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PROBLEMS OF VISUALIZATION OF TECHNOLOGICAL PROCESSES

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ABSTRACT

This paper deals with problems of visualization of dynamic phenomena. An effort to develop new visualization schemes has been described. The main idea is to extend approaches used in the case of visualization of phenomena of static nature into an environment where dynamic phenomena are investigated and visualized. We introduced the "level of detail" approach in time scaling in the environment of dynamic processes where time plays a primary role. In the case of visualization of dynamic phenomena the users are looking for specific dynamic patterns that should help them to understand in a better way the nature of dynamic processes under investigation. A new approach that should meet these requirements has been developed. This approach has been verified by means of two systems used for simulation and visualization of technological processes that are of a dynamic nature.

1 INTRODUCTION

Scientific visualization has proved during its existence to be superior in many applications. Without methods of scientific visualization it would not be possible to understand sets of data acquired either by measurements or by simulations. The visual presentation of data allows the user to process visually large amounts of data and thus makes it possible to discover some hidden relationships. This approach is supported by many visualization techniques developed in the last years. As the use of scientific visualization methods are more and more widely used – especially in new applications – it is obvious that the need for development of new methods for understanding data in visual form should be developed.

In this paper we give an overview of our research in the field of simulation and visualization of technological processes. We will show that the need for innovative methods in the field of scientific visualization is urgent as new problems related to visualizing and understanding data have emerged.

The main characteristics of technological processes is their dynamic behavior. As the data from most general applications can be visualized by means of static images the appropriate methods for visualization of technological processes should be developed. Some applications (will be discussed later) attempt to visualize dynamic processes, but the known approaches usually suffer from some disadvantages. Moreover most of the commercial solutions available do not cover problems for specific applications. Our attempt was to investigate problems of dynamic visualization for specific applications. This allowed us to develop and implement a specific approach where acceleration both of simulation and visualization processes could be used (which gave us an advantage over commercial solutions based on AVS and other systems).

The most important issue of this paper is definition of an approach to control visualization of dynamic processes – especially how to control time scale. This approach has been tested on two applications where technological processes were visualized under our new approach. Our solutions can serve as pilot solutions that will result in definition of research strategy for more general problems of a dynamic nature.

2 VISUALIZATION OF DYNAMIC PROCESSES

One application where problems of visualization of dynamic phenomena has been solved is cartography - see Morrison (1998). Besides visualization of standard geographical information visualized in the form of maps, the following dynamic phenomena. should also be visualized:

- Flows (of people, money, information, water, ice, lava)
- Events (forest fires, earthquakes, traffic accidents, military battles)
- Processes (global economic restructuring, global warming, stream sedimentation).

There has been an attempt to solve these sorts of problems in a systematic way that resulted in problem decomposition into several sub problems that should be treated by means of specific disciplines like cognitive sciences, human computer interaction, scientific visualization and others. We have tried to modify the schemes used in cartography to solve the above mentioned problems with schemes applicable in our field (visualization of technological processes). These problems in the field are of complex nature. On one hand it is necessary to determine how to represent dynamic phenomena to users and on the other hand how to develop methods for allowing the user to interact with these representations.

A traditional approach that covers (from our point of view to a certain extent) the need for investigation of dynamic processes is animation. The standard approach does not allow the user to manipulate interactively the course of animation presented to the user and thus the user can not study all aspects of dynamic processes under investigation. Besides this fact there are also some technical problems like time consuming calculations (both of simulation and visualization nature).

It is important to understand dynamic phenomena in specific cases when research in a specific field is being done. Another important aspect that is worth considering is the field of university education. The purpose of animation when used in an instructional setting is to serve as an aid to student learning. In order to achieve this purpose, students should be presented with the type of information that will help them to develop a conceptual understanding of the material. In our case (technological processes) the students have an idea about the nature of the process simulated and visualized from static descriptions in textbooks. They have also practical experience as they visited some sites where these processes run in reality. But this knowledge is knowledge “of the first level” only.

