UNIVERSITY OF CALIFORNIA SAN DIEGO

An Experimental Approach to the Blue Whirl

A Thesis submitted in partial satisfaction of the requirements for the degree Master of Science

in

Engineering Sciences (Engineering Physics)

by

Erik James Kolb

Committee in charge:

Professor Antonio Sánchez, Chair

Professor Stefan Llewellyn Smith

Professor Forman Williams

2018

The thesis of Erik James Kolb is approved and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California San Diego

2018

DEDICATION

I'd like to dedicate this thesis to the future. May we all find peace and happiness with one another in a world full of chaos.

EPIGRAPH

“A traveler who refuses to pass over a bridge until he has personally tested the soundness of every part of it is not likely to go far; something must be risked, even in mathematics.”

- Horace Lamb

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VITA

2009	B.S., Construction Management, California Polytechnic Institute, San Luis Obispo
2009-2012	Construction Engineer
2012-2014	B.S., Mechanical Engineering, Montana State University
2014-2017	Engineering and Construction Industry
2017-2018	M.S., Engineering Sciences (Engineering Physics) University of California San Diego

ABSTRACT OF THE THESIS

An Experimental Approach to the Blue Fire Whirl

by

Erik James Kolb

Master of Science in Engineering Sciences (Engineering Physics)

University of California San Diego 2018

Professor Antonio Sanchez, Chair

Abstract

This study focuses on the phenomena of the blue whirl. A structure was built to produce a blue whirl. The apparatus was built with the capacity to transition from a typical fire whirl to a blue whirl. Different fuels were used in order to analyze the fire whirl. Fins were used to control the circulation and entrainment of air into the system. One of the main focal points of this study was fuel consumption and how it varied with each change in the fin angle. It was discovered a blue whirl began to emerge when we rotated the fins to twenty degrees, and developed fully when rotating the fins to five degrees. It was also noted in our experiment a blue whirl used less fuel than a yellow whirl. Conclusions are offered at the end of the study which examine the implications of the findings.

Chapter 1 Introduction

1.1 Review of the literature

There are two main factors required to form a fire whirl. First, there needs to be the presence of an ambient swirl (circulation) [2]. Emmons and Ying, some of the first to study the fire whirl, stated that to produce a whirl there needs to be “available ambient vorticity…caused by wind.” [1]. Second, multiple papers have stated that the vortex in these whirls is created not only by the ambient swirl, but by the column of air created by heat [1-8]. The presence of heat induces a pressure minimum on the surface that pulls in air which ultimately creates an ambient vortex [2]. This air rises and creates a swirling column of air. Byram and Martin concluded that there exist three essential factors for the formation of a fire whirl: a thermally-driven fluid sink, an eddy, and a surface drag force to create a radial boundary layer [6]. A fire whirl differs from a general pool fire in multiple ways. Jaio et al. state that compared to a typical pool fire, a fire whirl has a significantly higher burning rate, flame temperature, and flame height in addition to a strong whirling motion [7]. An additional theory for the formation of a fire whirl is based upon vortex breakdown and turbulence suppression [3].

The most common place fire whirls have been observed is in nature. Larger fire whirls are sometimes called fire tornadoes. Mostly, fire tornadoes form during hot summer wildfires [8]. Fire whirls, also known as “fire devils,” most closely resemble whirlwinds and dust devils [8]. Some of these fire tornados can reach 1,000 feet in the air while burning at 2,000 degrees Fahrenheit [9].

Figure 1: Photo of a fire whirl in nature [11]

There have been various approaches to producing and analyzing fire whirls in the laboratory. Traditionally there have been two main methods to generate a fire whirl, either with a burner or pool fire [2]. A pool fire consists of a "pool" of fuel resting on a smooth surface, while a burner utilizes pressurized gas.

Emmons and Ying laid the foundational work in studying the fire whirl. They hypothesized that the mixing coefficient decreases while increasing the circulation. This would produce flame elongation [3] which is what we observed when we positioned our fins at 40-50 degrees from normal. They also theorized that the fire whirl is a modified free vortex over a ground plane; in essence, a plume flame is swept by radial velocity from the boundary layer and heated by convection. Their first attempt was placing an acetone fuel burner at the center of a rotating screen [4].

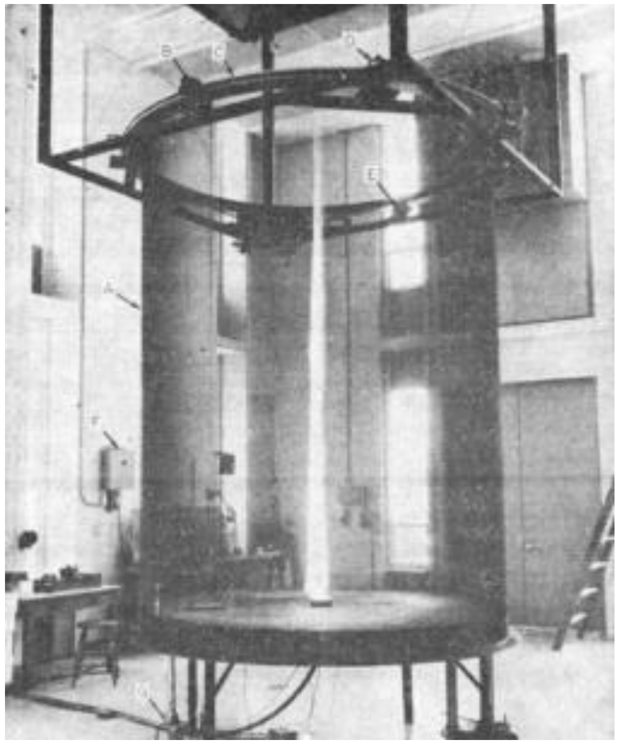

Figure 2: This is a photo of Emmons and Ying's experimental set up utilizing a four-inch diameter pool in the center of an eight-foot diameter table. The screen along the perimeter rotates between 0.8 and 10 rpm. [5]

The scale of the apparatus was an eight-foot diameter table with a four-inch diameter liquid pool at its center. We used this ratio to determine the diameter for our pool of fuel. The results from Emmons and Ying show increasing the rotation of the metal screen, shown in Figure 2, increases the burning rate of the fire whirl. Emmons and Ying kept observing flame wandering [4], an observation also present in the experiments of the presented work discussed later in Chapter 4. Other experiments have noticed a similar observation of "whirl wander" [2]. It is not yet fully understood what causes the "whirl wander." Shown in Figure 3, Emmons and Ying's data indicate an increasing rate of growth of plume radius with height.

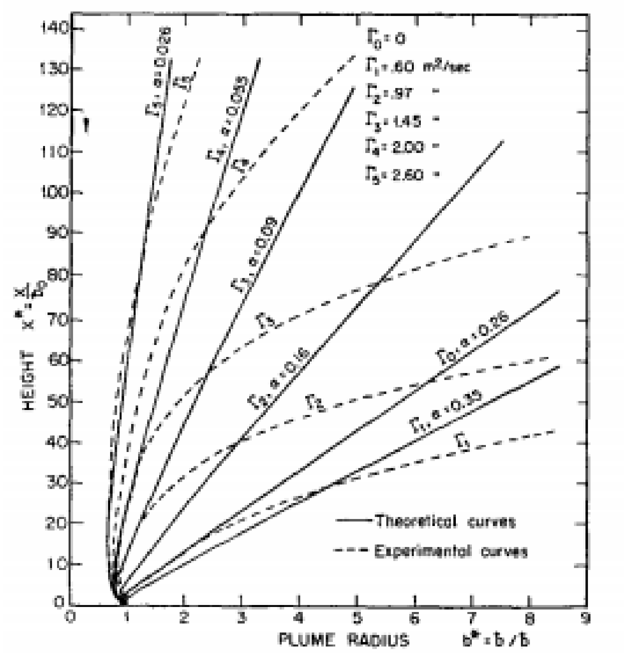

Figure 3: Emmons and Ying compare theoretical rate of growth of the plume radius versus experimental results [4].

Hartl and Smits produced a fire whirl using a Fisher Scientific 1201 Meker type burner [2]. Using a burner instead of a pool fire produces better results because the fuel rate is steady [2]. Hartl and Smit focus on whirl velocity distributions and scaling laws to obtain the average whirl height and centerline velocity [2]. Instead of using lateral wind, as in nature, Hartl and Smits used two plexi-glass semicircles offset from each other; see Figure 4. The dimensional analysis performed by Hartl and Smits identified circulation, heat release, and gap size as the three primary non-dimensional groups.

Hartl and Smits conclude that the entrainment region is located near the base of the whirl while outside of this region the circulation is constant [2]. They also demonstrate the velocity profiles closely follow a Rankine vortex [2]. They determined that the height of the flame is only a function of circulation, Equation 1. For a circulation much greater than 1, Hartl and Smit use Equation 1 to determine flame height, while Lei et al. use Equation 2 to determine the height. Hartl and Smit used PIV imaging, which can be seen in Figure 4 to plot radial velocities at the base of the burner [2]. Similar to Emmons and Ying, Hartl and Smit observed "flame wandering" [1,2].

Table 1: Two different equations for flame height. Equation 1 was developed by Hartl and Smit [2] while Equation 2 was developed by Lei et al. [7] H is the height of the flame and Γ is the circulation.

$H^* = (\Gamma^*)^{2/3}$	Equation 1 [2]
$H^* = K^*({}^{q^*}\Gamma^{*2})^m$	Equation 2 [7]

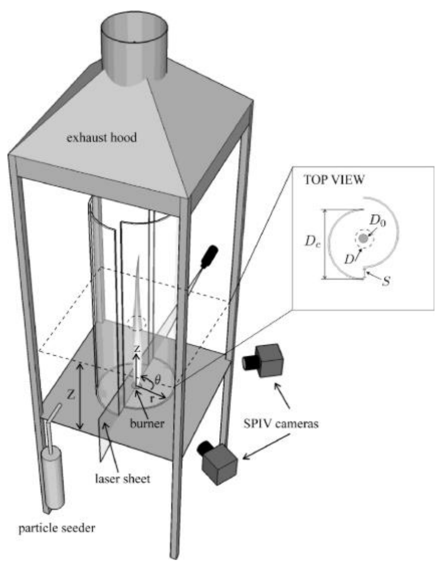

Figure 4: Experimental set up for Hartl and Smits. Note the use of a scientific burner instead of pool fire for the production of a fire whirl.

Tohidi et al. examined the governing equations of mass, momentum and energy, and also conducted dimensional analysis obtaining the influential parameters listed in Table 2.

Table 2: Parameters used by Tohidi et al.

$$(U_r, U_z, \Gamma, H, \dot{m}) = \phi(L_h, \dot{Q}, C_p, \Delta\rho, \rho, \Delta T, T, g, \mu, \beta, k, Ds). \qquad \text{Equation 3 [3]}$$

It should be noted that U in Equation 3 is a vector referencing the cylindrical coordinate system. This paper mainly focuses on $\dot{m}$, which is the total mass-loss (burning) rate of the fuel [3]. Tohidi et al. demonstrate that fire whirls emerge when terrain and wind coalesce over a strong self-sustaining source of buoyancy [3]. Tahidi et al. classified two main types of fire whirl: on-source and off-source. They also give a scale size of fires ranging from small, medium, and large-scale whirls. Our study focuses on an on-source small fire whirl. In contrast, an on-source whirling flame forms directly over the fuel source [3].

