

VISUALIZATION AND INTERACTION TECHNIQUES FOR CFD IN INTERNAL COMBUSTION ENGINES

NOVEL VISUALIZATION AND INTERACTION TECHNIQUES FOR GAINING INSIGHT INTO FLUID DYNAMICS IN INTERNAL COMBUSTION ENGINES

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SUMMARY

Future emission regulations and increased customer demands require the utilization of all available tools in developing engines of the next generation. 3D CFD simulation is one of these tools [1]. Due to well-advanced and well-developed simulation technology and improved computing power, the generated pack of data becomes complex and difficult to evaluate.

In principle, technical problems can be treated with simulation, but the analysis of data very often leads to unsatisfactory results due to the limited evaluation functionality of the tools available at present. On the one hand, the reason is to be found in the visualization of 3D data, which is nowadays almost always performed in 2D only, and on the other hand in the physical relation of parameters, which is usually not reproduced in the analysis.

Recently developed visualization techniques and modern graphics hardware make it possible to interact with vast amounts of multidimensional data in an intuitive way. A novel approach called SimVis [2] allows the engineer to specify certain subsets of the data – so-called features – in terms of data attributes under consideration (e.g., pressure, temperature, etc., and combinations thereof) and to immediately get a 3D view of the CFD data set with the selected features highlighted.

This is useful to understand statistical properties of the data and the corresponding spatial and temporal distribution. Geometric properties can be presented and explored by means of virtual reality (VR) methods [3], which allow the user to become immersed in the dataset and to interact with the model in a natural way. Progress in PC graphics hardware technology makes it possible to perform sophisticated tasks in real-time in such an environment.

By a simulation of a scavenge and combustion process in a 2-stroke engine, this paper investigates new solutions to the evaluation and visualization problem using SimVis and VR. Moreover, an outlook on further new developments is given.

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1: Introduction

Growing demands in terms of a reduction of emission and fuel consumption and an increase of specific power require the use of improved technologies for research and development of internal combustion engines. One of these technologies is the computer simulation of the internal fluid dynamic processes of the engine (*computational fluid dynamics* = CFD). These simulations provide the research and development engineer with data that cannot be made available with other technologies; either because these data are predictions and the engine has not been built in hardware yet, or because experimental data cannot give the same information depth as the simulation (i.e. spatial distribution of values).

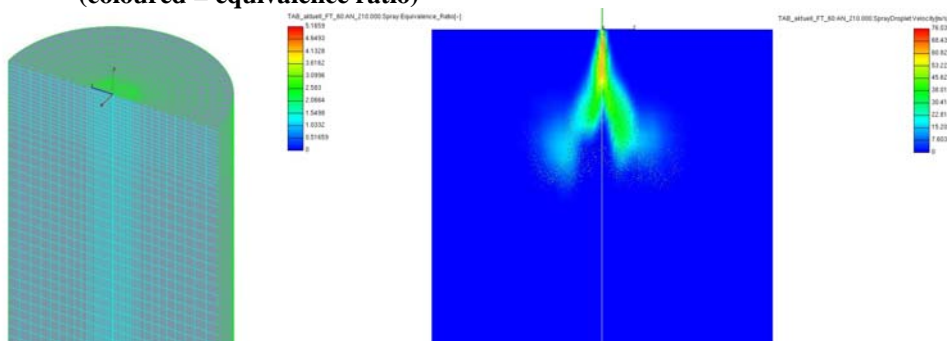
The procedure of such a CFD simulation comprises three major steps: 1. the model build-up, i.e., the generation of a mathematical representation of the 3-dimensional engine fluid space, 2. the solution of the generated mathematical problem, i.e., the actual simulation, and 3. the *examination* and *visualization* of the obtained results. While major improvements of the first two steps of the simulation process were done in the past, the visualization and examination of the data is still not satisfying with the present standard tools.

Two new approaches for both data examination and data visualization improve the expressiveness and the value of the results of the CFD simulation.

2: The use of CFD simulation in the development process of internal combustion engines

In the first phase of an engine development process, new technologies (i.e., new injection techniques) are validated according to their interaction with other technologies and according to their impact on the engine performance. With the use of CFD simulation these validations can be made without the need of prototype hardware. Additionally, unknown processes can be investigated and theories about the course of physical processes can be developed. All these investigations have to be made by specially trained scientists or engineers in cooperation with engineers from other departments, which requires a common language for visualization and examination.

