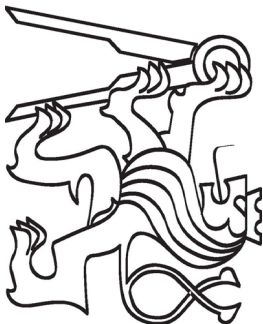


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Real-time Visualization Techniques for Modelling of Combustion and Fluids

by

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1 Introduction and motivation

1.1 Scope of our work

The goal of this thesis is to find a way to present and propose some original techniques and possibilities for interactive, real-time model of combustion processes, which will allow immediate, interactive visualization. The solution should be as general as possible to allow also parts of our work to be applicable and reusable in general fluid tasks and projects. The further text summarizes this effort. In this and the next chapter, we are presenting the reader general introduction of basics of modelling of fluids and some visualization methods as well.

1.2 The economical and ecological reasons

In recent years, the World's attention has focused increasingly on our use of energy as well as technologies for energy production available, and consequences of their use. By combustion, namely of fossil fuels, we face major problems and questions of pollution and influence to the global ecosystem. The energy resources are limited and therefore we should try not to waste them in both industry and our homes.

Today's coal power plants also cause pollution problems. The heart part inside the coal power plant is combusting boiler. A common goal is to improve design of boilers to reduce pollution, find optimal ways of preparing fuel, determine coal particle sizes and quantity, speed of combustion etc. Not only the ecological reasons, but also economical reasons (effective combustion) are important for boiler designers.

In engineering practice, it is very difficult to investigate the combustion processes of various kinds of combustibles directly in the boiler. Modelling of fluid based physical processes such as coal combustion processes is a very time consuming activity accompanied by immense financial costs. The traditional approach is based on theoretical boiler design and verification of the design on the real model of the boiler designed. The tests performed on the boiler are used for modification of the design. This cycle (design-verification-modification) is repeated several times until the quality of design reach some satisfactory level.

In last decades, this process has been accelerated considerably by using complex simulation applications. They allow the designer to experiment extensively with the computer model of the boiler designed without necessity to build a physical model of the boiler. These applications are widely used and several program packages (e.g. FLUENT [FluentInc-WWW]) are available on the market. The use of these systems led to increased quality of the design and their use has been widely adopted by designers around the World. Efficient boiler design is based on simulation accompanied by optimal visualization models.

1.3 Visualization and simulation of the problem

Firstly, simulation allows appropriate computation of most characteristics, that are the most important for designers (such as global and local temperature, pressures, velocities of combustibles and air, NO_x concentrations [Mägel55], problems with dry bottom ash [Carreau00], tendency to corrosion, slagging, and fouling [Kraen00] etc. Some of them can be verified by special methods such as Laser Doppler Velocimetry [Mos00] and measurements in scale models [Sapedo01], [Sayre99]. For that purpose, various modelling technology is being used [Eaton99]. It includes computation of the flow air and coal, combustion processes and heat transfers.

Secondly, visualization can give synoptical and optimal view and presentation readable even by non-experts. The visualization is probably the only general means of making the dynamic processes inside the boilers understandable to a human. In an ideal case, the visualization of these processes should be physically precise, interactive and real-time.

1.4 Interactive visualization and usability in education

The visualization of power engineering processes gives the students an opportunity to understand better the nature of these processes. This approach solves one of the main problems in power engineering education: the students usually have no chance to see various types of power plants in practice. The existence of models and their corresponding visualization allows students to perform experiments with various devices and in such a way acquire much deeper knowledge about the subjects taught [Slavik99].

1.5 Goal of the thesis

The goal of the thesis is to design and implement techniques that together could be used to form a solution allowing interactively visualize pulverized coal combustion processes in real time. Up to now, we do not know about any projects (with exception of some early projects and attempts made by undergraduate students at CTU for their master theses – their work is briefly discussed later in this document) that would have the same goal. These techniques should be general enough to be suitable for reusing in similar applications regarding real-time simulation and visualization of fluids. In addition, these techniques and proposals should be independent on each other. Such generality would eventually allow others to use our proposals in existing and new projects involved in simulation and modelling of fluids. If one or more of our proposals (components) would be not properly applicable – either by performance, desired precision, overall concept design or similar drawback to fulfil concrete task, it should be relatively easy replaced by a new one with more desirable results.

On the other hand, the goal of the thesis, namely due to requirement of interactive, real-time performance, is not to propose solutions, that would get closer to robustness, richness and precision offered by professional CFD packages and numerical methods. Such demanding goal would be nearly impossible to finish due to following reasons: 1) the fact, that current computers are not powerful enough to run such solution in real-time and 2) computer science, visualization and software design and engineering education specialization of the author. It would also limit the scale of the dissertation thesis (due to the effort directed to investigation of these methods), which is to offer the whole collection of techniques forming a complete solution, not only some very fine-tuned simulation method. The goal of the thesis was not to implement a perfect, production quality system. Instead of that, from the beginning, the intended purpose of the work was to create a solution, which could be used for the purposes of education at the Department of Mechanical Engineering CTU in Prague. These are not very demanding, especially considering the precision of physical model. There did not exist any team of software developers for implementation of the system, with an exception of implementation and testing of hardware, bicubic spline interpolation and IBFV visualization technique made by Petr Kadlec. No other persons, except author were involved in implementing and testing all techniques proposed in the thesis. The described goal of generality allowing to further enhance or redesign the proposed techniques, forming a complete solution, was intended to allow eventual future pioneers of interactive, real-time visualization of combustion processes, to carry on from the stage, which this thesis reached.

1.6 Our effort and structure of the thesis

Traditional methods of visualization and simulation of combustion and general fluids, which will be described in detail in Chapters 2 and 2.3, yield high-quality results. However, they usually have major drawback – today's common computer equipment does not offer computational power sufficient for running solutions based on these methods in real-time performance. Therefore, we have decided to propose some new solutions to attempt address this drawback.

In the field of combustion, namely combustion of pulverized coal, we are focused on creating interactive model and visualization methods. We are also focused on finding new methods and concepts, which can be easily used and implemented. Our effort has resulted in finding various

techniques, covering multiple directions leading to an interactive model and real-time of combustion processes.

Except of the implementation of high quality spline visualisation described in Chapter 1 and in paper [Kadlec04] by Kadlec, and proposal of suitable existing combustion equations used in the combustion model by Hrdlicka, all the presented results were proposed and implemented by the author of this thesis, Gayer. This also applies to all the papers of authors, with an exception of paper [Slavik03], which consists of parts that were invented and proposed by Gayer (covers approximately all the second half of the paper) and parts invented by Slavik, Hrdlicka and Kubečka (covers approximately all the first half of the paper).

1.7 The structure of the thesis

The structure of the thesis can be summarized as follows:

1. **Find a new way for fast generation of combustion data, which can be visualized in real-time:**
 - Isotherm free stream combined with air and coal particle system (Chapter 1, published in paper [Gayer02a])
 - Fast fluid simulation combined with virtual coal particle system (Chapter 1, [Gayer02b])
 2. **Special visualization data generators allowing real-time interpretation based on high capacity disk drives**
 - Fast data generator using Fluid Simulator States (Chapter 1, [Gayer03a])
 - Hierarchical data generators based on Fluid Simulator States (Chapter 1, [Gayer03b])
 - Hierarchical data generators based on unsteady data sets (Chapter 1, [Gayer04a])
 3. **Interactive visualization methods and concepts**
 - Fast, high quality visualization method using programmable shaders of new graphics accelerators (Chapter 1, [Kadlec04])
 - Interactive model for education, allowing real-time visualization of characteristics and statistics (Chapter 1, [Gayer03c])
- The results of our effort are more described in the chapters of the thesis.

2 Existing simulation and visualization methods suitable for fluids and combustion processes

2.1 The modelling of flow using CFD

Before visualization of physical processes, we must find a way for obtaining the numerical data, which represent simulated situation in combustion boiler. For that purpose, we are seeking for a mathematical model, which in some way approaches physical reality. By implementing and running such a model on computers, we simulate these processes. An important and complex task for simulation and visualization of the combustion processes is without doubt the modelling of flow (usually the flows of the air and of the coal during the combustion process). This area is subject to intensive research. The motion of fluids (gases, liquids) has been a topic of study for hundreds of years. Nowadays, Computational Fluid Dynamics (CFD) is used in almost all fields of fluid dynamics. CFD commonly represents broad family of numerical solutions and computational methods, which

solve governing equations describing fluid flow. CFD is thoroughly studied since '60s and is covered by many papers, handbooks and practical applications. For a brief introduction, overview and future of the CFD the reader could consult the paper [Gadella98]. For engineering practice, it is a good idea to start with books on Computational Fluid Dynamics - The basics with the applications [Anderson95] or Computational Fluid Dynamics: An Introduction for Engineers [Abbot89]. There are many others, which can be used as a replacement of these mentioned..

2.2 Fluid Simulator and Solvers

The fluid simulators and solvers based on the Navier-Stokes equations are used for the various practical computer graphics applications such as the animation of water and other liquids [Foster00], [Foster01], gases [Hm04], [Foster97] and smoke phenomena's modelling [Rasmussen03], [Fedkiw01], [Treuille03] (including smoke flow with obstacles - [Yoshida00]). Further, aerodynamics simulation [Wejchert91], animation of the water surface [Chen97], [O'Brien95] and waves [Enright02], fluid flows on smooth surfaces [Stam03a], and ocean [Lin03]. Many others are being investigated. Currently, utilizing results as the data for visualization, the CFD methodology by using these equations allows generation of very attractive pictures such as pictures of clouds [Stam99].

Some of them are even used for animations and special effects where the resulting pictures play decisive role for the applications such as movies [Witting99], [Rasmussen04] and games are [Stam03b]. Some of them are used for special effects such as melting [Carlson02], [Wei03] and viscoelastic fluids [Goktekin04]. They are also used in special modelling software packages such as Maya.

We can speak about two types of the Navier-Stokes based fluid simulators. Those such as [Foster96] use unstable, time step dependent solutions of the Navier-Stokes equations. Others – such as [Kas90] or [Stam99] – use stable fluid models that are able to determine the progress of flow independently on length of the time steps, but at cost of increased computational speed of single frames. In most cases, the solvers are built to meet requirements of particular applications, however usually they may be modified and reused in either general or similar applications. Fluid simulator proposed by [Stam99] can be implemented in just a few lines of code in the C language when using Fast Fourier Transformation [Stam01].

2.3 Selected existing visualization methods for fluids modelling

2.4 Visualization of vector fields

The vector fields can be easily visualized in real-time [Gelder92]. The flows can be visualized by arrow plots (sometimes called *heldehogs*) or by simple lines (with various ending) that represent the vectors. The arrows could be easily rendered using simple lines (for example by means of OpenGL). However, when visualizing many values organized in grids, arrow plots representing all the discrete values may become small, allowing only a limited amount of values to be displayed. Unlike surface rendering methods, direct volume-rendering methods can be used to visualize 3D scalar data without intermediate geometric primitives [Swann1], [Crawfis92], [Crawfis93].

We can use some enhancement and additions to these methods to visualize multiple data values. For example, we can use a combination of discrete and continuous visual elements arranged in multiple layers to represent visually the data. For example, [Kirby99] uses concepts of painting

inspired by the brush strokes the artists apply in layers to create an oil painting. With these techniques, we are able to visualize several levels of information.

2.4.1 Highlighting places of interest and feature extraction techniques

In some cases, the common flow visualization methods could yield images which would be either unclear, or would not give good overview of the visualized data, or in which it would be hard to recognize a selected behaviour of the flow. We need to find ways to highlight important places in flow fields. For that purpose, we use various methods. For example, a method for producing compact vector field visualizations, as described in [Telea94], uses a hierarchical simplification of the vector data. The simplification is based on the definition of the vector similarity function for visualization of different aspects of the vector field. The method can visualize vector data at different levels of detail by interactively choosing the simplification level. We can use various feature extraction concepts to focus visualization on interactively selected parts or simplify complex and/or dense flow fields, such as clustering methods for vector fields [Garcke00]. Others can be found in numerous papers, e.g. [Post02], [Westermann00], [Theisel03], [Polthner00], [Sohn02], [Sadayappan99].

