout has been determined, but before final equipment specifications are available. The abstract representation developed during initial brainstorming sessions would gradually become more concrete as the design develops. The virtual chemical plant could be displayed so as to indicate areas of high cost, energy consumption, safety concerns, etc. through the use of color, relative sizing, or other techniques. (Objects in the virtual world do not have to be displayed in strict conformance with their actual physical appearance.) This differs from the architectural walk-through, in that exact drawings would be unavailable and unnecessary during this phase of design. One possibility would be to develop a visualizer program which could simply read the results of a process simulation program such as AspenPlus or PROCESS, and then produce a virtual representation for the engineer to explore.

Process Monitoring and Control. The idea here is to attach sensors (temperature, pressure, flowrate, pH, etc.) to actual chemical processing equipment, and use the measured values as inputs to a virtual simulation of the process. This would allow the engineer to enter into operating equipment or other hazardous environments and monitor process conditions internally. The addition of virtual controls would further allow the engineer or operating personnel to control their processes from within. Simulations generated from recorded data could aid in the investigation of past performance, including disaster reconstruction.

Education is another area which holds great interest and potential for virtual reality researchers[6,7,11,14]. One reason for this is the power of experiential learning - Students learn and retain more from personal experience than they do from books, lectures, or other forms of less active and involved education[16]. Another benefit is the ability of virtual reality to provide tangible substance to intangible concepts, such as entropy and partial derivatives. Many educators are interested in using virtual reality to bring experiences into the classroom which would otherwise be impossible, however most published implementations involve students in grade school and / or high school levels only. The only known application of virtual reality to chemical engineering education is the work being done at the University of Michigan's Department of Chemical Engineering, as covered briefly in the following section, and in greater detail elsewhere[2,4].

Virtual Reality Development at the University of Michigan

Virtual reality holds great promise as an educational tool for undergraduate chemical engineering. However there are many aspects of this new technology which must be better understood before it can be applied effectively to technical education. These issues include not only the technical aspects of how to build a virtual world, but also representational issues (What does entropy sound like? What color is voltage?), interfacial issues (How do users interact with the world?), navigational issues (Which is more intuitive/effective, a mouse, joystick, keyboard, or HMD?), implementational issues (How should VR be integrated into course curriculum?), and hardware related issues (How much does a head-mounted display or 3-D vision add to the experience, and is the benefit worth the cost in terms of both dollars and speed.)

In order to address some of these issues, we here at the University of Michigan have developed a prototype virtual reality based educational module named Vicher. This is a natural extension to the interactive computing modules developed by Fogler and Montgomery[12], and the multimedia applications currently under development by Montgomery. The following sections will describe our development efforts, including Vicher, followed by a discussion of what we have learned in the development process and the new modules under development as a result of this experience.

General Background

One of the primary goals in our development efforts is to put the finished product into the hands of as many students as possible as quickly as possible. To that end, we have chosen to develop software for the IBM PC platform. Specifically, we are developing on 90MHz Pentium based computers, which are slightly above the average student's home computer, but only slightly, as evidenced by several students who own similar systems. We are also using and investigating certain low-cost peripheral devices, such as General Reality's head-mounted display unit, Logitech's ultrasonic head tracker, and Crystal River Engineerings 3-D audio card, the alphatron. While these latter devices are not yet commonly available to student budgets, they will become more accessible in the near future, and in any case are optional devices not required to run the programs.

We are also interested in future expandability to higher-end computing platforms, and have therefore chosen WorldToolKit from Sense8 as our primary software development platform. We are developing versions of our programs for both DOS and MS Windows, and plan to port the programs to other platforms at a later date. We also use Rend386, primarily for quick prototypes and preliminary proof-of-concept simulations.

Vicher - Virtual Chemical Reaction Module

Vicher, (**Vi**rtual **Che**mical **R**eaction module), is an educational application of virtual reality designed to aid in the instruction of undergraduate chemical reaction engineering, relating specifically to concepts covered in "Elements of Chemical Reaction Engineering" by H. S. Fogler[13].

Users interface with Vicher using a joystick for movement, a mouse for "activating" objects and requesting information, and a keyboard for various other tasks, where "activate" takes on a meaning appropriate to the object, such as turning on the television or increasing the reactor feed temperature. When using the head-mounted display, the user may simply look where they want to go and push the joystick forward to move in that direction. This has been found to be the simplest and most effective navigation technique. Another strong benefit of the head-mounted display is the sensory-deprivation effect - When users are unable to see the "real" world, they become much more immersed in the virtual one.