To understand deeply the process (running with different parameters in various environments etc.) it is necessary to get a feeling of the nature of the dynamics of the process by means of dynamic parameter and environment settings by the user. This is the specific role of animation the new visualization system should comply with. According to Morrison (1998), we can adopt an approach that could be described in the following way: Computer animation is going to become a standard tool of expression in the same way alphabets became. Animation is a potentially more complex form of illustration and as such the necessity to teach people how to utilize it may be greater than the need to teach the interpretation of illustrations.

3 SYSTEMS FOR VISUALIZATION OF TECHNOLOGICAL PROCESSES

Research at CTU Prague has been carried on in order to design and implement systems based on the above mentioned approach with the aim to develop visualization methods that support visualization of dynamics in the processes under investigations. As an example of results achieved we will describe two systems that were implemented in the (visualization) framework mentioned. These systems are used in the area of power engineering. They deal with problems of dynamic behavior of clean up filters and combustion processes.

One of the main problems we had to solve was the problem of creation of appropriate simulation model for both cases where the speed of simulation was a very important criterion. Traditional models of dynamic processes are mostly based on the use of differential equations or their systems. The main disadvantage of this approach are large time requirements. In case we would like to create an animated sequence of appropriate length we have to limit ourselves to a few examples of those sequences that can be generated within time we have at disposal. This means that we should understand the dynamics of processes on the basis of a few examples only. Because of the complex nature of these processes we can have a situation where these examples do not cover the wide spectrum of cases that describe the dynamics of the process to its full extent.

The solutions used in our case were based on a finite volume method approach and on the use of particle systems. Especially in the case of simulation and visualization of combustion process the approach used has shown itself as innovative because we used a combination of particle systems in finite element method environment. Our approach in general allows us to speed up significantly the simulation process and in such a way it makes it possible to perform many more simulations (and visualizations) than ever before. Some solutions will be less precise in comparison with sophisticated commercial products (from the point of view of analysis of single static images that are visualizations of single simulation steps) – see in the following text. But the advantage of flexible investigations of dynamics of processes significantly prevails.

4 SIMULATION AND VISUALIZATION OF DYNAMIC BEHAVIOR OF GAS FLUE FILTERS

New emerging technologies developed for efficient clean coal processing require research of phenomena used in these processes. In this paper we will deal with the problem of cleaning gas that was obtained by means of coal gasification. Realization of this process has form of filters with various properties. For in-depth coverage of these issues, see simulation texts such as Smid, Kuo, Hsiau, Wang and Chou (1997), Chou, Tseng, Smid, Kuo and Hsiau and Tsai (1999) and Hrdlicka, Kubelka and Slavik (2002).

The material with filtration capability fills the body of the filter, see Figure 6 (flow of granules) and Figure 7 (flow of gas through granules) for an illustration. In the case of static filters the material is adsorbing the dust particles and the adsorption capability quickly decreases. This is the reason why the material should move in the filter in a downward direction (as the result of gravity). At the bottom of the filter the material with a high share of dust particles is removed and is recycled (cleaned) outside the filter. The recycled material is used repeatedly in the filter.

The design of filters of this type is a rather complicated task and many parameters should be taken into account. The most important parameters are: the type of filtration material, size of filtration granules, internal filter configuration and the speed of the gas that should be cleaned – all these parameters should be visualized in some form in our system.

It is possible to say that the filtration process has several components:

- Physical component where the physical behavior of filtration granules is investigated (the speed the granules are moving downwards, creation of stagnant zones etc.). This behavior is influenced by the size of granules, the type of filtration material and the shape of the filter including the internal arrangement
- Adsorption component where the adsorption capability of the filtration material plays the decisive role. Also the speed of the gas plays an important role in this component.
- Chemical component where possible chemical reactions between the gas and flue gas into active surface of the filtration material are investigated.

4.1 Simulation Model

In our case we have developed a model where only the first two components (physical and adsorption ones) will be taken into account. This approach covers the technologies most widely used at the present time. From the point of dynamic behavior of the filter the chemical component does not play as important a role as the other two components, so we could afford to neglect it. Moreover this component requires development of a specific methodology which will be a topic for further research.