2.4.2 Spot noise

Another method of vector field visualization is based on random selection of data points. Only data in this subset are visualized. By combining all of these separate visualization methods, we can obtain an image, which well describes structure of the vector field. We can then use this image as a texture to visualize the flow field directly. These texture-based techniques differ in a way they visualize the value in discrete points. Spot noise techniques [Wiljk91], [deLeeuw95] draw spots of random intensity on random places. Every spot is altered regarding the direction of value of vector field in the corresponding point. On the picture, which is synthesized by drawing large amount of such spots, the global structure of field and feature details can be found.

2.4.3 Line Integral Convolution (LIC)

The Line Integral Convolution technique (LIC, [Cabrera93], [Forsell95]) is based on filtering the white noise texture (usually with same resolution as vector field) in corresponding places of streamlines found in visualized vector field. This technique is similar to spot noise [deLeeuw98].

Later, the LIC and spot noise methods have been improved and extended. OLIC [Wegenkittl97a] uses less dense texture than LIC and asymmetric filtering, which gives effect of colour drops inserted into the vector field. FROLIC does not use filtration of texture at all, which allow increase visualization speed [Wegenkittl97b]. UFLIC [Shen97], [Shen98] and AUFLIC [Lin02] optimizes LIC for unsteady flows animations. Other enhancements and extensions to this method can be also found for example in [Forsell95], [Stalling95], [Shen96], [Bordoloi02a], and [Interrante97].

Other methods of flow visualization include visualization of unsteady vector fields using Lagrangian-Eulerian Advection (LEA) scheme [Jobard02], and Advected Radial Basis Functions [Pghm04]. Further, Unsteady Flow Advection-Convolution (UFAO) [Weiskopf03], visualization of flows using streamlines [Zockle96], [Wischgo102], [Mattausch03] and streaklines [Sama00], Markov Random Field Texture Synthesis [Taponceco03], anisotropic nonlinear diffusion [Preusser99]. An interesting approach for rendering animated streamlines using textures is proposed in [Fuhmann98]. An attempt to visualize pulsative flow using special particle pathlines called Particle Flurries has been described in [Sobe104]. By combining flow visualization in 3D with light models, we can obtain even better results [Stock02]. A possibility of utilizing streamarrows for streamsurfaces visualization is discussed in [Loeffelmann97]. We recommend [Crawfis00], [Post02], [Post03], [Laramee04a] and [Laramee04b] for comprehensive overview of Flow Visualization method.

2.4.4 Image Based Flow Visualization

IBFV (Image Based Flow Visualization) is a technique suitable for 2D flow visualization [Wijk02] that gives visual results similar to previous described methods, even that the used algorithm considerably differs. Visualization works directly with resulting bitmap, which is transformed in each step according to values of vector field and mixed with filtered noise texture. The technique can be easily implemented on graphical accelerators, because it uses their features of texture processing and alpha blending. The visualization runs in real-time and has two steps. In the first, the image generated by previous visualization step is divided by grid. Each cell of the grid is transformed and deformed by values in its corners and modified cell is drawn over the original image.

In the second step, the image is blended with one of the prepared image of noise textures, created during initialization. The resulted image is then drawn and saved for next animation step.

In process of visualization, we can modify many parameters, which determine the visualization result, such as coefficient of transparency of noise texture, size and scale of noise texture etc. By altering these parameters, we can get results similar to spot noise, OLIC etc. The method offers great performance on current graphical hardware. It has been also extended to 3D [Tele03]. Together with [Lef04], this technique can be used for animation of steady vector fields.

2.4.5 Realistic visualization of fire and flames

Current models, which deal with simulation and visualization of behaviour of flames, are more concentrated on the visualization part of the combustion process. They use several other approaches such as cellular automata [Takai95] (which is also used for other physical simulation purposes – e.g. excellent clouds modelling in [Dobash99], [Dobash00]), diffusion processes [Stan95], Lattice-Boltzman model [Zha03], [Wei02] and tomographic method for reconstructing a volumetric model from multiple images fire [Hirke04]. [Nguyen02] presented a physically based method for modelling and animating of burning of either solid or gas fuels. This method uses the incompressible Navier-Stokes equations to model independently both vaporized fuel and hot gaseous products.

Models of this type are more concentrated on the visualization part of the combustion process. The resulting pictures can be used in applications where the quality of visual effect plays decisive role (e.g. movies, computer games etc.).

Remarkable research is being done by the Combustion Group of Utah [Smith-WWW]. Using special software CSAFE [C-Safe-WWW] on supercomputers equipped by hundreds of processors, they are able to study various types of fuels and bring the detailed and precise visualization and statistics of various fuels (especially jet-fuel fires). Of course, these and similar applications are very computationally expensive even on the today's specialized hardware (e.g. 30 seconds per animation frame in [Nguyen02]).

2.4.6 Particle systems

The particle systems have been introduced by Reeves [Reeves83]. He described a particle system as a collection of many small particles that together represent the visualized object(s). Over a period of time particles are inserted into a system, they move and change within the system, and are eventually removed from the system, depending on specified conditions. Each particle has assigned its individual attributes.

Visualization of particles provides intuitive and efficient means for the exploration and analysis of complex flow fields. With many particles simulated and visualized, it is possible to gain well-arranged overview of flow.

By using large number of particles with suitable distribution we can use them for visualization of flow volumes [Guth02]. Particle systems can be used for modelling of turbulent flows – e.g. [Gamito95].

Bruckshen at al. [Bruckshen01], [Kuester01] developed a method enabling to visualize up to

60000 particles into a flow field while maintaining an interactive frame rate. Their method was based on the pre-calculated particle trajectories stored in a scheme optimized for selection of sub-grids. They used high-capacity disk system (Redundant Array of Inexpensive Disk) for this application. They used data sets were for a classical problem: simulating the flow of a fluid around a spherical object.

An example of successful usage of particle system can be found in [Hrdlicka96], [Hrdlicka04]. They used a particle system as a solution for modelling the situation in gas cleanup filters. High precision simulation had been gained as well as the possibility to study in details the behaviour of these filters, and the possibility to perform large number of experiments in short time, thus proposing optimal cleanup filter design.

Particle systems by their nature offer an easy way for display particle tracks and easy construct streamlines. In CFD, particle tracing allows the visualization of vector fields resulting from simulation [Lane97], [Sadarjoen98].

2.4.7 Hardware acceleration for scientific visualization

Nowadays, real-time visualization of various unsteady data is more often maintained by using techniques and approaches regarding to new programmable abilities of current graphical accelerators, such as described in [Heidrich99], [Weiskopf01], [Tele03] and [Weiskopf04]. Bortoloi and Shen introduced hardware accelerated visualization of dense 2D vector fields with flexible level of detail control [Bortoloi02b], [Shen04]. Herrager [Herrager00] introduced new approach for accurate shading model of lightning models with multitexturing for volume rendering. Other projects aim toward acceleration of various phases of volume rendering process [Roetger03]. Abilities of current graphics hardware may be utilized even for raytracing [Weiskopf04b] simulation purposes performed directly on the graphics hardware as described in [Wu04], [Harris02], including simulation of fluids using Lattice Boltzman method [Wei04], [L03], Navier-Stokes [Liu04] and Euler equations [Harris03].

3 Summary and contribution of the thesis

3.1 Fast fluid simulation combined with virtual coal particles

In the beginning of our effort, we used a modelling based on the Isotherm-Free concept, described in Chapter 1 of the thesis. However, this approach had considerable limitations and was suitable only very simple boiler configurations. We had faced serious problems when using complex setup and changing the boiler configuration during the simulation.

As described in Chapter 1 of the thesis, our coal combustion system is currently based on a fast fluid simulator core. The fluid simulator allows real-time computation of the airflow. It utilizes Euler Equation and The Continuity Equation. The simulator is very easy to implement and thus can be reusable in various computer graphics and simulation tasks related to the airflow simulation and visualization.

The high speed of the fluid simulator and combustion system allows real-time visualization of the results (using the OpenGL graphics interface). The system has been implemented in a 2D structured cell grid (see Figure 1) with variable depth – z-axis, and considering the methodology used, it could be relatively easily to extended to 3D grid cell, namely due to easily adaptation of computational model, however the implementation would be demanding in terms of development time and computation requirements. The unique concept of the virtual coal particles, based on the interaction of the air mass inside the cell with the coal mass (see Figure 2), allows us to both speed up the combustion simulation and also gives us a possibility of easy tracking the flow of the combustibles. Virtual coal particles also allow visualizing dynamics of the combustion process.

We have tested our system by modelling a boiler of real dimensions, characteristics and parameters. The behaviour and quantitative features predicted by our system were comparable with those of a real boiler as well as with the results gained from the professional CFD software package

FLUENT 5.5. However, we had to use manual tuning, that are dependent on concrete solved tasks, to approach to these results.

On the other hand, our fluid simulator is conditionally stable, thus it needs to setup fix time step dependent on grid size (increasing with grids that are more precise) as similar existing methods. In addition, when requesting precise results, the professional CFD packages and software, or even possibly some other fluid simulators and solvers based on more precise mathematical and physical model could give better results, but at the cost of the computation speed. Our fluid simulator is made as a component, which could be possibly replaced by such another fluid simulators or solvers.

For cases, where more precise computations are used (by e.g. increasing size of computational grid in our fluid simulator), resulting in computational demands, which would disallow real-time visualization, we proposed further described approaches based on interpretation of generated data stored on disk drives. Our fluid simulator was used as source of such data in those cases.

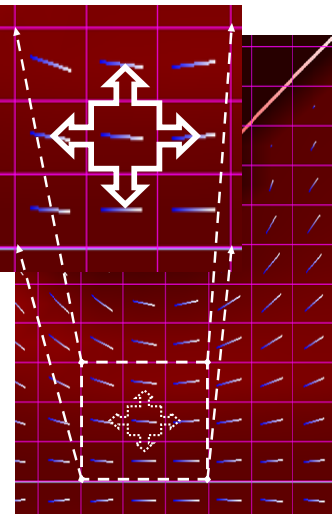


Figure 1: Division of the boiler area to 2D grid cells. The cell values in the next time step are computed from nearest neighbours only.

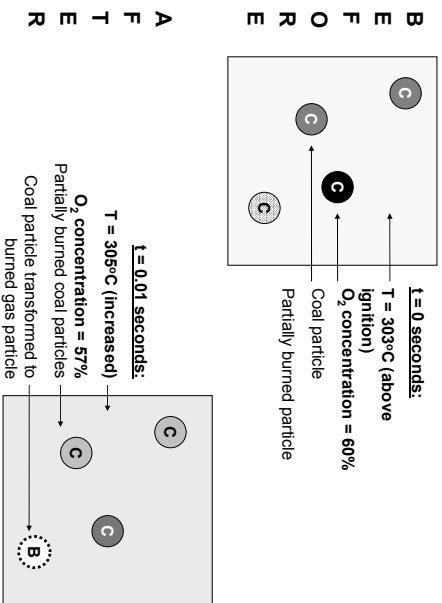


Figure 2: Example interaction of coal particles during the combustion process for the time dt in a selected cell

3.2 Fluid Simulator States (FSS)

As described in Chapter 6 of the thesis, the simulation with pre-calculated fluid simulator states extension is compound of partial computation with synchronous utilization of pre-calculated fluid simulator states stored on disk device, see Figure 3. This concept can drastically improve the simulation and subsequent visualization speed of wide spectrum of computer graphics applications based on fluid simulator while keeping the precision of computation unchanged. Pre-calculating states of the fluid simulator rather than storing complete unsteady data sets of simulation results in much less disk space requirements, with virtually unchanged acceleration. In visualization part, all interactive actions and features such as changing the visualization parameters and visualization of arbitrary characteristics are kept. Even simple and not performance-optimized applications based on 2D or 3D fluid simulators (even non-real-time) can benefit from our concept. In other words, pre-calculated fluid simulators extension can help to overcome performance bottleneck of time-consuming fluid simulator codes, namely when using high-resolution grids or more precise, complex computation methods. Our concept could be utilized by either replacing our simulator in our system, with another, more precise one, or adapting and incorporating described ideas to already designed system.

