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Interactive Educational System for Coal Combustion Modeling in Power Plant Boilers

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***Abstract*--We present our educational system for interactive education of combustion processes. The system is built on several concepts used mainly in the computer graphics area (fluid simulator, particle system) and combustion simulation field (simplified combustion process model and heat transfer engine). Together they combine unique and original concepts that offer real-time simulation and visualization of the combustion process. The user may have immediate interaction during simulation and visualization – e.g. changing coal inlets and combustible properties and other input parameters during simulation. The system allows real-time monitoring of about 40 basic cell volume characteristics inside the boiler and 10 pulverized coal particle characteristics. All these features are available immediately, without needing to wait hours for complex calculations to finish. The system is especially suitable for interactive education purposes in power-engineering.**

***Index Terms*—Interactive Education, Power Engineering, Coal Combustion, Real-time Simulation and Visualization, CFD**

I. Introduction

In recent years, modern high performance desktop and workstations have made a revolution to the power engineering industry and computer graphics area. Currently, there is a vast amount of research projects, applications and commercial products, which are able to simulate and visualize many natural production and technological processes. They are constructed for both the economical and ecological reasons – the possibility of relatively quick and precise analysis and design, which modern software tools offer, can save much engineering effort and money that would be needed for corresponding manual design and calculations. In other words, they allow the designer to experiment extensively with the model of the boiler designed without the necessity to build a physical model of the boiler.

Although today's commodity PC's have multiplied their performance, there are still many tasks for which the current computing power is still insufficient. The simulation of various fluid flow related tasks and combustion processes is a typical example. For these 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 commodity systems can take hours or more. This is just the price for reaching acceptable precision of computations needed for professional industry design. A good example of the above is modeling of the combustion in boilers using the well-known and widely used FLUENT package [1]. General disadvantage of this approach, especially in education, is the complexity of simulation which results in very time-consuming calculations.

We are in a different situation when we can dispense from the reliability and high precision required for industry and production applications. The reason for such decisions can be desire of unconditionally real-time, interactive combustion simulation available on today's commodity PC's and workstations. This can be especially useful when designing tools for engineering education and training.

A. Visualization of simulation

In a simulation field, visualization has major importance in presenting the simulated data in a natural, easily read, understandable and expressive form. This is especially required for real-time applications, when a suitable form of visualization is absolutely essential for synoptic presentation of the computed data.

B. Interactive education

Nowadays, common availability of high performance PC's, easy to use operating systems, high quality projectors and slightly increasing general computer knowledge, leads to choosing more effective, telling and visual forms of education. It can start by choosing illustrative schemes and pictures, or using common animation formats (like MPEG and AVI files).

One of the most interesting and favorite forms of education is interactive education (and derived forms, like distant education). It is especially suited for complex, practical tasks, when long, theoretical explanation would be ineffective or could even lead to confusion of students.

An interactive form of education (if used in a proper and meaningful way) offers "doing by learning" and "what if" features. It can fulfill dynamic requirements of the teacher and students. If it is used in an individual learning and practicing part of education, it can motivate the students to use their creativity and can easily answer some of their questions. Furthermore it can motivate them in the learning process, which now becomes more interesting and offers more "fun".

Usual problem of the seminar courses and lessons efficiency is individual works of each of the students. An interactive educational system for coal combustion modeling is one of the options for more efficient education. A challenging part of education in the field of combustion processes is the dynamic behavior of burning coal particles. An important task is to introduce and describe particle traces and their changes (with respective heat release). Also it is important to clearly demonstrate concrete power output (specified volume load) and its changes, heat transfers into the combustion chamber walls and temperature field into furnaces. All these requirements can be met when using our system, which will be described in the following text. The model respects a concrete fuel system, its specific features and the necessity to respect inlets of fuel and combustion air.

II. SIMULATION OF COMBUSTION PROCESSES

We use the following components to form our education system – the fast, structured fluid simulator and particle system. Both of these parts will be further described and explained in the following text.

