Physics-Based Combustion Simulation in Bifrost

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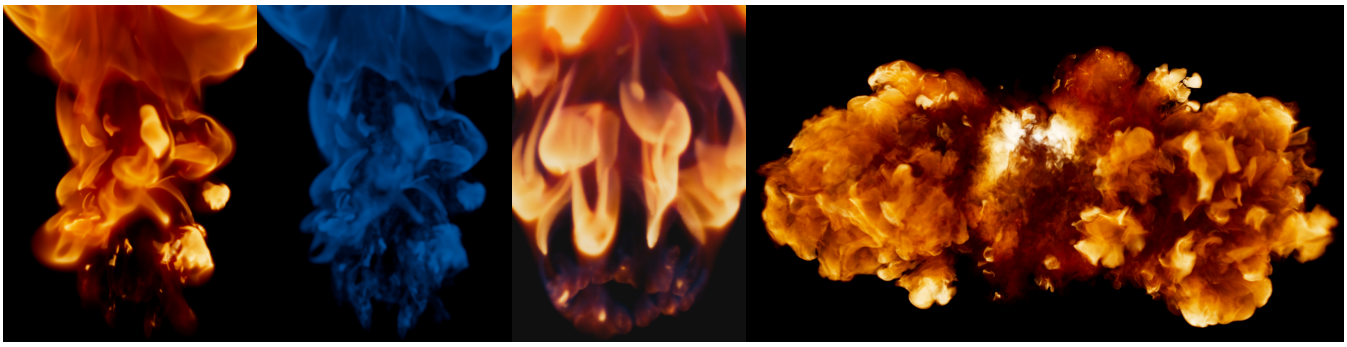

(a) Glowing soot (b) Blue flame (c) Subtle color nuances (d) Burning turbulent mixture of fuel and air

Figure 1: Our combustion simulation method includes physics-based models for real-world fuels, chemical kinetics, radiative heating, flame propagation as well as soot formation and oxidation. This enables physically plausible temperature distributions and flames for combustion phenomena ranging from small-scale fire to large-scale explosions. (a-c) A small scale diffusion flame simulated and rendered as a combination of (a) glowing soot and (b) a blue flame to create (c) subtle color nuances, particularly at the base of the flame. (d) A spark igniting a mixture of fuel and air governed by turbulent motion and oxygen diffusion resulting in flames propagating outwards from the point of ignition.

CCS CONCEPTS

• **Computing methodologies** → **Physical simulation**.

KEYWORDS

fluid simulation, smoke simulation, fire simulation, combustion

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Fire, from small-scale candle flames to enormous explosions, remains an area of special interest in visual effects. Even compared to regular fluid simulation, the wide range of chemical reactions with corresponding generated motion and illumination makes for highly complex visual phenomena, difficult for an artist to recreate directly. The goal of our software is to provide attractive physical and chemical simulation workflows, which enable the artist to automatically achieve "physically plausible" results by default. Ideally, these results should come close to matching real-world footage if the real-world parameters are known (such as what fuel is being burned). To support this, we aim to provide a user interface for artistic direction where the controls map intuitively to changes in the visual result. More user-demanding proceduralism will only occasionally be required for final artistic tweaks or hero shots.

With this in mind, we needed to expand the range of phenomena tackled by prior work on fire simulation in graphics to include effects such as radiative heating for ignition at a distance and faster fire propagation, as well as physically-based soot formation and oxidation: see figure 1 and the accompanying video. Our talk will present our exploration of nonlinear models from computational fluid dynamics (CFD) seeking out what is visually critical, as well as new (semi-)implicit integration methods for large time steps of the highly nonlinear chemical reaction differential equations, and how to combine this with our previous work [2018] on fluid simulation with dynamically spatially adaptive grids.

1 DYNAMICS

The dynamics of our solver are governed by the inviscid Euler equations in combination with the ideal gas law and the thermal energy equation. The thermal energy equation relates the change in temperature to the heat produced by combustion, conduction

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and radiation [Merci and Beji 2016]. To enable volume expansion during explosions without embracing a fully compressible model, we employ the approach of Feldman [Feldman et al. 2003] where a non-zero divergence term is added to the right-hand-side (rhs) of the Poisson equation when solving for pressure. Contrary to previous approaches in graphics, we derive the contribution to the rhs from first principles. In particular, it can be seen from conservation of mass that

$$\nabla \cdot v = -\frac{1}{\rho}\frac{D\rho}{Dt}$$

where v is velocity, ρ is density and T is temperature. We compute the density from the ideal gas law but decouple density and pressure by using a constant pressure in the evaluation of the ideal gas law. The equations are discretized using operator splitting and a finite difference approach on a spatially adaptive voxel grid.