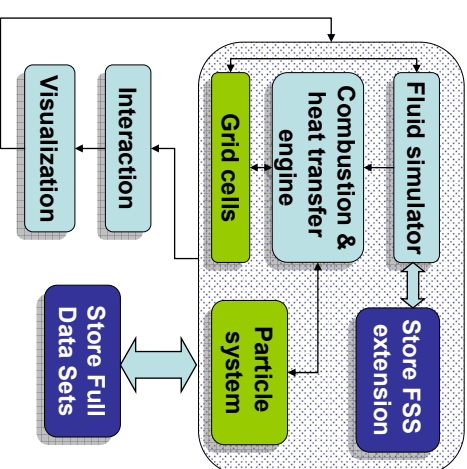


Figure 3: Schematic architecture of our interactive simulation and visualization system

We have performed tests of the architecture on our coal combustion simulation and visualization system based on fluid simulator and particle system. We have demonstrated that with this concept considerable acceleration of simulation and subsequent visualization can be gained, while requesting only small fraction of the disk space requirements (see Table 1). Such space would be needed for storing whole frames either as movie files (with total loss of interactivity) or complete unsteady data sets with much higher disk demands, while keeping the acceleration virtually either unchanged or better (in case of fluid simulator more demanding than the rest codes, which was the case of our application). The limitation of this method is namely in loosing the interactive possibilities, namely changing the simulated configuration and boundary conditions during replaying the stored data and impossibility to change the playback speed with the possibility to skip selected frames. We address these issues in data generators based on tree structures. We are also somehow limited by the disk drive storage requirements, but the demands are considerably less, then it would be needed for storing corresponding Unsteady Data Sets.

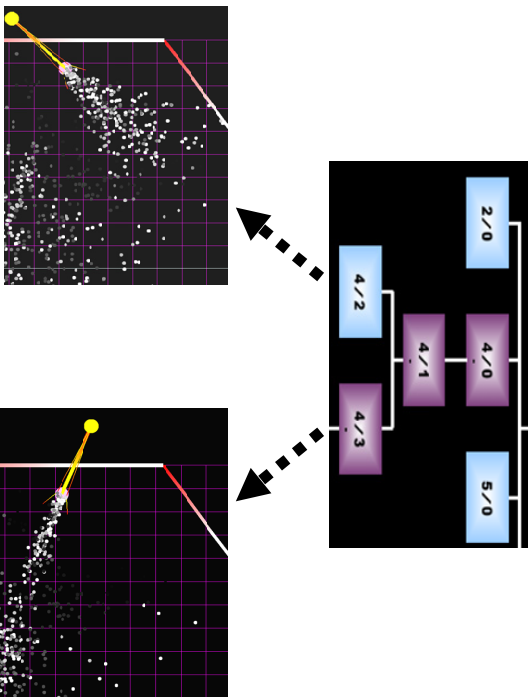


Figure 6: Illustration of interactive change of parameters of simulation in different FSS sub-trees. In the left sub-tree (4/2) – the inlet is kept in its original position; in the right sub-tree (4/3) – the position and spread angle of the inlet has been changed. The FSS accelerated simulation continues with changed configuration.

3.4 Unsteady Datasets Tree

As described in Chapter 8 of the thesis, we have proposed, implemented and tested the concept of hierarchical datasets tree structures in combustion processes simulation and visualization powered by the unstable fluid simulator. Choosing unsteady dataset helps us to avoid the common drawback of slow simulation of unstable fluid simulators, due to small timesteps.

Our concept overcomes the common drawback of the commonly used unsteady datasets, which results in loosing of interactivity on the simulation side. Proposed solution of hierarchical structures consisting of simulation results datasets over classical datasets allow incremental, progressive and easy construction and playback of various simulation configurations with interactive visualization of the results. The modifications of simulation boundary conditions are available in every node of the dataset tree. Every interactively selected path in the datasets tree corresponds to one modified simulation solution. We have proved that we can even use up to hundred thousand of particles without much worry about performance bottlenecks of the current commodity disk drives.

Our results can be easily utilized in general simulation and modelling applications, which use unsteady datasets for storage of the results. The users of simulation and visualization applications can extend the prepared and pre-calculated simulation results with their own modifications with possibility to use the results of previous solutions stored in tree while keeping a high speed of replaying, because of the utilization of unsteady datasets.

This method is limited by the speed of the disk drive, which should be enough to allow transfer large amounts of data into system memory, otherwise the acceleration could be considerably lower. However, we have demonstrated that on properly configured common Ultra ATA and Serial ATA drives, there is no problem with acceleration performance. In cases, that disk drive capacity storage is limited, we can still use the FSS and FSS Tree methods described earlier.

Store method / Grid size	SIM / 20×*40	UDT / 20×*40	SIM / 50×*100	UDT / 50×*100
Simulation time	1089s	1103s	4617s	4665s
Write [MB/s]	N/A	0.7	N/A	0.4
Replay time	1062s	49s	4659s	68s
Read [MB/s]	N/A	15.9	N/A	26.4
Drawing speed [FPS]	9.4	22.5	2.1	14.7
Disk space [GB]	N/A	0.78	N/A	1.8
Total acceleration	N/A	x 24	N/A	x 70

Table 2: Results gained using direct simulation (SIM) and unsteady datasets tree (UDT)

3.5 Hardware accelerated interpolation techniques

After having proposed methods for fast data generation based on fast simulation, and accelerated hierarchical storage, a question remains - how to visualize these data in optimal performance and quality. As we described in Chapter 9 of the thesis, our method achieves real-time rendering of grid-structured data using pre-calculated texture. We interpolate the data using spline interpolation that runs directly on the graphics accelerator, therefore leaving the CPU to compute the simulation in parallel. The texture used may be changed dynamically, which results in a possibility of interactive adjustments of visualization parameters. The method allows us to display isolines of the displayed data with no additional performance requirements. The isoline displaying may be enabled or disabled by simply choosing the texture, see Figure 8.

We used implementation of this technique to improve quality of visualization in our coal combustion and visualization system, see Figure 7. The success of the implementation proves the significant contribution of this hardware-accelerated technique for maintaining real-time, high-quality visualization of the cell characteristics. This concept can be used in similar applications regarding scientific, isocountour based visualization of computed or simulated data. Although, the new method is currently about 10 times slower than common raw OpenGL visualization using linear interpolated quads, it is still suitable for real-time visualization, with dramatic enhancement of the visual quality. In applications, which need to visualize 2D grids with up to 10,000 cells we can expect real-time performance on today's commodity graphics hardware. With more precise grids, we can still use mentioned simple OpenGL visualization.

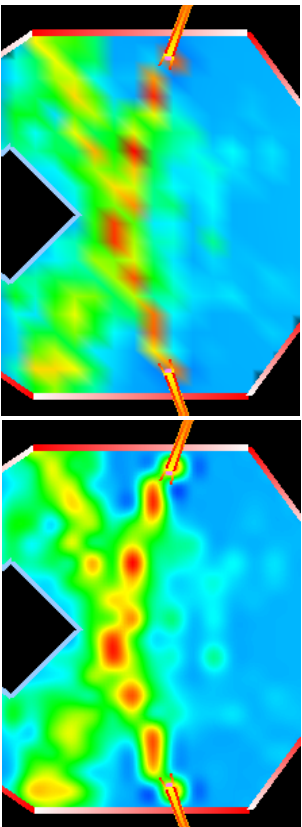


Figure 7: Original visualization of combustible masses inside the boiler area. Right: Visualization of the mass using the spline interpolation method

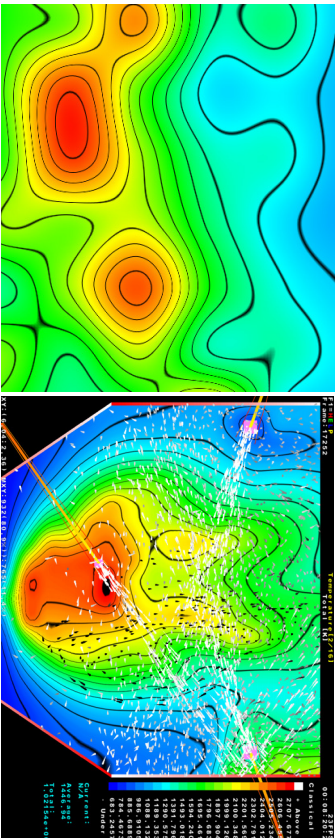


Figure 8: Left: Using the pre-calculated texture palette concept, we can easily visualize isolines, with no additional performance cost over the basic spline interpolation. Right: Visualization of isolines together with particle system

3.6 Educational System of Pulverized Coal Combustion

As we described, in Chapter 1 of the thesis, our educational system *My Pulverized Coal Combustion* for pulverized coal combustion is based on a simple fluid simulator and virtual coal particle system. The fluid simulator allows real-time computation of the air flowing inside the boiler. We selected particle systems for maintaining visualization of combustion process dynamics. By their nature, they can even be utilized in the simulation and computation part.

The high speed of the fluid simulator and combustion powered by the virtual coal particle system and simplified combustion engine allows real-time visualization of the resulting characteristics and dynamics using hardware accelerated contour visualization, Image Based Flow Visualization (IBFV) and particle system (using OpenGL graphics interface). The system has been implemented in 2D grid cell space, with variable depth – z-axis. The system is suitable for educational purposes, where clarity, real-time interactivity and universality of computation is important.

The most powerful and new feature of our system is the simulation and visualization interactivity, which is available during real-time computation of the combustion process, without needing to stop or restart the system. Tens of input parameters, including coal inlets setup can be modified on the fly.

Our results make it possible to get a good preview of the dynamics of combustion processes in a boiler. Based on this concept, the students and eventually designers of boilers, making use of the fast, preview based design and approach, could now test many configurations and modifications of the pulverized coal boilers interactively. The system by itself can in an interactive, efficient and attractive form, give an overview of how powerplant boilers work, with an overview of fundamental boiler parameters. The system optionally supports above described hierarchical tree storage and playback based on the pre-calculated Fluid Simulator States Trees and Unsteady Data Sets trees.

The interactive modelling can bring the student basic knowledge and fundamentals of constructing performance and efficient boiler solutions and more. We can recommend it as an introductory application for combustion processes overview in power plants. With this technique, we can get a good preview of the dynamics of combustion processes in a boiler. The stable version of the system, resulting from the work during PhD studies, will be used in the educational process in the Faculty of Mechanical Engineering at the CTU Prague. Quality and simulation precision is sufficient for these purposes.

Currently, our system is implemented in Microsoft Visual C++ and runs at interactive frame rates even on a commodity PC equipped with only AMD Athlon 1333 MHz and nVidia GeForce2 MX based graphics card. See the following Figure 9, Figure 10, Figure 11 and Figure 12 for the visualization outputs from the system.

