University of Colorado - Boulder

MCEN 5151
Flow Visualization

Team Third Report - Bialetti Flow

Samuel Hatton 4 December 2024

College of Engineering & Applied Science
UNIVERSITY OF COLORADO BOULDER

1 Introduction

1.1 Image Summary

The primary media focus of this report is my Bialetti Flow video, though I also produced a longer video as well as the cover image on this report. A Moka pot is a type of coffee brewer that uses pressure to force water coffee grounds, somewhat similar to an espresso machine but does so simply through heat addition from a stove or heating element into a boiling chamber separated from ambient conditions via coffee grounds and a series of filters. Moka pots are famously popular in Italy, where the brewing method was invented and popularized by the Bialetti company; The Bialetti Moka Express, used for this report, is perhaps the most iconic coffee brewer in the world.

1.2 Motivation

I love coffee and was given Bialetti Moka Express by a friend. After using it several times, I was fascinated by the way it works; after peaking under the lid during a brew, I was struck by the simple beauty of the coffee spilling into the catch chamber. I experimented with capturing this flow over many months before setting out to create the video for this project.

2 Methodology

2.1 Test Setup

The Bialetti Moka Express used in this demonstration is a typical 30/300-sized moka pot from Bialetti. "30/300" refers to the ratio of coffee grounds to water used to set up the brew: the coffee basket holds approximately 30 grams of finely ground coffee and the boiler chamber holds approximately 300 grams of water. Coffee brews are commonly described by this input ratio; a typical espresso brew is 1:2 or 1:3 coffee to water, a pour-over or French press coffee is typically around 1:15, and drip coffee is usually around 1:17 or so. The presented visualization is comprised of shots from multiple brews, but the general process shown in the video is enumerated below. Please note! This is not a great way to brew good-tasting coffee in a moka; you generally want to control the temperature more carefully than this, but that's not as convenient for filming.

1. Frame up the empty pot on the stove, setting up any camera equipment before starting the brew.

2. Fill the bottom chamber of the moka pot with water up to the fill line (about 300 grams of water).

3. Grind approximately 20 grams of coffee to a fine consistency; not as fine as espresso, but more fine than most other brews. Certainly at the "fine" end of any typical (not specialty) grinder.

4. Poor the ground coffee into the moka pot coffee basket and level without compressing.

5. Place the basket into the lower chamber and screw on the upper chamber.
6. Place the pot on a stove with the lid up and double-check the framing and exposure on cameras.
7. Roll cameras and set the burner to high to begin the brew.
8. As soon as coffee begins exiting the funnel into the catch basin, turn off the stove.
9. Once the coffee has completely stopped brewing (no more is coming out), stop the cameras.

2.2 Visualization Technique

The flow out of the central funnel and into the catch basin is easily visualized; it is colored by suspended coffee particles and contrasts well with the background of polished aluminum, so little work is needed to show the flow.

2.3 Photographic Technique

The project video was filmed on two cameras. The long shots are shot on a Canon EOS 6D Mark II DSLR with an EF 28-135mm f/3.5-5.6 IS USM lens. This footage is 60 fps 1920x1080p, 135mm (35mm equivalent: 205.1 mm) focal length, 1/500 shutter speed, f/8.0, and ISO 4150. The sorta choppy slow-mo shots come from a rapidly overheating Google Pixel 7 main back camera (6.81mm, 35mm equivalent 24.0 mm, f/1.85) at 240 fps 1920x1080p. Putting the phone close enough to the moka pot to get the shot also put it right in the hot air rising off the stove and out of the pot, so it got pretty hot. This is the easiest explanation for the numerous dropped/skipped frames in the full recording, which greatly limited the slow-mo in the final video. The video was edited entirely in DaVinci Resolve 19, and the cover image of this report was lightly edited in Adobe Lightroom Classic.

