



Flaming Marshmallows

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MCEN 5151 Flow Visualization 002

1 Context and Purpose

This 52 s video was shot for the Get Wet assignment in MCEN 5151 Flow Visualization at the University of Colorado Boulder. Its intent was to show how flow driven from heat changes character as its driving force changes. A hand torch ignites the top of a marshmallow and is then withdrawn, leaving a buoyant diffusion flame fed only by vapor from the marshmallow itself,

which burns until a growing char layer starves it. Visually, the goal was to play the clean pale foam against the warm flame and the black char it leaves behind, using a tight frame and a plain background so that the flame and the changing surface texture carry the video.

2 Experimental Setup

Figure 1 is a high level sketch of the camera angle arrangement. A regular-size Jet-Puffed S'more Vanilla marshmallow, about 2×2 in (51×51 mm), was suspended on four metal skewers whose lower ends were braced in a baking tray. A Harris 4300672 hand torch cylinder burning MAP-Pro gas, which the manufacturer rates at a flame temperature of 3730°F (4190°R) in air [1], was held 3 to 4 in (76 to 102 mm) above the top face with the flame aimed downward. The torch was withdrawn after roughly 4 s, visible from about $t = 6$ s to $t = 10$ s, and the rest of the clip records the marshmallow burning on its own. Filming took place at about 4:30 PM in 81°F (540.7°R) air, with the marshmallow about 7 in (178 mm) in front of a dark gray marble surface and 7 in from the camera lens. A range hood ran overhead the whole time, 10 in above the marshmallow. Figure 2 captures the three stages of flow that the video displays.

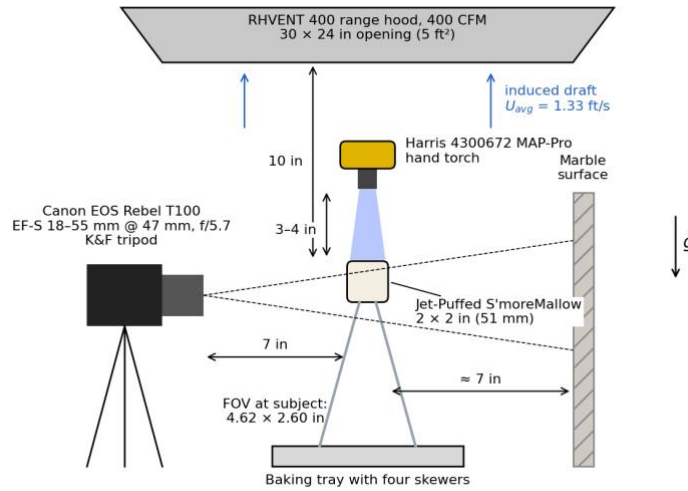


Figure 1. Side view of the setup.



Figure 2. Frames from the video: (a) the torch jet striking the top face, (b) the marshmallow's own flame once the torch is gone, and (c) the blistered, charring surface beneath a shrinking flame.

Stage 1, torch jet ($t = 6$ to 10 s). The torch burns MAP-Pro gas directly on the marshmallow. In Fig. 2a, the glowing jet spans about 0.5 in (12.7 mm). On reaching the marshmallow, the jet stagnates and spreads outward across the top face. Heating is strongest at that stagnation point [3], which is why browning first appears as a cluster of dark spots at the center of the top face and then works outward. Near $t = 10$ s the marshmallow ignites, and the new yellow flame is

driven sideways across the top face instead of rising, showing that the jet's momentum still governs the flow.

Stage 2, self-sustaining flame (t = 10 to 50 s): Heat returning from the flame to the surface breaks down the sugar and releases combustible vapor, while the browning comes from Maillard reactions between the sugars and the gelatin's amino acids, together with caramelization [4]. In terms of the main driving force of the flame at this stage, the jet's momentum is gone, leaving buoyancy from the flame itself, with a weaker draft imposed by the range hood above. The air that the hood directs is assumed to be steady and incompressible, so its average face velocity follows from the rated volume flow and the opening area,

$$A_{intake} = (30 \text{ in})(24 \text{ in}) = 720 \text{ in}^2 = 5 \text{ ft}^2 \quad (1)$$

$$U_{av} = \frac{\dot{V}}{A_{intake}} = \frac{(400 \frac{\text{ft}^3}{\text{min}})}{(5 \text{ ft}^2)} = 80 \frac{\text{ft}}{\text{min}} = 1.333 \frac{\text{ft}}{\text{s}} \quad (2)$$

