# Fire and Explosions in Avatar: The Way of Water


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**Figure 1:** A selection of shots from *Avatar: The Way of Water* involving combustion simulation: (a) fuel ignition on top of ocean surface, (b) fire pulled through an aircraft turbine, (c) flamethrowers, and (d) a massive explosion. ©Disney.


## ABSTRACT

Combustion workflows for the *Avatar* sequel(s) were built from the ground up, aiming at physical plausibility and predictability, facilitated by careful modeling from molecular-level chemical reactions to large-scale thermodynamics. Onset references for torches, flame bars, and burning Marui villages guided development work across simulation, look development, and rendering. Using chemical formulas and properties of real-world fuels, and tuning pre-mixing with oxygen, allowed faithfully capturing a number of desirable effects, such as “oxygen starvation” and flickering of thin flames, without the need for additional artistic variables. Using our new solver created a consistent look across sequences at different scales, allowing artists to replace library fires with hero solves when interaction or a particular behavior was required.



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## 1 INTRODUCTION

Ever since the production of *The Hobbit*, Wētā Digital has pushed the development of in-house solvers for smoke, fire, and explosion effects. Multiple systems have been developed over the years, most recently presented in [Aguilera and Johansson 2019]. For *Avatar: The Way of Water*, the requirements lead to the development of a completely new solver in the Loki framework [Lesser et al. 2022].

## 2 IMPLEMENTATION

We were inspired by the work of [Nielsen et al. 2022] and followed a similar approach, tracking real chemicals to faithfully model the combustion reaction, including soot formation and oxidation. Likewise, we used the ideal gas law with decoupled pressure to drive expansion via a divergence term. However, there are a few key differences.

[Nielsen et al. 2022] handles expansion as a mechanism that ensures that the pressure in the ideal gas law is maintained at the atmospheric value. Any deviations from it are resolved immediately on each timestep following a differential equation of density evolution. While this works great for simulating real-world experiments, we quickly discovered that artists consistently wanted to break the constraint of constant atmospheric pressure by either injecting more material in a unit volume than is physically “allowed” and/or stamping high temperature in a region of space instantly and expecting it to expand. The idea of “storing” the system state and using it to expand gradually over time was also attractive.

To accommodate this request we resorted to storing the actual amount of each chemical per voxel, rather than their relative fractions which add up to 1, see [Nielsen et al. 2022]. We expressed the amount of material using our new dimensionless measure of *concentration*, which was more intuitive for artists to work with compared to density or moles per unit volume. With that we could enforce the ideal gas law and associated expansion exactly by the end of each solver timestep. This also allowed for partial or delayed expansion and gave limited support for adiabatic cooling.



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We used a signed distance field (SDF) to track the flame front. The SDF was propagated in the normal direction based on the flame speed, which allows the burning region to expand to new areas where the fuel and oxygen mixture is sufficient for combustion.

We modeled the mass diffusion process of fuel and oxygen as well as temperature diffusion. We initially computed this as a linear system solve, but we found it to be too slow for production use. Instead we approximated diffusion with convolution using Gaussian kernels with negligible difference in the visual results.

To be able to handle massive simulations efficiently, we made use of spatial adaptivity techniques and a robust workflow for distributing simulations across multiple machines using MPI. This is described in more detail in [Lesser et al. 2022].

## 3 PRODUCTION USE

*Torches.* Reference footage of a curry pot fire and a flame bar, Figure 2c, was initially used to match corresponding simulations in Loki, Figure 2a. The result was then used to make a torch simulation, Figure 2e, with the correct fire oscillation frequency of 10Hz. Oxygen starvation phenomena ultimately gave the flickering effect that is natural and desirable in a fire simulation.

*Fire on water.* Chemiluminescence was essential for defining the look and intensity in the shots where fire spreads over water and surrounds the characters (Figure 1a). The emissive regions of chemiluminescence were estimated using a heat field output by the combustion reaction and masked based on the regions where the combustion reaction is fuel-lean (equivalence ratio < 1.0).