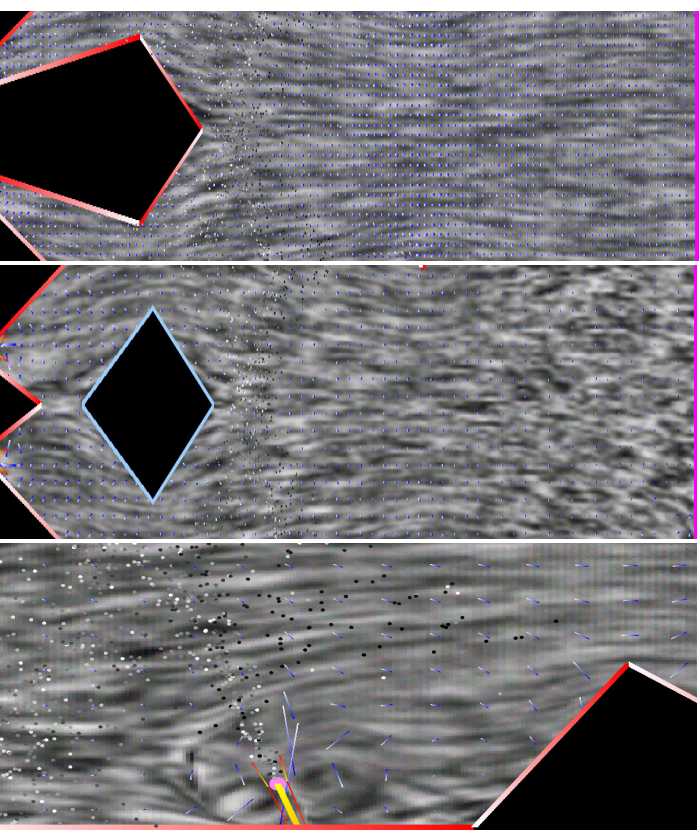


Figure 9: Visualization of flow in the boiler using IBFV. Left: Flow in boiler with grid 50 x 100 cells, Middle: Flow in boiler with grid 20 x 40, Right: Detail of flow with grid 20 x 40

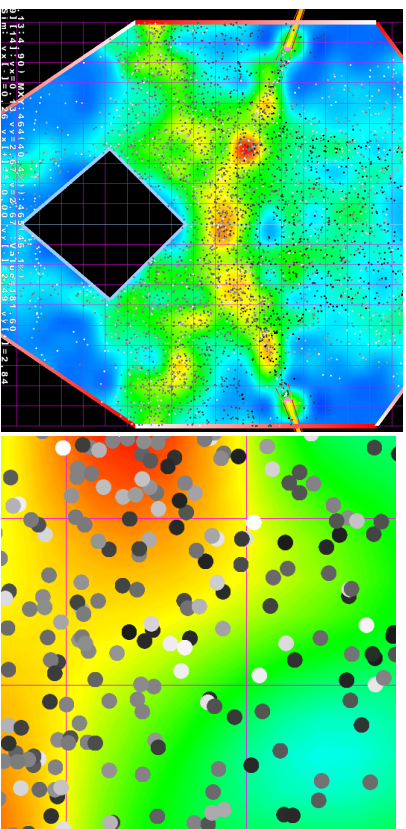


Figure 10: Visualization of thousands of virtual coal particles characteristics together with selected cell grid characteristic (drawn on the background).

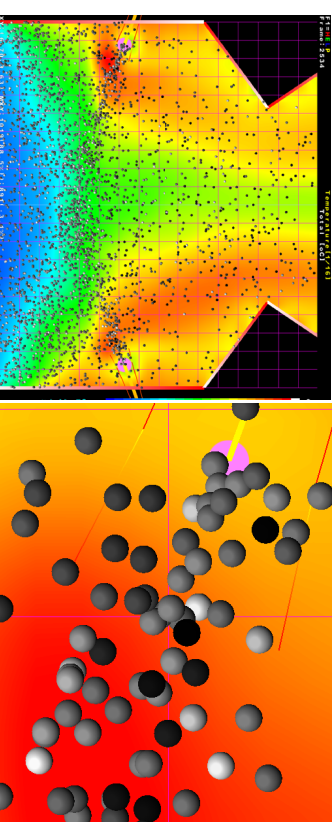


Figure 11: Visualization of virtual coal particles using point sprites, resulting in better picture quality

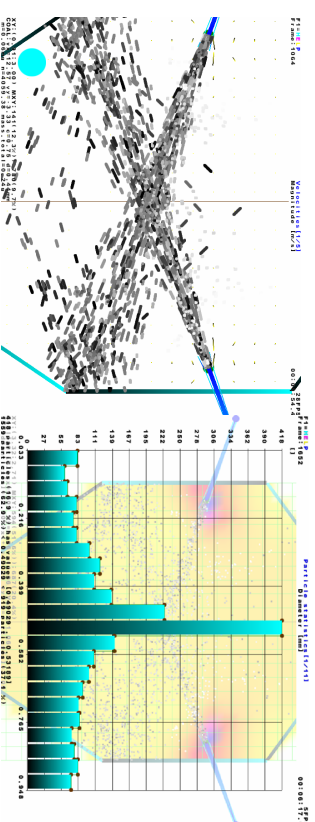


Figure 12: Tracking and monitoring of the characteristics of the selected particle and sample statistics

3.7 Particle and volume statistics

Another way of presenting the computed values is utilizing statistics feature offered by our system. The inputs for statistics are either values of any selected cell grids characteristics or values of any described characteristics of the particles. We can measure and visualize the values distribution in the grid cells and particles for all the above-described characteristics. The sample visualization output is shown on .

3.8 Interactive simulation

During the simulation, we can interactively modify any of about 45 simulation parameters. On the fly, we can for example increase the number of generated particles (improving the simulation precision at certain cost of visualization and simulation speed, see the) or change the mass of average coal particles flowing from the inlets of the boiler.

4 Conclusion

In this work, we have described effort during the PhD study and described possibilities useful for next possible research. We have described commonly used methods usable for the simulation and visualization of the fluids and combustion processes. We have presented existing visualization features and methods usable for the visualization of the general fluids and for combustion processes.

We have designed our fluid simulator and virtual coal particle concepts for both the simulation and visualization of the combustion processes. We use these components as data generators for storage techniques and visualization methods. For the simulation and visualization of a combustion system, our current investigation brings an interesting alternative to the classical CFD applications.

Major part of our work is concerned in using the speeding up the simulation using Fluid Simulator States. We extended this concept with tree structures allowing incremental and interactive concept of solution of fluid tasks including combustion. The hierarchical concept of computed data storage can be also well used for storing general unsteady datasets.

We had also worked on visualization of combustion processes and general fluids. Using the concept of virtual coal particles, we had created an attractive visualization allowing us to investigate the dynamics of the combustion process. We had used the features of the last generation graphics cards to propose and implement real-time and high quality visualization of flow fields by using hardware accelerated bicubic spline interpolation and IBFV.

The mentioned parts has been integrated and implemented into and tested in an application My Pulverized Coal Combustion that has been developed with demands of interactive enabled education being kept in mind. The system can be used for educational purposes in order to give students idea about the behaviour of boilers under various conditions. This application allows this with many interactive features. All of the presented techniques are independent and loosely bind together and thus parts of them, including concepts and ideas could be reused in other research projects or replaced by their more advanced versions.

We hope that some of the presented results would be used in either next research projects or practical projects trying to keep the environment we are living in clean. If we really still have to burn fossil fuels, at least let us try to do it effectively and ecologically.

5 Awards

The real-time pulverized coal combustion system and its portions formed by techniques presented at previous chapters of this thesis received the following awards:

- **2003, CTU FEE at Prague, Czech Republic**
Award of Dean of the Faculty of Electrical Engineering of the Czech Technical University in Prague for work Simulation and Visualization of Combustion Powered by Fluid Simulator, presented at conference CTU Poster 2003
- **2003, Brno University of Technology, Faculty of Electrical Engineering and Communication (BUT FEEC), Czech Republic**
Award of Dean for the best work in the International Competition of student creative projects Student EIECT 2003
- **2003, CTU in Prague, Czech Republic**
Price of the rector for placing between the best projects of PhD students, that were solved within the scope of CTU internal grants and that were presented on conference CTU Workshop 2003

6 References

- [Abbot89] M. B. Abbott. *Computational Fluid Dynamics: An Introduction for Engineers*. Wiley, New York, 1989.
- [CFD2000-WWW] Adaptive Research company. CFD2000 product information. <http://www.adaptive-research.com/cfd2000frm.htm>.
- [Algor-WWW] Algor, Inc. Finite element analysis software. <http://www.algor.com>.
- [CFDAnalyzer-WWW] Amtec company. CFD analyzer version 2.0. http://www.amtec.com/Product_pages/cfd_analyzer.html.
- [Tecplot-WWW] Amtec company. Tecplot 9.0 data visualisation software. http://www.amtec.com/Product_pages/tecplot9/index.html.
- [Anderson95] J. Anderson. *Computational Fluid Dynamics - The basics with the applications*. McGraw Hill, 1995.
- [Arques99] D. Arques, E. Felgines, S. Michelin, and K. Zampieri. Thermal convection in turbulent flow, image synthet and heat animation. In V. Skala, editor, *Proceedings of WSCG 1999*, volume 2, pages 337-345. University of West Bohemia Press, Czech Republic, Pizen, 1999.
- [Bauer02] D. Bauer, R. Peikert, M. Sato, and M. Sick. A case study in selective visualization of unsteady 3D flow. In *Proceedings of the conference on Visualization '02*, Boston, Massachusetts, pages 525-528. IEEE Computer Society, 2002.
- [Becker95] B. G. Becker, N. L. Max, and D. A. Lane. Unsteady flow volumes. In G. Nielson and D. Silver, editors, *Proceedings of the 6th IEEE Visualization Conference*, Atlanta, Georgia, US, pages 329-333. IEEE Computer Society Press, 1995.
- [Bordoloi02a] U. Bordoloi and H.-W. Shen. Hardware accelerated interactive vector field visualization: A level of detail approach. *Computer Graphics Forum*, 21(3):605-605, 2002.

[Bordoloi02a] U. Bordoloi and H. wei Shen. Hierarchical LIC for vector field visualization. Aug. 10 2002.

[Bruckschien01] R. Bruckschien, F. Kuester, B. Hamann, and K. I. Joy. Real-time out-of-core visualization of particle traces. In *Proceedings of the IEEE 2001 symposium on parallel and large-data visualization and graphics*, San Diego, California, pages 45-50. IEEE Press, 2001.

[Bryson96] S. Bryson and S. Johan. Time management, simultaneity and time-critical computation in interactive unsteady visualization environments. In *Proceedings of the 7th conference on Visualization '96*, San Francisco, California, United States, pages 255-4ft. IEEE Computer Society Press, 1996.

[Bryson99] S. Bryson, D. Kenwright, M. Cox, D. Ellsworth, and R. Haimes. Visually exploring gigabyte data sets in real time. *Communications of the ACM*, 42(8):82-90, 1999.

[Cabra93] B. Cabral and L. C. Leedom. Imaging vector fields using line integral convolution. In *Proceedings of the 20th annual conference on Computer graphics and interactive techniques*, pages 263-270, 1993.

[Carlson02] M. Carlson, P. J. Mueha, I. R. Brooks Van Horn, and G. Turk. Melting and flowing. In *Proceedings of the ACM SIGGRAPH symposium on Computer animation*, San Antonio, Texas, pages 167-174, 2002.

[Carrea00] E. Carrea, S. Orsino, and J. Barsin. Full-scale trials and numerical modeling of a dry bottom ash extraction system from a 330mw coal fired boiler. In *Proceedings of ASME IIPGC'00 International Joint Power Generation Conference Exposition*, 2000.

[Carmull74] E. Carmull and R. Rom. A Class of Local Interpolating Splines. In R. E. Barnhill and R. F. Resenfeld, editors, *Computer Aided Geometric Design*, pages 317-326. Academic Press, 1974.

[CFDOnline-WWW] CFD Online. CFD resources online an online center for computational fluid dynamics. <http://www.cfd-online.com/Resources/foames.html>.

[Chen97] J. X. Chen, N. da Vitoria Lobo, C. E. Hughes, and J. M. Moshell. Real-time fluid simulation in a dynamic virtual environment. *IEEE Computer Graphics and Applications*, 17(3):52-61, 1997.

[Chelka69] J. Chelka. *Výzkum a vývoj*. SNTL, Praha, 1969.

[C-Safe-WWW] Combustion research group of University of Utah. C-safe - center for the simulation of accidental fires and explosions. <http://www.csafe.utah.edu/>.

[Cox97] M. B. Cox and D. Ellsworth. Application-controlled demand paging for Out-of-Core visualization. In R. Yagel and H. Hagen, editors, *IEEE Visualization '97*. IEEE, 235-244 1997.

[Cox99] M. Cox. Large data management for interactive visualization design. In *Proceedings of the SIGGRAPH 99 System Designs for Visualizing Large-Scale Scientific Data course notes*, pages 5-29. ACM Press, 1999.

[Crawfis93] R. Crawfis, N. Max, B. Becker, and B. Cabral. Volume rendering of 3D scalar and vector fields at ILNL. In IEEE, editor, *Proceedings, Supercomputing '93: Portland, Oregon, November 15-19, 1993*, pages 570-576, 1109 Spring Street, Suite 300, Silver Spring, MD 20910, USA, 1993. IEEE Computer Society Press.