Due to the complicated nature of the problem it was necessary to solve our problem stepwise:

- The first step was development of the model that describes the mechanical behavior of filtration granules in filters with simple configuration
- The second step was development of a model that deals with the behavior of gas in the filter
- The third step was modification of the results achieved in the first step in such a way that the model deals with complex configurations of the filter.

The model developed was a 2D one in order to be able to compare results obtained from this model with the results obtained from the physical model, which is similar to concept of Hsiau and Tsai (1999) where a 2D physical model was used (Figure 6). Another reason for choosing the 2D case was the fact that the implementation of this model is considerably less demanding than the 3D one. Such an approach substantially reduces the computation time and thus allows the user to perform much more experiments within given period of time. The use of 2D models gives results that correspond very well with a real 3D filter – see Chou, Tseng, Smid, Kuo and Hsiau (1999), Smid, Kuo, Hsiau, Wang and Chou (1997).

The granules have the form of spheres with a typical diameter from 1 to 10 mm. These granules are able to adsorb dust and gas pollutants from the polluted gas that flows through the filter. Each granule was represented by an element in the filter bed. The principal assumption was that the movement of granules in the bed is the result of forces acting on each granule in the lower part of the filter. The nature of these forces is simply the weight of granules in layers above the granule in question. The solution to the problem (creating a satisfactory model) was to deal with the distribution of forces caused by the weight of granules in the filter bed. Due to the large number of granules the calculation of forces distribution was a rather time consuming process.

The model used for simulation of the movement of granules has been based on the partition of the filter volume into a finite set of volume elements. The elements have cubical form and are of the same size. This approach allowed us to deal uniformly with all elements in the filter volume which simplified the computational process. The state of a volume element is given by several parameters, like the number and positions of granules in the element. From the point of view of the adsorption process, we are interested in the parameter characterizing concentration of pollutants that is assigned to each element. This concentration is stepwise modified during the gas movement through the filter due to particle pollutants adsorption. The gas flow is modeled as the transition of concentration of pollutants between individual volume elements. The change in concentration of pollutants is determined by the number of granules in the volume element and by their adsorption capability. The adsorption capability is given by a formula (known as Dubinin linearized formula). For a more detailed overview and explanation, see Hrdlicka, Slavik and Kubelka (2001).

A complex method for simulation of behavior of granules in the filter was designed and implemented. Part of the granules have a different color in order to follow various velocities in various locations of the filter. The simulation results were verified by means of experimental results obtained from tests on a real model of the filter, see Figure 6 where comparison between results from physical tests and our simulations has been done (the simulation results match very well with physical ones). The matching has been done visually – in case of need of exact comparison, corresponding static images acquired from both processes could be matched by methods used in the field of computer vision.

Sample outputs of simulation and visualization of adsorption process can be seen in Figure 7 where the degree of gas purification in various locations inside the filter can be seen visualized by different colors.

5 HANDLING DYNAMIC FEATURES OF THE FILTER BEHAVIOR

The solution used has several interesting features that are based on the use of methods typical for computer graphics in a simulation environment. An example is the use of Bresenham algorithm – see e.g. Foley, Dam, Feiner and Hughes (1990) for dealing with non-horizontal gas flow (the non-horizontal trajectories were composed from horizontal chunks calculated by means of Bresenham algorithm). Also the general trajectories of the gas flow in complex situations were calculated not by flow equations but by means of Fergusson curves – see e.g. Foley, Dam, Feiner and Hughes (1990) that are applicable for this special case of gas flow in the dense (granules) environment.

From the point of view of the use of dynamic visualization it is necessary to point out, that approaches used in "static" visualization applications should be extended into the dynamic environment. The main framework for the use of visualization is the well known "visualization mantra" defined by Shneiderman (1998): "Overview, zoom, details-on-demand". In the case of dynamic visualization we have to control the time scale for dynamic visualization. At first we try to identify some interesting dynamic patterns in the dynamic process as a whole (with high speed of animation) and in case that such a pattern has been found (in case of dynamic filter behavior we are e.g. interested in the speed of flow of granules in particular locations - like stagnant zone where granules move with very low velocity) we can in detail investigate this pattern with lower speed. This approach has been to some extent implemented in the above given system for filter simulation.