*Fire tornado.* Fire pulled through an aircraft engine, Figure 1b, shows that with the help of correctly created force fields Loki was flexible enough to simulate this and other art-directed effects while maintaining physical accuracy.

*Marui village.* For one of the dramatic sequences of the movie the Metkayina village was set on fire, Figure 2h. Given the beach location, our fire simulations had to be accurate and stable even in highly windy scenarios. To model the wind, an airfield was simulated using the village geometry as a solid boundary condition. The geometry had large holes for ventilation, leading to interesting flow patterns. The wind field was applied to fire simulations by enforcing a velocity boundary condition on the border of the sparse simulation domain. This created realistic behaviors that would not attract any notes from the director. With Wellington being naturally windy, local reference shoots, Figure 2f, were helpful to achieve the desired fire fluctuation patterns during simulation, Figure 2g.

*Explosions.* Explosions played a key part in conveying a few story points in the movie, Figure 1d. On a couple of occasions they needed to be large and close to the camera, and even retimed to gradually transition into slow motion. We used animated point clouds to perform initial emission via stamping. This helped creatively direct early shapes but left the physically correct aspects of the simulation at later times to the Loki solver. Chemical concentrations and temperatures were defined on the points while expansion, evolution, and turbulence were dialed in with Loki controls. By using appropriate mixtures of fuel and oxygen and relying on our physically accurate solver, we were able to closely match the reference from *Terminator 2* (1991) requested by the director. Our *energy cascade turbulence* model helped add interesting detail by restoring and amplifying kinetic energy at multiple scales through procedural noise injection. For the burning bits thrown out of explosions, filtering using flame front SDF at render time was key to achieving sharp hollow flames with cellular patterns. Since Loki natively supports scaling time, we were able to directly apply requested time curves during simulation, rather than having to retime as a post process. Thanks to Loki's distributed simulation capabilities, we were able to simulate even the biggest explosions and subsequent fires with as many machines as needed.

*Flamethrowers.* Flamethrowers achieve long firing ranges, up to tens of meters, by shooting liquid rather than gaseous fuel. Napalm mixes can be used to extend the range even further. It was clear from the start that a simple gas emitter would not suffice, as it would lack the necessary inertia to be able to hit a distant target. We thus decided to use the capabilities of the Loki state machine [Lesser et al. 2022] to create a multi-state coupled simulation. A fluxed emitter was used to create a stream of FLIP fluid. The FLIP particles would split probabilistically based on their density, and transition to a separate *spray* particle system. We applied SPH forces to the *spray* to allow formation of interesting droplet features. The spray particles were also two-way coupled to the surrounding combustion volume via a drag force to achieve visually compelling breakup patterns. Those would eventually get rasterized to a volumetric fuel channel in a momentum conserving way and participate in the combustion reaction. The result can be seen in Figure 1c.

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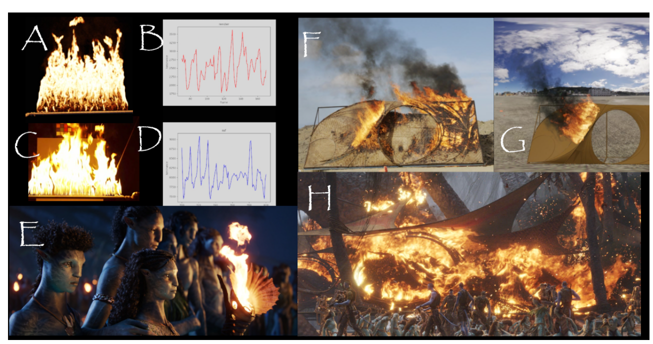


**Figure 2:** Simulated flame bar (a) vs real-world reference (c), with their corresponding temporal brightness plots (b) and (d), and a torch (e) simulated with the same settings. Marui fire reference (f), simulation (g), and the final shot (h). ©Disney and Wētā FX.