

Capillary and Thermally-Driven Flow in a Tapered Spiral "Metal Lamp Wick"

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1 Introduction

Capillary action is one of the most familiar microfluidic phenomena from everyday life, as well as one of the most useful from a viewpoint of microfluidic technology application. It is a fundamental part of the principle of operation of most microfluidic devices, from inexpensive paper-based microfluidics to cutting-edge lithography-based devices [4]. One of the most widespread technological applications of capillary action is the humble lamp wick. The simplest lamp wicks consist of a length of string or bundle of fibers; some contain additional elements such as mesh cladding to direct the flow along the axis of the wick. Universally, capillary action is a necessary part of their operation since it drives the initial conveyance of fuel to the site of ignition [3]. Thereafter, different types of wick behave differently, with simple open-pore designs continuing to rely strongly on capillary action during steady-state burning while more intricate designs allow for larger or more controlled flames by exploiting other physical effects such as of thermal gradients and their associated partial pressure differentials, among others.

This is an experimental demonstration of a lamp wick concept that utilizes no fibrous material but rather directs flow along micro-channels formed between successive layers of rolled sheet metal, which might be advantageous in applications such as where longevity is a concern. Wicking geometries made of metal, and in particular of aluminium, have been studied in the past [2][1][5]. However, these have generally been expensive to manufacture, relying on 3D printing or micro-machining. This demonstration uses readily available materials and does not require specialized skill, but involves handling of flammable material and potential for unstable flame growth, and so should only be performed in controlled environments by responsible researchers; however, the aspiration is that such construction may be adapted in the future to commercial lamp or lighter wicks or other industrial or scientific applications involving combined capillary and thermally-driven flows.

1.1 Preliminary Literature Review

The field of capillary-driven microfluidics and wick structures has seen significant advancements in recent years. Olanrewaju et al. (2018) laid the foundation for capillary circuits, identifying critical elements like capillary pumps and valves while emphasizing advancements in microfabrication. Ma (2020) further analyzed capillary flow in parallel microchannels with varying geometries, offering insights into optimizing flow dynamics.

Li and Joshi (2020) explored capillary-assisted evaporation and boiling in PDMS microchannels integrated with wicking microstructures, focusing on heat transfer applications. Their work demonstrated the benefits of structured wicks for fluid transport. Similarly, Jiang et al. (2022) and Wu et al. (2023) advanced the design of microgroove wicks with dual-scale and multi-scale textures, achieving enhanced capillary performance in compact configurations, but their designs remained planar.

In contrast to these works, this study introduces the novel concept of rolled wicks, leveraging their ability to enhance capillary performance by combining high surface area with compact geometry. This design builds on the principles established in previous studies but represents a distinct innovation in construction, potentially offering new opportunities in applications requiring efficient liquid transport in constrained spaces.

2 Theory

The operation of the tapered spiral metal wick leverages the combined effects of capillary action and thermally-driven vapor pressure gradients, which are key to priming and sustaining steady fluid flow in vertical channels against gravitational forces.

2.1 Capillary Action in Vertical Channels

As previously described, capillary action enables liquid fuel to ascend narrow channels by generating a capillary pressure that counteracts gravitational forces. In vertical channels, this is governed by Jurin’s Law:

$$\Delta h_{\text{capillary}} = \frac{2\gamma \cos \theta}{\rho g r_0} \quad (1)$$

Here, the capillary rise $h_{\text{capillary}}$ represents the maximum height to which the liquid can ascend, determined by the surface tension γ , contact angle θ , liquid density ρ , gravitational acceleration g , and channel radius r . For very narrow channels, r becomes small, resulting in high capillary pressure and significant fuel transport heights. Although Jurin’s law is strictly only applicable to cylindrical channels, it is nevertheless very informative since the nature of relationships it implies generally apply in qualitative sense to other channel geometries, often only differing by a constant scalar multiple. We can therefore

expect that capillary column height in the rolled wick would roughly obey

$$\Delta h_{\text{capillary}} = \frac{C_1 \gamma \cos \theta}{\rho g l_0} \quad (2)$$

where C_1 is a constant and l_0 describes an effective channel thickness. Since channel thickness would be inversely proportional to the sheet thickness and number of rolls or layers,

$$\Delta h_{\text{capillary}} = \frac{t N_l C \gamma \cos \theta}{\rho g} \quad (3)$$

for some other constant C , if t is the sheet thickness and N_l is the number of layers.