Mullen and Maxworthy made similar observations to Tahidi et al. in that they observed and studied how buoyancy and vorticity interact within a dust devil [5]. Although they only discussed how buoyancy and vorticity interact within a dust devil and did not experiment with an actual flame, their apparatus could be utilized to form a fire whirl and subsequently a blue whirl. Their use of fins was incorporated into the design of our apparatus, which can be seen in Figure 6. Their laboratory model showed two essential criteria needed to form a dust devil: a source of buoyancy and a source of vorticity [5]. The reference to buoyancy has been noted in almost all the other literature written about fire whirls [1] – [7].

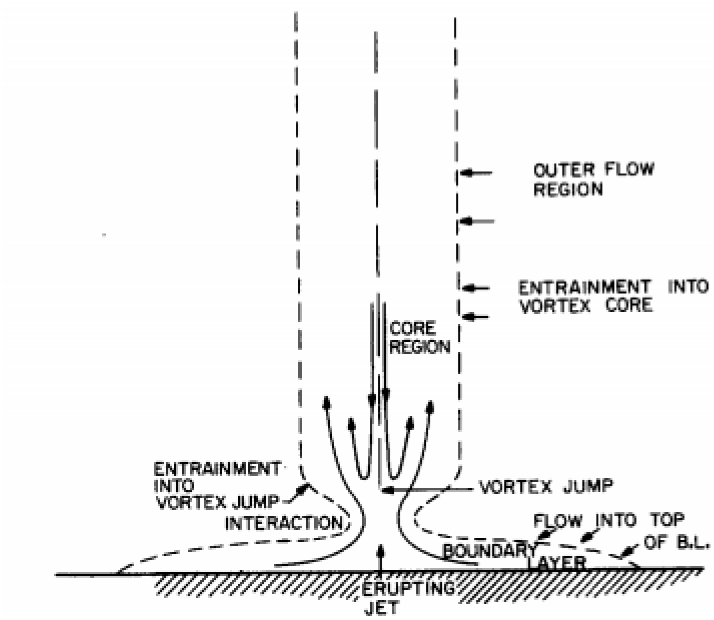

Figure 5: This figure shows vortex flow regions highlighting details of the boundary layer [8].

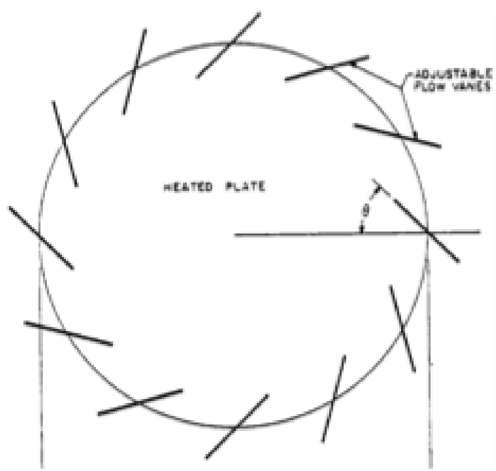

Figure 6: Mullen and Maxworthy used fins to create circulation which ultimately creates dust devil [8].

Recently discovered, the blue whirl is a form of a fire whirl that develops under specific conditions. Xiao et al. theorized that when a fire whirl underwent bubble-mode of vortex breakdown, a blue whirl is formed [3]. Gollner et al. postulated a blue whirl is a highly strained diffusion flame that sits a small distance above the fuel surface [3]. Hariharan et al. discovered a blue whirl while controlling the gap width between half-cylinders and the amount of fuel deposited in the water [1]. Gollner observed two distinct regions of the blue whirl, a vortex rim and a blue cone, which can be seen in Figure 8. They also observed above the inverted blue cone was a purple haze. Hariaharan et al. also observed that a blue whirl only formed under specific airflow and burning-rate conditions [1].

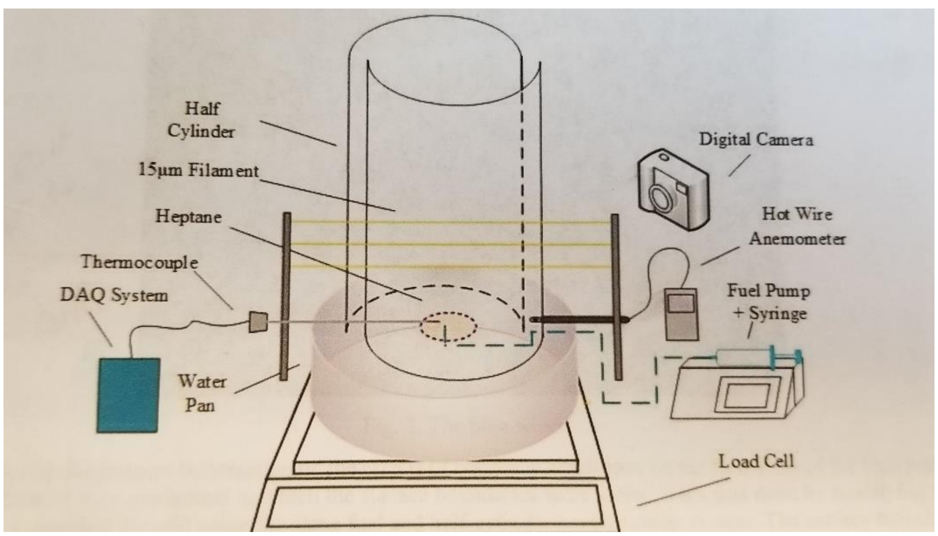

Figure 7: Hariharan et al. experimental set up that produced a blue whirl [1].

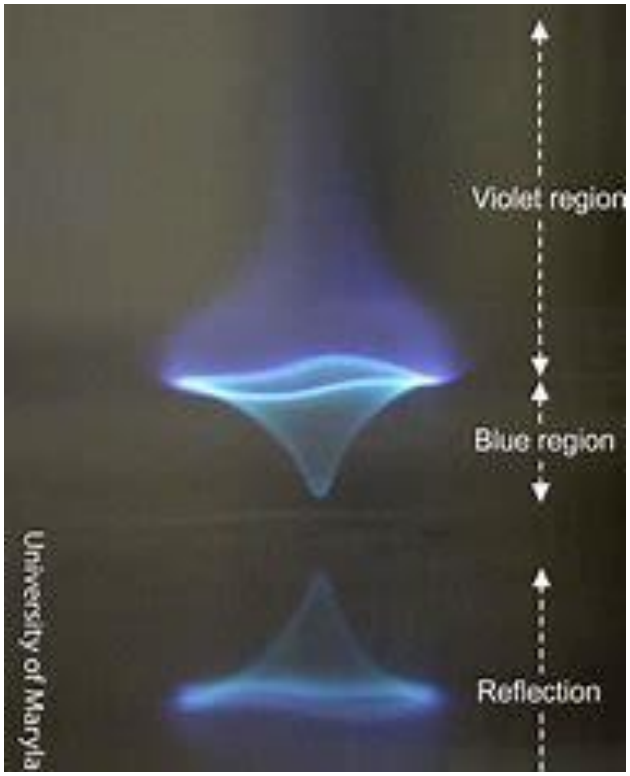

Figure 8: A blue whirl produced by the University of Maryland [3].

The review of the literature revealed several important conclusions. Firstly, an overall understanding of the current and past research as related to fire whirls, specifically the blue whirl. Second, an understanding of fire whirls was crucial in the development of an experimental approach to study the blue whirl for this project. Lastly, knowledge of the efficacy of past experimental design projects was critical in the development and design of our testing apparatus.

This paper focuses on an alternate approach to producing and studying the fire whirl, specifically the blue whirl. We combined experimental techniques from Mullen and Maxworthy along with Emmons and Ying, utilizing fins and a pool of fuel to produce a fire whirl. One of the goals of our project was to continuously transition between a plume flame, yellow fire whirl, and blue whirl. We wanted our flame to stay continuously lit while we changed the angle of the fin. Past experiments have produced results from a transient solution. When our fuel source was lit, a fire whirl formed and then finally transitioned to a blue whirl as is the case for Gollner et al. [3]. Our experiment allowed us to control the angle parameter. This gave us the ability to produce steady solutions from one angle to another. We also wanted to determine both the burning fuel rate and fin angles where the blue whirl develops. Our results were similar to Gollner et al. in that a blue whirl was produced given a specific diameter for the pool of fuel and specific orientation of the fins.

Figure 9: These are blue whirls developed in the laboratory at the University of California San Diego. Note the similar structure of the flame compared to Gollner in Figure 8. The diameter of the blue whirl is approximately 2 centimeters.

1.2 Theoretical considerations and Dimensional Analysis

In this work, we will study how, for an increasing amount of ambient swirl, a pool fire transitions into a fire whirl and eventually into a blue whirl. It is therefore instructive to first begin by discussing the scales for a regular pool fire without swirl. If the size of the fuel pool is *a*, and ν_A and $D_{T,A}$ are the values of kinematic viscosity and thermal conductivity of the ambient air respectively, then in the non-slender region just above the fuel pool, the typical velocities are of the order of ga^2/ν_∞ as given by a balance between the buoyancy and the viscous forces in the Navier-Stokes equations. A bit further downstream, the hot combustion products are accelerated by buoyancy, stretching the flame shape in the vertical direction. Finally, even further downstream, i.e. at a height above the fuel pool that is large compared to the fuel pool diameter, a buoyant plume is formed. Dimensional analysis shows that, for a fixed fuel, for example, ethanol or heptane, as was used in the experiment in this work, the only dimensionless parameter that governs the pool fire is the Rayleigh number.

Table 3: Dimensionless parameter that governs the pool fire.

$$Ra = ga^3/\nu_a D_{T,A} \qquad \text{Equation 4}$$

Note this Rayleigh number is a Péclet number based on the pool diameter and the characteristic velocity in the flame.

The pool fire and its buoyant plum entrain ambient air radially inwards, $-v_r$, at a rate that depends on the characteristics of the plume, such as it being laminar or turbulent. If the radially entrained air is given a certain amount of swirl at a distance far away from the pool flame, then this swirling component will be advected towards the central flame/plume zone, and by conservation of angular momentum, be concentrated greatly. This can cause the pool fire to transform into an elongated standing vortical structure with a concentrated burning vortex core, i.e. a fire whirl. Note the swirling motion is best quantified through the circulation, which is defined as $\Gamma = r * v_\Theta$ where r is the distance to the axis of symmetry of the flow and v_Θ is the azimuthal velocity component with respect to the axis. The specific manner in which we induce the swirl in the experiments is similar to that used by Mullen & Maxworthy [2] and will be discussed in the next section. Dimensional analysis shows that now, with the addition of a swirling component, the flow is not only governed by the Rayleigh number, but also by the Reynolds number associated with the circulation Γ_A that is applied at a certain distance away from the fire whirl.

Table 4: Reynolds number based off circulation from dimensional analysis.

$$Re_\Gamma = \frac{\Gamma_A}{v_A} \qquad \text{Equation 5}$$

Note in our experiments, as will be explained in the next chapter, we do not have an exact control of the Reynolds Number (R_e), but instead control the angle α that a series of fins make with respect to the tangential direction.

We developed a relation with the fin angle, α, and the circulation Γ. This relation uses the azimuthal velocity along with the radial velocity to relate the mass flow of air to circulation.