A. The fluid simulator

Nowadays, simulation and visualization of various physical and natural phenomena using fluid simulators and solvers based on the Navier-Stokes equations has major theoretical and practical importance in simulation and especially the computer graphics field. These simulators and solvers are widely used for various research projects and practical applications such as animations of liquids and water [2], fire [3], gas and smoke [4], and many others. Some of them are used for special effects such as melting [5] and animations in movies [6]. In most cases, the fluid simulators are suited for specialized applications, but in most cases, with certain effort, they can be modified and utilized in general applications. For example, a fluid simulator originally developed for animation of liquids could be modified for air flow computation.

We can divide fluid simulators into two types. First are complex and stable (but computationally more expensive) methods such is in [7], that are able to determine the flow progress independently of the time steps, but at some cost to the computational speed of the single frames. The second are unstable, where an acceptable time step is dependent on the type of task we solve. Our simulator, as well as others [8], is unstable. It is based on the principle of local simulation and uses a 2D structured grid [9]. The simulated area is divided into grid cells. In each step we calculate the new characteristics (e.g. velocities, masses) for all grid cells. All calculations are based on nearest neighbors of the calculated cells (see Fig. 1). We periodically repeat these computations in each time step of the simulation. The stability of unstable solvers depends on proper selection of dimensions of the selected grid cell, and time step in regards to speed of value changes (such are velocities and mass) in cells during simulation.

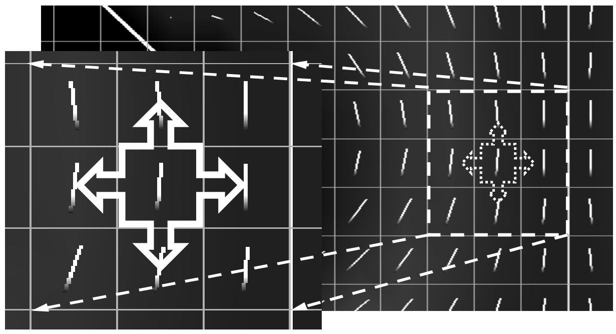

Fig. 1. Division of the boiler chamber into 2D grid cells. The cell values in the next time step are computed from nearest neighbors only.

B. Coal particle system

Particle systems in computer graphics can clearly simulate and visualize various natural phenomena such as dust, rain and other models which could involve particle object primitives. Particle object abstraction is also used for industrial technology [10]. By its nature, particle systems also represent a suitable way for modeling the pulverized coal combustion process.

We use a coal particle system, enabling easy and fast computation of the combustion processes. 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 the corresponding mass of coal in the cell under investigation. The quality and speed of both simulation and visualization can be altered by increasing or decreasing the amount of particles. Currently, the amount of particles being used for simulation varies between thousands and ten thousands.

The combustion process of the pulverized coal and resulting heat convection is a quite complex problem. Again we are exploring some simplifications due to the need for fast computation. We use a simple, statistical view of the combustion process [11]. The combustion and heat transfers and fluxes are being computed separately for single grid cells and corresponding particles inside them.

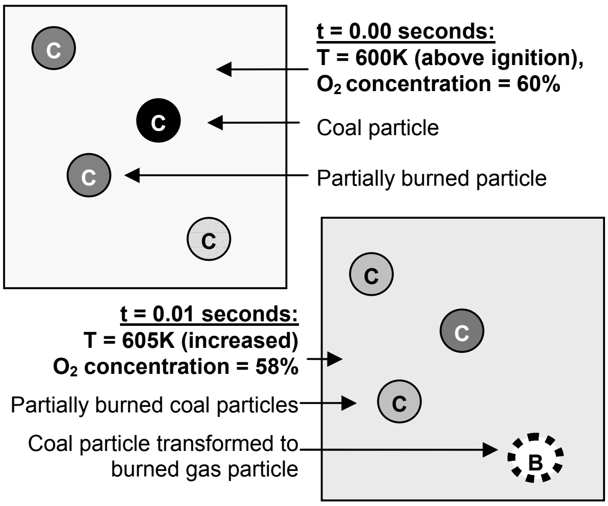

Fig. 2. Example schematic interaction of coal particles with air mass during the combustion process for the time dt in a selected grid cell

Our education system uses the industry standard OpenGL platform for reliable and fast visualization. This means that our system could be used on a standard low-cost graphics accelerator. The values of characteristics are visualized using color attribute of drawn graphics primitives (e.g. darker color values correspond to greater values, see Fig. 3).