2 COMBUSTION

We explicitly model the combustion as a single-stage chemical reaction of the form

$$a \times \text{Fuel} + b \times \text{Oxidizer} \rightarrow c \times \text{Products}$$

where a, b and c are stoichiometric coefficients. Unlike previous work in graphics, we support real-world fuels and oxidizers and make use of actual measurements of the physical constants involved — including the stoichiometric coefficients, specific heat and the heat of combustion. This facilitates the accurate prediction of adiabatic flame temperatures, for example. Our solver currently supports a number of hydrocarbon fuels (like propane) and allows the mixing of these to form other types of fuels often used in practical special effects (like methylacetylene-propadiene propane — or simply MAPP — gas). We track the spatially varying mass fraction fields of oxygen, nitrogen and each type of fuel. Optionally, we also track products such as carbon dioxide and water vapor. If tracked, the products influence radiative heating calculations. The water vapor can be rendered by way of a simple condensation model. In state-of-the-art CFD, a mixture fraction approach is often used, representing several species by a single scalar field (the mixture fraction)[Merci and Beji 2016]. However, the mixture fraction approach imposes strict limitations on the variation of fuel and oxidizer at inlets; while often acceptable for CFD, it does not apply well to graphics where the user must have complete freedom in specifying temporally and spatially varying emission of fuel and oxidizers.

3 FLAME PROPAGATION

In graphics, previous works have modeled the flame propagation by either explicitly computing the reaction rate [Feldman et al. 2003] — which requires very small time steps or an infeasible amount of temperature diffusion to achieve realistic flame propagation speeds — or by tracking the flame using the thin flame model at a constant flame speed [Nguyen et al. 2002]. In contrast, our solver does not impose extra restrictions on the time step and facilitates flames propagating at speeds that depend on the spatially-varying temperature and mixture of fuel, oxidizer and products. By default, our computation of the local flame speed is based on interpolation and extrapolation of actual measurements reported in the literature, but we also allow the user to override and tweak these speeds for artistic effects. The actual flame front is tracked as a level set using the thin flame model. By combining this with an explicit oxygen diffusion step we can simulate flames covering the whole spectrum of fuel-lean to fuel-rich conditions (including diffusion flames) using the same method. To facilitate large time steps, we track the propagation of the flame level set ϕ using a spatially varying dilation that is accurate away from the medial axes of ϕ and when $|\nabla\phi| = 1$. Nguyen et al.[2002] rendered the thin flame level set as a blue core, but in general, the blue flame corresponding to spectral line emission is *not* a closed surface, and we instead choose to render the blue flame based on the reaction rate.

4 SOOT FORMATION AND OXIDATION

In graphics, several works have modeled the formation of soot by a linear dependence on the reaction rate [Feldman et al. 2003]; however this is not always physically plausible. For example, given a hydrocarbon fuel at stoichiometric conditions, all available fuel and oxidizer will react to form carbon dioxide and water vapor with no excess soot. To simulate non-smoking flames it is also important to take soot oxidation into account. Soot oxidation is the process by which oxygen in the air will attack clusters of soot and generate other by-products. Visually this leads to interesting flame shapes and the disappearance of glowing soot mid-air (at the "top" of the flame). While this effect is often approximated by various heuristic approaches in graphics, we were not able to find any previously published work on this subject. We have adopted physically validated soot formation and oxidation models from CFD, and contribute semi-implicit discretizations of the ODEs involved to facilitate large time-steps important for graphics applications.

5 RADIATIVE HEATING

Traditionally in graphics, radiative cooling is accounted for by the Stefan-Boltzmann Law [Nguyen et al. 2002], but radiative heating is ignored under the assumption that the radiated energy is absorbed by the ambient surroundings. However, radiative heating can play a significant role in the overall heat transfer of combustion and we have found it to give rise to interesting visual phenomena as well. For example, radiative heating tends to give an additional glow to the look of flames and fireballs, and is also the effect that can cause flames to ignite fuel at a distance without heating up the air in-between. Radiative heating and cooling is governed by the Radiative Transfer Equation (RTE) and, following approaches in CFD and volume rendering, we approximate it by the $P-1$ equations [Merci and Beji 2016]. The $P-1$ equations simplify the RTE to a non-linear diffusion problem to which we apply a flux limiter approach and solve the discretized equations using non-linear multigrid.

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