[Crawfis92] R. Crawfis and N. Max. Direct volume visualization of three-dimensional vector fields. In *VI/S '92: Proceedings of the 1992 workshop on Volume visualization*, Boston, Massachusetts, United States, pages 55-60. ACM Press, 1992.

[Crawfis00] R. Crawfis, H.-W. Shen, and N. Max. Flow visualization techniques for CFD using volume rendering. In *Proceedings of the 9th International Symposium on Flow Visualization*, Edinburgh, Scotland, UK, 2000.

[DeCorro02] C. DeCorro and R. Pajarola. XFastMesh: Fast view-dependent meshing from external memory. In R. Moorhead, M. Gross, and K. I. Joy, editors, *Proceedings of the 13th IEEE Visualization 2002 Conference*

- [VIS-02], pages 363-370, Piscataway, NJ, 27-2002. IEEE Computer Society.
- [Deutsch96] L. Deutsch. ZLIB compressed data format specification version 3, 1996.
- [deleuw95] W. C. de Leeuw and J. J. V. Wijk. Enhanced spot noise for vector field visualization. In *VIS '95: Proceedings of the 6th conference on Visualization '95*, page 233. IEEE Computer Society, 1995.
- [deleuw98] W. de Leeuw and R. van Liere. Comparing lie and spot noise. In *Proceedings of the conference on Visualization '98*, Research Triangle Park, North Carolina, United States, pages 359-365. IEEE Computer Society Press, 1998.
- [Dobash00] Y. Dobashi, K. Kaneda, Y. Yamashita, T. Okita, and T. Nishita. A simple, efficient method for realistic animation of clouds. In K. Akeley, editor, *Siggraph 2000, Computer Graphics Proceedings, Annual Conference Series*, pages 19-28. ACM Press / ACM SIGGRAPH / Addison Wesley Longman, 2000.
- [Dobash99] Y. Dobashi, T. Nishita, and T. Okita. Animation of clouds using cellular automaton. In *Computer Graphics and Imaging '99 (CGIM'99)*, pages 251-256, 1999.
- [Dvorak96] R. Dvořák and K. Kozel. *Matematické modelování v aerodynamice*. Vydavatelství ČVUT Praha, 1996.
- [Eaton99] A. Eaton, L. Smoot, S. Hill, and C. Eatough. Components, formulations, solutions, evaluation, and application of comprehensive combustion models. *Progress in Energy and Combustion Science*, 25:387-436, 1999.
- [Ellsworth00] D. Ellsworth and H. wei Shen. Accelerating time-varying hardware volume rendering using TSP trees and color-based error metrics, 22 2000.
- [Gadelhak98] M. G. el Hak. Fluid mechanics from the beginning to the third millennium. *International Journal of Engineering Education*, 14:177-185, 1998.
- [Enright02] D. Enright, S. Marschner, and R. Fedkiw. Animation and rendering of complex water surfaces. In *Proceedings of the 29th annual conference on Computer graphics and interactive techniques*, San Antonio, Texas, pages 736-744. ACM Press, 2002.
- [Faltyn99] R. Faltyn. Simulation and visualization of combustion processes in vortex furnace. Master's thesis, CTU FEE Prague, 1999.
- [Fedkiw01] R. Fedkiw, J. Stam, and H. W. Jensen. Visual simulation of smoke. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, pages 15-22. ACM Press, 2001.
- [Feldman03] B. E. Feldman, J. F. O'Brien, and A. Arkan. Animating suspended particle explosions. In J. Hodgins and J. C. Hart, editors, *Proceedings of ACM SIGGRAPH*, volume 22(3) of *ACM Transactions on Graphics*, pages 708-715, 2003.
- [Fluent-WWW] Fluent Inc. Flow modelling software and services. <http://www.fluent.com/>.
- [Forsell95] L. K. Forsell and S. D. Cohen. Using line integral convolution for flow visualization: Curvilinear grids, variable-speed animation, and unsteady flows. *IEEE Transactions on Visualization and Computer Graphics*, 1(2):133-141, 1995.
- [Fortk02] M. Fortk. Visualization of combustion processes. Master's thesis, CTU Prague, 2002.
- [Foster01] N. Foster and R. Fedkiw. Practical animation of liquids. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, pages 23-30, 2001.

- [Foster96] N. Foster and D. Metaxas. Realistic animation of liquids. *Graphical Models and Image Processing*, 58(5):471-483, 1996.
- [Foster97] N. Foster and D. Metaxas. Modeling the motion of a hot, turbulent gas. *Computer Graphics (SIGGRAPH 97 Conference Proceedings)*, 31(3A):181-188, 1997.
- [Foster00] N. Foster and D. Metaxas. Modeling water for computer animation. *Communications of the ACM*, 43(7):60-67, 2000.
- [Fuhrmann98] A. L. Fuhrmann and E. Grölller. Real-time techniques for 3D flow visualization. In D. Ebert, H. Hagen, and H. Rushmeier, editors, *IEEE Visualization '98*, pages 305-312. IEEE, 1998.
- [Gaminio95] M. N. Gaminio, P. F. Lopes, and M. R. Gomes. Two-dimensional simulation of gaseous phenomena using vortex particles. In D. Terzopoulos and D. Thalmann, editors, *Computer Animation and Simulation '95*, pages 2-15. Eurographics, Springer-Verlag, ISBN 3-211-82738-2 1995.
- [Garcke00] M. Garcke, T. Preulber, M. Rumpf, A. Telea, U. Weikard, and J. van Wijk. A continuous clustering method for vector fields. In *Proc. of the 11th Ann. IEEE Visualization Conference (Vis) 2000*, Salt Lake City, Utah, United States, pages 351-358. IEEE Computer Society Press, 2000.
- [Gillespie01] J. Gillespie. The use of CFD in design of combustion equipment. *Progress in Computational Fluid Dynamics*, 1(1/2/3):80-90, 2001.
- [Gilmartin81] P. P. Gilmartin. The interface of cognitive and psychophysical research in cartography. *Cartographica*, 18(3):9-20, 1981.
- [Goktekin04] T. G. Goktekin, A. W. Bargteil, and O. O'Brien. A method for animating viscoelastic fluids. *ACM Transactions on Graphics*, 23(3):463-468, 2004 2004.
- [Guth02] S. Guth, S. Gunhold, and W. Strasser. Interactive visualization of volumetric vector fields using texture based particles. In V. Skala, editor, *Journal of WSCG 2002*, volume 10(3), 2002.
- [Guth01] S. Guth and W. Strasser. Real-time decomposition and visualization of animated volume data. In T. Ertl, K. Joy, and A. Varshney, editors, *Proceedings of the Conference on Visualization 2001 (VIS-01)*, pages 349-356, Piscataway, NJ, 21-26 2001. IEEE Computer Society.
- [Guth04] S. Guth and W. Strasser. Advanced techniques for high-quality multi-resolution volume rendering. *Computers and Graphics*, 28(1):51-58, 2004 2004.
- [Harris03] M. J. Harris, W. V. Baxter, T. Scheuermann, and A. Lasta. Simulation of cloud dynamics on graphics hardware. In *HWTIS '03: Proceedings of the ACM SIGGRAPH/EUROGRAPHICS conference on Graphics hardware*, San Diego, California, pages 92-101. Eurographics Association, 2003.
- [Harris02] M. J. Harris, G. Coombe, T. Scheuermann, and L. Lasta. Physically-based visual simulation on graphics hardware. In *SIGGRAPH/Eurographics Workshop on Graphics Hardware*, Saarbrücken, Germany, pages 109-118. Eurographics Association, 2002.
- [Heckbert91] P. Heckbert and H. Moreton. Interpolation for polygon texture mapping and shading. In *State of the Art in Computer Graphics: Visualization and Modeling*, pages 101-111. Springer-Verlag, 1991.
- [Klein02] F. M. A. D. Heide, J. Klein, K. Krokowski, M. Fischer, M. Wand, and R. Wanka. The randomized sample tree: A data structure for interactive, 19 2002.
- [Heidrich99] W. Heidrich, R. Westermann, H.-P. Seidel, and E. Ertl. Applications of pixel textures in visualization and realistic image synthesis. In *ACM Symposium on Interactive 3D Graphics*. ACM/Siggraph, 1999.

- [Henzal01] K. Henzal. *Aerodynamika větrání*. Vydavatelství ČVUT Praha, 2001.
- [Hietinger00] B. H. Hietinger, T. Solberg, and M. Mathiesen. Predictions of gas/particle flow with an eulerian model including a realistic particle size distribution, 24 2000.
- [Hrdlicka04] F. Hrdlicka, P. Slavík, O. Kubelka, and P. Hartel. New methodology for design of moving bed filters. *WIT Transactions on Ecology and the Environment*, 2004(78):57-65, 2004.
- [Hrdlicka96] F. Hrdlicka, P. Slavík, and O. Kubelka. Simulation model of the moving granular bed gas cleanup filter. *Air Pollution*, 8:573-582, 2000.
- [Ibarría03] L. Ibarria, P. Lindstrom, R. Rossignac, and A. Szymczak. Out-of-core compression and decomposition of large n-dimensional scalar fields. *Computer Graphics Forum*, 22(3):343-343, 2003.
- [Ihm04] I. Ihm, B. Kang, and D. Cha. Animation of reactive gaseous fluids through chemical kinetics. In *SCA '04: Proceedings of the 2004 ACM SIGGRAPH/Eurographics symposium on Computer animation*, Grenoble, France, pages 203-212, 2004.
- [Ihite04] I. Ihite and M. Magnot. Image-based tomographic reconstruction of flames. In *SCA '04: Proceedings of the 2004 ACM SIGGRAPH/Eurographics symposium on Computer animation*, Grenoble, France, pages 365-373, 2004.
- [FluentMan-WWW] Information server FSI CTU. Complete gambit, FLUENT and ANSYS documentation at fsid. <http://www.fsid.cvut.cz/man>.
- [iLight-WWW] Intelligent Light company. Fieldview 8 web site. <http://www.ilight.com/>.
- [Irrerane97] V. Irrerane and C. Grosch. Strategies for effectively visualizing 3D flow with volume LIC. In *Proceedings of Visualization '97*, pages 421-424, 1997.
- [Jensen02] H. W. Jensen and J. Buhler. A rapid hierarchical rendering technique for translucent materials. In J. Hughes, editor, *SIGGRAPH 2002 Conference Proceedings*, Annual Conference Series, pages 576-581. ACM Press/ACM SIGGRAPH, 2002.
- [Jobard02] B. Jobard, G. Eitelbacher, and M. Y. Hussaini. Lagrangian-eulerian advection of noise and dye textures for unsteady flow visualization. *IEEE Trans. Vis. Comput. Graph.*, 8(3):211-222, 2002.
- [Jobard97] B. Jobard and W. Lefter. The motion map: efficient computation of steady flow animations. In *Proceedings of the 5th conference on Visualization '97*, Phoenix, Arizona, United States, pages 323-328. IEEE Computer Society Press, Los Alamitos, US, 1997.
- [Jobard00] B. Jobard and W. Lefter. Unsteady flow visualization by animating evenly-spaced streamlines. In *Computer Graphics Forum (Proceedings of Eurographics 2000)*, volume 19 of 3. Blackwell Publishers, 2000.
- [Kadlec04] P. Kadlec, M. Gayer, and P. Slavík. Visualization using hardware accelerated spline interpolation. In V. Škala, editor, *WSCG Short Communication Papers proceedings*, Pilsen, Czech republic. UNION Agency - Science Press, Pilsen, Czech Republic, 2004.
- [Kass90] M. Kass and G. Miller. Rapid, stable fluid dynamics for computer graphics. In *Proceedings of the 17th annual conference on Computer graphics and interactive techniques*, pages 49-57, 1990.
- [Kirby99] R. M. Kirby, H. Marmaris, and D. H. Laidlaw. Visualizing multivalued data from 2d incompressible flows using concepts from painting. In *Proceedings of the conference on Visualization '99 : Celebrating ten years*, San Francisco, California, United States, pages 333-340. IEEE Computer Society Press, 1999.
- [Klassen00] T. Klassen and K. Gomer. The use of cid for the prediction of problem areas inside a waste incinera-