The brews were filmed in a dark room, lit from directly above by a white LED light panel held approximately 2 feet above the pot. This provided consistent, strong lighting across the whole pot. The stove top is a fairly reflective black glass and makes up the majority of the background around the pot. The panel light did a good job of lighting the Moka pot without causing reflections off of the stovetop to show up in the camera images. One difficulty with these shots is that the total light in the frame changes drastically as the dark coffee fills the pot: without coffee in it, the catch chamber is very bright, as it reflects light very well and bounces it all back up into the camera sensor. The coffee is very dark and not very reflective, so not as much light makes it up and out of the pot once the coffee covers the bottom of the catch chamber. The main DSLR shots used in the video were manually exposed with the pot empty; being in manual with no auto setting changes means the camera did not adjust as the coffee brewed. In the future, experimenting with various auto-exposure methods may yield more consistent video lighting throughout the brewing period.

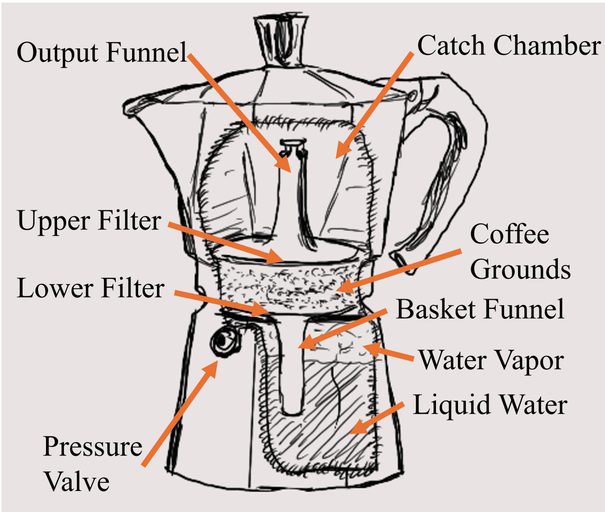

Figure 3.0.1: The anatomy of a moka pot.

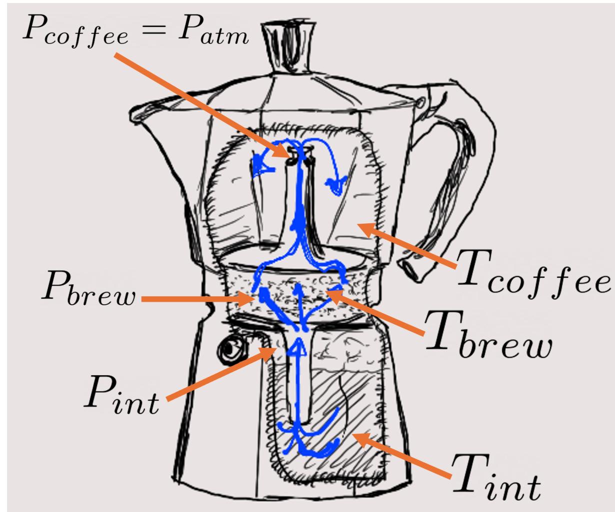

Figure 3.0.2: The flow within a moka pot.

3 Flow Discussion

Understanding a bit more about the physical design of a typical Moka pot will help explain the Bialetti flow that gives rise to the thick, textured coffee pouring out in the video. The Bialetti used in the video is perhaps the simplest of moka pots; there are lots of other designs that are more complicated for one reason or another.

The fundamental moka pot is beautiful in its simplicity. Figure 3.0.1 shows a labeled sketch of the Bialetti Moka Express. The output funnel and catch chamber are the main things visible in the video. The water is contained and boiled in the boiling chamber, or the bottom half of the pot. This chamber has a pressure release valve on it to avoid potentially explosive over-pressure events. Suspended in the joining ring between the upper and lower chambers is a basket that holds the coffee grounds. The ”floor” of the basket that the grounds sit on is a metal filter with holes that allow water through but hold up the coffee. Below this lower filter, the basket necks down into a funnel that extends nearly to the bottom of the boiling chamber, well below the surface of the water. At the bottom of the upper chamber is another filter that becomes the ”roof” of the coffee basket when the upper and lower chambers are screwed together. Above this upper filter is the output funnel, through which the coffee spills down into the catch chamber.

