Dynamic Flame Simulation of Ceramic Roller Kiln Based on Particle System

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Abstract

Particle systems are an effective way for visualizing “fuzzy” objects in a variety of context and the simulation of flame spreading is very useful in the combustion research of ceramic roller kiln. This paper has presented a visual model of particle system for simulating flame, and introduced a turbulent flow model which can impact the flame spreading. According to this model, the flame spreading, turbulence and temperature field of ceramic roller kiln were simulated, it is better to understand the combustion of ceramic roller kiln. To strengthen the effect of three-dimensional visual simulation, the mechanism of particle collision and detection was provided, particle blending, texture mapping, and other techniques in computer graphics were also employed. It’s shown that this visual model was feasible and high performance.

1. Introduction

Ceramic roller kiln is a new type of continuous industrial kiln which has been developed in recent years and widely used in the industrial production of architectural ceramics, daily use ceramics, and sanitary ceramics. It represented the developmental direction of modern industrial kiln. Although ceramic roller kiln late start, it made rapid progress in China. As the basic conditions for human survival and development, energy and the environment are important subjects to China’s sustainable development; therefore, it is necessary to make the best of ceramic roller kiln under the conditions of limited emissions, fuel economy and so on. So the combustion research of ceramic roller kiln has become more important and urgent.

In the process of combustion research, either experimental or numerical calculation will make a large amount of data. It contains large and complex information which is not easy to understand and analyse. So how to account for a large number of complex data and analyse them in an intuitive, simple and intelligible way is necessary, which is the visualization.

As a computer technology, visualization can turn symbols into geometry, express data in visual way, so that researchers can observe their research and enrich the way of scientific discovery. In many research areas, visualization play a important role, therefore, it is also an available method for more intuitionistic, in-depth analysing in the combustion research of ceramics roller kiln [1]. However, as we know in our knowledge, there are hardly relevant literatures about the three-dimensional visual simulation of ceramic roller kiln now.

In this paper, combined with the knowledge of computer graphics and display technology, a visual model based on particle systems was proposed according to the data from calculation and burning test of ceramic roller kiln. The model can reflect the main features of burning; visualize the dynamic spreading process of flame, and the turbulence.

2. Ceramic roller kiln

Ceramic roller kiln is a tunnel-shaped kiln; its cross-section is long and narrow. Unlike car tunnel kiln, it is not load products with the kiln car to move, but by an array of parallel rollers which have high-temperature and cross the cross-section of kiln working zone. Ceramic products on the rollers are delivered into the kiln along with the roller’s rotation and their firing process is completed in the kiln, so call this type of kiln “ceramic roller kiln” [2]. This kind of kiln is mainly composed of the preheating zone, the firing zone and the cooling zone. In the firing zone, each section have a couple of burners which are
staggered, symmetrical, alternately upward and downward, the flashboard and firewall are arranged at the top and bottom of the kiln. Because the combustion products of ceramic roller kiln directly contact with the ceramic products which could improve the heat transfer efficiency and form well-proportioned temperature fields, so this kind of kiln could save the energy resources [3].

3. The visual model of ceramic roller kiln combustion based on particle system

3.1. The basic principle of particle system

Modeling phenomena such as smoke, water, and fire has been proved successful with particle systems. In modeling these “fuzzy” objects, particle system approach has several important advantages over classical surface-oriented techniques. Firstly, a particle is a much simpler primitive than a polygon, the simplest of the surface representations. Therefore, in the same amount of computation time one can process more of the basic primitives and produce a more complex image. Because a particle is simple, it is also easy to motion-blur. The second advantage is that the model definition is procedural and is controlled by random numbers. Therefore, obtaining a highly detailed model does not necessarily require a great deal of human design time. Because it is procedural, a particle system can adjust its level of detail to suit a specific set of viewing parameters. Thirdly, particle systems model objects that are “alive”, that is, they change form over a period of time [4].

A particle system is a collection of many minute particles that together represent a fuzzy object. Over a period of time, particles are generated into a system, move and change from within the system, and die from the system.

To compute each frame in a motion sequence, the following sequences of steps are performed:

1. new particles are generated into the system and each new particle is assigned its individual attributes;
2. any particles that have existed within the system past their prescribed lifetime are extinguished;
3. The remaining particles are transformed and moved according to their dynamic attributes;
4. an image of the living particles is rendered in a frame buffer.

The particle system can be programmed to execute any set of instructions at each step. Because it is procedural, this approach can incorporate any computational model that describes the appearance or dynamics of the object. So we could take advantage of Models which have been developed in other scientific or engineering disciplines.

The original particle systems method was based on stochastic processes. Each particle is independent and moves according to its own characteristics. There was no interaction among particles in a particle system. Structured particle systems, which are used to simulate objects that are more structured, were also proposed by Reeves [5]. Other persons extended the work and allowed the independent particles to interact with the environment. Now, there are many publications on particle systems. The interactions among particles in a particle system and among particle systems are very important for simulating some phenomena [6, 7].