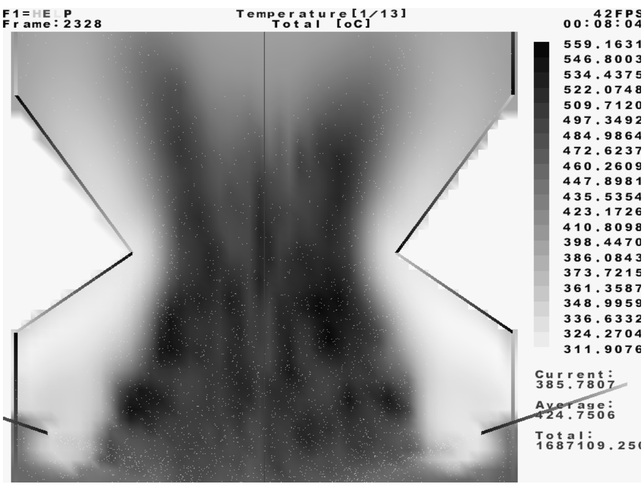

Fig. 3. Visualization of the combustion temperatures of the power-plant boiler. The greatest temperatures are in the core of the flame tube

C. Volume characteristics

The selected local characteristics 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 several others (about 40 total) can be visualized. We use OpenGL linear interpolated quads with the support of the graphics hardware acceleration for visualization of the grid cell characteristics (see Fig. 3). This concept allows easy, real-time visualization which gives results similar to the widely used isosurfaces technique.

D. Particle characteristics

The coal particles are visualized using the standard OpenGL capability of drawing pixels (see Fig. 4). We utilize built-in hardware support for visualization of smoothed pixels and alpha blending, available and supported in today's commodity available graphics accelerators. Thus, even at higher zoom levels and/or used particle sizes we obtain visually acceptable representation of the particles (see Fig. 5).

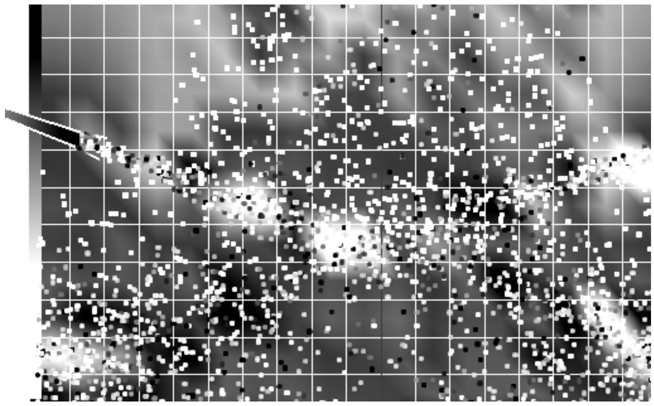

Fig. 4. Visualization of thousands of virtual coal particle characteristics together with selected cell grid characteristic (drawn on the background).

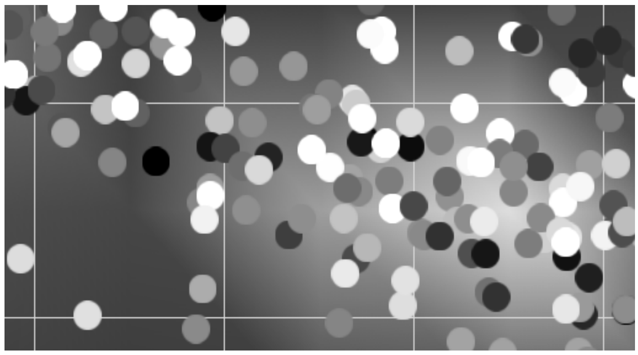

Fig. 5. Visualizing particles using full hardware accelerated, combined smoothing and blending of pixels gives an acceptable visual quality even with a high zoom level.

We can visualize in this way the particle diameters, mass of particles, the time and distance particles spend in boiler, the distance it arrived inside the boiler chamber, combustible part of the particle and a few more (about 10 total).