Figure 1: a.) Calculation mesh of a cylindrical volume. b.) section with impressed variable (coloured = equivalence ratio)



As described before, there are three steps of the CFD simulation process, which are called *pre-processing* (1), *solution* (2), and *post-processing* (3). In

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the first step, a *discretization* of the engine's fluid space into small volumes takes place followed by a definition of the boundary conditions (Figure 1 a.) shows a discretized volume). In addition to the spatial coordinates, there are several variables which are significant for the representation of the condition of the fluid. These are, among others, the physical values of pressure, velocity, the mass fraction of several fluid components. All these variables or attributes can be examined and visualized during post-processing after the solution of the model.

As the CFD simulation does not end in itself, it is necessary to communicate with other scientists and engineers about the input (geometry, boundary conditions, etc.) and the output. Depending on the purpose of the simulation, different groups of people are the partners for this communication. Among others these groups are test bench engineers, combustion specialists, or even the management board. Therefore different presentation, visualization, and examination methods have to be used.

3: Commonly used visualisation and examination techniques

Standard evaluation techniques can be classified into two different approaches: the first is the 2-dimensional presentation of 3-dimensional spatial fluid conditions or processes. This is done by showing one or more sections or views of the calculation mesh with one impressed attribute (variable) as colouration of the cell (see Figure 1 where the colour represents the *equivalence ratio*)(4). This can also be done for a sequence of different time steps. With this visualization the spatial effect only emerges in the head of the viewer, which in general is difficult, especially if the person is not used to generate a 3-D view out of several 2-D's. The second method is to display two or three variables against each other in a spreadsheet or graphic outline. Usually these spreadsheets use the time as one axis and a different variable as the other one. These variables are integral values over the total sum of the cells or over a certain subset of the cells. In this kind of presentation, 3-dimensional distributions of variables are reduced to global, integrated variables. This examination technique offers the benefit of comparability of these 3-D simulation results with the results of other simulation techniques such as 1-D CFD simulations and/or the results of experimental data. The information of the spatial distribution of the variable, however, will get lost.

Some questions which emerge during engine research do not focus only on the quantity but also on the spatial distribution. A combined method of the two described approaches would bring additional benefits. In the following, two new methods of data visualization and exploration are presented both in principle and through their application to a CFD simulation which demonstrates their use in practice.

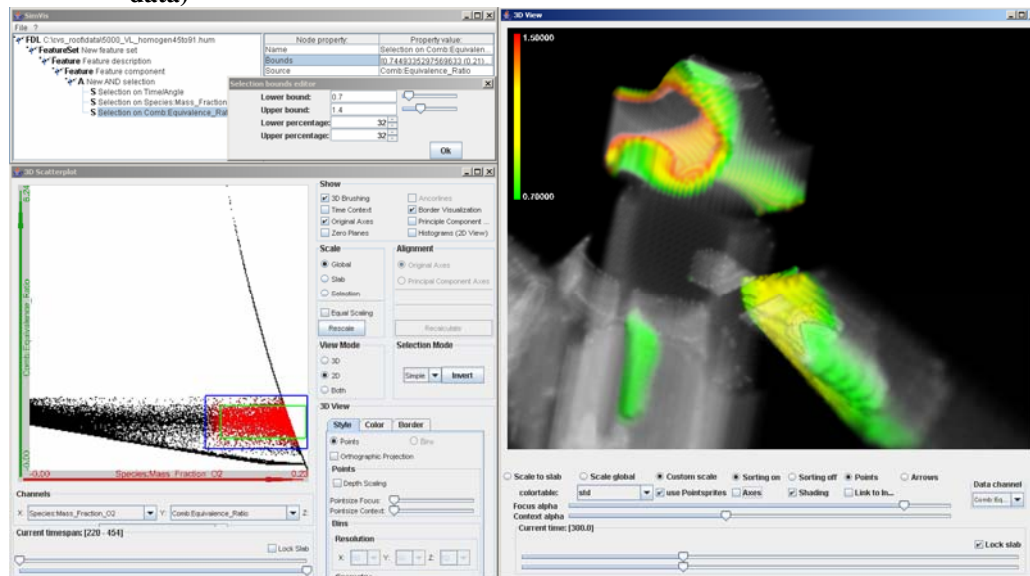
⁴ The equivalence ratio is the ratio of fuel to air and indicates an ignitable mixture when the value is between 0.7 (lean mixture) and 1.4 (rich mixture)