3.2. The flame model of ceramic roller kiln based on particle system

3.2.1. The definition of roller kiln flame. The data structure of flame particle is a six-dimensional vector of the real domain, such as the formula:

\[ Rn = (Pos, Spe, Aspe, Col, Lif, Alp) \] (1)

This is the elementary particle composed of the flame [8]. For each new particle generated, the particle system should determine values for the following attributes:

1. The position
2. The velocity (both speed and direction)
3. The acceleration
4. The color
5. The lifetime
6. The transparency

According to relevant function, all the attribute values will change over time. So the model could describe the appearance or dynamics of the flame.

Particles are generated into a particle system by means of controlled processes. One process determines the number of particles entering the system during each frame. The number of particles generated is important because it strongly influences the density of the flame.

In this paper, the number of new particles depends on the different lifetime of each particle (in this particle system, if a particle’s lifetime is extinguished, it will get a new lifetime again). According to the data from the burning tests of ceramic roller kiln, the max number of particles generated and its variance are set. The actual number of particles generated at a frame is:

\[ PartNum = MaxParts - RandDieParts \] (2)

Where MaxParts is the max number of particles, and RandDieParts is the “die” particle number at a frame.
3.2.2. Flame particle initialization. Some parameters of a particle system control the initial position of its particles. The particle system has a position which is determined by the burner position of ceramic roller kiln in three-dimensional space that defines its origin. Two angles of rotation about a coordinate system through this origin give it an orientation. The particle system also has a generation shape which defines a region about its origin into which newly born particles are randomly placed. The generation shape that we have implemented is: a rectangle of length $l$ and width $w$ in the $x$-$y$ plane of its coordinate system.

The generation shape also describes the initial direction in which new particles move. In the rectangular shape, particles move leftward or rightward from the origin of the particle system, but are allowed to vary from the transverse according to an “ejection” angle. The initial speed of a particle is determined by:
\[
\text{InitSpeed} = \text{MeanSpeed} + \text{Rand}() \times \text{VarSpeed}
\]  

(3)

Where MeanSpeed and VarSpeed are two other parameters of the particle system, the mean speed determined by the data from burning tests and its variance. Rand is a procedure returning a uniformly distributed random number between -1.0 and +1.0.

The particle system is given different color to set a particle’s initial color, Particle transparency is also determined by mean values and maximum variations. The equations are similar to the one given above for initial speed.

3.2.3. Flame particle dynamics. Each particle in the particle system moves in three-dimensional space and also changes over time in color, transparency.

To move a particle from one frame to the next is a matter of adding its velocity vector to its position vector. The particle system also uses an acceleration factor to modify the velocity of its particles from frame to frame. With this parameter we can simulate gravity, vortex force and cause particles to move in parabolic arcs rather than in straight lines. The corresponding equation is:
\[
\text{PositVect} = \text{Velocf} \times \text{Timef}, \\
\text{Velocf} = \text{Accelef} \times \text{Timef}
\]  

(4)

Where Velocf and Accelef are the velocity and acceleration at a frame, Timef is the time from one frame to the next.

A particle’s color changes over time as prescribed by the relevant parameter. The transparency of particles is controlled in exactly the same way. In our implementation, these rates of change are stochastic for all particles in our particle system.

In this paper, particles generated at random positions in the rectangle, move leftward or rightward away from origin. The initial direction of the particles’ movement was constrained by the system’s ejection angle to move out the region bounded by a dextrogyrate or laevogyrate cone. As particles move leftward or rightward, the gravity and other parameters pulled them down or up, giving them parabolic motion paths.

3.2.4. Flame particle extinction. Normally, there are two conditions that lead to the extinction of particles.

(1) When it is generated, a particle is given a lifetime measured in frames. As each frame is computed, this lifetime is decremented. A particle is killed when its lifetime reaches zero.

(2) Another mechanisms, a particle that moves more than a given distance in a given direction from the origin of its parent particle system may also be killed. This mechanism can be used to clip away particles that stray outside the region of ceramic roller kiln in this paper. If the intensity of a particle, calculated from its color and transparency, drops below a specified threshold or could contribute nothing to the image, the particle also should be killed.

4. The visualization of flame spreading, turbulence and temperature field of ceramic roller kiln

4.1. Particle collision and detection on the chamber wall

The general collision and contact problem is difficult [9]. Fortunately, here we only consider the simplest case of particles colliding with plane (the chamber wall of ceramic roller kiln). Even these simple collision models can add significant interest to the simulation.

There are two parts to the collision problem: detecting collisions, and responding to them in ceramic roller kiln, we need test if any particle contact with the chamber wall, if it’s position match with any one of the conditions following, the particle collides with the chamber wall.
\[
XWallef \leq x \leq XWalright, \\
YWallup \leq y \leq YWalledow, \\
ZWalledow \leq z \leq ZWallefro
\]  

(5)

Where $XWallef$ and $XWalright$ are the boundary positions of ceramic roller kiln on the $x$ axis, the others seem like that.
Set the particle’s lifetime zero to kill it is the response to collision in our model, because it’s an inelastic collision, the particle doesn’t bounce at all.