The virtual environment being modeled in Vicher consists of a small portion of a modern chemical plant, plus some microscopic exploration areas. The rooms consist of a welcome center, in which users learn how to use the program and receive other pertinent information, a transport reactor room where students can study the effects of catalyst fouling, and a non-isothermal packed bed reactor area for the study of energy effects on reaction kinetics and reactor design. All of the reaction equipment may be operated by the students at different operating conditions to observe the effects of changing feed rates, inlet temperatures, etc. on reaction conditions. The microscopic areas are the inside and the outside of a catalyst pellet, and a highly magnified section of a catalyst surface.
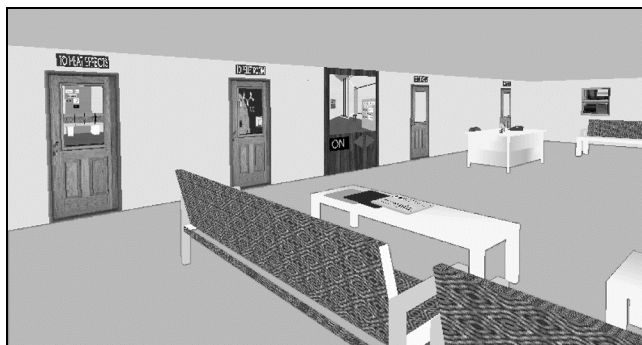
The Welcome Center

Figure 1: The welcome center, where users become accustomed to virtual reality and learn to navigate.

The welcome center provides two main functions in Vicher. First, it provides a familiar, comfortable environment in which the user can become

accustomed to the virtual reality experience and equipment and learn how to navigate. We have found that this goes a long way to combat the disorientation effects which some users experience when first encountering virtual reality. Secondly, it provides a convenient base of operations from which to branch out and explore the other areas of Vicher. A large-screen virtual television in this room provides a preview of the other areas of the simulation. The other areas of Vicher will also have televisions, providing engineering information and other instructions appropriate to each area in the plant.
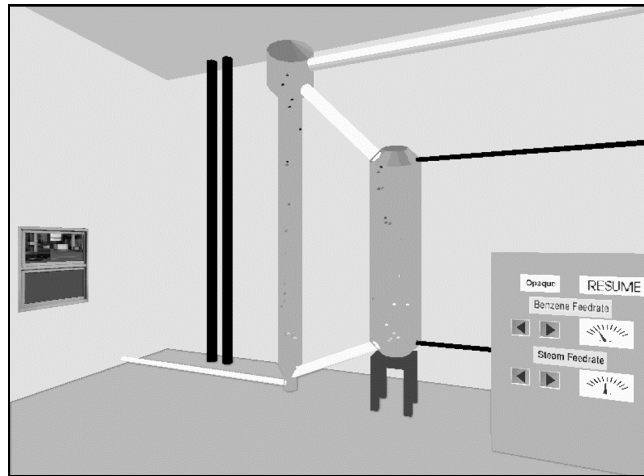
The Transport Reactor Room

Figure 2: The transport reactor room, for the study of catalyst deactivation processes.

The transport reactor room contains a vertical straight-through transport reactor, (STTR), and its associated catalyst regenerator and control panel. The engineering principles being illustrated in this room are: 1) What does an industrial reactor look like, and how does it operate, 2) The effects of flowrates on coking and decoking of catalyst pellets, and 3) the shrinking-core model of catalyst decay and regeneration. By turning the equipment transparent, (or by simply stepping inside), students can observe the coking and de-coking of the catalyst pellets as they move through the equipment, and how the process changes as various flowrates are adjusted. Gauges on the control panel indicate current operating conditions, and students can teleport into the microscopic worlds described below, either by "activating" or by stepping into the pellets within the reaction equipment. This room also contains a three-foot diameter model of a catalyst pellet, sliced in half and linked to one of the pellets in the reactor, the purpose of which is to illustrate the shrinking core model of catalyst decay and regeneration.
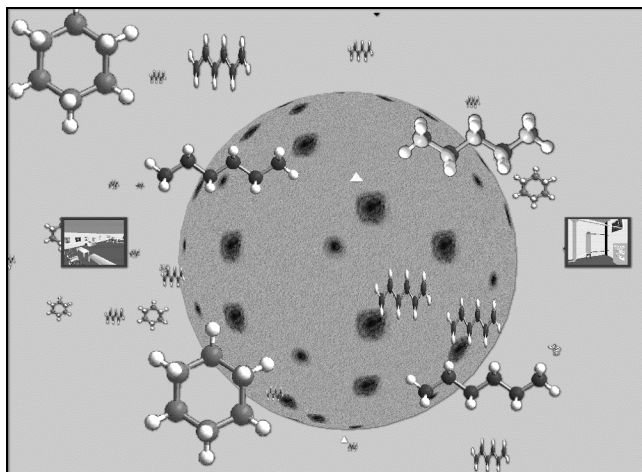
Microscopic Areas