The most important problem when dealing with dynamic visualizations is the speed both of simulation and the visualization. In our projects we concentrated ourselves on both of these aspects. In the first case (filters) we developed a special approach to simulation based on the use of a finite element method, see Hrdlicka, Slavik and Kubelka (2001) and Hrdlicka, Kubelka and Slavik (2002). The movement of granules and their behavior from the point of gas adsorption was simulated in volume elements. The visualization (the dynamic aspects) part of the system allowed us to change the speed of visualization.

6 VISUALIZATION OF DYNAMICS OF COMBUSTION PROCESSES

The second system developed (combustion process simulation and visualization in power-plants boilers) allows more complex investigations. As the combustion process is more complex than the previous one we can assume that the volume of data generated by simulation will be rather extensive. This situation negatively influences the speed of visualization process and also handling extensive data files in general.

6.1 Classical Modeling and Simulation

The simulation of various fluid flow related tasks and combustion processes in power-plant boilers are generally computationally expensive. This is a reason why we must use large simplifications in the description of corresponding physical descriptions and equations. But even with these simplifications, modeling and solving complex tasks such as combustion processes in today's packages and commercially available systems like FLUENT (Fluent 2003), can take hours or more. This is just the price for reaching acceptable precision of computations needed for professional, industrial design.

6.2 Dynamics Simulation and Visualization

A general disadvantage of the approach mentioned is the complexity of simulation which results in very time consuming calculations. This has negative influences or in most cases completely disables the possibilities of dynamic presentation and visualization of results. Nevertheless, dynamics of the combustion is an interesting part of combustion process study, namely at the start of the process.

We therefore make certain dispensations from the high precision and reliability required for industry and production applications. Our main goal is to construct components and methods allowing dynamics study.

7 THE BASIC COMPONENTS

We use the following components to form our system – the fast, structured fluid simulator and the particle system. Both of these parts are described and explained more fully in the following text.

7.1 The Fluid Simulator

Nowadays, simulation and visualization of various physical and nature phenomena using fluid simulators and solvers based on the Navier-Stokes equations has major theoretical and practical importance in simulation and especially in the computer graphics field. These simulators and solvers have been widely used for various research projects and practical applications such as animations of liquids and water (Foster and Metaxas 1996), fire (Nguyen, Fedkiw and Jensen 2002), gas and smoke (Fedkiw, Stam and Jensen 2001), effects in movies (Witting 1999) and many others.

Our fluid simulator is based on the principle of local simulation and uses a 2D structured grid (Gayer, Slavik and Hrdlicka 2002). The simulated area is divided into grid cells. It is necessary to take into account that the cell has some volume (we can speak about volume elements) and thus the model is in fact of 2.5 nature where the third dimension (depth) is also considered in contradiction to models of purely 2D nature (like a simulation option in FLUENT). In each step we calculate the new characteristics (e.g. velocities, masses) for all grid cells. All calculations are reduced on nearest neighbors of the calculated cells, see Figure 1. We periodically repeat these computations in each time step of the simulation. Such an approach has acceptable requirements on computation speed allowing for study of dynamics of the combustion process.