Table 5: This table shows the relationship between the fin angle, alpha, and the circulation.

$$\tan(\alpha) = -\frac{V_r}{V_\Theta} = -\frac{2*\Pi*r*V_r}{2*\Pi*r*V_\Theta} = \frac{Q}{\Gamma} \qquad \text{Equation 6}$$

Chapter 2: Experimental Build

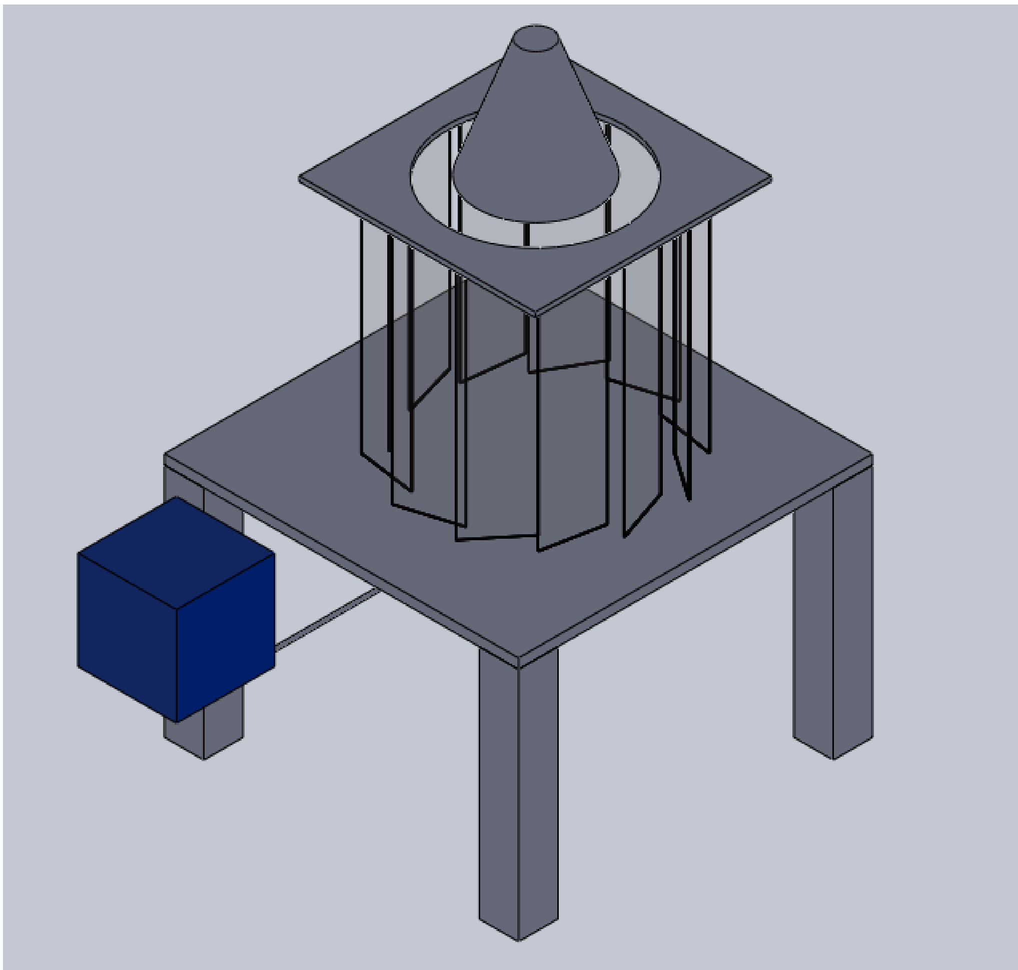

Figure 10: An Isometric view of our experimental apparatus. The blue box represents the fuel source.

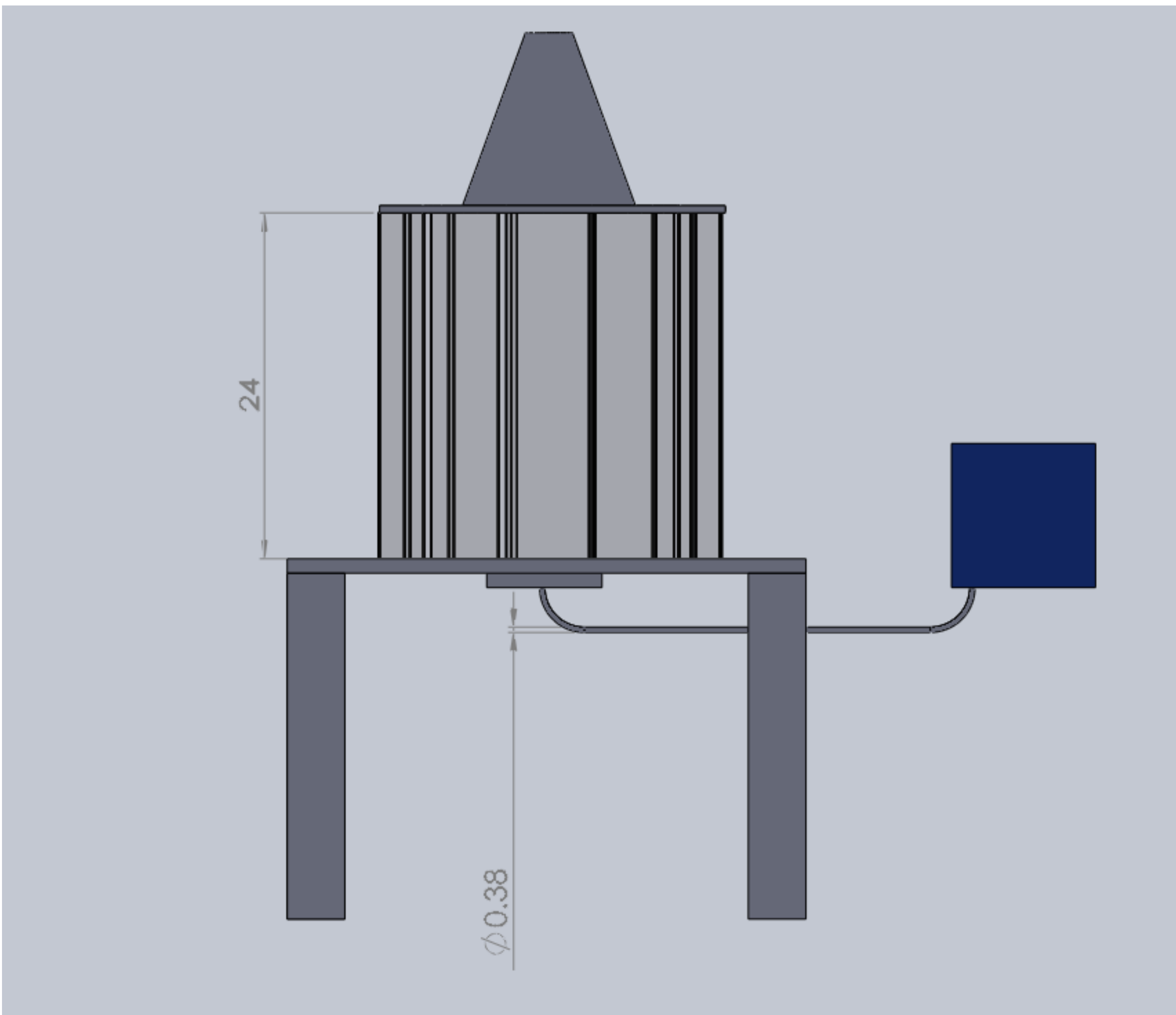

Figure 11: Experimental apparatus with the fuel source on the left, side view.

Chapter 2.1: Fin Assembly.

As stated in the introduction, we chose to design and build our experimental apparatus based on the laboratory model of Mullen and Maxworthy used to study dust devils [5]. We also integrated the pool of fuel from Emmons and Ying [3]. As with Mullen and Maxworthy, the fins were used to create circulation within the apparatus. The fuel was ignited and initially there was a plume flame, but after the fins were rotated to a specific angle, a yellow fire whirl began to emerge. The exhaust was directly linked to the system to prevent a draft which could possibly perturb the flame.

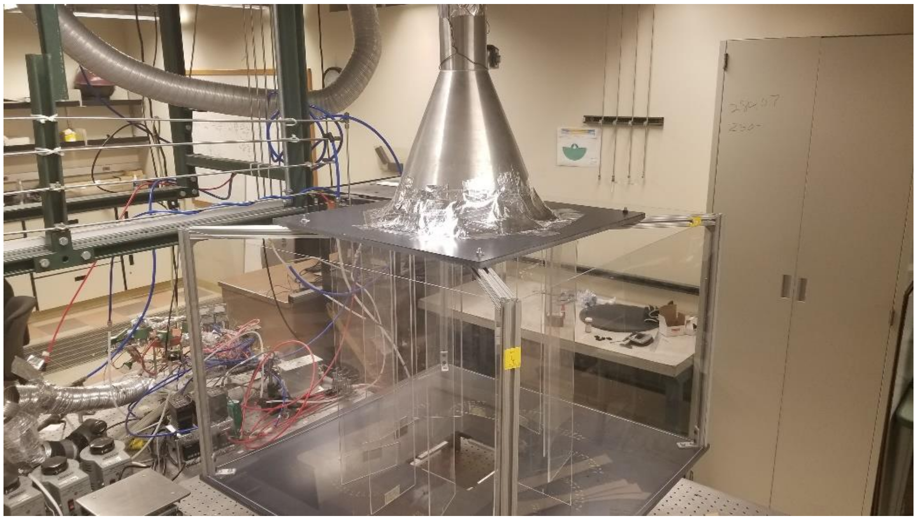

Figure 12: A skeleton view of the fins which create the circulation inside.

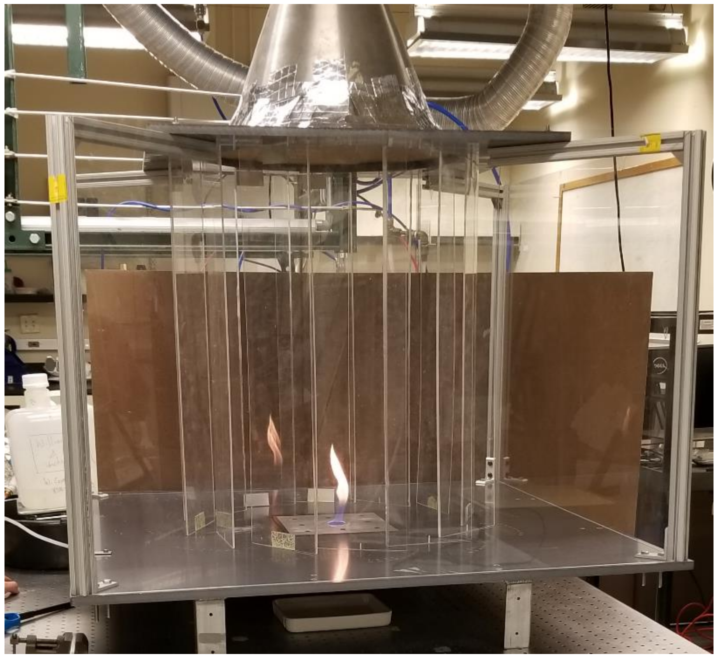

Figure 13: A side skeleton view of the fins and how they produce a fire whirl.

There were a few criteria established before building the structure. First and foremost, the ability to produce a blue fire whirl. It was also desired to continually transition from a regular yellow fire whirl to a fully developed blue whirl. A continuous transition was defined as the ability to adjust the fins without having to re-ignite the pool of fuel. This was achieved by using 12 adjustable fins. Each fin was approximately six inches wide by two feet tall. The fins were placed in a circular fashion as seen in Figure 14. The diameter of the circle formed by the fins was 22.75". A one-half inch thick square piece of plastic was used for the top part of the structure removing an 18" diameter hole for the exhaust of the flame. Four struts were used to stabilize the top portion of the experiment. The height of the bars were two feet. This ensured there was no gap between the fins and the top and bottom plates which can be seen in Figure 13.