Utilizing the advantage of the particle system concept, we can easily construct the particle traces. We produce this effect by keeping the previous particle positions and characteristics in main memory. After that we can draw the particles in current time step together with the kept ones. The particle traces can clearly indicate the velocities and direction of movement of coal particles, which are visible even on the static state picture (see Fig. 6).

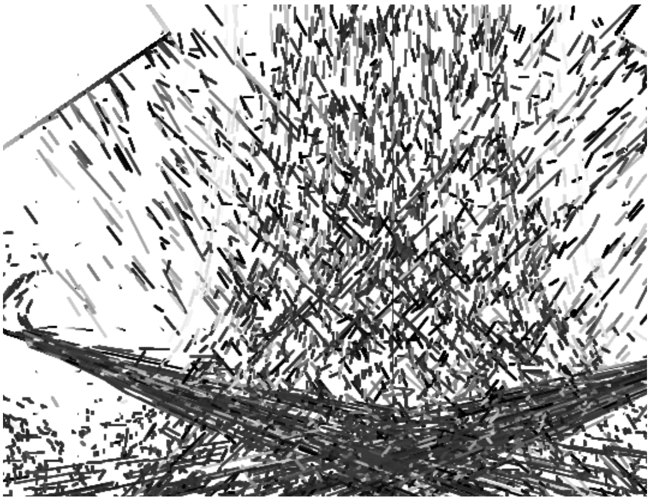

Fig. 6. Real-time visualization of partial particle traces helps in determining particle speed, direction and dynamics even in static images. However, the visually best overview of dynamics is gained in real-time mode of our system.

E. *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 grid characteristics or values of any described characteristics of particles. We can measure and visualize the value distribution in the grid cells and particles for all the above described characteristics. The sample visualization output is shown in Fig. 7.

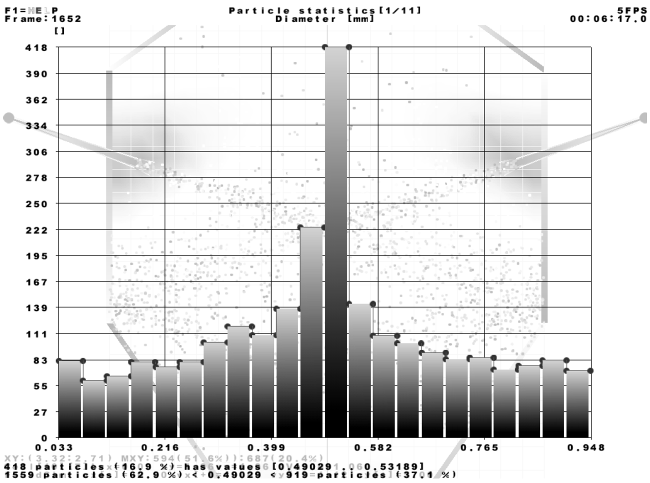

Fig. 7. Sample statistics of coal particle diameters distribution inside the boiler chamber.

III. Interactive Features of Our System

We can divide the interactive features of our system into the two following parts – interactive simulation and interactive visualization of results.

A. *Interactive simulation*

During the simulation, we can interactively modify any of about 30 simulation parameters. We can for example, on the fly, increase the number of generated particles (improving the simulation precision at a certain cost of visualization and simulation speed, see Fig. 8) or change the mass of average coal particles flowing from the inlets of the boiler.

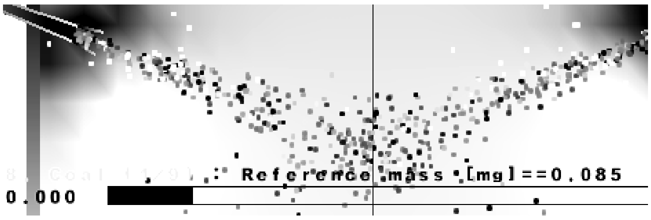

Fig. 8. The count of new generated coal particles is being modified and immediately applied to the simulation computation on the fly

Moreover we can interactively change the parameters of the inlets – completely change velocities, position, direction, and angle of spread, air and coal masses, diameters and coefficients of air and coal flowing to the boiler chamber. The interactive modification of boiler inlet is shown in Fig. 9.