Figure 3: Students observe diffusional effects surrounding a porous catalyst pellet.
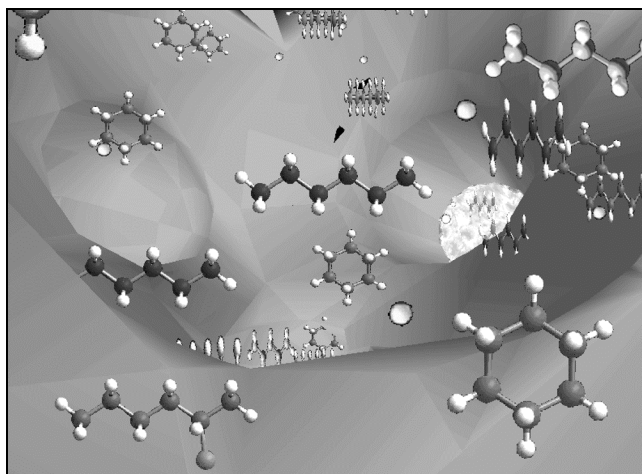

Figure 4: Catalytic reactions occurring inside a catalyst pore.

In addition to the macroscopic worlds, students can also observe catalyst activity on a microscopic scale, in the form of a single highly detailed catalyst pellet. From the outside of this pellet, students observe external diffusion; On the inside, students witness internal diffusion and the mechanism of catalytic reaction on a molecular level, including undesired side reactions and coke production. A recent refinement to this areas is to reduce the light levels inside the pore as the pellet cokes up, thereby making the world progressively darker. Conversely while the user rides the pellet through the regenerator, the light levels increase as the pellet cleans up. Students may observe reactions either by following random reactants until they absorb and react, or by observing "staged" reaction sites, which are rigged so that there is constantly reaction activity to be observed. Stepping through these staged areas transports the user to a more highly magnified view, where the catalyst

surface appears nearly flat and there is a single reaction which occurs repeatedly, and is labeled for easier viewing.
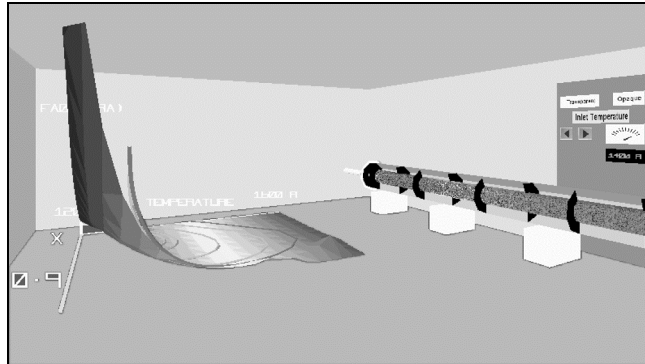
Non-Isothermal Reaction Area

Figure 5: The kinetics surface and the reactor internals are color coded to indicate temperature.

The most recently developed room in Vicher is the non-isothermal packed bed reactor exploration area. In this area, students examine an exothermic reaction occurring in a packed bed reactor surrounded by a cooling jacket. In addition to the reactor itself and the associated control panel, this room also contains a mathematical surface, which describes the reaction kinetics as a function of temperature and fractional conversion. Overlaid on top of the surface are a number of lines, indicating reactor conditions along the length of the reactor, with different lines corresponding to different reactor operating conditions. Both the mathematical surface and the reactor internals are color coded, from blue to red, to indicate the temperature at any given point. This temperature indication mechanism allows students to quickly and easily determine where the hot spots are within the reactor, and to observe how those hot spots change in both intensity and location as reactor operating conditions are varied. The interaction between the kinetics surface and the physical reality of the reactor goes a long way to bring "meaning " to the mathematics, by showing students a tangible link between the equations, formulas, and mathematics and the physical situations being modeled by those equations.

Lessons Learned From the Development of Vicher

Much has been learned during the development of and subsequent testing of the Vicher prototype program. Some examples of this knowledge can be broken down into a number of categories:

- **Technical:** The worlds which we are developing now are more complex and require less development time than the worlds developed for Vicher.

this reflects the experience and examples developed during that earlier work.