During the brewing process, the lower chamber is heated directly by the stove. Most of this heat goes into the water within the boiling chamber. As the water heats up, it gives off steam. This steam is trapped between the surface of the water and the walls of the boiling chamber (made up of the actual walls and the outer surface of the basket funnel). As the steam builds up the pressure in the boiling chamber rises, eventually pushing water up the basket funnel and into the coffee grounds. As the water pushes through the coffee grounds, particulates are infused into the flow, turning it into coffee; the coffee is then pushed up the output funnel and into the catch chamber. Figure 3.0.2 shows how the flow travels through the pot, and labels some key quantities that allow us to characterize the flow within the moka pot. We'll call the pressure of the atmosphere in the room P_{atm}, the pressure of the

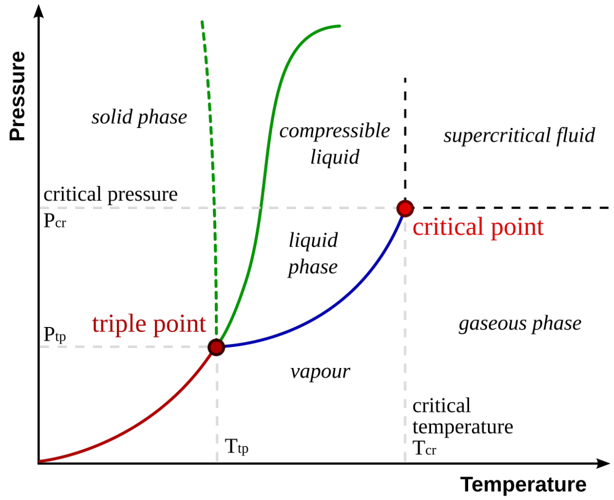

Figure 3.0.3: While it's boiling, water lies along the blue line[6].

brewed coffee P_{coffee}, the pressure in the brewing chamber P_{brew}, and the pressure of the air inside the boiling chamber P_{brew}.

We've also got temperatures at all of these points; temperature is mainly important because of how it relates to pressure and boiling: When liquid water heats up, more and more of it changes phase to become water vapor. Phase transitions like this start happening before water reaches its boiling temperature, but once the water hits its boiling temperature (about $203°F$ at our ambient pressure here in Boulder), the rate at which water vaporizes perfectly matches the rate at which heat energy is added to the water. This means that usually, water is at a constant temperature the whole time it is boiling. This is true of water in a pot, for example, that you might use to cook noodles. The boiling temperature and pressure of a fluid are often described by the Clausius-Clapeyron relation[6][2], a set of equations that generate a set of curves like that shown in Figure 3.0.3.

Why does this matter? Well, as water vapor builds up in the space between the surface of the water and the bottom of the coffee basket, the pressure in there has to go up. The more water vapor there is in that space, the higher the density of the gas. For gas at a given temperature (in this case, about boiling temperature), if density goes up, then pressure must also go up. This relationship is effectively modeled by the Ideal Gas Law, shown in the relevant form in Equation 3.1, where R is the gas constant of the gas.

$$P = \rho RT \tag{3.1}$$

So, as the water boils, the density of the gas (ρ) goes up, which pushes up the pressure in the boiling chamber. As the pressure rises, however, the state of the chamber has to adjust according to the Clausius Clapeyron relation: A higher chamber pressure also means a higher boiling temperature. This is mostly important because of how the temperature of the water affects the brew of the coffee: generally the hotter the water the faster coffee particulates are picked up. Cold brews take a long time to reach a tasty saturation, and it's easy to over-brew with water that is too hot, leading to harsh-tasting coffee.

This whole boiling process happens pretty slowly; it can take up to 10 minutes for all of

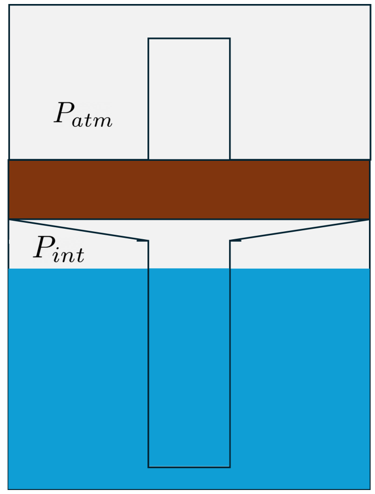

Figure 3.0.4: State 0: Before brewing, the pressures are equal: $P_{int,0} = P_{brew,0} = P_{atm}$