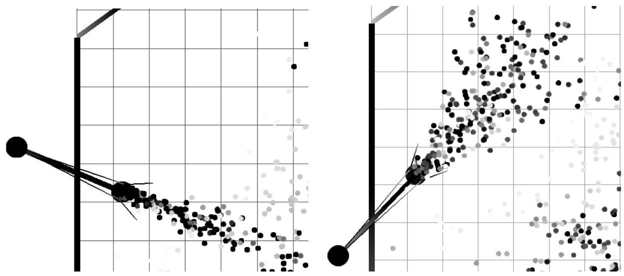

Fig. 9. Interactive modification of coal inlet parameters. The state of the inlet and particles before change is on the left side. The changed state after the next 5 seconds of interactive simulation is shown on the right side.

Furthermore we can select any one of the particles (representing corresponding mass of the coal under investigation), change it's parameters on the fly, including position and then watch how it behaves after applying such changes (see Fig. 10).

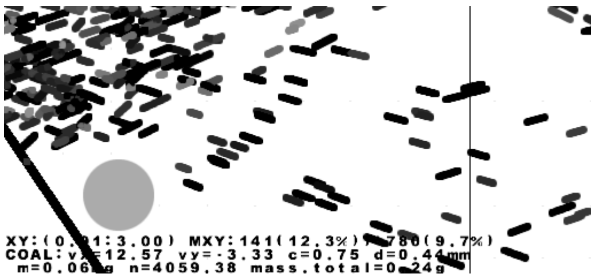

Fig. 10. Tracking and monitoring of characteristics of the selected particle (highlighted as the light gray disc) inside the boiler chamber. We can lock the viewing area to its position and watch the coal particle as it flows through the boiler with any zoom level.

B. *Interactive visualization of results*

We can select any combination of the particle characteristics, grid cell characteristics and statistics. We can change visualization parameters, e.g. size of the particles, select area in the boiler under investigation, change the visualization method of drawing pixels and set zoom level. We can also adjust color palettes and color ranges for visualization, setup brightness or invert the screen colors (choosing a color scheme of light background and dark particles and grid cells) suitable for printing and many others.

IV. FEEDBACK FROM STUDENTS

Response of students to this new way of education was a very positive one. This new way allows students to perform their own experiments individually and in a practical way answer questions emerging from theoretical foundations of the theory of combustion. The system allows for individual experience based on concrete choice of correct and incorrect parameters (like size and other properties of particles, ratio between amount fuel and air, velocities of the air flow, positions and directions of inlets etc.), their influence on the combustion process and watching corresponding dynamic behavior. This possibility to gain an individual experience based on experiments has been valued very much by our students. This fact is especially important because the subject where this system has been used belongs to a very basic subject in the power-engineering study track.

V. CONCLUSION

Our educational coal combustion system is based on a simple fluid simulator. 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 particle system and simplified combustion engine allows real-time visualization of the results (using OpenGL graphics interface). The system has been implemented in 2D grid cell space, and regarding the methodology used, can be easily extended to 3D space. But even with the 2D grid version, the system is fully sufficient for educational purposes, where clarity and real-time interactivity demonstrate both the universality and preciseness of computation. However, conversion of all our concepts and architecture of the system to 3D grid cell space is also planned.

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. The students and developers of the combustion boilers could now test many configurations and modifications of the pulverized coal boilers interactively with an immediate response. The system by itself can in an interactive, efficient and attractive form, give an overview of how power-plant boilers work, with an overview of fundamental boiler parameters. The interactive way of modeling can bring the student basic knowledge and policies of constructing performance and efficient boiler solutions and more. We recommend it as an introduction application for a combustion processes overview when studying power plants.

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.

The system has been used in the educational process in the Faculty of Mechanical Engineering at the CTU, Prague. The result of practical usage of our interactive system can be described as a very successful one. It is a transition from the traditional way of education based on the mediation of knowledge (from professors to students) to the education based on gaining an individual experience. In such a way students can master new knowledge in a more interesting way and much deeper than in a traditional approach.

VI. ACKNOWLEDGMENT

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