Visual Simulation of Spreading Fire

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Abstract

Visual simulation of fire is used as special effects in movies, applications of fire simulation for the training in disaster prevention. In this paper, we propose techniques for simulating fire spread taking into account the various properties of materials, and for an effective visualization of combustion phenomenon. In our simulation method, the flame dynamics is obtained by combining the Navier-Stokes equations and the heat conduction equation. The various combustion processes are simulated by specifying ignition points, the thermal diffusivity and calorie of chemical reaction depending on the types of materials. Moreover, in our method, fire is extinguished by reducing the fuel concentration. The reduction ratio of the fuel is based on the reaction kinetics theory developed in the field of chemistry. In our fire visualization method, the volume representing the fire is considered as a set of point light sources. The intensity distribution on objects illuminated by the fire is calculated by accumulating the illumination due to the point light sources.

1 Introduction

The modeling of natural phenomena such as fire and flames remains a challenging problem in computer graphics. Simulations of fluid behavior are in demand for special effects depicting smoke, water, fire and other natural phenomena. Fire simulations are also of interest for virtual reality effects, for example to help training fire fighters. In fire simulation, for example in a room, it is important to consider the material of the combustible (like the combustibility of materials). As a result, the variations of the materials affect the entire combustion process of the room. To consider the material, we introduce several physical equations. The user easily controls the combustion process by modifying the parameters in the equations.

The combustion processes can be roughly classified into two distinct types of phenomena: detonations and deflagrations. In both of these processes, chemical reactions convert fuel into hot gaseous products. Deflagrations are low speed phenomena such as the fire and flames we address in this paper, while detonations are high speed phenomena such as explosions where shock waves and other compressible effects are important. In the proposed simulation method, the combustion processes from the ignition to extinction are expressed according to a physical rule.

In the rendering process, our method can compute the change of the illumination on objects due to the flickering of flames. Fire is considered as a volumetric light. We approximate the volumetric light by a set of point light sources to calculate intensities on the objects. Our method can generate an image of a scene illuminated by the flickering flame. Fire is a blackbody radiator and participating medium. The properties of the participating medium include the scattering, absorption and emission properties. Since fire emits light, fire is more complex than the other participating media (e.g. smoke and fog) that are typically used in computer graphics. So, we propose an effective method for rendering scenes including fire.

2 Previous Work

Particle systems are most widely used for modeling fire. Particles can interact with other primitives, are easy to render, and the computational complexity is $O(N)$ if there are no inter-particle forces. Flame coherence has been modeled directly using chains of

connected particles [1]. This retains many advantages of particle systems while also allowing animators to treat a flame as a high level structural element. But this method does not consider the conduction of heat. Moreover, there are a few physical rules when the flame spreads on the object. Chiba computed the exchange of heat between objects [2]. The spread of flame is a function of both the temperature and the concentration of fuel. However, they calculated the heat conduction only in two-dimensional space. In addition, the ignition point and the extinction of fire are not considered. Nguyen *et al*. modeled the chemical reaction surface in the flame [3]. They calculated the behavior of the gas fuel and the gas products. However, in this method, they introduce neither calorific power of combustion nor the variations of the burning process depending on the combustible materials. Especially, in the field of computer graphics, there are few flame models that take into account the chemical reaction of the flame.

To handle the combustion processes such as the ignition, extinction, and heat generation, we introduce the physical and the chemical rules.

Stam and Fiume render the fire using a diffusion approximation that takes into account multiple scattering [4]. In this method, the fire consists of a number of particles and the illumination due to the fire is calculated by taking into account all the particles. However, this is computationally very expensive. Nguyen *et al*. computed the scattering, absorption and emission properties based on physical rules [3]. Though their method is suitable for computing the color of fire, the change of the light intensity due to the flickering of fire is not taken into account.

There are a lot of methods that regard the flame as a volumetric light source. Recently, Assarsson *et al*. proposed a geometry-based algorithm for computing penumbra [5]. However, it is difficult to apply this method to the volumetric light source like the flame whose intensity distribution changes dynamically. Moreover, in these methods, the center of the flame has to be defined. However, it is also difficult because the motion of the flame is complex.