With a tapered channel, θ becomes increasingly acute with meniscus height, thereby increasing the net achievable column height. However, capillary action alone cannot fully sustain the continuous flow needed for steady-state combustion in the wick. Once the flame is lit, the thermal effects at the exposed end of the wick come into play.

2.2 Thermal Effect

The term suction pressure is used to describe the negative pressure (or the partial vacuum) created at the interface between the liquid and vapor due to evaporation. This pressure difference causes the liquid to be drawn upward in a wick or capillary tube to replace the evaporated liquid.

The suction pressure is therefore the difference between the vapor pressure of the liquid and the surrounding ambient pressure:

$$P_{\text{suction}} = P_{\text{vap}} - P_{\text{ambient}} \quad (4)$$

where vapor pressure itself depends on temperature, as described approximately by the Clausius-Clapeyron equation:

$$P_{\text{vap}} = P_{0\text{vap}} \left(e^{\frac{\Delta H_{\text{vap}}}{R} \left(\frac{1}{T_0} - \frac{1}{T} \right)} \right) \quad (5)$$

where P_{vap} and $P_{0\text{vap}}$ are the vapor pressures at temperatures T and T_0 of a fluid with vaporization enthalpy ΔH_{vap} . When the suction head plus the capillary rise equal or exceed the total wick height, fuel will continue to rise to the ignition site and burn.

A simple condition for steady-state operation can therefore be written:

$$\frac{P_{0\text{vap}}}{\rho g} \left(e^{\frac{\Delta H_{\text{vap}}}{R} \left(\frac{1}{T_0} - \frac{1}{T} \right)} \right) - P_{\text{ambient}} + \frac{t N_l C \gamma \cos \theta}{\rho g} \geq \Delta h \quad (6)$$

where Δh is the height of the wick. This model can be used for basic design synthesis and evaluation but contains arbitrary constant C that must be fit to data, and cannot account for geometrical effects apart from packing density, such as taper.



Figure 1: Wick demonstration: Coke can in Nutella lid

3 Construction

The basic construction of the wick proposed here consists of a strip of sheet metal rolled to form a spiral cylinder, such that a combination of small and large channels is arbitrarily formed between successive layers. The fuel used is Ronsonol brand lighter fluid. The shape of the strip and variation of roll axis along the edge determines the taper angle of the channels formed, and a range of geometries at the tail (submerged) end and the mouth (exposed end) can be achieved, each of which gives rise to unique performance characteristics. While this work cannot offer a comprehensive investigation of all such effects, it aims to highlight, in broad strokes, some general trends that might be studied in further detail in the future.

The simplest geometry of the class being explored here consists of a straight rectangular strip of metal rolled to form a parallel spiral cylinder. This arrangement requires a fairly tightly-packed structure to work, since it relies on small spacing between the layers to create capillary-sized channels for the fuel to climb. Both ends of the formed wick are flat. The first and easiest modification to the parallel spiral is to squeeze or spread one end to introduce a general taper to the channels. If this is done without changing the shape of the strip or the roll axis orientation, however, it affects the shape of the ends, resulting in a cupped profile at the narrower end and a protruding profile at the wider end.