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4: SimVis: a new approach for visualization and analysis of CFD data

SimVis is a new technology for the interactive visual analysis of large, multi-dimensional, and time-dependent datasets from CFD simulation. In SimVis, different forms of data visualization are combined and form a new feature-based approach to a user-driven visual analysis of CFD data. This feature-based visualization for data exploration and analysis (SimVis), enables the user to generate multiple views (usually also views of different kind) of simulation results. Scatterplots (standard 2D scatterplots, but also new 3D scatterplots), for instance, are used to plot two (or three) variables against each other. In Figure 2 (lower left), for example, every cell in the data is represented as one dot which is placed with dependent on the amount of O₂ in this cell (X) and the equivalence ratio (ER) value of this cell (Y). Additionally, a truly 3-dimensional view of the simulation domain is used for spatial orientation and color-coding is used to visualize one selected variable in 3D (Figure 2, right).

Figure 2: a typical multi-view setup for a visual analysis session with SimVis (engine data)



One key element of the SimVis approach is to allow the user to interactively select certain subsets of the data (so-called features) dependent on the simulated variables (and combinations thereof). All views then utilize so-called *focus-plus-context visualization* (4) to visually enhance the selected subset against all the rest of the data. In Figure 2 the selected subset is shown in red in the scatterplot and coloured in the 3D view (as compared to the rather transparent and grey-scale context). Usually, the selection of a feature is interactively performed directly on a view, e.g., by interactively “drawing” a rectangle on the scatterplot and thereby marking all the dots underneath the rectangle as being part of the feature (in visualization, this form of interaction is usually called *brushing*). It is important that all views which concurrently show one dataset be consistent among each other with respect to the selected features (called *view linking*). Figure 2 shows a (typical) multi-view setup of a visual analysis of the data from the 2-stroke engine as presented further below.

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For interactive feature specification, views such as scatterplots, histograms, or others, are used in SimVis. The user first chooses to visualize selected variables within such a view—thereby gaining first insights into relations within the data—and then interactively brushes certain subsets of the data directly on the view. The result of such a brushing operation is re-integrated in the data in the form of an additional, synthetic data attribute $DOI_i \in [0,1]$ per cell, called a *degree of interest (DOI) attribution* of the data (a DOI value of 1 means that the respective cell is part of the feature, context cells carry DOI values of 0). Another specific property of SimVis is that it also allows for fractional DOI values ($0 < DOI_i < 1$), which is useful to represent smooth feature boundaries. Furthermore it has proved to be very useful to also allow for logical combinations of DOI attributes (feature := ER in the order of 1 AND lots of O₂ left). Brush attributes and their composition are explicitly represented in the system [2] and can be interactively adjusted through a separate user interface (upper left in Figure 2). They can be saved and reapplied to other data sets (for example after changing the boundary conditions and re-running the simulation). This has already been successfully employed during the analysis of several application case studies in the field of the automotive industry [5],[6].

With this kind of linked visualization of the multi-dimensional attribute space as well as of the 4D simulation domain (3D + time), it is possible to perform the data exploration and analysis according to (at least three) different patterns. The probably most standard pattern of data exploration/analysis is the so-called *feature localization*. Features are brushed in views of the attribute space, e.g., in a scatterplot or a histogram, and the 3D view is used to evaluate the spatial distribution of the respective feature. An example of feature localization would be to specify a feature “unburnt mixture” by means of the related physical variables (good ER, enough O₂ left, etc.) and to then evaluate (over space and time) where the unburnt mixture remains during the combustion. Other patterns include, for example, the multi-dimensional cross-evaluation in attribute space (a feature is specified by variables *a* and *b*, and then it is examined in a linked visualization of variables *c*, *d*, and *e*) or the evaluation of attribute space with respect to spatial and temporal locations (a data subset is selected by space and time, e.g., near the outlet and late in the combustion, and the selected subset is evaluated in attribute space).

As already mentioned, we use 3D and time-dependent focus+context visualization of the simulation data in the sense that flow features are visually emphasized in the 3D depiction through colouring and reduced transparency. For each 3D view one (fractional) DOI attribute DOI_i is used to (smoothly) discriminate the visually enhanced focus (the feature) from the comparably transparent and grey-scale context (Figure 2, on the right).