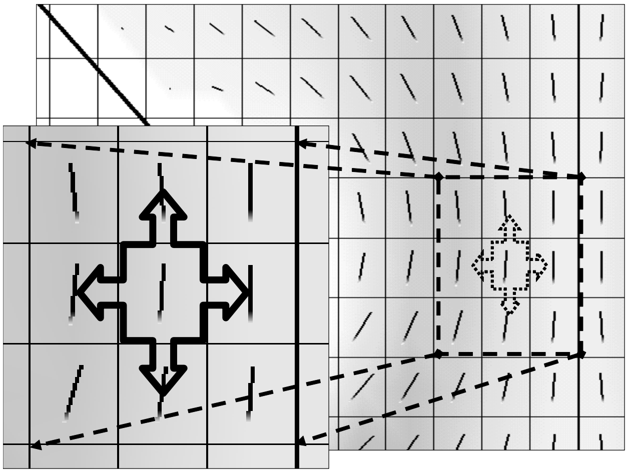

Figure 1: Division of the Boiler Chamber to 2D Grid Cells

7.2 Coal Particle System

By their nature, particle systems also represent a suitable way for modeling the pulverized coal combustion process. In our system, the particle system allows us both the computation and visualization of coal mass elements in the boiler. The particles displayed and calculated do not correspond to the real coal particles in the boiler. Instead, they represent a corresponding mass of coal in the cell under investigation. Thus we have a set of virtual particles in each cell. From this point of view we can neglect some physical phenomena like mutual particle collisions. The quality and speed of both simulation and visualization can be altered by increasing or decreasing the amount of particles.

The combustion process of the pulverized coal and resulting heat radiation and transfer is a quite complex problem. Again we are using some simplifications due to the need for speeding up the computation. Instead of simulation of these processes using the classical complex differential equations approach, we use a simple, statistical view of the combustion process. The combustion and heat transfers and fluxes are being computed separately for single grid cells and corresponding particles inside them. This is shown in Figure 2.

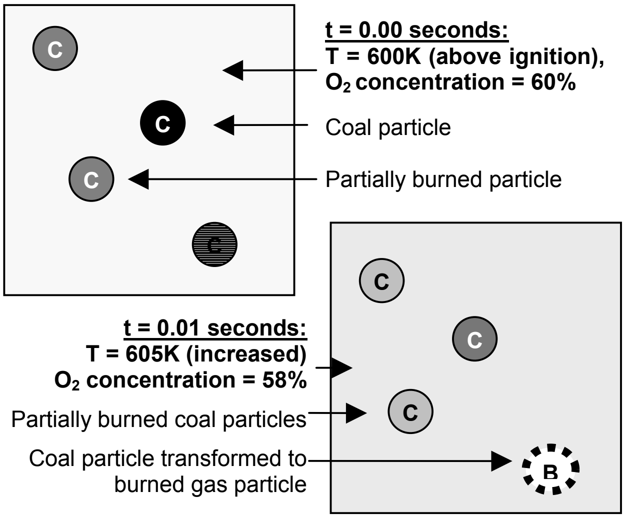

Figure 2: Example Schematic Interaction of Coal Particles with Air Mass During the Combustion Process for the Time dt in a Detected Grid Cell

7.3 Saving the Pre-Calculated Data Sets and States

In many cases, direct simulation of complex tasks with subsequent real-time visualization cannot used. For maintaining unconditionally real-time dynamics study even in these complex tasks, we use pre-calculated data sets and fluid simulator states (FSS) extensions. They in general allow speed-up of the simulation and visualization by either storing all computed data or storing only partially computed data with subsequent computations. The incorporation of these extensions into the simulation scheme of our system is shown in Figure 3.

The disk requirements for pre-calculated states are in orders less than the ones needed for storing the full data sets. However, the full data sets are important for maintaining easy time navigation and increasing the replaying speed of results availability of the visualization speed change. Also with full data sets, we can for example save only every 10th or 100th frame and considerably lower the disk space requirements, at the cost of losing availability of small time steps selections (for slowing the simulation) when replaying of the combustion process.

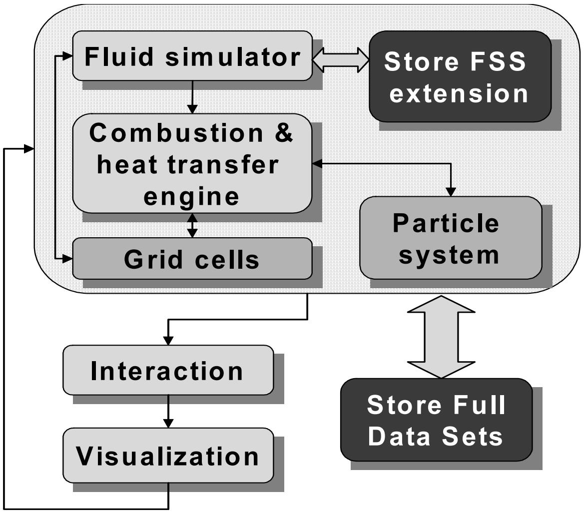

Figure 3: Incorporation of Storing Fluid Simulator States (FSS) and Data Sets Extensions to Architecture or Our Simulation System