The Reynolds number for that imposed draft, with a flame height of $L = 0.25 \text{ ft}$ and the kinematic viscosity of air at 81°F corrected to the $\sim 85 \text{ kPa}$ ambient pressure in Boulder is

$$Re = \frac{U_{avg} L}{\nu} = \frac{(1.333 \frac{\text{ft}}{\text{s}})(0.25 \text{ ft})}{(2.03e-4 \frac{\text{ft}^2}{\text{s}})} = 1641.6 \quad (3)$$

well short of the $Re \approx 5e5$ at which an external boundary layer turns turbulent [5], so the draft itself is laminar. Buoyancy is scaled with the Grashof number, which compares buoyancy to viscous forces and plays the role for a buoyancy driven flow whereas the Reynolds number plays for a forced flow [6]. Its inputs come from the film temperature, the average of the hot surface and ambient temperatures, at which fluid properties are evaluated [6]. Here T_s is the flame temperature, estimated to be 2700°R [7], and T_∞ is the 81°F (540.7°R) ambient. Both must be absolute temperatures, because β and the density ratio behind the buoyancy term come from the ideal gas law, which is written in absolute temperature:

$$T_f = \frac{T_s + T_\infty}{2} = \frac{2700^\circ\text{R} + 540^\circ\text{R}}{2} = 1620^\circ\text{R} \quad (4)$$

The volumetric thermal expansion coefficient of an ideal gas is the reciprocal of that film temperature,

$$\beta = \frac{1}{T_f} = \frac{1}{1620^\circ\text{R}} = \frac{6.17e-4}{^\circ\text{R}} \quad (5)$$

and the Grashof number can be calculated, given the kinematic viscosity of air at 1620°R , again corrected to 85 kPa ,

$$Gr_L = \frac{g\beta|T_s - T_\infty|L^3}{\nu^2} = \frac{(32.2 \frac{\text{ft}}{\text{s}^2})(6.17e-4^\circ\text{R}^{-1})(2160^\circ\text{R})(0.25 \text{ ft})^3}{(1.28e-3 \frac{\text{ft}^2}{\text{s}})^2} = 4.1e5 \quad (6)$$

This is more than 3 orders of magnitude below the $Gr \approx 10^9$ transition to turbulence [6], so the buoyant flow is laminar. That agrees with the smooth, sheet-like flame surfaces in Figure 2b. Additionally, even a laminar buoyant flame flickers. Buoyancy accelerates the hot gas just above the fuel surface and rolls it into a ring vortex that periodically pinches off the flame tip [8, 9]. Cetegen and Ahmed [8] correlate the flicker frequency with the fuel-source length in meters, which for $L = 0.25 \text{ ft} = 0.0762 \text{ m}$ gives

$$f = 1.5L^{-1/2} = \frac{1.5}{\sqrt{0.0762 \text{ m}}} = 5.4 \text{ Hz} \quad (7)$$

The correlation was built from pool fires in still air, so this is only an estimate; the flicker is too fast to follow by eye, though the flame tip visibly changes shape from frame to frame.

Stage 3, charring ($t = 25$ to 50 s). As the char crust thickens it insulates the interior and traps the volatile gases inside. Starved of fuel, the flame retreats to the two side lobes where fresh sugar is still exposed, then goes out, leaving a black, layered shell. The small red orange specks visible on the surface through this stage are pieces of char glowing from heat, a smoldering solid rather than a gas phase flame [2].

3 Visualization Technique

No seed particles, dye, or smoke were added; the flow is visible through its own light, namely chemiluminescence in the blue torch flame, glowing soot in the yellow marshmallow flame, and glowing char on the surface. The only illumination was ambient daylight. The overhead range light was tried many different times and ultimately rejected because it washed out the flame and flattened its contrast against the marble background. Additionally, the scene was deliberately underexposed so the flame would stay the brightest element in the frame.