SimVis allows also to interactively visualize and analyze simulation results from CFD simulation which are based on *time-varying grids* [7]. Especially in the automotive industry, simulation often has to deal with moving parts, and accordingly the computational grids adapt their spatial layout over time.

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With SimVis, interactive visual analysis of simulation data is possible for a wide range of applications (as, for example, the one presented in this paper) on standard PC-based systems at interactive speed. For the results shown here, we used a PC with the following hardware setup: Intel Pentium4, 2.8GHz, 2GB RAM, with an NVidia GeForceFX 5900 graphics card.

More information about SimVis, application case studies, and related visualization research is available via <http://www.VRVis.at/simvis/>.

5: VR a new approach for visualization and interaction

The term „Virtual Reality“ describes a set of techniques that allow the user to interact with data directly in three-dimensional space instead of using two-dimensional metaphors such as mouse and screen. There are some common properties associated with a typical VR application. The most important one is *immersion*, meaning the coincidence of the coordinate systems of the real and the virtual world. This is achieved by tracking the user's location and orientation and by rendering stereo images with the virtual camera placed at the point of the user's eyes. The immersed user can *interact* with the virtual environment. Finally, the application provides for a certain level of *imagination* to allow the users to easily perform this task [8].

The idea of using Virtual Reality (VR) techniques for visualization of simulation data in general and CFD data in particular is not new. The virtual wind tunnel project at the NASA Ames Research Center [9] was the first approach to visualize unsteady flow fields in a virtual environment. The user enters the dataset (without disturbing the pre-computed flow as in a real wind tunnel) and insert tracers into the flow field to explore its properties. Visualization techniques for scalar fields have been discussed by Meyer, et al [10]. They propose interactive drawing of iso-surfaces, where the threshold is taken at the tip of a tracked probe. Moreover, cutting planes can be defined by manipulating a virtual rectangle within the dataset. Recent work includes parallel VR-based visualization of CFD data [11] and a force feedback pencil [12] to achieve more detailed insights into the data.

Our prototype is based on the „Studierstube“ Virtual and Augmented Reality platform [13], a software infrastructure for building immersive and interactive 3D applications. It provides the programmer with flexible tools to build user interfaces and object interaction techniques in the virtual world. Moreover, it can easily be configured to work with a wide range of input and output devices (traditional 2D devices as well as typical 3D devices).

We are using some of the interaction and visualization concepts developed for the liver surgery planning system [14] since both medical and engineering applications involve 3D data and tasks. The system is controlled by a hand-held panel and a pen, allowing the user to select the mode of operation (e.g., resizing or translating the data set).

When flipped around, the panel becomes the cutting plane tool, onto which the intersection with the volume data is rendered. For easy integration into the existing visualization framework developed for medical datasets, the CFD dataset has to be sampled at regular intervals. This allows to efficiently use nowadays common 3D texture hardware to achieve interactive frame rates. It

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is, however, clearly suboptimal from the image quality point of view since it leads to sampling artefacts visible under high magnification. This problem has early been realized, and a proposed solution is an analytical intersection of the (non-regular) grid cells with the cutting plane [10]. We will use this approach in our future work.

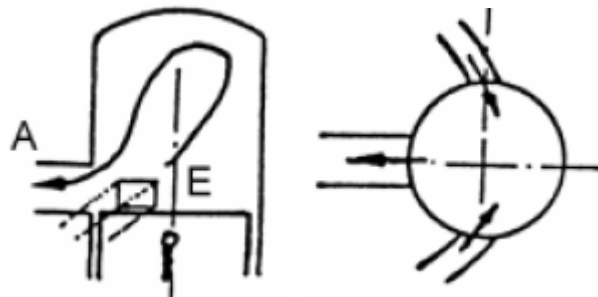
The geometric relation to the boundary of the dataset is established by a wire frame model of the object(s) enclosing the CFD dataset. While a transparent representation of such geometry might look more appealing on the desktop, we use wire frame models, which provide important depth cues to the user when displayed by a stereo visualization system. Therefore the 3D structure of the mesh and the embedded cutting plane can easily be recognized.

Data exchange is accomplished by means of ASCII-based file formats which can be exported by various CFD simulation applications and imported by the customized front end of our VR system.