As stated, 12 fins were used to create the azimuthal velocity that produces the blue whirl. The fins were made of clear acrylic. This gave the fins enough flexibility and strength when rotating between 5 and 90 degrees. The transparency of the acrylic also allowed the ability to see everything that was happening inside. The fins arrived in 2-feet by 1-foot sheets. They were then cut in half. Once the fins were cut in half, a grinding machine was used to create a 45-degree angle on the long edge. This was done on one edge to attempt to smooth the flow of the air entering the apparatus.

The fins are kept in place using stainless steel dowels (5/62" diameter by 1" long) placed in the midpoint of their bottom and upper ends seen in Figure 14. The holes were drilled using a Milwaukee power drill and a 5/62" drill bit. The goal was to pivot or rotate the fin on its center axis to accurately measure the entrance angle.

To obtain the various angles for the fins, a protractor was used based on the diameter of the larger circle. This circle can be seen in the Figure 14. This ensured all fins were equidistant from each other. The angles for the fins are indicated on the base board, as seen in Figure 14.

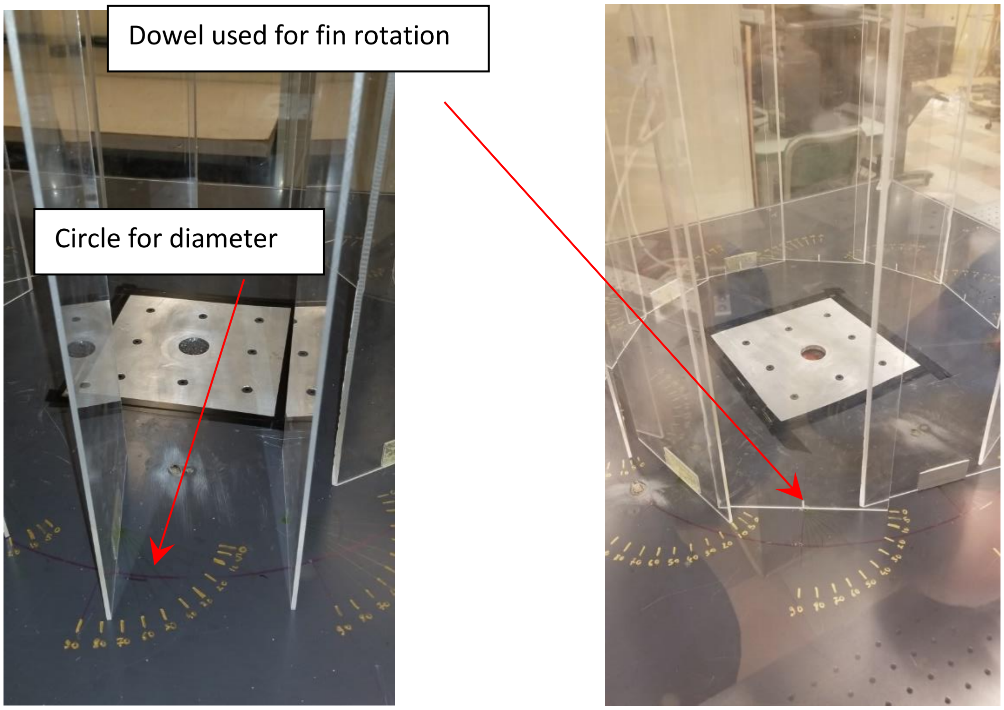

Figure 14: These two photos show the fin orientation. The experiment began with the fins starting at ninety degrees from normal, incrementally moving the fins towards five degrees.

Chapter 2.2 Fuel Supply

Heptane and ethanol were chosen to compare a carbon-based fuel to an alcohol. The fuel reservoir was made from two pieces of aluminum and a single piece of rubber gasket. One block of aluminum was used as the actual fuel reservoir that held approximately 90 percent of the fuel. This block began as an 8" x 8" x 1" thick piece. Then a small 4" x 4" x ½" void was cut out using the Bridgeport Milling Machine. This piece was then bolted to the 8" x 8" plate where a 1.25" hold was cut out in the middle using the drill press. In between the two aluminum pieces was the rubber gasket to avoid leaking. The bottom piece of the full reservoir was drilled out with a 3/8’’ drill bit. The hole was then threaded using a tap set.

Once the hole was tapped, a 90-degree elbow was threaded to allow for fuel passage. Glass beads were used to damp out the possible convective currents in the fuel induced by the large temperature gradients. The glass beads were placed in the fuel reservoir and filled within 1 mm of the top plate.

The fire whirl experiment was carried out using two different pool sizes. The first size, shown in Figure 14, was 1.25" diameter. A second plate was made utilizing a 2" diameter pool. The results of the different size pools will be shown in Chapters 4 and 5.

Figure 15: Bottom view of fuel reservoir. Reference Figure 12 for entire fuel set-up.

The fuel was gravity fed seen in Figures 15 and 16. The fuel was then placed on a scale in conjunction with a variable height mechanism. This enabled us to use Bernoulli's principle to continuously feed the fuel. We assumed the velocity of the fuel in the container was zero with respect to the pool fuel. Using this assumption, we measured the rate of fuel loss in the container, thereby giving us the fuel consumption of the flame.

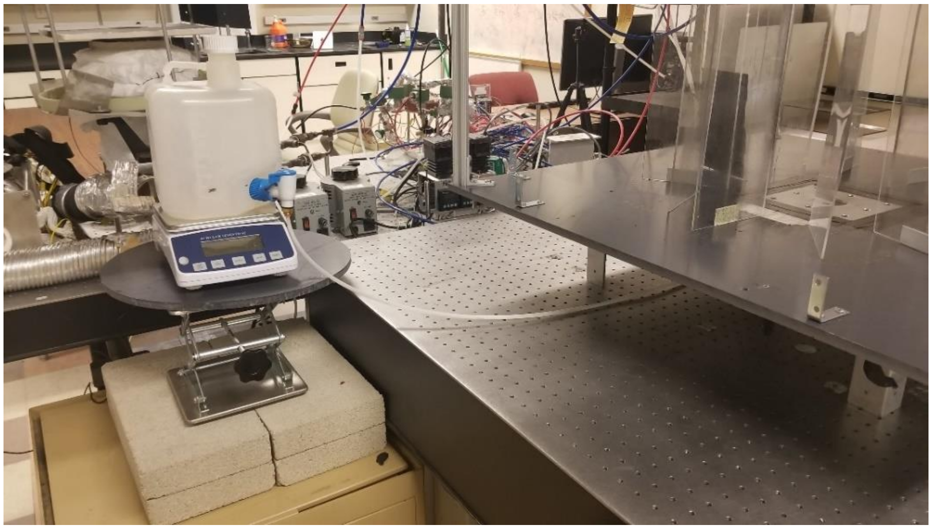

Figure 16: Scale and fuel container used for the experiment.

Figure 17: Glass beads placed within fuel reservoir.

Chapter 2.3 Support and Exhaust

The top of the fins were also connected to the upper support plate using stainless steel dowels. These dowels were connected to a 30-inch square. An 18-inch diameter hole was cut out of the middle of the square to allow exhaust gases to escape directly into an exhaust duct, which can be seen in Figure 18. The upper support plate was bolted on top of four struts that were fastened to the base. To safely contain the flame, we used HVAC tape from the top of the apparatus to the exhaust hood. The exhaust hood could be manually regulated from closed to fully open to allow for suction. All experiments were carried with no suction, so as not to perturb the flame.

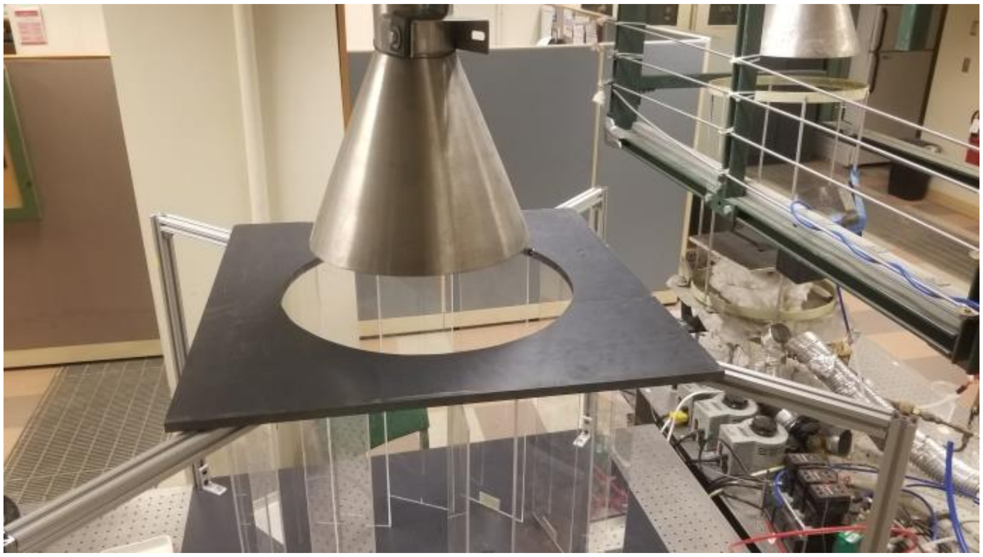

Figure 18: Exhaust manifold being placed directly above apparatus.

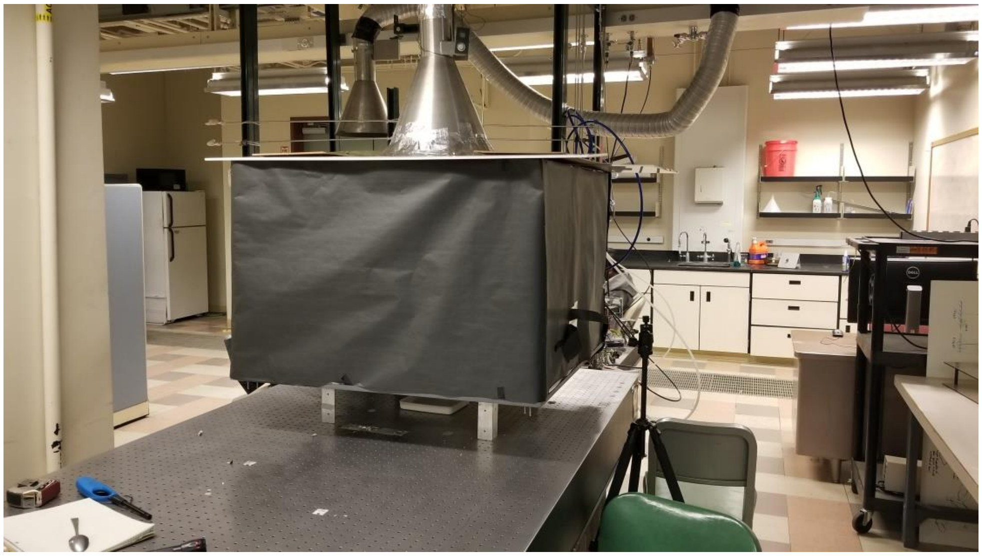

Figure 19: Complete build where black paper was used to prevent any glare for photos. The camera that was used to capture the flames is on the right. A small opening was created for the camera lens to photograph the flames.