By changing the roll axis of a rectangular strip, it is possible to intention-

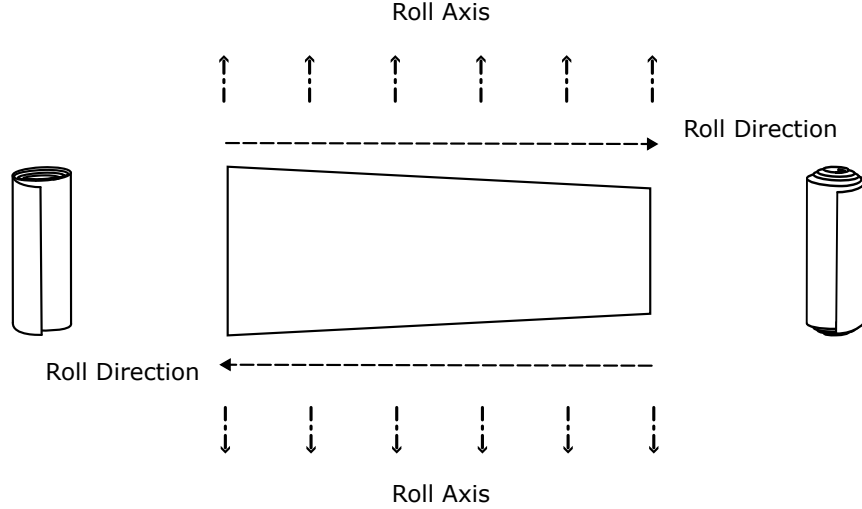


Figure 2: A tapered strip can be rolled to have cupped or protruding ends

ally induce a cupped profile on one end of the wick and a protruding profile on the other; this can be used to compensate for the effect of introducing taper. However, with a rectangular strip, the two profiles cannot easily be independently controlled, with any changes to the profile of one end generally causing the opposite effect on the other end.

Simultaneous control over the taper angle and the profile at both ends of the wick can be achieved through the introduction of choice in strip shape. As discussed, a simple rectangular strip rolled perpendicular to its edge leads to a parallel wick with flat ends, or to one cupped and one protruding end. If a tapered strip is used, both ends can be made cupped or protruding, depending on whether the wider side of the strip is on the inside of the spiral or the outside. As with the rectangular strip, this effect can be used with a tapered strip to counteract cupping or protrusion on one or both sides of a tapered wick.

One of the most promising strip shapes discovered in this preliminary investigation has one concave arc-shaped edge, normal to which it is rolled. This results in tapered channels and a flat mouth profile which seem to lead to good performance.

4 Materials and Methods

The material of Coca-Cola cans was selected as the sheet metal for this experiment, as it is easy to cut and roll by hand. Each can was cut into four pieces, which were then refined in shape and rolled into spiral cylinders. In each case, the final strip shape and choice of roll axis were chosen to achieve the desired

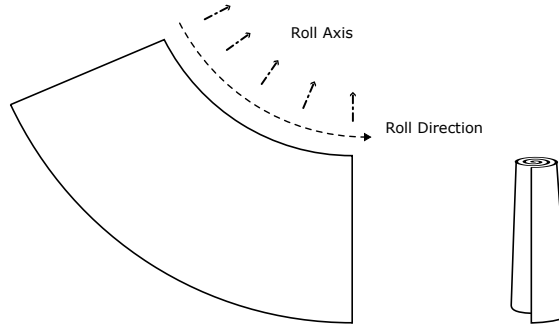


Figure 3: Rolling along a curved edge and about an axis perpendicular to it results in a tapered wick with a flat mouth



Figure 4: Tapered and curved strip cut from soda can

mouth profile and taper.

A mini Nutella jar is selected as the fuel reservoir due to appropriate size and an easily drilled plastic lid. A hole is first created in the lid, then the wick is passed through it making sure to maintain any desired taper. For a narrowing taper as used here it is helpful to pass the wick through the lid from the inside rather than from the outside, since the narrower part then enters the hole first. Finally the jar is filled with fuel and the lid is screwed down.

5 Factors Tested

Although a thorough quantitative study has not been conducted, several versions of the metal wick were rolled and tested to gain insight into the general effects on performance of various geometrical parameters.



(a) Shorter strip: loosely packed wick (b) Longer Strip: tightly packed wick

Figure 5: Combination of small and large channels arbitrarily formed between successive layers of rolled soda-can material



Figure 6: Tapered rolled wick

5.1 Packing Density

Two strips cut from a Coca-Cola can, one 5 cm long and the other 10 cm long, were rolled to the same net diameter of approximately 5 mm (determined by the hole drilled in the Nutella Jar's lid) and tested, to verify the effect of channel size on capillary behavior.

5.2 Mouth Profile

Mouth profile was found to be one of the most important factors influencing the size and stability of a flame, once lit. Tapered and straight wicks with cupped and protruding mouth profiles were therefore tested. The profile of the tail or submerged end was not found to have any noticeable effect on performance beyond whether or not it was fully submerged, and discussion of the effects of tail-end profile has therefore been omitted here.

5.3 Taper

Tapered and straight-rolled wicks were tested to verify the difference in performance due to capillary-driven flow in straight and tapered channels.