4.2. The simulation of turbulence

By the knowledge of turbulence structure, we can see that turbulences are composed of a variety of different vortices, the large vortices are the main carriers of pulsatile energy, they are energetic, but the small vortex is the one which dissipates energy [10]. The size of turbulence vortex also is a transport volume. The transport and interaction of a variety of vortices, lead to the convection, diffusion, agglomeration and dissipation of vortex-size in the flow field. A large number practices show that there are more or less the same results got from various two-equation models, in which the application and test of \( k - \varepsilon \) model are most common, it is also a usual model used in the calculation of project. In this paper, the turbulence was simulated according to analyze the characters of vortices.

The equations of the standard \( k - \varepsilon \) turbulence model are:

**Turbulent kinetic energy \( k \):**

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \frac{\varepsilon}{\sigma} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + G_k - \rho \varepsilon \tag{6}
\]

**Turbulent kinetic energy dissipation rate \( \varepsilon \):**

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \frac{\varepsilon}{\sigma} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{C_{1\varepsilon} \varepsilon}{\kappa} G_k - C_{2\varepsilon} \rho \varepsilon^2 \tag{7}
\]

**Turbulent energy produced items:**

\[
G_k = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_i}{\partial x_j} \right) \frac{\partial u_i}{\partial x_j} \tag{8}
\]

**Turbulent viscosity:**

\[
\mu = \rho C_{\mu} \frac{k^2}{\varepsilon} \tag{9}
\]

<table>
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<th>( C_{1\varepsilon} )</th>
<th>( C_{2\varepsilon} )</th>
<th>( C_{\mu} )</th>
<th>( \sigma_\varepsilon )</th>
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In these equations, \( C_{1\varepsilon} \), \( C_{2\varepsilon} \) and \( C_{\mu} \) were constant experience, \( \sigma_\varepsilon \) and \( \sigma_\varepsilon \) were respectively the Prandtl number of turbulent kinetic energy \( k \) and Turbulent kinetic energy dissipation rate \( \varepsilon \).

Table 1 shows the parameters of the standard \( k - \varepsilon \) turbulence model given above.

In the paper, the data structure of vortex is a five-dimensional vector of the real domain, the formula is:

\[
V_n = (P_v, R, \text{Rainc}, \text{Angle}, \text{Ainc}) \tag{10}
\]

Where \( P_v = \{P_{x, y, z}, P_{x', y', z'}\}^T \) and \( R \) are the central position and the radius of vortex, \( \text{Rainc} \) is the disturbance quantity, \( \text{Angle} \) and \( \text{Ainc} \) are the rotation Angle and Angle increment of particle.

Vortex field is simulated by the particle system. In the beginning, all attributes of vortex have been initialized; their values will change over time.

If a particle comes into the vortex field at frame \( i \), at the next frame \( i+1 \), the value of Angle is:

\[
\text{Angle}_{i+1} = \text{Angle}_i + \text{Ainc} \times \text{Timef} \tag{11}
\]

If the particles circumrotate in the \( x-y \) plane of its coordinate system, the position of this particle at frame \( i+1 \) is:

\[
\begin{align*}
P_{x, y, z}' &= [P_{x, y, z}] + \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} P_{x, y, z} - P_v \end{bmatrix} \\

\text{At expression: 12, we obtain the expression:}
\end{align*}
\]

\[
P_{x, y, z}' = P_{x, y, z}' + (P_x - P_{x, y, z}) \sin \theta + (P_y - P_{x, y, z}) \cos \theta
\]

\[
P_{x, y, z}' = P_{x, y, z}'
\]

Where \( P' = \{P_{x', y', z'}\}^T \) is the particle’s position at frame \( i+1 \), \( P = \{P_x, P_y, P_z\}^T \) is its position at frame \( i \) and \( \theta = \text{Angle}_{i+1} \).
The three-dimensional space of ceramic roller kiln was simulated with OpenGL. To simulate the temperature field, a temperature-color mapping table was established. Therefore, when particles moving, the change of colors can express the change of temperatures. Particle blending, texture mapping, and other techniques to achieve better results are employed.

Figure 1 is the three-dimensional space of ceramic roller kiln; Figure 2 shows the firing zone of the three-dimensional space, the figure is not show the turbulence. The turbulence is shown in Figure 3 around the ceramic product; Figure 4 represents the temperature field of ceramic roller kiln, the camera can get into the temperature field to roam.

5. Conclusion

A visual model based on particle system was presented in this paper, and it showed how to make the flame of the ceramic roller kiln. Particle systems have been used as a modeling tool for other effects and appear promising for the modeling of phenomena like clouds and smoke.

The most important aspect of particle systems is that they move: good dynamics are quite often the key to making objects look real. In order to achieve realism, the forces and factors and construct physically based empirical models to generate particles were analyzed and the mechanism of particle collision and detection to control the flame behavior accordingly was also provided. Therefore, the visualization of flame spreading, turbulence and temperature field of ceramic roller kiln can provide developers with direct insight to the combustion process.

Motion blur, texture mapping, and other techniques in computer graphics were also employed to achieve better results. The work is a useful addition to many applications in simulated virtual environments.

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