6: The practical use of VR and SimVis: 3D CFD simulation of a 2-stroke engine with high pressure GDI injection

Thanks to its unsurpassed power-to-weight ratio, its low package space and low-maintenance design, the *loop-scavenged two-stroke engine* with conventional mixture preparation is still widely used in some sectors of vehicle engineering, such as boat drives, snow mobiles and motor scooters, as well as in hand-held applications. To maintain the potential of the 2-stroke engine for the future it is necessary to take adequate steps against the system-dependent disadvantage of the simple 2-stroke engine, namely that of higher emissions compared to 4-stroke engines. One possible solution is *gasoline direct injection* [15], [16]. Its more frequent use will increase the production numbers, making it an interesting technology even in the above-mentioned cost-sensitive applications. Intense investigations have been carried out in the past by the two-stroke research team at the Institute for Internal Combustion Engines and Thermodynamics in order to reach the goals of reducing *emissions* and *fuel consumption*. These investigations were supported by the use of 3-dimensional CFD simulations [17], [18].

Figure 3: Principle sketch of a loop-scavenged two-stroke engine (A...exhaust, E...intake)

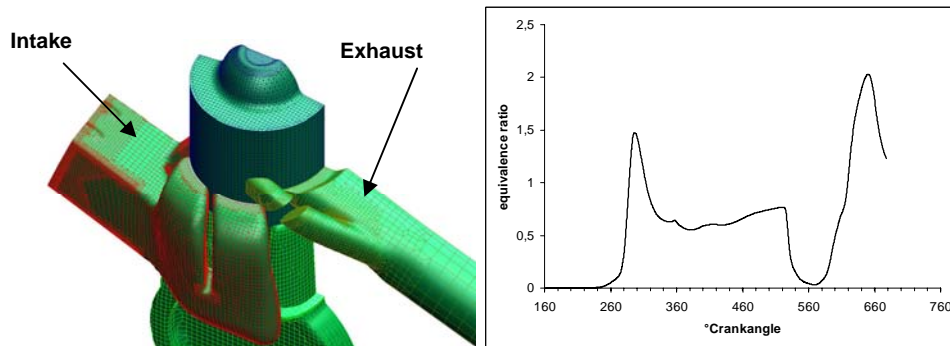


Due to the fact that, contrary to the 4-stroke engine, the flow movement (gas dynamics) in the intake and outlet ducts is essential for the charge and therefore for the power and the scavenging losses, the whole engine including these sections has to be considered for the 3D CFD simulation (see Figure

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4 a.)). This very complex fluid motion has to consider also the influence of *spray* and *vaporization* on the mixture preparation. The result of the simulation should be an exact prediction of the mixture and charge during the scavenging and combustion process and additionally, new insights into the course of the physical processes should be gained. This leads to a very time-consuming simulation, producing an enormous amount of data which has to be examined and brought to visualization. In the following, two examples of usual visualization and data examination techniques are complemented with the new approaches of VR and SimVis. As an example of important variables, the equivalence ratio (ER) and the mass fractions of oxygen (O_2) and hydrocarbons (N-octane) are used.

Figure 4: a.) Calculation mesh of the 2-stroke simulation
b.) Average ER of a volume of 5mm radius around the spark plug versus the time



6.1: Classic data exploration of 3-D CFD data

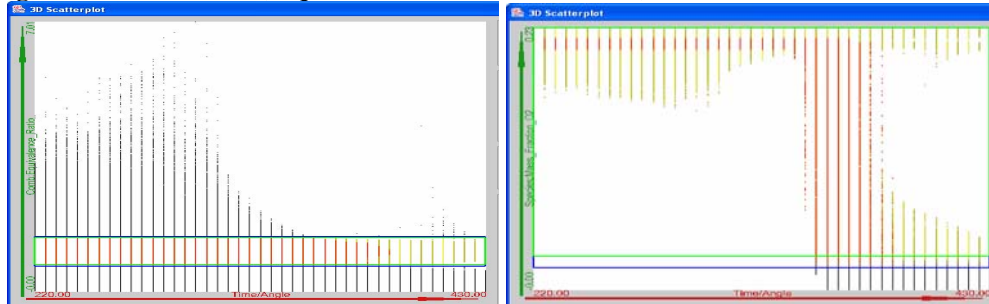
As an example, the integrated (and averaged) value of the ER in a volume of 5mm radius around the spark plug is shown versus the time axes in Figure 4 b.). This allows the estimation of the ignitability of the mixture in the area of the spark plug. For each value or variable, such a spreadsheet has to be made; complex relations between various variables cannot be detected.