the water to either boil off or fall out of the funnel as brewed coffee. This means that the water isn't moving very fast at any point in the process. The flow area of the upper funnel is around $20e-6\ m^2$; if 250 grams of coffee flow through the funnel in 5 minutes, then the average mass flow rate is $\dot{m} = 0.05\ kg/min\ = 0.00083\ kg/s$. Mass flow rate is related to area via Equation 3.2 [3]. Using this, we can estimate the average flow velocity of coffee through the moka pot to be something like 0.04 m/s

$$\dot{m} = A\rho v \tag{3.2}$$

It's reasonable to assume that the flow is well within the incompressible regime, generally considered to be flow at a Mach number under 0.3. The speed of sound in water (and so probably coffee) is nearly a mile per second; there's no chance the Bialetti flow is moving that fast at any point in the brewing process (0.04 m/s is much much less than 1.6 km/s). As an aside, the flow is also most likely laminar throughout the process: For a laminar-turbulent transition critical Reynolds number of 3500, a density of 1000 kg/m^3, and a dynamic viscosity of $1e-3\ kg/ms$, transition begins when the flow reaches around 0.07 m/s.

The flow properties at any two points in an incompressible flow can be related through Bernoulli's Principle (Equation 3.3), arising from applying incompressible assumptions to the Navier-Stokes conservation equations for fluid flows. It's important to point out that pressure, height, and velocity can be different at different points, but the density ρ of the fluid is constant; this is the incompressible assumption at work.

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \tag{3.3}$$

If we neglect the velocity of our brewing flow and instead look only at pressure and relative height, we get Equation 3.4.

$$P_1 + \rho g h_1 = P_2 + \rho g h_2 \tag{3.4}$$

This equation must hold everywhere in the brewing flow, so we can use it to understand how it is the water in the lower chamber gets pushed up through the coffee and into the upper chamber simply by getting hot. Unfortunately, the answer is not magic, although it can feel that way when you taste a well-brewed cup of Moka coffee. Figure 3.0.4 is something of a diagram showing a cross-section of the moka pot before any heat is added to the system; this is State 0. At this point, all of our pressures are equalized ($P_{int,0} = P_{brew,0} = P_{atm}$).

As the water starts to heat up and water vapor starts to build up in the brewing chamber, the pressure inside the chamber grows. This means that our pressures are no longer all the same. P_{brew} and P_{atm} are still about the same, but P_{int} has grown larger than the other two. The height of the water in the center column needs to change according to Eq. 3.4 to maintain pressure equilibrium. Let's call this point in the process where pressure is building but the coffee hasn't started flowing State 1; this state is illustrated in Figure 3.0.5. We can solve for the difference in height of the two water surfaces; this relationship is shown for State 1 in Equation 3.5.

$$\Delta h_1 = h_{atm,1} - h_{int,1} = \frac{P_{int,1} - P_{atm}}{\rho g} \tag{3.5}$$

Eventually, the pressure in the brewing chamber grows enough to push the coffee up and out of the upper funnel; We can call this State 2, illustrated by Figure 3.0.6. At this point, there is no more height for the fluid column to gain upwards; it all falls away from the system, effectively. This means that Δh_2 is a direct measure of the level of water remaining in the chamber relative to the top of the output flute. At some point, the pressure inside the brew chamber gets high enough and the water level low enough that vapor starts to sneak up the lower funnel, through the coffee, and out the top. This is the sputtering observed towards the end of the flow. If brewing for flavor, you should try to avoid this phase altogether as it makes for yucky-tasting coffee, but it is a cool flow phenomenon. If left to continue boiling, eventually the flow of water stops altogether as its level drops below the bottom of the basket funnel, and the remaining water boils away and exists the system as vapor.

4 Conclusion: Revelations

There is endless beauty in the smallest of things; it is easy to take for granted everything that goes into a morning cup of coffee. By exploring our world with curiosity and attention to detail, we can unlock a great joy that is otherwise missed out on. Joy is found at several points during a moka pot brew; I am joyful at the thought of having coffee, of course. I am buoyed in real-time by the immediate beauty of the coffee flowing out into the pot before me, and I find great pleasure in trying to capture that beauty in some form of art. Further joy is found in sharing the art, however poor it ended up. Yet further joy is found in studying and understanding the underlying science of the brew: Learning about the flow physics, as well as the chemistry involved in brewing, the global logistics of coffee, and the cultural/historical significance of moka pots are all an opportunity for further joy. Of course, none of this creative or cognitive work is possible without the clarity of mind afforded by actually drinking the coffee! To say nothing of the taste; moka pots are the most effective brewing tool from a cost-per-taste perspective.