There is little previous technique for rendering the flame as a volume source light whose intensity distribution is calculated by the simulation. Therefore in our method, the object illuminated by the flame is calculated by reflecting the simulation results.

3 Combustion Phenomenon

In general, there are three requirements to cause the combustion phenomenon. That is, 1) there must be a combustible, 2) the density of oxygen must be sufficiently high, and 3) the temperature must be higher than the ignition point of the combustible. The combustion causes if these three requirements are satisfied. We assume that the oxygen is supplied sufficiently in the simulation space.

Flow and diffusion of the burning gas, the generation of heat due to the chemical reaction, and the conduction of heat causes simultaneously in the combustion field. Therefore, the equations that describe the flow with combustion include the conservation of mass and the momentum, the temperature rising due to the heat released by the chemical reaction, and the evolution of temperature.

4 Physical and Chemical Modeling of Fire

We first explain the equations for fire simulation including the Navier-Stokes equations and the heat conduction equation, and then propose our method for simulating the ignition, fire spreading and extinguishment. The simulation space is subdivided into cubic voxels. The side length of each voxel is *dh*. And we use the finite difference method to calculate a set of partial differential equations.

4.1 Evolution of Velocity Field

In our method, the behavior of flame is simulated by calculating the velocity field and updating the temperature. The semi-Lagrangian stable fluid approach [6] is used as the fluid solver. The flammable gas can be treated as incompressible as long as the reaction rate is less than the speed of sound. Given that the velocity $\mathbf{u}$ and the pressure p at time t are known, then the evolution of $\mathbf{u}$ and p over time is given by the Navier-Stokes equations:

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \cdot \nabla)\mathbf{u} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}, \tag{2}$$

where ρ is a density of gas, ν is a coefficient of viscosity and $\mathbf{f}$ is an external force, which includes the

buoyancy and the vorticity confinement [7]. **f** is assumed to be fixed within a time step Δt. Equation (1) means that the inflow and the outflow of a unit cell are balanced, and is called the "continuity equation". This equation is a constraint which projects the velocity vector to the divergent free field. The first term of the right hand of Equation (2) means the advection of the velocity vector, and is called the "advection term". To calculate this term, we use the semi-Lagrangian advection scheme, which is a stable even if the time step is large. The second term means the variation of the velocity caused by the gradient of the pressure, and is called the "pressure term". The third term means the diffusion due to viscosity of fluid, and is called the "diffusion term". The fourth term means that the velocity is varied by the external force, and is called the "external force term".

4.2 Buoyancy

Buoyancy occurs due to the difference between the temperature of fire and an ambient temperature, and it affects the velocity field.

$$\mathbf{f}_{buo} = \alpha\left(T - T_{amb}\right)\mathbf{z}, \tag{3}$$

where α is a positive constant which controls the strength of the buoyancy, **z** is a vertically upward unit vector, and T_{amb} is an ambient temperature.

4.3 Evolution of Temperature

The temperature T is advected by the velocity field, and diffuses.

$$\frac{\partial T}{\partial t} = -\left(\mathbf{u}\cdot\nabla\right)T + a_{air}\nabla^2 T, \tag{4}$$

where a_{air} is the thermal diffusivity of air. The first term of the right hand of Equation (4) is the "advection term". The second term is the "diffusion term". T becomes smaller due to the "diffusion term", that makes the temperature cool down.

4.4 Heat Conduction in Fuel

The heat conduction in the fuel is calculated by:

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial^2 x}. \tag{5}$$

a is called thermal diffusivity. The heat transmission ratio is controlled by setting parameter a depending on the fuel material.

4.5 Discriminant of Ignition

A voxel becomes an ignited state when the temperature in each voxel satisfies Inequality (6) after the conduction of heat is calculated in each time step.

$$T^{(t)} \geq T_{ign}, \tag{6}$$

where $T^{(t)}$ is the temperature at time t. T_{ign} is the ignition point. T_{ign} depends on the material.