- tor with regard to slagging, fouling and corrosion. In *5 th European Conference on Industrial Furnaces and Boilers*, 2000.
- [Kozel00] K. Kozel. *Numerické řešení parciálních diferenciálních rovnic*. Vydavatelství ČVUT Praha, 2000.
- [Kozel01] K. Kozel. *Numerické metody řešení problémů proudění I*. Vydavatelství ČVUT Praha, 2001.
- [Krevel04] M. V. Krevel. Efficient methods for isoline extraction from a digital elevation model based on triangulated irregular networks. In *Sixth International Symposium on Spatial Data Handling*, volume 2, pages 835-847, Edinburgh, Scotland, 1994.
- [Kuester01] F. Kuester, R. Bruckshen, B. Hamann, and K. I. Joy. Visualization of particle traces in virtual environments. In *Proceedings of the ACM symposium on Virtual reality software and technology*, Banff, Alberta, Canada, pages 151-157, 2001.
- [Lamorlette02] A. Lamorlette and N. Foster. Structural modeling of flames for a production environment. In *Proceedings of the 29th annual conference on Computer graphics and interactive techniques*, San Antonio, Texas, pages 729-735, 2002.
- [Lane97] D. A. Lane. Scientific visualization of large-scale unsteady fluid flows, 23 1997.
- [Langtangen01] H. P. Langtangen and O. Munthe. Solving systems of partial differential equations using object-oriented programming techniques with coupled heat and fluid flow as example. *ACM Transactions on Mathematical Software*, 27(1):1-26, 2001.
- [Laramee04a] R. S. Laramee, H. Hauser, H. Doleisch, P. Post, B. Vrolijk, and D. Weiskopf. The State of the Art in Flow Visualization: Dense and Texture-Based Techniques. *Computer Graphics Forum*, 23(2):203-221, 2004.
- [Laramee04b] R. S. Laramee. *Interactive 3D Flow Visualization Using Textures and Geometric Primitives*. PhD thesis, Vienna University of Technology, Institute for Computer Graphics and Algorithms, Vienna, Austria, 2004.
- [Laszlo92] M. J. Laszlo. Fast generation and display of iso-surface wireframes. *CVGIP: Graph. Models Image Process.*, 54(6):473-483, 1992.
- [Lefter04] W. Lefter, B. Jobard, and C. Leduc. High-quality animation of 2d steady vector fields. *IEEE Trans. Vis. Comput. Graph.*, 10(1):2-14, 2004.
- [Lichtenbelt98] B. Lichtenbelt, R. Crane, and S. Naqvi. *Introduction to volume rendering*. Prentice-Hall, Inc., 1998.
- [Liu04] Y. Liu, X. Liu, and E. Wu. Real-time 3d fluid simulation on gpu with complex obstacles. In *Pacific Conference on Computer Graphics and Applications*, pages 247-256, 2004.
- [Liu03] Z. Liu, R. J. Moorhead, and S. B. Ziegeler. Ocean flow visualization in virtual environment. Technical Report MSSU-COE-ERC-03-03, Engineering Research Center, Mississippi State University, 2003.
- [Liu02] Z. Liu and I. Robert James Moorhead. Aulife: an accelerated algorithm for unsteady flow line integral convolution. In *VISSYM '02: Proceedings of the symposium on Data Visualisation 2002*, Barcelona, Spain, pages 43-ff. Eurographics Association, 2002.
- [Liu03] W. Li, Z. Fan, X. Wei, and A. Kaufman. Gpu-based flow simulation with complex boundaries. Technical Report 031105, Computer Science Department, SUNY at Stony Brook, 2003.
- [Loeffelmann97] H. Löffelmann, L. Mroz, G. Groeller, and W. Purgathofer. Stream arrows: enhancing the use of stream surfaces for the visualization of dynamical systems. *The Visual Computer*, 13(8):359-369, 1997. ISSN

- 0178-2789.
- [Lokovic00] T. Lokovic and E. Yeach. Deep shadow maps. In K. Akeley, editor, *Siggraph 2000, Computer Graphics Proceedings*, Annual Conference Series, pages 385-392. ACM SIGGRAPH / Addison Wesley Longman, 2000.
- [Lum01] E. B. Lum, K. L. Ma, and J. Clyne. Texture hardware assisted rendering of time-varying volume data. In *Proceedings of the conference on Visualization 2001*, San Diego, California, pages 263-270. IEEE Computer Society Press, 2001.
- [Machiraju98] R. Machiraju, Z. Zhu, B. Fry, and R. Moorhead. Structure-significant representation of structured datasets. *IEEE Transactions on Visualization and Computer Graphics*, 4(2):117-132, 1998.
- [Mason98] W. Mason, N. Jackie, T. Davis, D. Shreiner, and OpenGL. Architectural Review Board. *The OpenGL Programming Guide*. Addison-Wesley, 1998.
- [Matusch03] O. Matusch, T. Theußt, H. Hauser, and E. Gröler. Strategies for interactive exploration of 3d flow using evenly-spaced illuminated streamlines. In *SCCG '03: Proceedings of the 19th spring conference on Computer graphics*, Budmerice, Slovakia, pages 213-222, 2003.
- [Max94] N. Max, R. Crawfis, and C. Grant. Visualizing 3d velocity fields near contour surfaces. In *VIS '94: Proceedings of the conference on Visualization '94*, Washington, D.C., pages 248-255. IEEE Computer Society Press, 1994.
- [Ma00] K.-L. Ma and D. M. Camp. High performance visualization of time-varying volume data over a wide-area network status. In *Proceedings of Supercomputing 2000 (CD-ROM)*, Dallas, TX, 2000. IEEE and ACM SIGARCH. Univ. of California, Davis.
- [Ma99] K. Ma, D. Smith, M. Shih, and H. Shen. Efficient encoding and rendering of time-varying volume data. ICASE Report No. 98-22. NASA/CR-1998-208424, Institute for Computer Applications in Science and Engineering, NASA Langley Research Center, 1998. Presented at SIGGRAPH 99.
- [McAllister00] D. McAllister. The design of an api for particle systems, 2000.
- [Most00] J.-M. Most, P. Trouillet, P. Mandin, F. Marchand, C. Le-Masson, P. Wilwicz, and D. Rempelberg. Development of a ldy probe for velocity measurements in a 600 mw pulverized coal power plant. In *10th International Symposium of Applications of Laser Techniques to Fluid Mechanics*, 2000.
- [Nguyen02] D. Q. Nguyen, R. Fedkiw, and H. W. Jensen. Physically based modeling and animation of fire. In *Proceedings of the 29th annual conference on Computer graphics and interactive techniques*, San Antonio, Texas, pages 721-728. ACM Press, 2002.
- [O'Brien95] J. F. O'Brien and J. K. Hodgins. Dynamic simulation of splashing fluids. In *CA '95: Proceedings of the Computer Animation*, page 198. IEEE Computer Society, 1995.
- [Pighin04] F. Pighin, J. M. Cohen, and M. Shah. Modeling and editing flows using advected radial basis functions. In *SCA '04: Proceedings of the 2004 ACM SIGGRAPH/Eurographics symposium on Computer animation*, Grenoble, France, pages 223-232. ACM Press, 2004.
- [Polthier00] K. Polthier and E. Preu. Variational approach to vector field decomposition, 29 2000.
- [Post03] F. H. Post, B. Vrolijk, H. Hauser, L. Laminee, and H. Doleisch. The State of the Art in Flow Visualization: Feature Extraction and Tracking. *Computer Graphics Forum*, 22(4):775-792, 2003. forthcoming.
- [Preuss99] T. Preuter and M. Rumpf. Anisotropic nonlinear diffusion in flow visualization. In D. Ebert, M. Gross, and B. Hamann, editors, *IEEE Visualization '99*, pages 325-332. San Francisco, 1999. IEEE.

- [Rais97] D. Rais. Visualization of combustion processes in fluidized bed boilers. Master's thesis, CTU FEE Prague, 199.
- [Rasmussen04] N. Rasmussen, D. Enright, D. Nguyen, S. Marino, N. Summer, W. Geiger, S. Hoon, and R. Fedkiw. Directable photorealistic liquids. In *SCA '04: Proceedings of the 2004 ACM SIGGRAPH/Eurographics symposium on Computer animation*, Grenoble, France, pages 193-202, 2004.
- [Rasmussen03] N. Rasmussen, D. Q. Nguyen, W. Geiger, and R. Fedkiw. Smoke simulation for large scale phenomena. In J. Hodgins and J. C. Hart, editors, *Proceedings of ACM SIGGRAPH 2003*, volume 22(3) of *ACM Transactions on Graphics*, pages 708-715, 2003.
- [Reeves83] W. T. Reeves. Particle systems - a technique for modeling a class of fuzzy objects. In *Proceedings of SIGGRAPH 83*, vol. 17, n. 3, pages 359-376. ACM Computer Graphics, 1983.
- [Rhodes98] M. Rhodes. *Introduction to particle technology*. John Wiley Sons Ltd., 1998.
- [Mage1995] B. Ristio, H. C. Mage1, K. R. G. Hein, S. Schneider, and U. Schnell. Numerical simulation of utility boilers with advanced combustion technologies, 11 1997.
- [Robbins00] K. A. Robbins and M. Gorman. Fast visualization methods for comparing dynamics: A case study in combustion. In *Proceedings of the 11th IEEE Visualization 2000 Conference (VIS 2000)*, IEEE Computer Society, 2000.
- [Roettger03] S. Roettger, S. Guthe, D. Weiskopf, T. Ertl, and W. Strasser. Smart hardware-accelerated volume rendering. In C. D. H. G.-P. Bonneau, S. Hammann, editor, *Proceedings of the symposium on Data visualisation 2003*, Grenoble, France, pages 231-238. Eurographics Association, 2003.
- [Sadarjoen98] I. A. Sadarjoen, A. J. de Boer, F. H. Post, and A. E. Mynett. Particle tracing in σ -transformed grids using tetrahedral 6-decomposition. In D. Bartz, editor, *Visualization in Scientific Computing '98*, Eurographics, pages 71-80. Springer-Verlag Wien New York, 1998.
- [Sadarjoen99] I. Sadarjoen and F. Post. Geometric Methods for Vortex Detection, pages 53-62, 1999.
- [Sanna00] A. Sanna, B. Montucchio, and R. Arina. Visualizing unsteady flows by adaptive streaklines, 22 2000.
- [Sapedo01] J. SAPEDE, J.-L. HARRION, S. CAILLAT, and B. BAUDOUIN. Complex coaxial rectangular jet with density differences : Numerical simulations vs. experimental data. In *Proceedings of the 2nd International Conference on Computational Heat and Mass Transfer*, 2001.
- [Sayre99] A. Sayre and M. Miliobowski. Validation of numerical models of flow through set units. In *EPRI-DOE-EP4 Combined Utility Air Pollution Control Symposium*, 1999.
- [Schroeder96] W. J. Schroeder, K. M. Martin, and W. E. Lorenson. The design and implementation of an object-oriented toolkit for 3D graphics and visualization. In R. Yagel and G. M. Nielson, editors, *IEEE Visualization '96*, pages 93-100, 1996.
- [Schulz99] M. Schulz, F. Reck, W. Barthelemer, and T. Ertl. Interactive visualization of fluid dynamics simulations in locally refined cartesian grids (case study). In *Proceedings of the conference on Visualization '99 : Celebrating ten years*, San Francisco, California, United States, pages 413-416. IEEE Computer Society Press, 1999.
- [Shen99] H.-W. Shen, L.-J. Chiang, and K.-L. Ma. A fast volume rendering algorithm for time-varying fields using a time-space partitioning (TSP) tree. In D. Ebert, M. Gross, and B. Hamann, editors, *IEEE Visualization '99*, pages 371-378. San Francisco, 1999. IEEE.
- [Shen96] H.-W. Shen, C. R. Johnson, and K.-L. Ma. Visualizing vector fields using line integral convolution and