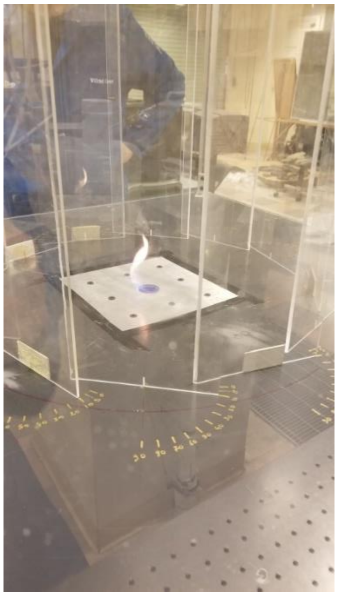

Figure 20: This photo gives an overall view of the fin angle to create a yellow whirl. The fins in this photo are placed at 10 degrees from normal.

Chapter 3: Experimental Procedure

As stated in the introduction, we tested two different fuels with two different pool sizes, 1.25” and 2.00” with the fuels being heptane and ethanol. The fuel was filled to just below the top of the metal plate, approximately one millimeter. The fuel was then ignited using a manual lighter, through the access door. This process was the same for each experiment. A Panasonic FZ300 camera was setup on a tripod and used to capture the different stages of the whirl.

Once the fuel was lit, the experiment began. To start, the fins were first placed at 90 degrees normal to the circle. The experiment was transient, in that the “system” had to heat up. We would ignite the pool of fire and it would take 2-3 minutes before the experiment could begin. Further explanation of this will be given in the Results chapter.

The fuel consumption was measured along with photos taken at each iteration. From 90 degrees, the fins were then moved to 60 degrees. When the fins were at 80 and 70 degrees, there was no noticeable difference from the flame produced at 90 degrees. Therefore, no experiment or recordings occurred for those two angles. From 60 degrees, the fins were incrementally rotated 10 degrees until they reached 20, all the while measuring the fuel consumption and taking photos of the flame. Moving on from 20 degrees, the fins were then rotated five degrees between measurements until reaching their final value of five degrees. The order of testing was heptane at 1.25”, then ethanol at 1.25”, then ethanol at 2.00” and finally heptane at 2.00”.

Chapter 4: Results

Chapter 4.1 – Heptane with a 1.25” diameter pool

Figure 21: Fins at 90 degrees normal to circle. No noticeable fire whirl. Only a fire plume is visible.

The experiment began when the fuel was lit and the fins were at 90 degrees. As seen in Figure 21, the flame representative of a typical pool fire. There was no noticeable whirl or flame wandering. Puffing was the only behavior observed at 90 degrees. Given that there was no whirl and the flame was just puffing, the fins were then moved to 60 degrees, skipping 80 and 70 degrees.

At 60 degrees there was still no noticeable fire whirl, though there were two distinct characteristics of the flame. First, the flame seemed smoother and elongated, possibly being affected by the circulation. Then, the flame began to slowly rotate at approximately five to eight revolutions per minute around the boundary between the fuel and aluminum plate. This rotation around the boundary continued until the blue whirl was fully developed, this was found for both fuels and pool diameters. This could be caused by the vortex inside the fins building, but not yet strong enough to “rotate the flame” around the boundary of the fuel reservoir. This is what was assumed when Emmons and Young described the flame as wandering [4].

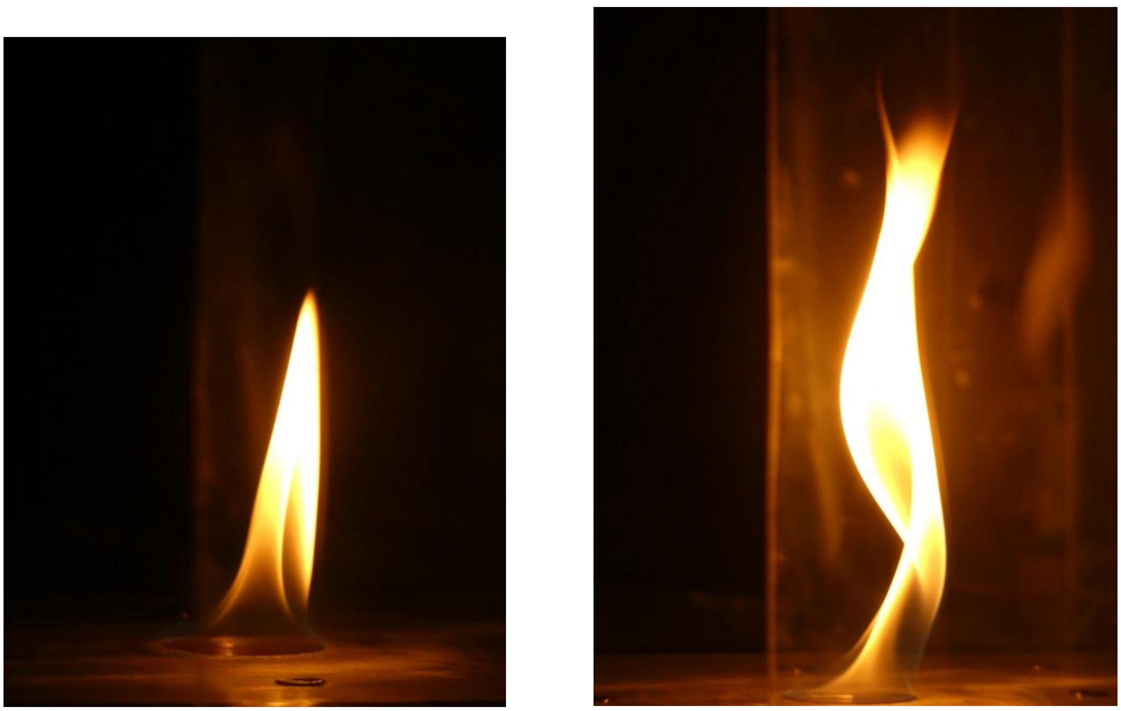

Figure 22: On the left, the fins at 60 degrees. As stated, the flame is now elongated and rotating. On the right, the fins are at 50 degrees with a yellow whirl becoming apparent.

50 degrees showed the first resemblance of a fire whirl. The fire is technically "whirling" about an axis. The flame at 50 degrees represents more of a small helical-whirl than a true fire whirl. The vortex isn't strong enough to create a fire whirl; the vortex is only strong enough to "bend" the flame.

A true fire whirl begins to emerge at 40 degrees. There was a stronger, helical shape with procession around the perimeter. The procession of the flame was approximately 10 revolutions per minute. It should also be noted the height varied between four and 10 inches. Also note the "tighter" helical shape. This is more than likely due to the vorticity increasing.

Figure 23: Fins at 40 degrees. Here the height variation can be seen as it ranges from 4-10 inches.

Placing the fins at 40 degrees produced a variable height flame. There was no consistency or pattern to the variable flame height, but as seen in Figure 23, sometimes the flame would be small and lean over the surface-fuel boundary, sometimes there would be a helical yellow whirl.

Figure 24: At 30 degrees, a very stable fire whirl is produced.

Placing the fins at 30 degrees produced a very stable traditional yellow whirl. The fire whirl itself was centered with no noticeable procession around the perimeter of the pool. The height of the yellow whirl did not change, nor did the whirl rotate at the boundary.

At 20 degrees, the blue whirl began to emerge. The transitioning fire whirl produced vorticity and procession around the boundary at rates faster than had ever been seen before. The rotation or “flame wandering” was approximately 20 revolutions per minute. Another major observation was the change in height. At 20 degrees, the height fluctuated between three and twelve inches, which can be seen in Figure 25.

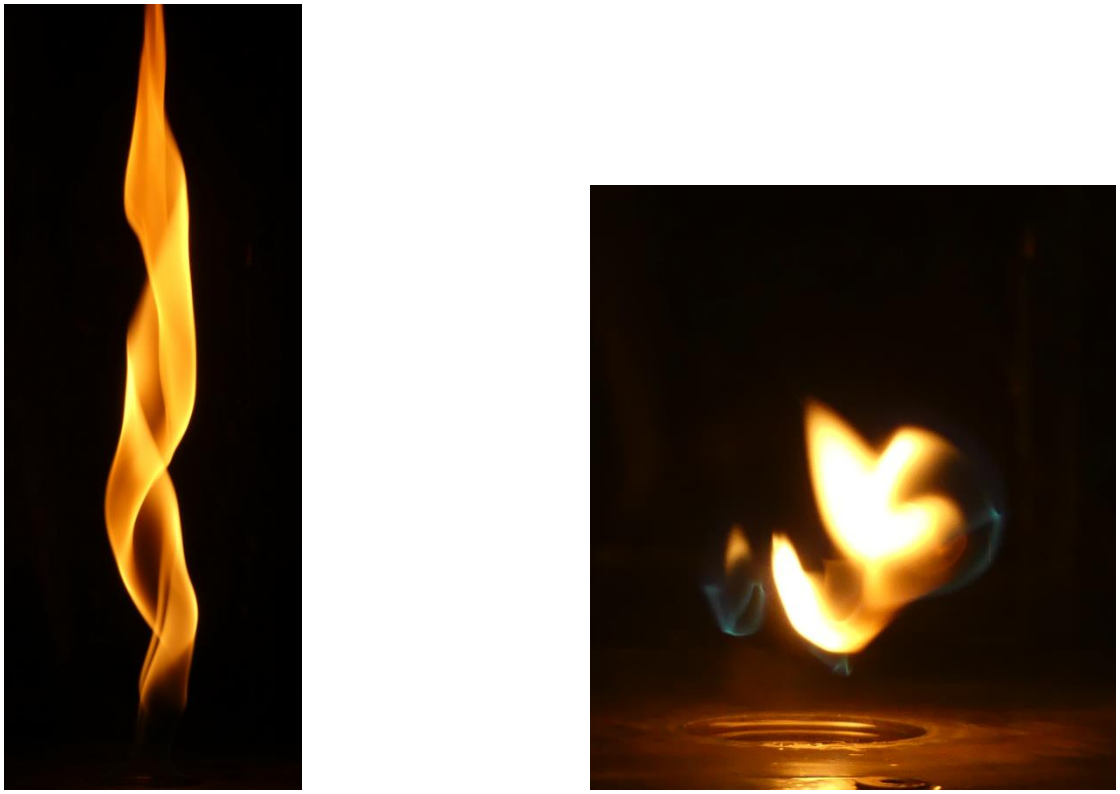

Figure 25: Fins at 20 degrees. Some transition to a blue fire whirl is noticeable. Height fluctuation between 3 and 12 inches.

Figure 26: Fins at 15 degrees. Noticeable bubble vortex.

With the fins at 15 degrees, the whirl began to increase its frequency and signs of a blue whirl could be seen. The same conical shape shown in Goller [4] can be seen in Figure 26. This could be considered the transition phase from a yellow to a blue whirl. The height variation was greatly reduced. The height changed between three and eight inches. Another significant phenomenon occurred at 15 degrees that had not been observed before. The fire whirl began to actually create noise. This could be attributed to high turbulence and/or vortex breakdown.

By moving the fins to 10 degrees, we greatly increased the predominance of the blue whirl. At this point the transition phase is at, or near the end of, a blue whirl. The color was 90 percent blue with small sporadic yellow flames. The height of the flame drastically decreased, only fluctuating between one to three inches.

Figure 27: With the fins at 10 degrees, the vortex continued to break down while transitioning into a blue whirl.

5 degrees gave a fully sustained blue whirl. This blue whirl was very stable and consequently did not rotate around the perimeter of the reservoir. Instead its placement was at the center and only varied slightly on top of the fuel, i.e. no significant precession around the perimeter of the fuel. The sound of the vortex also became much more significant.

Figure 28: Blue whirl, 1.25" diameter with heptane fuel and fins at 5 degrees.