4.6 Decrease in Concentration of Fuel

If the reaction continues, the fuel must be lost. When the fuel disappears, the flame extinguishes because it does not satisfy the combustion requirements. A reaction speed follows the law of Arrhenius. Though combustion is actually caused by numbers of chemical reactions, we consider the combustion phenomenon as the following single reaction process because it is difficult and impractical to simulate all the reactions.

$$F + O \rightarrow M, \tag{7}$$

where F is a combustible that is a fuel, O is oxygen and it is assumed that oxygen is supplied sufficiently in the simulation space. Though M corresponds to water and the carbon dioxide generated by the combustion process, they are not considered in our simulation. A rate of the reaction expressed by the above formula is given by the next equation,

$$\frac{dC_F}{dt} = -AT^n C_F C_O \exp\left(-\frac{E}{RT}\right). \tag{8}$$

C_F is a molar concentration of F, and C_O is a molar concentration of O. C_O is assumed to be constant. A is a reaction frequency factor, E is activation energy, R is a gas constant and n is the parameter based on a rule derived experimentally, and is a real number, commonly $n = 0.5$. The concentration C_F is updated at each time step by computing Equation (8). C_F decreases due to combustion and the fire is extinguished when C_F is below a threshold specified by the user.

4.7 Calorie of Chemical Reaction

Combustion is an exothermic reaction and its calorie is measured experimentally. If the measured calorie is not available, we can estimate it using the

Hess's law. The calorific value Q is assigned to each voxel. The heat generated by combustion is proportional to the fuel consumed by the combustion. The temperature at each voxel is updated by adding the heat due to combustion:

$$T^{(t+\Delta t)} = T^{(t)} + K_r \frac{Q}{c}, \tag{9}$$

where K_r is a reduction ratio of the fuel during the time interval Δt, and c is a specific heat.

The above-mentioned four equations, from (5) to (8), are calculated for the voxels corresponding to the fuel. In these equations, there are the parameters that depend on the material of the fuel. We can simulate not only the spreading fire but also the variations of the burning process depending on the combustible materials by controlling these parameters.

5 Rendering of Spreading Flames

To compute the illumination due to flame, the point light sources are placed at the centers of the voxels. The intensity of light by the flame is calculated from the temperature distribution obtained by the simulation, and the color of the point light source is determined by Planck's formula:

$$E_\lambda(x) = \frac{2C_1}{\lambda^5\left\{\exp\left(C_2/\lambda T\right)-1\right\}}, \tag{10}$$

$$\begin{cases} C_1 \approx 3.7418\cdot 10^{-16}\left[Wm^2\right] \\ C_2 \approx 1.4388\cdot 10^{-2}\left[m^0K\right] \end{cases}$$

where λ is the wavelength, T is the temperature, and C_1 and C_2 are constants measured by experiments [8].

The radiation of light by flame and absorption when light passes through the flame depend on the size, shape, and the temperature of the flame etc. Let us consider point x_0 on a wall as shown in Figure 1. The intensity of point x_0 is I_i. The intensity I_0 of light reaching the viewpoint is the sum of the intensity of the flame on path AB (see Figure 1) and the intensity of point x_0 attenuated by the flame. The absorption due to air is ignored because it is very small compared to the absorption due to the flame. As a result, the intensity of light reaching the viewpoint, I_0, is calculated by the following equation,

$$\begin{aligned} I_0 = {} & I_i \exp\left(-\int_A^B K_{flame}(x)\,dx\right) \\ & + \int_A^B E_\lambda(x)\left\{1-\exp\left(-\int_A^B K_{flame}(x)dx\right)\right\}dx, \end{aligned} \tag{11}$$

where A and B are intersections between the viewing ray and boundary of the flame. $E_\lambda(x)$ is a radiation of the flame, and $K_{flame}(x)$ is an attenuation ratio.

