

Interactive Simulation of Fire

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Abstract

In this paper we describe a fast and interactive model to simulate and control the fire phenomenon. We use a modified interactive fluid dynamics solver to describe the motion of a 3-gas system. We simulate the motion of oxidizing air, fuel gases, and exhaust gases. The burning process is simulated by consuming fuel and air based on the amounts of fuel and air inside each grid cell. By modeling heat distribution, we also simulate the spread of fire to and self-ignition in other combustible solids.

1. Introduction

There has been an increasing interest within the computer graphics community for simulation and visualization of natural phenomena such as water and smoke motion. Generally, the applications require visually compelling but not strictly accurate models. However, the models need to be capable of capturing the visual characteristics of the phenomenon, and still be interactive and easy to choreograph. In this paper, we focus on the simulation of fire.

2. Models of Flames

In the combustion process fuel is preheated by ignition, and the gases that are mixed with air (the oxidant) in "good" concentration start the combustion, giving an exothermic reaction. Besides water and carbon dioxide, the burning process results in other combustion byproducts, some of which might be subject to further combustion themselves.

The fuel gas mixes with the oxidizing gas creating a mixture zone. As fuel approaches the mixture zone, the increasing amount of oxidizing gas allows the chemical combustion reaction to occur. The heat generated during the reaction keeps the reaction zone at the maximal temperature, triggering more combustion, thus creating more heat and combustion byproducts [1]. The heat produced by

the flame can also radiate to vaporize combustible products from nearby matter through chemical decomposition. This process is called pyrolysis. Thus, when an object (such as a piece of wood) burns, the flames are formed from combustible portions of the object being vaporized and then oxidizing in the region just beyond the surface.

3. Gas Motion

In our model, we transport the fuel and exhaust gases with the motion of the air, creating a dynamic 3-gas system. Heat is also transported with the flow of the air, enabling us to model heat distribution inside the computational domain more accurately than any other known fire model. To model the air flow, we use a modified version of Stam's Stable Fluids [4, 5, 2, 3] approach. The fluid motion (air) solution is then applied to advect three quantities, fuel gas g , exhaust gas (including smoke) a , and heat T . The radiation effect is simulated using a large diffusion step for the heat, which is solved using an implicit integration step, which gives a sparse linear system when discretized.

The external force is found using the densities of fuel and smoke taking the heat at the given cell into account such that hot air will rise, and cold air fall, creating convection currents necessary to give the correct flame shape.

4. Combustion

The combustion (burning) in a cell is defined by:

$$C = r \min(d_A, b d_g) \text{ if } T > T_{thres} \quad (1)$$

$$\frac{\partial d_g}{\partial t} = -\frac{C}{b} \quad (2)$$

$$\frac{\partial d_a}{\partial t} = C \left(1 + \frac{1}{b}\right) \quad (3)$$

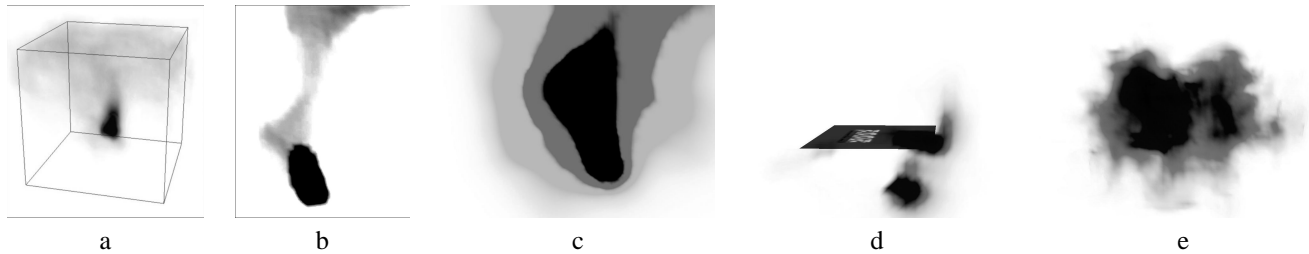


Figure 1. Our 3-gas fluid system. (a) flame and smoke in a closed environment, (b) motion of the gas (black is the fuel and gray is the smoke), (c) temperature distribution around the flame, (d) burning solids, (e) a simulated fireball.

$$\frac{\partial T}{\partial t} = T_0 C \quad (4)$$

where d_x is the density, and oxygen density d_A is defined such that the total amount of gas in each cell is constant. Conceptually, four parameters are used to control the shape and the stability of the flame. r is the burning rate ($0 < r \leq 1$) defining the percentage of the fuel gas that can be burned in a second. T_{thres} is the lower flammability temperature where burning can occur, and T_0 is the output heat from the reaction. It can be sufficient to start a reaction in a neighboring cell. Or it might not be sufficient, extinguishing the flame. bis the stoichiometric mixture, controlling oxygen requirement of the combustion and used to model different reactions.

The fuel gas is ignited either by reaching a sufficient temperature, or by a special “ignition” step. This combustion increases the heat in the system and can provide enough heat to the neighboring cells to continue the burning process on the next time step. Smoke is produced as a by-product of the combustion, and tends to rise with the hot air produced by the flame.

5. Representing Solids and Flame Spread

Solid materials inside the computational domain are voxelized and the corresponding grid cells in the computational domain are marked as filled, and this information is used in flow calculations [4, 2]. For the unfilled cells, heat both diffuses through the system and advects along with the gas flow. Thus, we have temperature values at the boundary between the solid and the air. Each filled grid cell is a potential fuel source. Active fuel sources emit fuel gas density into the neighboring unfilled cells at every time step. Potential fuel sources can later self-ignite, becoming active fuel sources. Every filled grid cell has a pyrolysis temperature, which is a material property (nonflammable materials simply have an arbitrarily high pyrolysis temperature). When a filled grid cell reaches its pyrolysis temperature, it becomes a fuel source.

6. Conclusions

We have presented a physically based approach for interactive simulation of fire. Some of the previous approaches simulate parts of the physical process, but usually use computationally expensive approaches. Our approach is capable of capturing the properties of simple flames together with the motion of the hot air/smoke and the heat distribution within the computational domain at interactive rates. The approach can also handle several realistic effects such as propagating flame to nonadjacent objects (self-ignition) and extinction of flames by using up all available air. We have implemented our approach, using a fluid flow solver based on the Stable Fluids approach of [4, 2] and created an interactive hardware-based OpenGL renderer that, while not producing “eyecatching” visualizations, is able to show the strength of our model. We are exploring the possibilities to extend the model. For more information refer to [3].

References

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