- **Navigational:** Vicher originally contained hallways which users had to traverse in order to move from room to room. The replacement of these structures with teleports has greatly eased user navigation, and has provided the added benefit of flexibility in the interconnection of rooms. Results are mixed on the usefulness of the joystick as a navigational device - Once users become accustomed to the joystick, it is an effective navigational method, however some users experience some initial difficulty. The head-mounted display is also effective for navigation once the learning curve has been overcome.   The keyboard is a poor navigational tool.

- **Interfacial:** Vicher uses the mouse for user actions, which is generally effective, but has some drawbacks. The keyboard is also used during program development, but makes a poor input device for users, particularly when the head-mounted display is being used. One area where we have found virtual reality to be limited is in the presentation of text-based materials, such as written descriptions, formulas, or equations. We have had some limited success using various different methods of presenting text in virtual worlds, and will be working on this area further, but in the meantime have concluded that VR is not an appropriate medium for large amounts of printed information. Auditory narration, on the other hand, as well as other auditory input, adds a great deal to the overall impact of VR, and should be used extensively.

- **Representational:** Students particularly like the mathematical surface in the heat effects room, and the use of color to indicate temperature and show the relationship between the mathematics and the physical reactor. Alternate color schemes are being explored, as well as other applications of data presentation (thermodynamic properties, fluid flow velocities.) The molecule portrayal is quite effective, but the catalyst pore interior is an area of difficulty, due to its unfamiliar nature.   (A familiar environment, such as a room, can be rendered quite crudely and still be recognizable, whereas unfamiliar environments may be unrecognizable even if rendered perfectly.)

- **Implementational:** One of the difficulties we have encountered is that although the IBM PC platform is very widely available in general, the University of Michigan engineering network is primarily a Macintosh environment. This meant that the only way for students to experience Vicher was to schedule an appointment during normal business hours, which was inconvenient for many students. This limited access, coupled with the heavy course load taken by most students in the related course,

yielded a lower than expected participation rate when Vicher was offered as a voluntary activity. In order to see significant student usage of any program, (computer or otherwise), it must be a required activity, or at least convenient for students to perform at their leisure.

- **Hardware related issues:** We have identified a number of key trade-offs involved in the choice of hardware platforms. For example, the head-mounted display adds greatly to the immersion and thereby the impact of the experience, however HMDs have lower resolution than computer monitor screens, which results in loss of details when using HMDs, and their cost and fragility inhibits their widespread use in undergraduate computing labs. Hopefully the next generation of high-quality, low-cost head-mounted displays will alleviate some of this problem. Another trade-off involves 3-D vision, which adds a lot to certain worlds, but reduces the display speed by 50%. In our case, we are also somewhat constrained by our choice to support multiple hardware platforms. Not only are we limited to a software platform which runs on all of the hardware chosen, (i.e. WorldToolKit), but we are further limited to using only features which are implementable on all platforms, or else dealing with multiple versions of the programs.

Continuing and Future Developments

Much has been learned during the development of Vicher; However further progress must be made before the module is ready for widespread classroom use. For one thing, Vicher has grown to about the limit of what will run well on 16 Megabytes of memory. (The executing program requires about half of that, but we are also utilizing 8 MB of memory as a RAMdisk to allow for faster access to data files at run time.) In order to add additional areas to the simulation without requiring users to purchase large amounts of memory, it has been decided to split Vicher into two new modules - one dealing with catalyst decay issues and the other covering non-isothermal effects in chemical reactor design. Progress has been rapid on these two modules, and it is hoped that preliminary classroom testing can commence this fall. Additional student testing, program refinements, and supplemental materials development will be required before widespread distribution can commence.

In additon, a series of small, simple modules are being developed, relating to other areas of chemical engineering, to determine how VR can best be applied in different contexts. For example, a fluid flow module has been developed with a moving, color-coded, velocity profile, and similarly colored flow tracers. Another application explores thermodynamic properties and the best ways to represent partial derivatives, relationships between variables, and intangible properties such as entropy. The lessons learned from these and

other mini-applications can then be incorporated into larger, more complex simulations, or the best of the small applications may be expanded, as appropriate. Some of the other topics of interest include safety studies, crystal structures, unit operations, heat transfer mechanisms and equipment, phase equilibrium, and semiconductor fabrication (both microscopic and clean-room environments.)

Summary and Conclusions

Virtual reality is a powerful tool, growing in popularity and ease of access. Prices are coming down and capabilities are improving for entry level systems. Simple virtual reality can be implemented using public domain programs on an ordinary PC with no special hardware. A few hundred dollars adds 3D vision and a powerglove. To add a true head mounted display with tracker, sound and a toolkit for development costs more - starting at $1300 for minimal quality, up to $15,000 and more for higher quality. These prices will continue to drop as VR gains in popularity. A reasonable approach is to start developing virtual reality solutions now, using low-cost, low-tech equipment, and then applying the knowledge learned to more advanced implementations once the equipment becomes financially accessible.