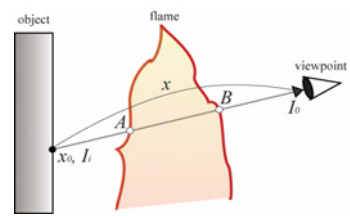


Figure 1: Radiation and absorption in flame.

To compute Equation (11), we first calculate an attenuation ratio α for each voxel. An attenuation ratio is assumed to be constant within a voxel. And α_i of a voxel i is calculated by the following equation,

$$\alpha_i = \exp\left(-K_{flame}(i)\cdot ds\right), \tag{12}$$

where ds is the length of intersection of the viewing ray and voxel i. And the exponential term in Equation (11) is calculated by the following equation,

$$\exp\left(-\int_A^B K_{flame}(x)\,dx\right) = \alpha_1\alpha_2\cdots\alpha_n. \tag{13}$$

Then, textures are created for efficient rendering of the flame. The color of each element of the texture is determined by calculating Equations (10) and (12). The final image is created by mapping the textures onto quadrilaterals placed at the centers of voxels and by drawing them using graphics hardware.

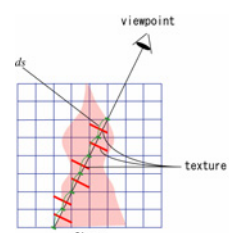
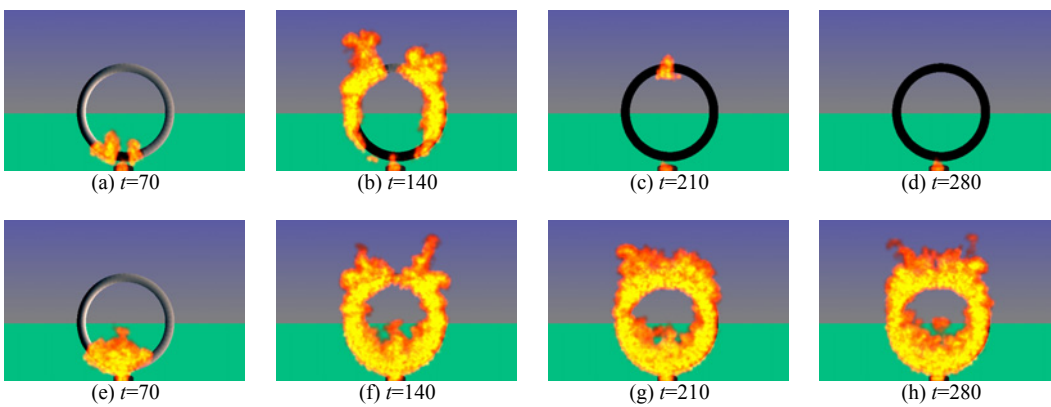


Figure2: Concept of the rendering process.

6 Results

Figure 3 shows the effects of the reaction rate. t is the number of time step. The reaction rate in Figures 3 (a) through (d) is three times as high as that used in Figures 3 (e) through (h). In these figures, the torus object is specified as a combustible. The higher the reaction rate is, the more the loss of the fuel is. The number of voxels is 50×50×80 for these figures. The time step in the simulation is 0.02[s]. The calculation time for each time step of the simulation is about 0.6[s] using a desktop PC with a Pentium 4 1.69 GHz.