4 Photographic Technique

The camera was a Canon EOS Rebel T100 (EOS 4000D) on a K&F Concept tripod, recording $1920 \times 1080 \text{ px}$ progressive video at 29.97 fps (H.264, 47.7 Mbps average); the clip runs 52 s, or 1552 frames. The lens was a Canon EF-S 18–55 mm f/3.5–5.6 III set to 47 mm (73.9 mm full-frame equivalent) and focused manually in Live View. The front of the lens sat 7 in (178 mm) from the marshmallow, and the camera recorded a focus distance of 0.35 m (13.8 in), measured from the sensor. From that focus distance and focal length, the field of view is $117 \times 66 \text{ mm}$ ($4.62 \times 2.60 \text{ in}$), the image scale is 16.4 px/mm (416 px/in), and the horizontal angle of view is 27.4° . As a check, the marshmallow spans about 754 px in the video,

$$w = \frac{754 \text{ px}}{16.4 \text{ px/mm}} = 46 \text{ mm} \quad (1.8 \text{ in}) \quad (8)$$

which is close to its nominal length of 2 in. The aperture was f/5.7, essentially wide open at this focal length. The camera metadata reports a depth of field that rounds to zero at this distance (circle of confusion 0.019 mm), which is why the background falls away so cleanly and why only a thin slice of the marshmallow is sharp at any moment. The camera ran in automatic movie exposure (Program AE) with Auto ISO, 0 exposure compensation, and center-weighted metering, at EV 7.12. The T100 does not store shutter speed or ISO in movie files, and in Program AE both drift as the flame brightens and dims, so no single value can be reported. White balance was automatic at 5200 K, and the flash did not fire. The interval between frames was

$$\Delta t = \frac{1}{29.97 \text{ fps}} = 33.4 \text{ ms} \quad (9)$$

and in that time, gas moving at the average velocity scale travels

$$\Delta x = U_{avg} \Delta t = \left(1.333 \frac{\text{ft}}{\text{s}}\right) (0.0334 \text{ s}) = 0.0445 \text{ ft} = 0.53 \text{ in} \quad (14 \text{ mm}) \quad (10)$$

roughly a quarter of the frame width. Because each exposure lasts no longer than the frame interval, gas parcels are not frozen and flame edges appear soft. The 15 Hz Nyquist limit comfortably exceeds the estimated 5.4 Hz flicker, and the number of frames per flicker cycle is

$$N = \frac{29.97 \text{ fps}}{5.4 \text{ Hz}} = 5.5 \quad (11)$$

so the flicker is captured, though coarsely. The surface is well resolved by comparison. Each pixel spans

$$\frac{1}{16.4 \text{ px/mm}} = 0.061 \frac{\text{mm}}{\text{px}} \left(0.0024 \frac{\text{in}}{\text{px}}\right) \quad (12)$$

and the blister pits in Figure 2c measure roughly 7 to 21 px across, a median of 13 px, or 0.43 to 1.3 mm (0.017 to 0.050 in). The shallow depth of field, not the pixel size, is what limits surface detail. The camera applied its own processing before any editing: Picture Style Auto; contrast, saturation, and color tone at Normal; sharpness 3 of 7; standard tone curve; Auto Lighting Optimizer at Standard; Highlight Tone Priority, high-ISO noise reduction, and peripheral illumination correction off; sRGB color space; and no digital zoom. The frames are otherwise unedited, and the final video is 1920 × 1080 px at 29.97 fps.

5 Video Dissection

The video captures three distinct regimes: the torch's momentum pushing the flame sideways at ignition, a laminar flame rising on its own once the torch is gone, and the flame shrinking back to the side lobes as the char thickens. The tight framing and deliberate underexposure work well, since the flame reads as the brightest element and the shallow focus separates the marshmallow cleanly from the marble. The main weaknesses are a dim, structureless torch jet and a flame tip that rises past the top of the frame during early flaming, losing the full flame height. The running hood also means the flow is not pure natural convection. The two largest assumptions behind the analysis are the flame temperature, which was estimated rather than measured and which sets both the film temperature and the buoyancy term in the Grashof number, and the treatment of the hood's rated 400 CFM as a uniform face velocity at the opening. Because the marshmallow sat 10 in below that opening, where the induced velocity is weaker, the calculated draft velocity is an upper bound, and a cooler flame would lower Gr without changing the laminar conclusion. Natural next steps are more headroom above the flame, switching the hood off safely or measuring its airspeed, measuring the flicker frequency frame by frame against the 5.4 Hz estimate, testing the $L^{-1/2}$ scaling with other marshmallow sizes, and schlieren imaging to reveal the hot plume that stays invisible here.

6 References

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