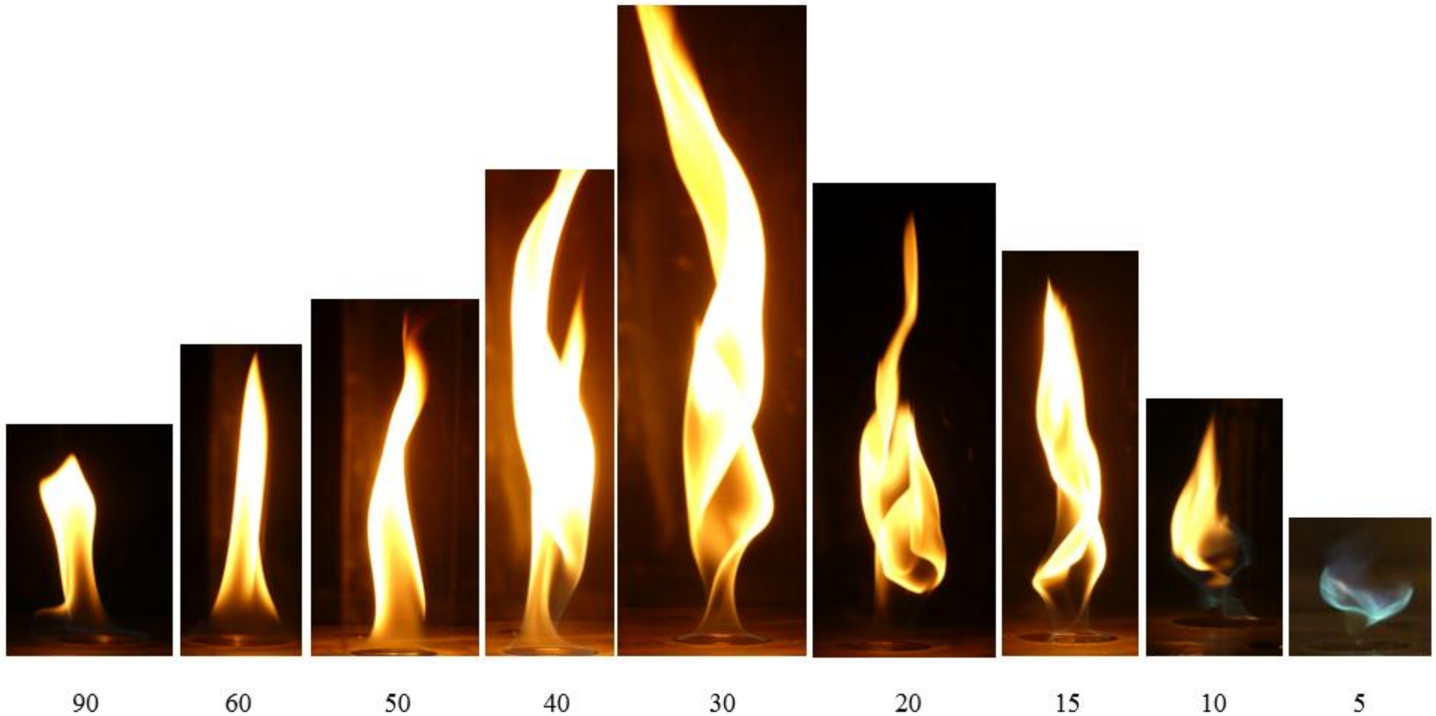

Figure 29: Progression from plume, to yellow whirl, to blue whirl from a heptane fuel with a pool diameter at 1.25”, with respective fin angles.

Chapter 4.2 – Ethanol with a 1.25" Diameter Pool

A major difference between heptane and ethanol was the size and intensity of the flame. Heptane produced a larger whirl, by a factor of approximately two. This is to be expected based on their respective chemical composition. Another major difference was with heptane, a typical yellow whirl was noticeable when the fins were at 40 degrees. With ethanol, a similar shape was produced until the fins were between 10 and 15 degrees. It should be noted that although the development of the yellow whirl was different between ethanol and heptane, both fuels produced a blue whirl when the fins were at 7.5 degrees.

Figure 30**:** A helical fire whirl with fins at 20 degrees.

The ethanol blue whirl emerged when the fins were approximately 7.5 degrees. The blue whirl produced by ethanol was much smaller than the blue whirl composed of heptane.

When the fins were once again moved to five degrees, the blue whirl blew out. We have postulated two reasons for this. One, the pool and consequently the blue whirl were not exactly centered with the circle created by the fins. A second reason could have been the azimuthal velocity overcame the strength of the blue whirl and broke down the vortex because of too much turbulence. Although the ethanol blue whirl was smaller, it seemed to be a more stable flame that the blue whirl associated with heptane fuel. In Figure 31, part of the flame has a blue rim. This blue rim was also seen in the Tohidi et al. experiment [3].

Figure 31: On the left is a photo of a yellow whirl transitioning into a blue whirl when the fins were changed from 10 to 7.5 degrees. On the right, this is the formation of a blue whirl with the fins at 7.5 degrees.

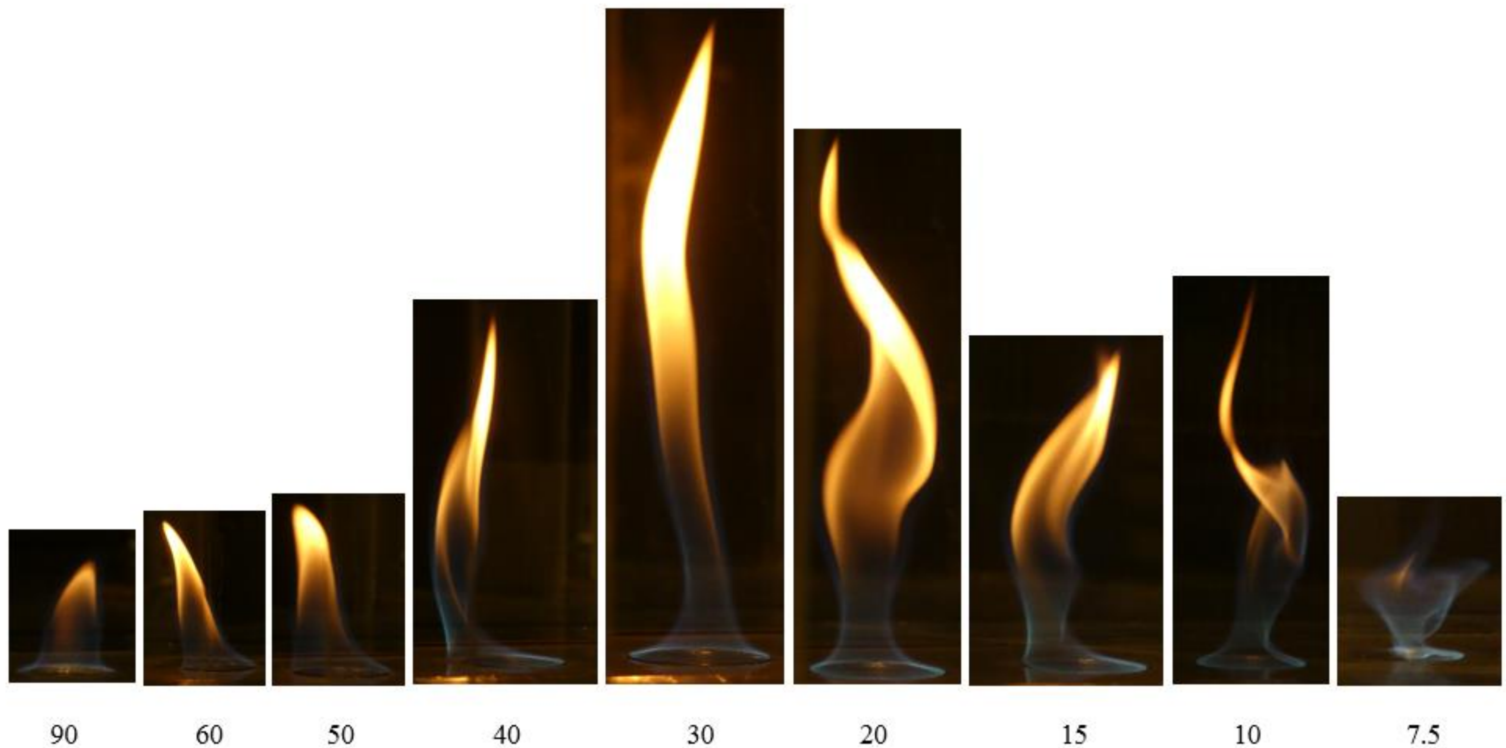

Figure 32: Transition from yellow whirl to blue whirl with ethanol. This transition is much more gradual than ethanol with a pool diameter of 1.25”.

Chapter 4.3 – Ethanol with a 2.00" diameter pool

Using a two-inch diameter pool of fuel created results that were different from the diameter of 1.25". For a two-inch diameter pool, a yellow whirl was noticeable at 40 degrees, compared to 20 degrees for a 1.25" diameter pool. We postulated that the difference in whirl could be due to the actual size of the flame. The two-inch pool creates a bigger flame, possibly giving the flame more surface area to be affected by the vorticity.

Figure 33: Both fins are at 40 degrees. The left is a 2.00" diameter pool and the right is a 1.25" diameter pool.

At 30 degrees, the intensity of the yellow whirl increases. The helical whirl shape becomes "tighter," meaning more revolutions around itself. The flame also becomes brighter as a result of burning more fuel. The yellow whirl with fins at 30 degrees showed some signs of a whirl. See Figure 34 for comparative results.

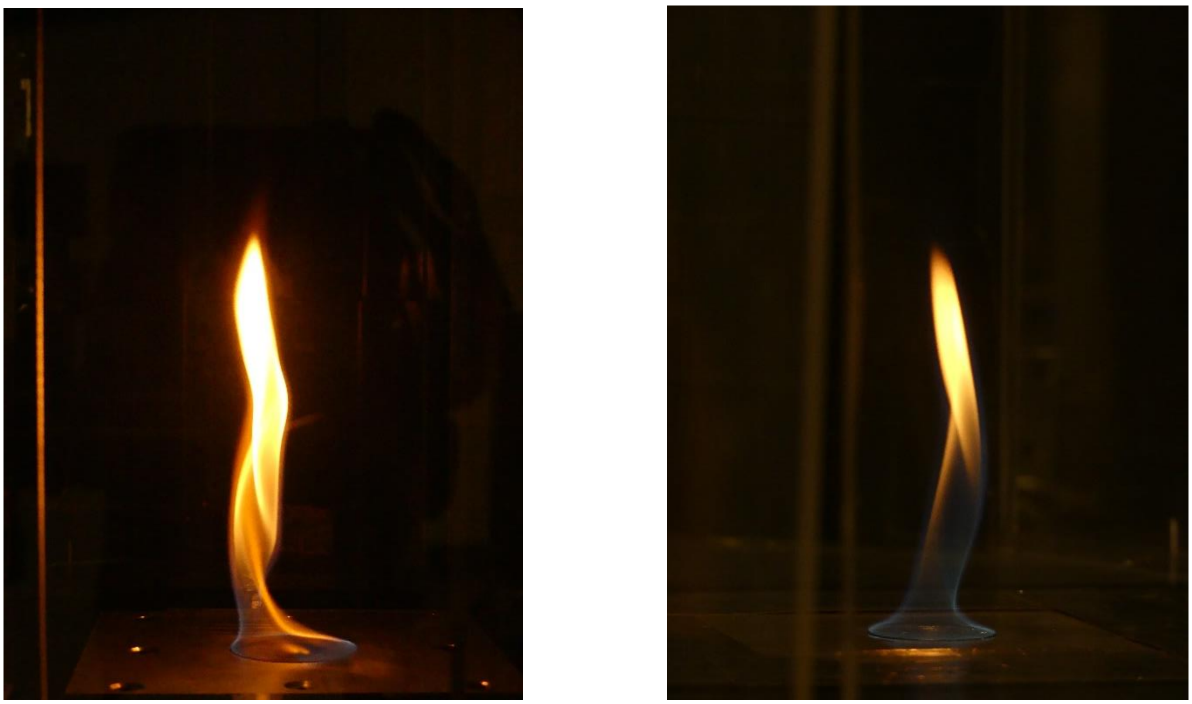

Figure 34: Fins at 30 degrees. The left is a pool size of 2.00" and the right is a pool size of 1.25", both using ethanol as a fuel source.