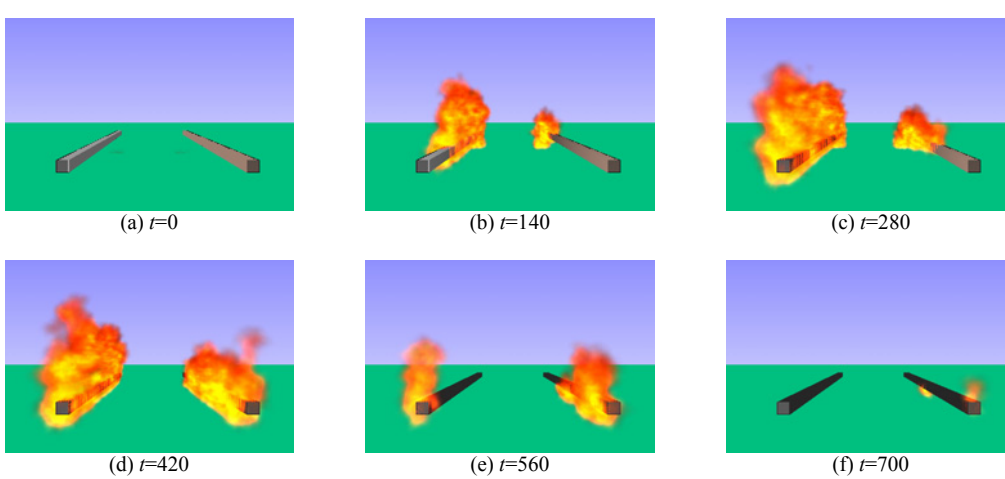
Figure 4 shows effects of thermal conductivity and ignition point. Figures 4 (a) through (f) show spreading fire along rectangular lumbers. The left lumber is charcoal and the right lumber is Japanese cypress. The images at every 140 steps are shown. Figures 4 (b) and (c) show that charcoal burns earlier than the Japanese cypress. This is because thermal conductivity and ignition point of charcoal is larger and lower, respectively. Figures 4 (e) and (f) show that fire goes out due to the decrease of the concentration of the fuel. The number of voxels is 100×60×60 for these figures. The calculation time for each time step of the simulation is about 0.7[s]



(a) t=70 (b) t=140 (c) t=210 (d) t=280

(e) t=70 (f) t=140 (g) t=210 (h) t=280

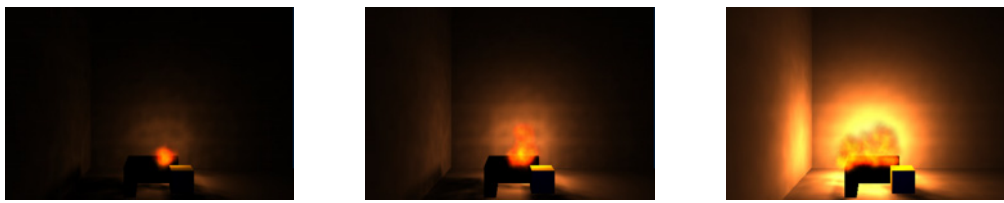
Figure 3: Difference of how to burn by difference of reactive rates.



(a) t=0 (b) t=140 (c) t=280

(d) t=420 (e) t=560 (f) t=700

Figure 4: Difference of thermal conductivity and ignition points.
Left wood is assumed to charcoal and right wood is assumed to Japanese cypress.



(a) t=10 (b) t=40 (c) t=70

Figure 5: A room illuminated by a fire.

Figure 5 shows example images of a room illuminated by a fire. The number of voxels is 32×32×32 in this case. The walls are divided into 40×60 patches. The calculation time for each time step of the simulation and the rendering are about 0.3[s] and 1[s], respectively. The illumination on the wall changes according to the motion of the fire. The penumbra regions also change. As shown in this example, our method can compute the illumination/shadow variations due to the motion of the flame.

7 Conclusion and Future Work

We have simulated fire spreading using physical and chemical models, introducing four parameters called thermal diffusivity, ignition point, reaction rate and calorie value. The behavior of the flame is based on the Navier-Stokes equations. In addition, we have presented the method for rendering objects illuminated by fire. The illumination is calculated by representing the fire as a collection of point light sources. Our method can create realistic images of scenes including fire.

Finally, let us mention about future work. In our current simulation method, the reaction rate is calculated by assuming that the density of oxygen is constant in Equation (8). However the reaction rate changes depending on the density of oxygen. Therefore, we need to improve our method to simulate this. Moreover, our rendering method is computationally very expensive. One possible solution to this problem is the use of graphics hardware to speed up the computation.

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