8 DYNAMICS VISUALIZATION

The system built on the above concepts allows comprehensive study of the dynamics of the combustion process. This concerns mainly situations when the sudden change of some parameters occurs (like amount of oxygen, amount of fuel etc.). The visualization module deals with visualization of volume characteristics changes, flowing coal particles, dynamics statistics, zooming and modifying of time position and speed.

8.1 Volume Characteristics Changes

The selected local characteristics changes in the grid cell, such as the total temperature, mass values of combustibles and air, local wattages, and heat fluxes, heat radiations, pressures, burned mass, released heat, oxygen concentrations and others (total about 40) and their changes in selected time steps can be visualized, see Figure 4. In Real-time Mode, the Screen Immediately Reflects the Change of the Parameters (Such as Temperature)

8.2 Characteristics of Flowing Coal Particles

Simply using moving points representing flowing (virtual) coal particles, we can visualize particle diameters, mass of particles, the time and distance particles spend in the boiler, the distance it arrived inside the boiler chamber, combustible part of the particle and a few more (total about 10).

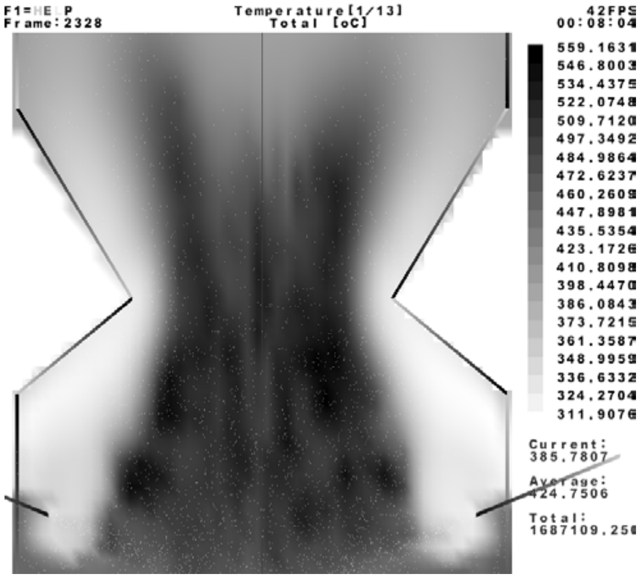

Figure 4: Real-Time Visualization of the Combustion Temperatures Grows Inside the Power-Plant Boiler

8.3 Dynamic Particle and Volume Statistics

Another way of presenting the computed values is utilizing the statistics feature offered by our system. The inputs for statistics are either values of any selected cell grids characteristics or values of any above described characteristics of 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 Figure 5. The statistics are available in real-time and immediately react on the dynamic changes inside the boiler.

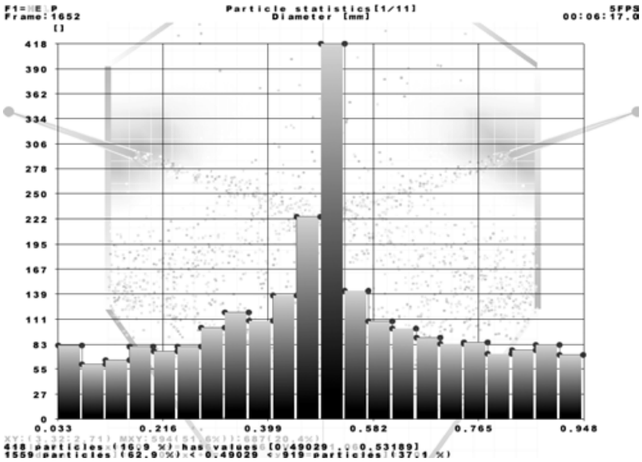

Figure 5: Sample Statistics of Coal Particle Diameters Distribution Inside the Boiler Chamber