At 20 degrees, the shape of the yellow whirl had an elongated helical shape. We concluded that this is mostly due to increased vorticity which increases the burning rate. With the fins at 20 degrees and a pool size of 2.00", the yellow whirl became similar to the yellow whirl with a pool size of 1.25" and fins at the same 20 degrees, as can be seen in Figure 35.

Figure 35: Fins at 20 degrees, 2.00" pool on left and 1.25" on the right. The shapes are very similar with the whirl on the left being more elongated.

The phenomenon of vortex breakdown began to happen at 15 degrees. This is when the yellow whirl began to transition into a blue whirl. Examples of the blue whirl forming can be seen when the fins were at 10 and 15 degrees, in turn illustrating the vortex breakdown. This is different when the pool size was 2.00". With the fins at ten degrees and a pool size of 2.00", there was no indication of a blue whirl.

Figure 36: Both fins are at 10 degrees. It is very apparent the 2.00" pool is almost a blue whirl. The right illustration shows no vortex breakdown and is still a typical fire whirl.

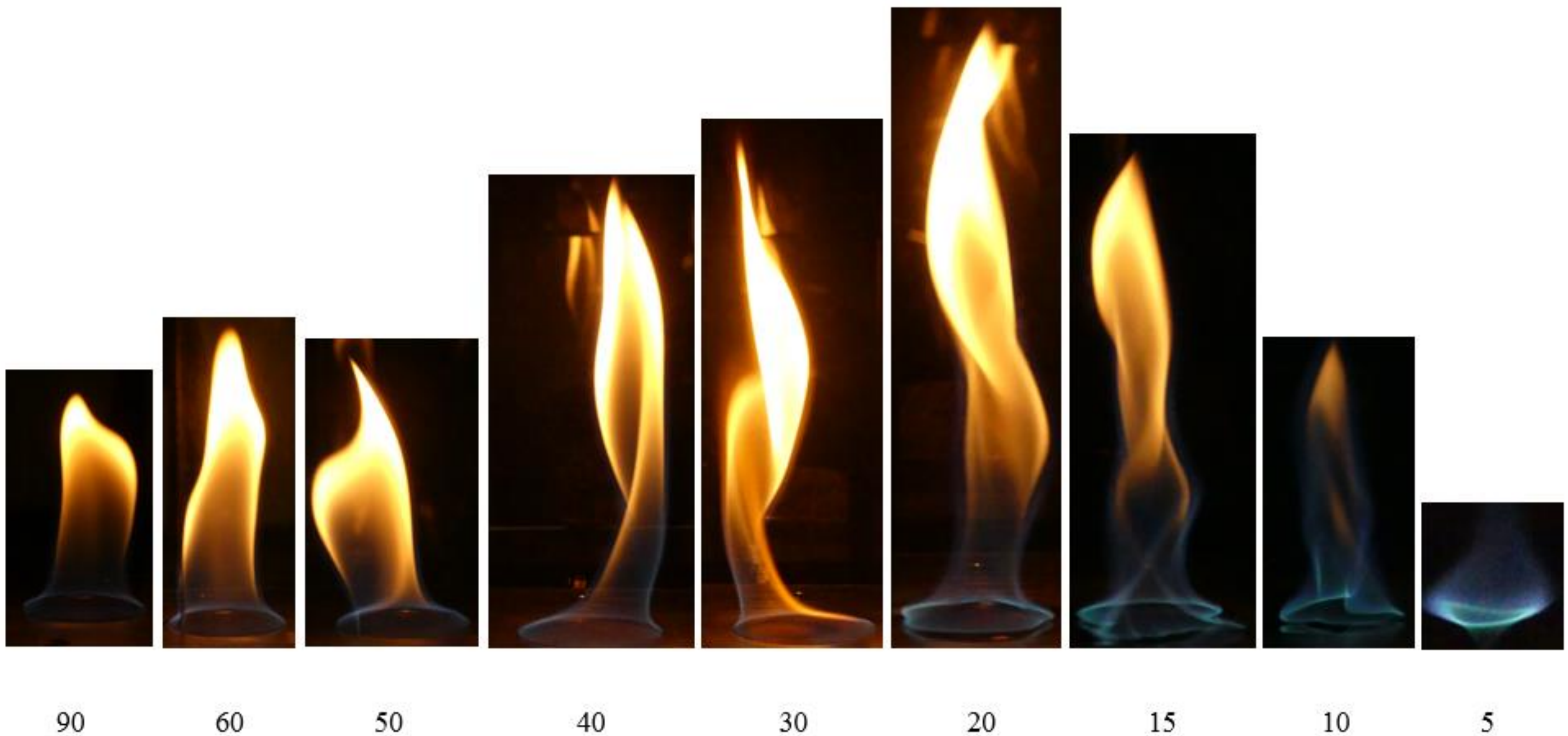

Figure 37: The transition from 90 degrees to 5 degrees resulting in a blue whirl. Ethanol, 2.00" diameter pool.

Chapter 4.4 – Heptane with a 2.00" diameter pool

Our final experiment consisted of a two-inch diameter pool of heptane. This produced the biggest flame, which consequently burned the most fuel. The progression from the fire plume, to yellow whirl, to blue whirl was similar to that of the previous three experiments. This specific incident did not produce a pure blue whirl. It seemed we could only achieve 90% of a blue whirl based on the apparatus. This could be due to lack of vorticity or the blue whirl being too big, in turn radiating too much heat.

At 50 degrees, a fire whirl began to emerge. The shape was similar to that of a yellow whirl with a pool diameter at 1.25" but the tip of the flame was turbulent.

Figure 38: Fins at 50 degrees. 2.00" diameter pool on the left, 1.25" diameter pool on the right.

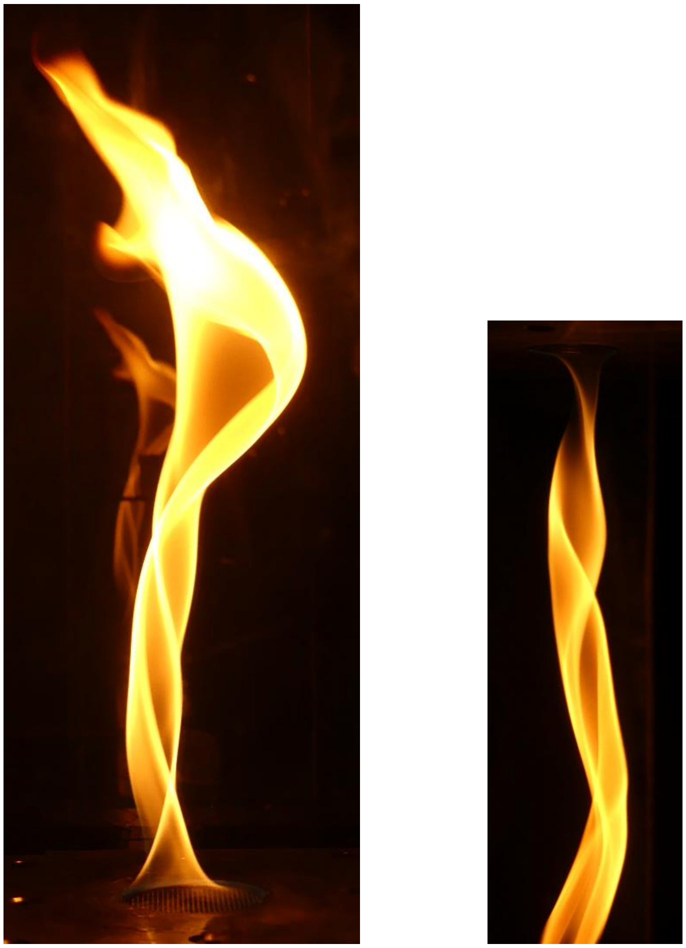

Figure 39: Fins at 40 degrees. 2.00" diameter on the left, 1.25” on the right.

The fins at 40 degrees produced a very similar fire whirl for both diameters of pools. The only major difference, again, was the turbulent end. The flames were also similar when the fins were at 30 degrees; both produced an elongated yellow whirl.

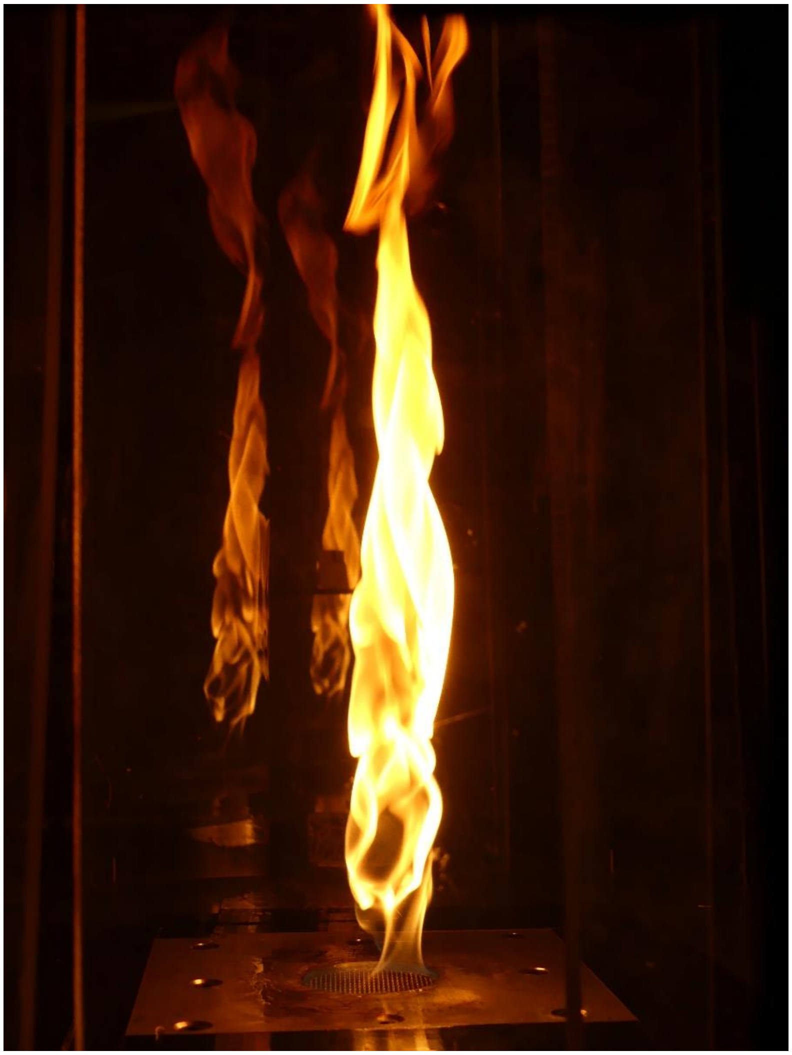

Figure 40: Yellow whirl with fins at 20 degrees and pool siz of 2.00"

When the fins were moved to 20 degrees, the yellow whirl became similar to a fire tornado [11]. The vortex could be heard and the intensity of the heat was felt at least two feet from the flame. The heat was so hot that the fins began to warp. We made an immediate decision to move the fins to five degrees to produce a fire whirl and dramatically reduce the heat.