6.2: Data exploration using SimVis

In SimVis, several scatterplots can be used to explore interesting combinations of variables and to display the resulting cells in a time-dependent 2D view. In the following example, the variable ER is supplemented by the mass fraction of O_2 and N-octane. The reason for the choice of these variables is that the ER remains in the area between 0.7 and 1.4 even after the mixture has been burned. In fact, the burned products have an ER of 1 which means that ER is 1 after all charge has burned completely. Therefore a statement about ignitability can only be given by considering ER as well as the O_2 and N-octane mass fraction. Figure 5 a.) shows a feature set of ER vs. time. The framed (brushed) area represents an ER of between 0.7 and 1.4 and Figure 5 b.) shows the mass fraction of O_2 , the brushed area represents an O_2 value above 3%.

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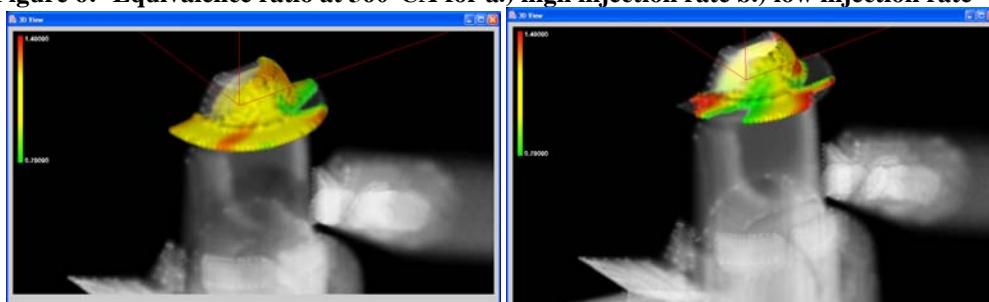
Figure 5: Feature set a.) equivalence ratio versus time b.) mass fraction O_2 vs. time



The result of this data exploration is the area of ignitable mixture which has not burned yet, whereas all other cells are deemphasized in the visualization. In Figure 6 a.) and b.) this result is shown for two different injection pressures at a time-step of 360°CA which is TDC. Clearly visible is the burned area and the difference of the distribution of ER (cell colour represents the ER) resulting from different injection pressures.

With this new method of data exploration, the relations between different variables become visible and the set of cells resulting from the exploration can be displayed with their spatial distribution as well. This leads to very detailed and novel insights into the physical processes simulated by the CFD. Additional information about this simulation case including pictures and videos are available via <http://www.VRVis.at/simvis/cases/2-stroke-engine/>.

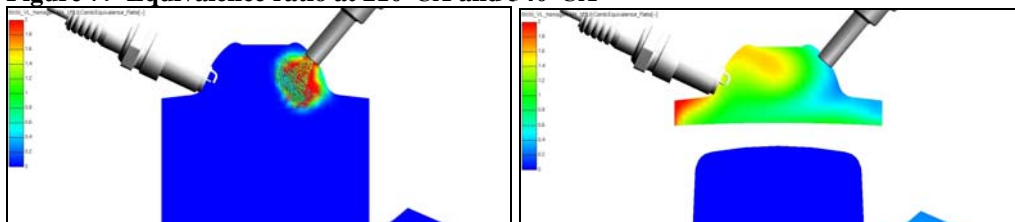
Figure 6: Equivalence ratio at 360°CA for a.) high injection rate b.) low injection rate



6.3: Classic visualization of 3-D CFD data

The typical visualization of CFD results is shown in Figure 7 which is a sectional view of the combustion chamber at time steps 210°CA and 340°CA . The colouring is the ER. Several displays like these are necessary to create a 3-dimensional impression and it is very difficult for an untrained person to imaging this virtual 3D impression.

Figure 7: Equivalence ratio at 210°CA and 340°CA



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6.4: 3-dimensional visualization using virtual reality VR

The visualization with VR is based on the intuitive interaction of the viewer with the 3-dimensional display of the mesh. Figure 8 a.) shows pictures of this interaction. In addition to the 3-dimensional impression, features like “creation of sections”, etc., are used for a detailed investigation of fluid [5]. The personal interaction panel (PIP) is shown in Figure 8 b.) where a section of the 3D model is created with the PIP. This section gives information on the velocity of the fluid by using coloured cells and can be moved through the whole 3D mesh with the PIP. “Zoom” functions as shown in Figure 9 can be used to investigate interesting details of the fluid. In the pictures the shutter glasses and the interaction pen can be seen; both equipped with tracking targets (small balls on the pen end and the glasses used for tracking the devices). A stereo back-projection system using shutter glasses provides the user with a stereo image. These shutter glasses are synchronized with the projector via infrared signals.