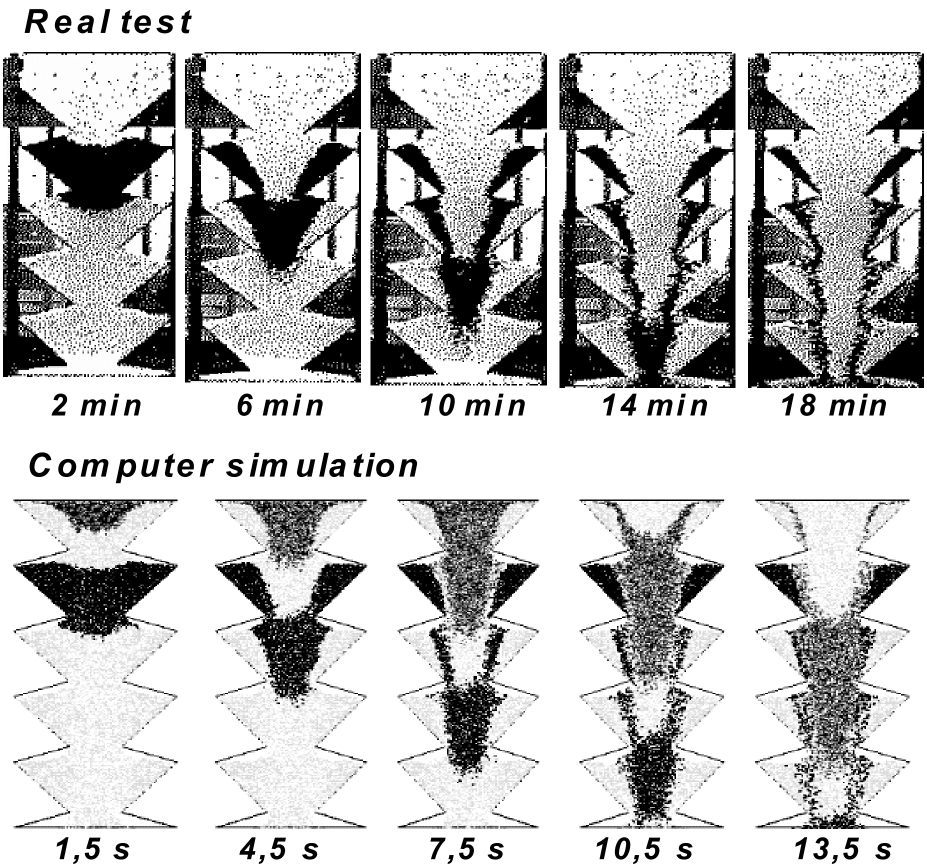

Figure 6: Comparison between Reality and Computer Simulation in Different Time Moments (the Time Scales for Real Test and Simulation were Different – the Matching Image Pairs are Placed Vertically)