- dye advection. In *Proceedings of the 1996 symposium on Volume visualization*, San Francisco, California, United States, pages 63-67. IEEE Press, 1996.
- [Shen97] H.-W. Shen and D. L. Kao. UFLIC: A line integral convolution algorithm for visualizing unsteady flows. In R. Yagel and H. Hagen, editors, *IEEE Visualization '97*, pages 317-323. IEEE, 1997.
- [Shen98] H.-W. Shen and D. L. Kao. A new line integral convolution algorithm for visualizing time-varying flow fields. *IEEE Transactions on Visualization and Computer Graphics*, 4:98-108, 2 1998. Abstract: <http://www.computer.org/tvcg/tg1998/v0098abs.htm>.
- [Shen04] H.-W. Shen, G.-S. Li, and U. D. Bordoloi. Interactive visualization of three-dimensional vector fields with flexible appearance control. *IEEE Transactions on Visualization and Computer Graphics*, 10(4):434-445, July Aug. 2004.
- [OGL-ExReg-WWW] Silicon Graphics, Inc. OpenGL® Extension Registry. <http://oss.sgi.com/projects/ogl-sample/registry/>.
- [Slavik99] P. Slavik. Scientific visualization as a tool for power engineering education. In *Gve '99 Computer Graphics And Visualization Education '99*, pages 165-170, 1999. http://www.siggraph.org/education/conferences/GVE99/papers/GVE99_P_Slavik.pdf.
- [Sobel04] J. S. Sobel, A. S. Forsberg, L. Laidlaw, R. C. Zelezniak, D. F. Keefe, I. Pivkin, G. E. Karniadakis, R. Richardson, and S. Swartz. Particle flurries: Synoptic 3D pulsatile flow visualization. *IEEE Computer Graphics and Applications*, 24(2):76-85, 2004.
- [Sohn02] B.-S. Sohn, C. Bajaj, and S. Siddavanahalli. Feature based volumetric video compression for interactive playback. In S. N. Spencer, editor, *Proceedings of the 2002 IEEE symposium on Volume visualization and graphics (IOLVIS-02)*, pages 89-96, Piscataway, NJ, 28-29 2002. IEEE.
- [Stalling95] D. Stalling and H. Hegge. Fast and resolution independent line integral convolution. In *Proceedings of the 22nd annual conference on Computer graphics and interactive techniques*, pages 249-256, 1995.
- [Stam95] J. Stam and E. Fiume. Depicting fire and other gaseous phenomena using diffusion processes. In R. Cook, editor, *SIGGRAPH 95 Conference Proceedings*, Annual Conference Series, pages 129-136. ACM SIGGRAPH, Addison Wesley, held in Los Angeles, California, 06-11 August 1995 1995.
- [Stam99] J. Stam. Stable fluids. In *Proceedings of Computer Graphics and interactive techniques*, volume 33, pages 121-128. ACM Press, 1999.
- [Stam00] J. Stam. Interacting with smoke and fire in real time. *Communications of the ACM*, 43(7):76-83, 2000.
- [Stam01] J. Stam. A simple fluid solver based on the FFT. *Journal of Graphics Tools: JGT*, 6(2):43-52, 2001.
- [Stam03a] J. Stam. Flows on surfaces of arbitrary topology. *ACM Trans. Graph.*, 22(3):724-731, 2003.
- [Stam03b] J. Stam. Real-time fluid dynamics for games, 2003.
- [Stock02] M. J. Stock. Creative flow visualization using a physically accurate lighting model. In *2nd Conference on Computational Semantics for Games and New Media*, pages 77-83, 2002.
- [Swann91] P. Swann and S. Sennar. Volume rendering of flow-visualization point data. In *In Proceedings of IEEE Visualization '91*, pages 25-32. IEEE Computer Society Press, Los Alamitos, CA, 1991.
- [Takai95] Y. Takai, K. Echū, and N. Takai. A cellular automaton model of particle motions and its applications. *The Visual Computer*, 11(5):240-252, 1995.

- [Taponecco03] F. Taponecco and M. Alexa. Vector field visualization using markov random field texture synthesis. In C. D. H. G.-P. Borneau, S. Hahmann, editor, *Proceedings of the symposium on Data visualisation 2003*, Grenoble, France, pages 195-202. Eurographics Association, 2003.
- [Tele94] A. Telea and J. J. van Wijk. Simplified representation of vector fields. In *Proceedings of the conference on Visualization '99 : Celebrating ten years*, San Francisco, California, United States, pages 35-42. IEEE Computer Society Press, 1999.
- [Tele03] A. Telea and J. J. van Wijk. 3D IBFV: Hardware-accelerated 3D flow visualization. In *Proceedings of the IEEE Visualization '03*. ACM Press, 2003.
- [Teyssler88] J. Teyssler. *Spolovní popelných hřetých uhlí*. SNTL Praha, 1988.
- [Theisel03] H. Theisel and H.-P. Seidel. Feature flow fields. In C. D. H. G.-P. Borneau, S. Hahmann, editor, *Proceedings of the symposium on Data visualisation 2003*, Grenoble, France, pages 141-148. Eurographics Association, 2003.
- [Smith-WWW] The University of Utah. Combustion research group. <http://www.combustion.utah.edu>.
- [Tomeczek95] J. Tomeczek. *Coal Combustion*. Krieger Publishing Company, 1994.
- [Treuille03] A. Treuille, A. McNamara, P. Popovic, and J. Stam. Keyframe control of smoke simulations. In J. Hodgins and J. C. Hart, editors, *Proceedings of ACM SIGGRAPH*, volume 22(3) of *ACM Transactions on Graphics*, pages 716-723, 2003.
- [Upson89] C. Upson, J. T. Faulhaber, D. Kamins, D. Laidlaw, D. Schlegel, J. Vroom, R. Gurwitz, and A. van Dam. The application visualization system: A computational environment for scientific visualization. *IEEE Computer Graphics and Applications*, 9(4):30-42, 1989.
- [Gelder92] A. van Gelder and J. Wilhelms. Interactive visualization of flow fields. In *Proceedings of the 1992 workshop on Volume visualization*, Boston, Massachusetts, United States, pages 47-54, 1992.
- [Wijk91] J. J. van Wijk. Spot noise texture synthesis for data visualization. In *Proceedings of the 18th annual conference on Computer graphics and interactive techniques*, pages 309-318, 1991.
- [Wijk02] J. J. van Wijk. Image based flow visualization. In *Proceedings of the 29th annual conference on Computer graphics and interactive techniques*, San Antonio, Texas, pages 745-754, 2002.
- [Post02] B. Vrolijk, F. H. Post, H. Doleisch, H. Hauser, and R. S. Laramée. EUROGRAPHICS 2002 STAR - state of the art report feature extraction and visualisation of flow fields, 08 2002.
- [Warnatz95] J. Warnatz, U. Maas, and R. Dibble. *Combustion Physical and Chemical Fundamentals, Modelling and Simulation, Experiments, Pollutant Formation*. Springer-Verlag Berlin Heidelberg, 1995.
- [Waterman00] P. J. Waterman. CFD in the trenches - desktop engineering. <http://www.desking.com/articles/00/July/CFD/index.htm>, 2000.
- [Wegenkittl97a] R. Wegenkittl, E. Grolzer, and W. Purgathofer. Animating flow fields: Rendering of oriented line integral convolution. In *C4 '97: Proceedings of the Computer Animation*, page 15. IEEE Computer Society, 1997.
- [Wegenkittl97b] R. Wegenkittl and E. Grolzer. Fast oriented line integral convolution for vector field visualization via the internet. In *IEEE Visualization '97 Proceedings*, pages 309-316. IEEE Computer Society, 1997 1997.
- [Weimer99] H. Weimer and J. Warren. Subdivision schemes for fluid flow. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, Malaga, Spain, pages 111-120, 1999.

- [Weiskopf03] D. Weiskopf, G. Ertlbacher, and T. Ertl. A Texture-Based Framework for Space-time-Coherent Visualization of Time-Dependent Vector Fields. In *Proceedings of IEEE Visualization '03*, pages 107-114, 2003.
- [Weiskopf04a] D. Weiskopf and T. Ertl. GPU-based 3D texture advection for the visualization of unsteady flow fields. In V. Skala, editor, *WSCG Short Communication Papers proceedings*. UNION Agency - Science Press, Pízen, Czech Republic, 2004.
- [Weiskopf01] D. Weiskopf, M. Hopf, and T. Ertl. Hardware-accelerated visualization of time-varying 2D and 3D vector fields by texture advection via programmable per-pixel operations. In T. Ertl, B. Girod, G. Greiner, H. Niemann, and H.-P. Seidel, editors, *Proceedings of the Vision, Modeling, and Visualization VMV'01 Conference*, Stuttgart, Germany, pages 439-446, 2001.
- [Weiskopf04b] D. Weiskopf, T. Schaffitzel, and T. Ertl. Gpu-based nonlinear ray tracing. *Comput. Graph. Forum*, 23(3):625-634, 2004.
- [Chiang01] B. Wei, C. T. Silva, and R. Farnas. A unified infrastructure for parallel out-of-core isosurface extraction and volume rendering of unstructured grids, 06 2001.
- [Wei03] X. Wei, W. Li, and A. Kaufman. Melting and flowing of viscous volumes. In *CASA '03: Proceedings of the 16th International Conference on Computer Animation and Social Agents (CASA 2003)*, page 54. IEEE Computer Society, 2003.
- [Wei02] X. Wei, W. Li, K. Mueller, and K. Kaufman. Simulating fire with texture splats. In R. Moorhead, M. Gross, and K. I. Joy, editors, *Proceedings of the 13th IEEE Visualization 2002 Conference (VIS-02)*, pages 227-234, Piscataway, NJ, 27-2002. IEEE Computer Society.
- [Wei04] X. Wei, Y. Zhao, Z. Fan, W. Li, F. Qiu, S. Yoakum-Stover, and K. Kaufman. Lattice-based flow field modeling. *IEEE Transactions on Visualization and Computer Graphics*, 10(6):719-729, 2004.
- [Weichert91] J. Weichert and D. Haumann. Animation aerodynamics. In *Proceedings of the 18th annual conference on Computer graphics and interactive techniques*, pages 19-22, 1991.
- [Westermann00] R. Westermann, C. Johnson, and T. Ertl. A level-set method for flow visualization. In *Proc. of the 11th Ann. IEEE Visualization Conference (Vis) 2000*, pages 147-154, 2000.
- [Wischgoll02] T. Wischgoll and G. Scheuermann. Locating closed streamlines in 3D vector fields. In *Proceedings of the symposium on Data visualisation 2002*, Barcelona, Spain, pages 227-232. Eurographics Association, 2002.
- [Witting99] P. Witting. Computational fluid dynamics in a traditional animation environment. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, pages 129-136, 1999.
- [Wu04] E. Wu, Y. Liu, and X. Liu. Journal of computer animation and virtual world. *Communications of the ACM*, 15(3-4):139-146, 2004.
- [Yoshida00] S. Yoshida and T. Nishita. Modelling of smoke flow taking obstacles into account. In *8th Pacific Conference*, pages 135-144, 2000.
- [Zhao03] Y. Zhao, X. Wei, Z. Fan, A. Kaufman, and H. Qin. Voxels on fire. In *IEEE Visualization 2003*, San Diego, California, pages 271-278. Eurographics Association, 2003.
- [Zockler96] M. Zockler, D. Stalling, and H. C. Hege. Interactive visualization of 3d-vector fields using illuminated stream lines. In *Proceedings of the conference on Visualization '96*, San Francisco, California, United States, pages 107-113. IEEE Computer Society Press, 1996.

7 Publications of the author

Publications in refereed journal papers

- [Gayer02a] M. Gayer, F. Hrdlička, and P. Slavík. Dynamic visualisation of the combustion processes in boilers. *Journal of WSCG*, pages 25-32, 2002.