Figure 41: The fins are now at five degrees. On the left is a whirl without added flow. The photo on the right shows a whirl with added flow in the form of suction.

With the fins placed at five degrees, a pure blue whirl was not formed. Instead a “quasi-blue whirl” was formed which can be seen in first photo of Figure 41. The second photo in Figure 41 shows a whirl that is much closer to an actual blue-whirl. This was caused by inducing a suction motion from the exhaust vent. The exhaust vent was fully opened which pulled more air through the fins, in turn creating a higher vortex resulting in a blue whirl.

Figure 42: The transition from 90 degrees to 5 degrees resulting in a blue whirl; ethanol with a 2.00" diameter pool.

Chapter 5 – Comparative Results and Conclusions

Four different scenarios were tested throughout this experiment: alternating between fuel types heptane and ethanol, and the size of pool of fuel from 1.25” to 2.00”. Our goal was to produce a blue whirl while controlling the fin angle parameter. Although the blue whirl had been observed in the laboratory, the fin angle had not. We also documented the fuel consumption of the different stages of the fire whirl.

A pool diameter of 1.25" and ethanol fuel required the least amount of fuel for the experiment. Heptane with a 2.00" diameter pool used the most fuel. The fuel consumption rate for all four experiments were recorded versus the specific fin angle. The information was gathered and input into MATLAB where the graph in Figure 43 was plotted.

It is interesting to note when a plume transitioned into a yellow whirl, it did so helically. From intuition, one would infer introducing a circulation to a plume would create a taller, thinner conical flame. Instead, a helical whirl with one, two, or three internal pairs of whirls developed. It was as if the flame was “bending” on its axis.

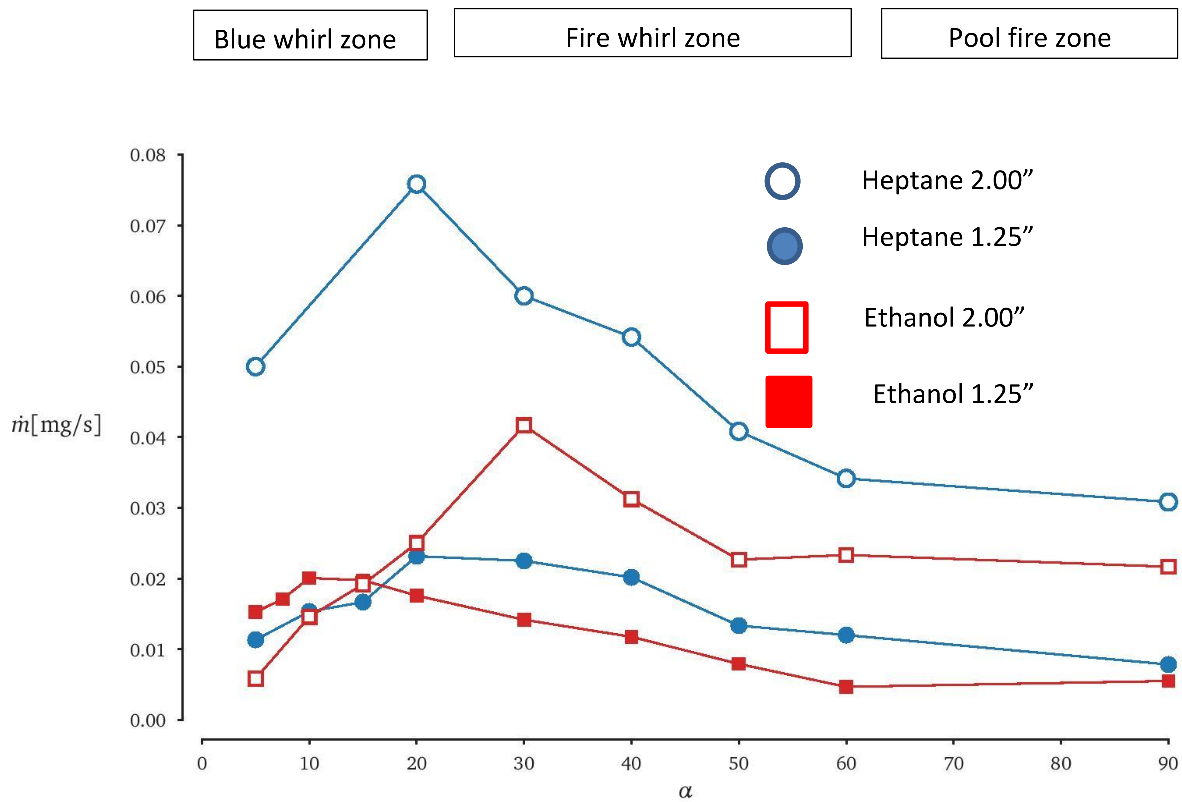

Figure 43: Fuel consumption plotted against fin angle α. Experiments began when the fins were at 90 degrees normal to the circle and finished at 5 degrees normal to the circle.

All fins started out at 90 degrees normal to the circle and their final angle was five degrees. It was generally observed the fuel rate increased until a critical angle was reached. This angle is different for each experiment but ranges from a low of 10 degrees to a high of 30 degrees. Once that critical angle was reached, a steep drop-off in fuel consumption was recorded. Transitioning to a blue whirl was also when the flame height began to decrease. This can be seen in Figures 29, 32, 37, and 42. When the whirl became a blue whirl, there was very little wandering around the perimeter. The flame tended to stay in the center of the pool.

As others have stated, vortex breakdown occurs when the flame transitions from a yellow whirl to a blue whirl [1-8]. Throughout our experiment we noticed that our critical parameter was circulation. We were able to transition in and out of a blue whirl by simply rotating the fins. When all the fins were positioned at five degrees, rotating just one of them to 10 degrees had a major effect on the whirl. The whirl was no longer centered and began to drift away from the pool of fuel. This showed the sensitivity of the blue whirl.

Using the analysis of Muellen and Maxworthy, we can conclude what the vorticity and vortex breakdown should look like [5]. However, to achieve an exact representation of the airflow inside the apparatus, the use of a laser to observe airflow would greatly increase the understanding of the nature of the swirling motion [1]. Understanding the vorticity/airflow would add another parameter in understanding the development of the blue whirl.

There are a few procedures that should be introduced in order to obtain better results. A first suggestion is to increase the size of the apparatus, similar to Emmons and Ying. Transitioning from a two-foot diameter to a four-foot diameter apparatus and also increasing the size of the pool of fuel would likely give better results. Creating a bigger apparatus would ultimately increase the size of the blue whirl. A bigger blue whirl could be more stable and easier to analyze. One problem that was encountered near the end of the experiment occurred when we were tested with the two-inch pool of heptane fuel. The yellow whirl produced too much radiant heat and permanently warped the fins, rendering the system useless. Creating a wider circle would help to protect the fins from heat damage.

Another test performed was a transient experiment, in that the system had to warm up. This experiment was comparable to that of Gollner's in which the whirl transitioned from a yellow whirl to a blue whirl; similar to that of the two semi-circles offset from each other [3]. This was discovered when all fins were placed at five degrees and the fuel was lit. The goal was to induce a blue whirl when the system was "cold." After the fuel was lit and all fins placed at five degrees, the flame meandered around the pool for two minutes, ultimately transitioning into a blue whirl. This was most likely caused by the system having to "heat" up alongside developing the vortex.

After reviewing all photos and experimental data, it was observed the blue whirl occurred when all fins were positioned at five degrees. With the two-inch ethanol pool, we were able to achieve a blue whirl when all but two of the fins were at five degrees. We placed the other two fins (opposite ends of each other) at 7.5 degrees. When the fins were all at five degrees, we sometimes achieved a stable blue whirl, and other times it seemed to blow itself out. Placing two fins at 7.5 degrees seemed to stabilize the whirl. Opening the fins a slight amount seemed to have a profound effect on the whirl. This result could possibly lead the way for perturbation/stability analysis.

A critical way to improve this experiment which would enable us to simulate the fire whirl numerically, would be to measure the air flow. By double insulating the apparatus with plexiglass, it would allow us to accurately measure the airflow. Measuring the airflow is very plausible as air flow is easily measured in the HVAC industry. Specifically, I would recommend utilizing a hot wire anemometer.

There are some possible practical applications to the blue whirl. Because fire whirls occur mostly in nature and are destructive, the United States Forest Service could benefit from further studies of the fire whirl. The soot free burning properties studied from the blue whirl could be applied to the natural gas industry or to oil spills. In conclusion, there is still much more to be learned from the blue whirl.

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APPENDIX A

Technical Drawings

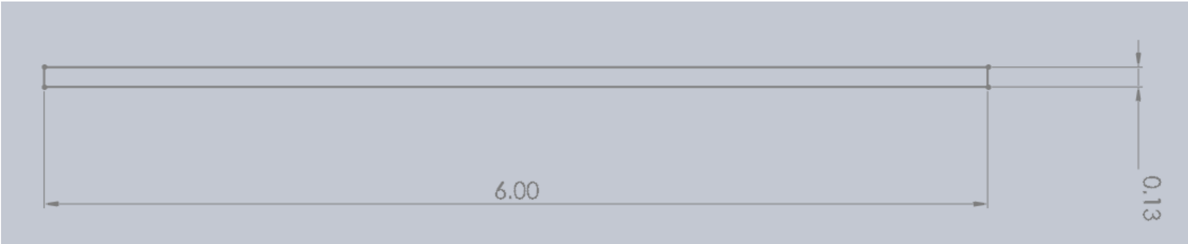

Figure 44: Side View of fin, dimensions are in inches

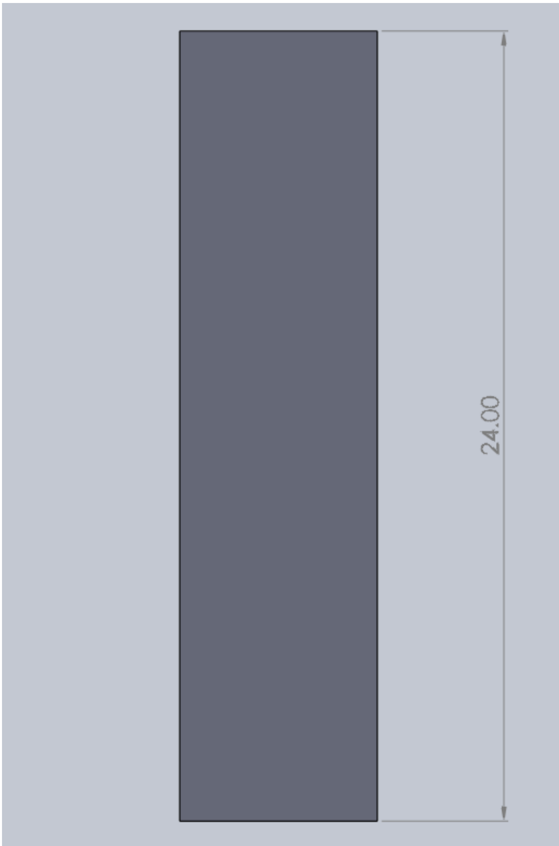

Figure 45: Full view of a single fin, dimension in inches.