There are many ways in which virtual reality can be applied profitably to chemical engineering problems. Several of the ideas presented here are realizable today with little or no new development required. Others will require some effort but are still attainable. At this point there is little use of virtual reality in chemical engineering, but this is expected to change rapidly as engineers realize the potential of this new technology and as prices continue to drop.

The application of virtual reality to chemical engineering education is making rapid strides at the University of Michigan. The first virtual reality based educational application has been developed and extensively beta-tested, and is currently being split into two modules, hopefully to be used in a few classes by this fall. Additional educational applications are developing rapidly, as the knowledge base grows. Some of these applications, include safety studies, crystal exploration, mathematical function visualization, thermodynamics, and process design related projects.

References

1. Bajura, Mike, Henry Fuchs, and Ryutarou Ohbuchi, "Merging Virtual Reality with the Real World: Seeing Ultrasound Imagery Within the Patient", *Proceedings of SIGGRAPH '92*, August, 1992.

2. Bell, John T., and H. Scott Fogler, "Virtual Reality in Chemical Engineering Education", *Proceedings of the 1995 Illinois / Indiana ASEE Sectional Conference*, March 16-18, 1995, Purdue University, West Lafayette, Indiana, http://kind.ecn.purdue.edu:80/asee/sect95/proc95.html.

3. Bell, John T., and H. Scott Fogler, "Low-Cost Virtual Reality and its Application to Chemical Engineering - Part One", *Computing and Systems Technology Division Communications*, **18**(1), American Institute of Chemical Engineers, New York, 1995.

4. Bell, John T., and H. Scott Fogler, "The Investigation and Application of Virtual Reality as an Educational Tool", *Proceedings of the American Society for Engineering Education Annual Conference*, Anaheim, CA, June 1995.

5. Bethel, Wes, "Chemical Flooding in a Virtual Environment - A Survivors Guide to VR Development", *Proceedings of AVS94*, May 1994, http://blondie.lbl.gov/publications/avs94/avs94.html.

6. Brelsford, John W. "Physics Education in a Virtual Environment", *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting*, 1993.

7. Bricken, Meredith, "Virtual Reality Learning Environments: Potentials and Challenges", *Computer Graphics*, Volume 25, Number 3, July 1991.

8. Britton, Benjamin, "Cave of LASCAUX", *DISCOVER*, June 1995.

9. Brooks, Frederick P. Jr., Ming Ouh-Young, James J. Batter, and P. Jerome Kilpatrick, "Project GROPE - Haptic Displays for Scientific Visualization", *Computer Graphics: Proceedings of SIGGRAPH '90*, 24(4), Dallas Texas, 6-10 August 1990, pp177-185.

10. Byron, S. and C. Levit, "The Virtual Windtunnel: An Environment for the Exploration of Three-Dimensional Unsteady Flows", *Proceedings of IEEE Visualization91*, pp 17-24, 1991.

11. Byrne, Chris, "Virtual Reality and Education", HITL Technical Report No. R-93-2, Human Interface Technology Laboratory, Seattle, WA, 1993.

12. Fogler, H.S., S.M. Montgomery, and R.P. Zipp, "Interactive Computer Modules for Chemical Engineering Instruction", *Computer Applications in Engineering Education*, **1**(1), 11-24, 1992.

13. Fogler, H. Scott, "Elements of Chemical Reaction Engineering, Second Edition", Prentice Hall, 1991.

14. Helsel, Sandra, "Virtual Reality and Education", *Educational Technology*, May, 1992.

15. Hollands, Robin, "Technology Review: Sourceless Trackers", *VR News*, **4**(3), April 1995.

16. Kolb, D. A., "Experiential Learning: Experience as the Source of Learning and Development", Prentice-Hall, Englewood Cliffs, N.J., 1984.

17. Pimentel, Ken and Teixeira, Kevin, "Virtual Reality: Through the New Looking Glass", second edition, Windcrest Books, 1995.

18. Staff, "Immersive VR Tests Best", CyberEdge Journal, Issue #24, Vol. 4, No. 6, November / December, 1994.

19. Vacca, John, "NASA VR Projects: Part 1", *VR World*, March/April 1995.

20. Zwern, Arthur, "How to Select the Right HMD", *VR World*, March/April 1995.