6 Results and Discussion

The results of these tests are somewhat promising, with most attempts to "roll a wick" by hand succeeding to some degree. At least three distinct aspects of wick performance were identified, and their dependence on geometrical parameters was recorded in qualitative, and in some cases rough quantitative terms.

6.1 Start-up Time

With any lamp wick, heat must be applied to its exposed end to initiate ignition. With some examples of rolled wick, it is observed that ignition is instant, whereas for others it takes varying amounts of time for a steady flame to become established.

The hypothesized mechanism for this ignition delay is that heating the top of the wick causes the pressure within it to drop, thereby causing fuel and fuel vapors to be driven up through the channels by the pressure differential. As the flame stabilizes, a steady thermal gradient is established between the lit free end and the submerged end held at the bulk liquid fuel temperature, which can maintain the flow required for the steady-state flame. The pressure head that the fuel must overcome driven by thermal gradients, and therefore the time over which heat must be applied to achieve ignition, is dependent on the resting capillary height of fuel in the channels. Clearly, such pressure-driven flow is less natural in an open-pore wick since it does not contain sealed vertical channel walls and therefore cannot make effective use of suction from evaporation.

It is observed that tapered wicks tend to ignite far quicker than straight or parallel ones, confirming that the taper affects capillary 'priming' of the wick. Additionally, tightly packed wicks ignite more quickly than loosely packed wicks, which agrees with the hypothesized delay mechanism since capillary column height increases with decrease in channel dimension.

It was observed that a tightly packed, tapered wick with a flat mouth profile generally ignited instantly upon application of a butane lighter flame to the free end, while loosely-packed and straight wicks took 2-10 seconds to start up. Reverse-tapered wicks that spread out towards the top generally failed to ignite.

6.2 Flame Stability

It was observed that some rolled wicks held a stable flame for extended periods, while others had flames that were either small and easily extinguished, or that grew steadily and had to be extinguished to prevent alarming flame sizes.

The strongest factor affecting flame stability was found to be mouth profile, and the second packing density. Tightly packed wicks with a flat mouth profile



(a) Cupped-mouth wick (b) Flat-mouth wick (c) Protruding wick

Figure 7: Lit examples of rolled wicks with different mouth profiles

tended to ignite quickly and hold the most stable flame. Cupped-mouth wicks were difficult to light and were easily extinguished, and wicks with a protruding mouth often caused flames to grow. Flames on loosely packed wicks, when they ignited, often grew quickly and had to be extinguished. The flame stability generally went up with higher packing density, but over-packing to the point of excessive constriction negatively affected performance.

It is speculated that flat mouth geometries lead to stable performance due to steady mixing between fuel and air at the channel openings. With a cupped geometry, the oxygen within the cupped end is rapidly depleted upon ignition, after which combustion is drastically reduced by the inability of more atmospheric oxygen to reach the stagnation region inside of the cupped end amidst rising thermal currents. With a protruding end, oxygen delivery to the channel openings is enhanced by the same rising currents and this causes the flame to grow.

The role of packing density on flame stability is ultimately to limit the maximum flow (and thereby combustion rate) by introducing viscous resistance. In addition to inadequate priming, using loosely rolled wicks reduces the resistance to the thermally-driven flow during burning, which can lead to runaway flame size.

6.3 Flame Size

Flame size is one of the most immediately apparent performance characteristics of any wick and lamp. The observed correlation between flame size and the wick's geometrical parameters, however, is less easily isolated than for startup time or flame stability, since not all wicks were able to be tested at their 'preferred steady state', such flames often being either too small to sustain themselves or too large to be safely contained and observed.

However, it was generally observed that wicks with a cupped mouth gen-

erated a smaller flame than those with flat or protruding profiles. Among the latter two classes, however, packing density appeared to have the dominant effect on flame size, with loosely packed wicks generally creating larger flames if they ignite at all.

6.4 Inferences

From the experimental observations, several inferences can be drawn.

One of the initial objectives of this experiment was to verify that tapered wicks show superior capillary performance, and such has been observed, likely due to the gradual narrowing of channels, which increases capillary pressure and aids in faster fuel priming. This makes tapered designs more suitable for applications requiring quick ignition. Higher packing density generally improves both ease of ignition and flame stability by more effectively priming the exposed end with fuel and limiting excess fuel flow through increased viscous resistance. However, over-packing can hinder performance by excessively restricting fuel movement. It has been found that mouth profile strongly dictates flame behavior and the geometry of the wick’s mouth has a pronounced effect on both flame stability and size.