I have learned a ton about the science of coffee from James Hoffmann, whose YouTube channel has become something of a coffee Bible for aspiring coffee fanatics. Much of my

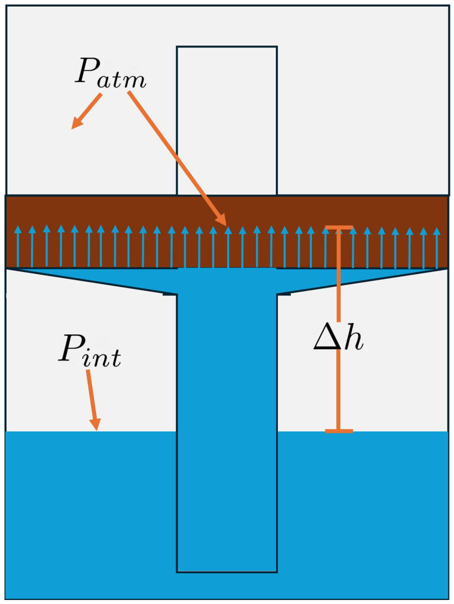

Figure 3.0.5: State 1: Internal pressure starts to push water up through the coffee.

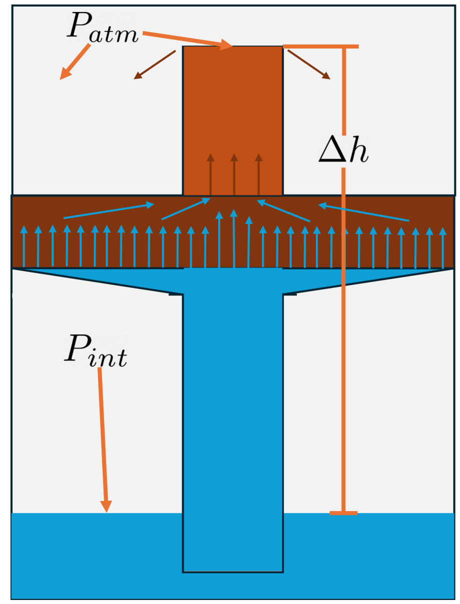

Figure 3.0.6: State 2: Eventually all of the water is forced through the coffee.

understanding of the internal workings of moka pots comes from watching his videos and studying patent documents of similar pots [4][1]. If you are at all curious about coffee, please give his channel a look. For more on moka pots specifically, I highly recommend this playlist [5].

References

[1] Ugo Morono and Francesco Ranzoni. *Pressure coffee maker for preparing coffee infusions*. Dec. 1996. URL: https://patentimages.storage.googleapis.com/c0/12/b3/a5da717dcf8d69/EP1208781A2.pdf (visited on 12/04/2024).

[2] Chung Chieh and Albert Censullo. "Clausius-Clapeyron Equation". In: *UC Davis LibreTexts in Chemistry* (2014).

[3] OpenStax. "Flow Rate and Its Relation to Velocity". In: *UC Davis LibreTexts in Chemistry* (2014).

[4] ames Hoffmann. *Understanding The Moka Pot*. Jan. 2022. URL: https://youtu.be/zK0F5PqJ1Gk?si=_lGv19-6L5QJ5nLx (visited on 12/04/2024).

[5] James Hoffmann. *The Moka Pot Series*. Jan. 2022. URL: https://youtube.com/playlist?list=PLxz0FjZMV0l1Zot3qiJ-wseRXyO-XoVNx&si=QHnChJGDhKsVtE5l (visited on 12/04/2024).

[6] Wikipedia. *Clausius-Clapeyron relation*. Dec. 2024. URL: https://en.wikipedia.org/wiki/Clausius%E2%80%93Clapeyron_relation (visited on 12/04/2024).