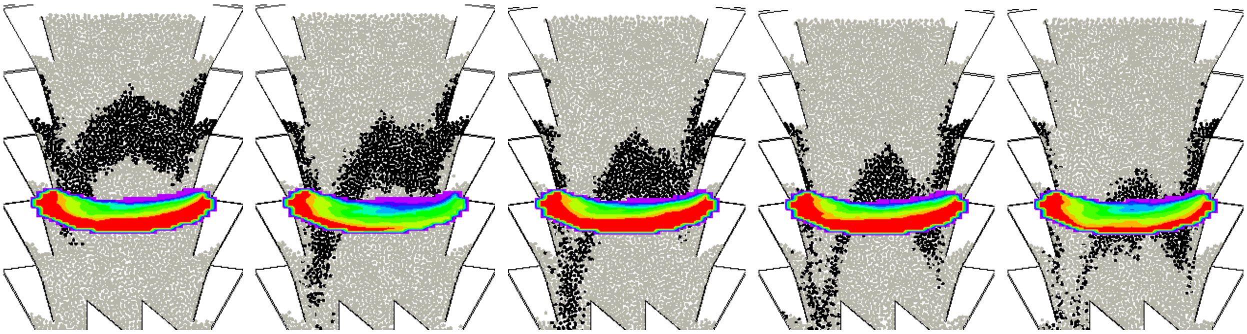

Figure 7: Simulation and Visualization of Adsorption Process in Filter

We also plan to add time parameters for studying the changes of the statistics in time step (adding time to the Z axis), allowing for clearly finding the extremes and variations of values and grow-up of these parameters. Also, dependence of one parameter on the other (e.g. diameter changes of the particles in regards to particle burnout) would be interesting to be studied this way.

8.4 Zooming Features and Time Navigation

We can select any zoom level and set the current position to any area of the boiler chamber under investigation. With utilizing the pre-calculated datasets, we can furthermore arbitrary seek to selected time position, easily change the replaying speed (slower, faster) of the simulation (similarly as described in gas flue filters part) or even back-reverse the combustion process. Without pre-calculated data sets, increasing of the playing speed can be emulated, but with considerable slowdown of the system speed. The reversing of replaying is not available at all in such a case.

8.5 Evaluation of Results Achieved

Our experiments have shown that our set of results differ from results obtained by means of FLUENT (that was chosen as a reference platform) in the following way: about 60% - 80% of volume elements have their attribute values (temperature, pressure etc.) different from values obtained by FLUENT by less than 30% (Gayer, Slavik and Hrdlicka 2002). This error is considered to be acceptable in this type of application – see Stastny, Ahnert and Spliethoff (2002). Another criteria for evaluation of our results could be derived from parameters describing the global state of the boiler (like global boiler fuel and combustion air input, heat output etc.). In this case our values of almost all global parameters differ from values obtained by FLUENT by less than 25% - see Gayer, Slavik and Hrdlicka (2002). The comparison between different simulated configurations of boiler furnace (with immediate gain of results and possible interactivity) corresponds to a similar situation obtained by FLUENT. This type of correspondence is important in practical use of the model.

Taking into account that generation of static images by means of FLUENT takes hours and our system is able to generate dynamic visualizations in real time (this means at least 25 images per second) we can conclude that the loss in accuracy is sufficiently compensated by the gain in speed. The main goal of our research was to develop new visualization methods. The simulation system was a sort of test bed for development of new visualization methods. In principle it would be possible to substitute our simulator (in our visualization environment) by another simulator with higher precision. Nevertheless our simulator generates results that describe the simulated phenomena with satisfying accuracy – especially in applications like power engineering education etc.

9 CONCLUSION AND FUTURE WORK

Design and implementation of systems allowing the user investigation of dynamic phenomena was described. Visualization of dynamic phenomena offers a new quality in visualization of various processes and as such deserves careful investigation both from the point of technical aspects of visualization and from the point of human perception. There are a lot of unsolved questions (e.g. another kind of pollutant in the filter) that should be investigated in the future. Both of our systems show that these questions are of great practical use.

The first system covered some basic problems of dynamic visualization while the other one showed a way to a potential solution of a more complex approach to dynamic visualization. The first system been used for the design of filters that will be used in practice. The second system is currently used for students in power-engineering at CTU Prague.

Due to the fact that the visualization part is separated from the simulation part and the results of the simulation part are stored in an interpretable form, we can interactively control the visualization process. Besides the possibility of the change of the time scale we have also the possibility to change the region of interest in various scales. The combination of both of these approaches gives the user a good opportunity to investigate dynamic phenomena both in various time scales and also in various levels of detail. This combination offers a new quality for visualization of dynamic phenomena and gives a good base for further research in the future.

Last, but not least, it is necessary to point out that questions regarding visual perception of dynamic problems are subject to intensive research in the field of psychology. This situation offers good opportunity for development of new visualization methods that will offer more deep insight in data describing various phenomena. We see the main contribution of this paper in modification of "visualization mantra" for the dynamic environment.

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