Publications on international conferences

- [Gayer02a] M. Gayer, F. Hrdlička, and P. Slavík. Dynamic visualisation of the combustion processes in boilers. *Journal of WSCG*, pages 25-32, 2002.
- [Gayer02b] M. Gayer, P. Slavík, and F. Hrdlička. Interactive system for pulverized coal combustion visualization with fluid simulator. In *Proceedings of the Visualization, Imaging, and Image Processing Conference*, Pilsen, Czech republic, pages 288-293. IASTED, Anaheim: Acta Press, 2002.
- [Gayer03a] M. Gayer, P. Slavík, and F. Hrdlička. Real-time simulation and visualization using pre-calculated fluid simulator states. In *Proceedings of the Visualization, Imaging, and Image Processing Conference*, London, UK, pages 440-445. IEEE Computer Society Press, Los Alamitos, 2003.
- [Gayer03b] M. Gayer and P. Slavík. Pre-calculated fluid simulator states tree. In *Proceedings of 12th IASTED International Conference on Applied Simulation and Modeling*, Marbella, Spain, pages 610-615. IASTED, Anaheim: Acta Press, 2003.
- [Gayer03c] M. Gayer, P. Slavík, and F. Hrdlička. Interactive educational system for coal combustion modeling in power plant boilers. In *Proceedings of the EUROCON 2003 - Computer as a Tool*, Ljubljana, Slovenia, volume 2, pages 220-224. IEEE Computer Society Press, 2003.
- [Gayer03f] M. Gayer. Modeling and visualization of combustion using fluid simulator and particle systems. In *Proceedings of the International Conference and Competition STUDENT EICIT 2003*, pages 306-309. VUT Brno, 2003.
- [Slavik03] P. Slavík, M. Gayer, F. Hrdlička, and O. Kubelka. Problems of visualization of technological processes. In *Proceedings of the 2003 Winter Simulation Conference*, pages 746-754. IEEE, VA: Omnipress, 2003.
- [Gayer04a] M. Gayer and P. Slavík. Hierarchical trees of unsteady simulation datasets. In *Proceedings of 13th IASTED International Conference on Applied Simulation and Modeling*, Rhodes, Greece, pages 303-308. IASTED, Anaheim: Acta Press, 2004.
- [Kadlec04] P. Kadlec, M. Gayer, and P. Slavík. Visualization using hardware accelerated spline inter-

polation. In V. Skala, editor, *WSCG Short Communication Papers proceedings*, Pilsen, Czech republic, UNION Agency - Science Press, Pizeň, Czech Republic, 2004.

Other publications

[Gayer00] M. Gayer. MGL graphics library. In *User Interfaces Visualization, 8th Bilateral student workshop*. HTW Dresden, 2000.

[Gayer01] M. Gayer and M. Snorek. Modern graphical accelerators. *Software noviny*, 12(7):72-84, 2001.

[Gayer02c] M. Gayer. Simulation and visualization of combustion processes in pulverized coal boilers. In *Proceedings of Workshop 2002*, volume B, pages 782-783. CTU in Prague, 2002.

[Gayer02d] M. Gayer. Coal combustion processes visualisation using particle system. In *Proceedings of CTU Poster 2002*. CTU in Prague, 2002.

[Gayer02e] M. Gayer and P. Slavík. Interactive simulation of pulverized coal combustion. In *User Interfaces Visualization, 10th Bilateral student workshop*. HTW Dresden, 2002.

[Gayer03d] M. Gayer. Simulation and visualization of combustion processes in pulverized coal boilers. In *Proceedings of Workshop 2003*. CTU in Prague.

[Gayer03e] M. Gayer. Simulation and visualization of combustion powered by fluid simulator. In *Proceedings of Poster 2003*, page PE10. CVUT FEE Prague, 2003.

[Gayer04b] M. Gayer. Fast simulation of fluids. In *Proceedings of Workshop 2004*. CTU in Prague, 2004.

8 Abstract

Nowadays, complex simulation programs are used for modelling of combustion processes in power plant boilers. They allow designers to experiment extensively with the computer models of the boilers without necessity to build their physical models. These simulation methods are widely used and several program packages (e.g. FLUENT) are available on the market. The use of these systems led to increased quality of the design and their use has been widely adopted by designers around the world. General disadvantage of these simulation programs is the complexity of simulation, which results in very time-consuming calculations. This situation does not allow quickly investigate various conditions in the boiler and the results of parameter changes during the combustion process and study in the real-time the dynamics of the combustion process.

We present techniques, which together form a solution allowing real-time simulation and visualization of these processes. We propose simplified fluid flow and combustion process computation. We use structured cell representation of the combustion space. We use fast fluid simulation, based on Euler equation and continuity equation. Thus, for the specified time step, we compute changes of the mass flow pressure, velocity and other characteristics inside each cell. The changes of the cell characteristic are also based on the characteristics of the nearest neighbours of the cell. The results of the flow simulation are immediately used for the other parts of the computation.

The concept of the virtual coal particles, based on the interaction of the air mass inside the cell with the coal particles, allows fast combustion simulation. It also gives possibility of easy tracking of the flow of combustibles and thus visualizing dynamics of the entire combustion process.

We also describe our concept of pre-calculated Fluid Simulator States. It is an extension for structured fluid simulators and solvers, which are used widely in computer graphics and simulation applications. It is based on storing pre-calculated fluid simulator states (FSS). The simulation using our extension is based on partial computation with synchronous utilization of pre-calculated fluid simulator states stored on high-capacity disk drives. The disk space requirements are less demanding by several orders than the ones needed for saving corresponding unsteady data sets. This allows better scalability and storing and replaying results of complex tasks with large grids and/or ten thousands of particles.

We organize pre-calculated Fluid Simulator States (FSS) in hierarchical tree structures allowing incremental solving, interactive replaying and modifications of the simulated tasks. Thus, the parameters and boundary conditions of the simulation can be modified in real-time during replaying. We proposed hierarchical tree structures with Unsteady (time-varying) Datasets, which brings interesting interactive features to applications using these datasets.

We have also proposed, designed and implemented visualization of the results from our fluid simulator. We use the OpenGL graphics library for fast and portable visualization of our results, including fast visualization of virtual coal particle system and high quality and grid cell visualization using interpolation using bicubic splines. For that purpose, we developed hardware-accelerated visualization using the current generation of graphics accelerators. The presented method offers real-time rendering of grid-structured data. The method uses bicubic spline interpolation running on common current graphics hardware to map numeric values to a texture. It allows us also to render isolines of the visualized data and dynamically change the visualization parameters. We have compared the visual quality of produced images with the commonly used linear interpolation visualization methods.

The implementation of the above-described techniques has been used to develop the application *My Pulverized Coal Combustion*, which allows real-time interaction with the boiler model – e.g. changing up the inlet characteristic, such as mass flow of the air and coal, velocity of the flow, positions without need to restart the simulation. A low-cost hardware is used to perform all computations and render the visualization. The overall solution allows real-time, immediate interaction of the user during simulation and visualization – e.g. changing coal inlets, combustible properties and other input parameters during simulation. The solution allows real-time monitoring of about 50 basic cell volumes characteristics and statistics inside the boiler, and about 10 pulverized coal particle characteristics. All these features are available immediately, without need to wait hours for complex calculations to finish. Our solution is especially suitable for education purposes in power engineering.

The concept of our fluid simulator and the other techniques are implemented in 2D. They may be used in general fluids computation and modelling, thus not only for the combustion applications. The components have been designed as independent blocks reusable in other projects.

Keywords: Combustion, Visualization, Particle systems, Simulation, Unsteady datasets, Hardware acceleration, Education

Abstrakt

V současné době se pro modelování spalovacích procesů v elektrárnách kotlích používají komplexní simulační programy. Ty umožňují návrhářům provádět experimenty s počítačovými modely kotlů bez nutnosti konstrukce jejich modelů. Tyto simulační metody jsou široce používány a různé programové balíky (jako např. FLUENT) jsou dostupné na trhu. Použití těchto systémů vedlo ke zvýšení kvality designu a jejich používání bylo široce přijato návrháři kotlů po celém světě. Obecnou nevýhodou těchto simulačních programů je složitost simulace, která má za následek velmi časově náročné výpočty. Tato situace nedovoluje rychle vyšetřovat různé podmínky v kotli a výsledky změn parametrů během spalovacího procesu, ani studovat v reálném čase dynamiku spalovacích procesů.

V této disertaci představujeme techniky, které společně vytvářejí řešení umožňující v reálném čase simulovat a vizualizovat tyto procesy. Navrhujeme řešení založené na výpočtech zjednodušeného fluidního proudění a spalovacích procesů. Používáme strukturovanou reprezentaci buněk mřížky spalovacího prostoru. Používáme rychlou fluidní simulaci, založenou na ruletové rovnici a rovnici kontinuity. Takto, ve specifickém časovém kroku počítáme v proudící hmoty změnu tlaku, rychlosti a dalších charakteristik uvnitř buněk. Změny charakteristik buněk jsou také odvozeny od charakteristik nejbližších sousedů dané buněk. Výsledky fluidní simulace jsou ihned použity v dalších částech výpočtu.

Koncepci virtuálních částic, založených na interakci vzduchu uvnitř buněk s částicemi uhlí, umožňuje rychlý výpočet spalování. To umožňuje možnost snadno sledovat proudění spalín a umožňuje vizualizaci dynamiky celého spalovacího procesu.

Také popisujeme náš koncept předpočítaných stavů fluidního simulátoru (FSS). Jde o extensi pro strukturované fluidní simulátory a řešiče, které jsou široce používány v počítačové grafice a simulačních aplikacích. Základem je ukládání předpočítaných stavů fluidního simulátoru. Simulace s použitím naší extenze je založena na částicím výpočtu se současným využitím předpočítaných stavů uložených na vysoce kapacitních discích. Nároky na diskový prostor jsou řádově menší než nároky potřebné pro uložení odpovídajících datových souborů pro časové proměnnou simulaci. To umožňuje lepší škálovatelnost a ukládání a přehrávání výsledků složitých úloh s rozsáhlými mřížkami a/nebo deskami tisíc částic.

Předpočítané stavy uspořádávané do hierarchických stromových struktur umožňující postupné řešení, interaktivní přehrávání a změnu simulovaných úloh. Takto, parametry a hranici podmínek simulace mohou být měněny v reálném čase během přehrávání. Navrhli jsme také hierarchické stromové struktury s časové proměnnými datovými soubory, které přinášejí zajímavé interaktivní možnosti do aplikací, které používají tyto datasey.

Navrhli jsme a implementovali vizualizaci výpočtaných výsledků z našeho fluidního simulátoru. Používáme grafickou knihovnu OpenGL pro rychlou a přesnou vizualizaci našich výsledků, včetně rychlé vizualizace virtuálních uhelných částic a velmi kvalitní vizualizaci mřížky buněk s použitím interpolace pomocí bikubických křivek. Pro tento účel jsme vyvinuli hardwarově akcelerovanou vizualizaci s použitím současné generace grafických akceleratorů. Předložení metoda nabízí renderování mřížky strukturovaných dat v reálném čase. Metoda používá interpolace pomocí bikubických křivek, a využívá možnosti grafického hardwaru mapovat numerické hodnoty do textury. To nám také umožňuje renderovat isočary vizualizovaných dat a dynamicky měnit vizualizační parametry. Porovnali jsme vizuální kvalitu vytvořených obrázků s běžně používanými metodami lineární interpolace.

Implementace výše popsaných technik byla použita pro vývoj aplikace *My Pulverized Coal Combustion*, která umožňuje v reálném čase interakci s modelem kotle – např. umožňuje změnit parametry vstupu do kotle, jako je množství vzduchu a uhlí, rychlosti proudění, umístění vstupu bez nutnosti provést restart simulace. Běžný, laciný hardwar byl použit pro provedení výpočtů a vizualizaci. Řešení umožňuje v reálném čase, okamžitou interakci uživatele s modelem během simulace a vizualizace – např. změnu vstupu uhlí, spalovacích parametrů a dalších vstupních parametrů během simulace. Řešení nabízí v reálném čase monitorovat zhruba 50 základních objemových buněk a statistik uvnitř kotle a zhruba 10 charakteristik drceného práškového uhlí. Všechny tyto možnosti jsou dostupné ihned, bez nutnosti čekat hodiny na dokončení složitých výpočtů. Naše řešení je zvláště vhodné pro výukové účely v oborech energetika.

Koncepci našeho fluidního simulátoru a ostatní techniky byly implementovány ve 2D. Mohou být použity pro obecné fluidní výpočty a modelování, tedy nejen pro spalovací aplikace. Komponenty byly navrženy jako samostatné bloky.

KLÍČOVÁ SLOVA: Spalování, Vizualizace, Čističové systémy, Simulace, Datasets, Hardwarová akcelerace, Výuka