Flat profiles allow for consistent oxygen delivery and fuel-air mixing, resulting in stable and steady flames. Cupped profiles restrict oxygen flow, leading to small, unstable flames. Protruding profiles enhance oxygen supply, often causing rapid flame growth and potential instability. Flat-mouth wicks consume fuel at a steady rate, while protruding geometries result in faster consumption. Cupped and tightly packed wicks exhibit slower fuel use, but at the expense of reduced flame size or stability.

One of the most immediately apparent takeaways from the experiment is that thermal gradients drive performance. The role of thermal gradients, especially in loosely packed or un-tapered wicks, is obvious from the observed ignition delay. These configurations optimize the interplay between evaporation-driven suction and fuel supply, allowing control over the net behavior of the flame.

Trade-offs have been found to exist between flame size and stability; while larger flames may be desirable in certain applications, they often come at the cost of stability. Adjusting packing density and mouth profile provides a means to fine-tune this balance. Reverse-tapered wicks demonstrate poor performance due to their inability to sustain capillary-driven flow. This confirms that channel narrowing toward the flame end is critical for successful operation.

7 Applications and Potential Future Work

Although the wick proposed here cannot be described as categorically superior to traditional fiber-based wicks, some niche applications can be imagined. The key advantage of this wick lies in its simplicity of construction and potential for longevity. Metal-based wicks, particularly those made from commonly available materials such as aluminum or steel, can offer greater durability than

fiber-based designs, which may degrade over time due to heat exposure or wear. In environments where durability and resistance to mechanical stress are critical—such as in industrial or outdoor applications—this metal wick could serve as a viable alternative. Additionally, the versatility in adjusting the geometry of the wick, such as varying the taper or packing density, could make it adaptable to different combustion conditions, allowing for more control over flame size and stability.

Future work in this area could attempt to experimentally or numerically find representative values for C in (6), develop design equations that account for taper and end profile, or could explore the scalability and manufacturability of these wicks for commercial applications. Their potential use could be studied for portable heating devices or specialized laboratory equipment that requires specific flame behavior. Further investigations could also focus on optimizing the material properties and geometry to improve thermal efficiency and fuel delivery over extended periods of use. It would also be beneficial to explore the potential of combining this type of wick with other technologies, such as thermoelectric generators or other forms of heat-driven energy harvesting, where such a device could serve as a critical component in a closed-loop system.

Long-term improvements could be made by refining the construction techniques, such as automating the rolling process or using advanced materials that offer superior thermal conductivity and strength. Studies on the exact relationship between wick geometry, packing density, and heat transfer would help fine-tune the design for specific applications. Additionally, integrating computational fluid dynamics (CFD) simulations could provide more precise insights into the behavior of liquid fuels within the wick under varying thermal conditions, enabling the development of even more efficient wicks tailored to particular use cases.

References

- [1] Davoud Jafari, Wessel W. Wits, and Bernard J. Geurts. Metal 3d-printed wick structures for heat pipe application: Capillary performance analysis. *Applied Thermal Engineering*, 143:403–414, 2018.
- [2] Guochen Jiang, Ze Tian, Xiao Luo, Changhao Chen, Xinyu Hu, Lizhong Wang, Rui Peng, Hongjun Zhang, and Minlin Zhong. Ultrathin aluminum wick with dual-scale microgrooves for enhanced capillary performance. *International Journal of Heat and Mass Transfer*, 190:122762, 2022.
- [3] Binjian Ma. Analysis of capillary flow in a parallel microchannel-based wick structure with circular and noncircular geometries. *Langmuir*, 36(45):13485–13497, 2020. PMID: 33151083.
- [4] Ayokunle Olanrewaju, Maïwenn Beaugrand, Mohamed Yafia, and David Juncker. Capillary microfluidics in microchannels: from microfluidic networks to capillarie circuits. *Lab Chip*, 18:2323–2347, 2018.

- [5] Chunxia Wu, Yong Tang, Shiwei Zhang, Xuepeng Yuan, Caiman Yan, and Heng Tang. Analytical and experimental on the capillary rise of aluminum multi-scale microgroove wick structures. *Physics of Fluids*, 35(5):052016, 05 2023.