This very easy, quick and intuitive handling of the 3D model and its results gives a wide range of people access to the 3D CFD simulation. Well-trained engineers will also benefit from this new approach and will gain surprising new insights into fluid motion. For additional information including pictures and videos refer to http://cfd.icg.tu-graz.ac.at/nafems_2005.

Figure 8: a.) Handling of the 3D mesh of a 2-stroke cylinder
b.) Investigation of the velocity of the fluid motion using sections on the PIP

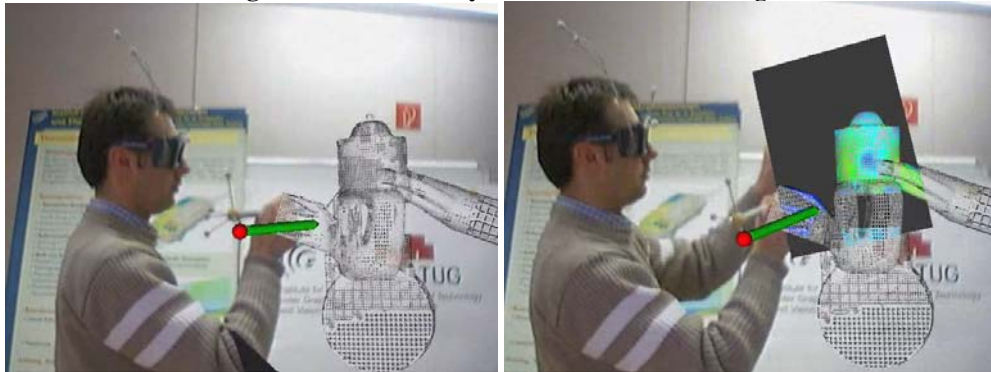
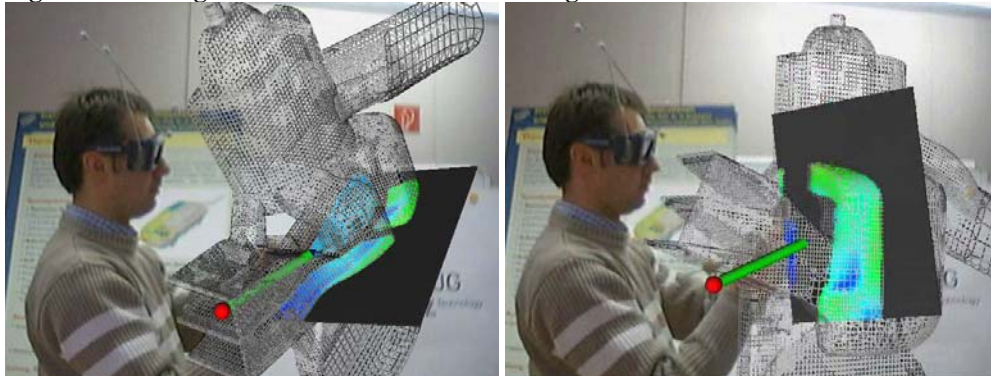


Figure 9: Investigation of details of the mesh using the “zoom” function and the PIP.



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7: Summary

The 3-dimensional CFD simulation as it is used during the development and research of internal combustion engines allows access to an enormous amount of data for each spatial point and for various time steps. With the use of the two novel visualization and data exploration approaches, Virtual Reality and SimVis, it is possible to gain new insights into the processes of internal combustion engines using the data resulting from the CFD simulations. On the one hand, VR provides an intuitive and quick method for the assessment of the spatial distribution of variables. On the other hand, SimVis allows very deep data exploration on the basis of multiple, linked views (e.g., scatterplots) to view and select various variables. The combination of these two approaches together with standard data evaluation methods leads to a deeper understanding of the processes in the internal combustion engines and therefore to further developments of these engines.

8: Outlook

Further enhancements of the tools VR and SimVis will focus on the interfaces for standard CFD codes as well as on the possibility of saving the output of the tools in form of pictures, videos, reports and so on. In the VR visualization environment it is planned to include the handling of moving meshes. In SimVis, several extensions are planned, including, for example, a formula editor allowing interactive derivation of additional data attributes or other interesting measures.

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