Experimental Analysis of an Impinging Two-Dimensional Jet Using Liquid Crystal Thermography

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At this point in time, there is no general CFD code for analyzing the stagnation area of jet impingement. This experiment provides qualitative and quantitative understanding the stagnation area under a jet of air. The experiment consists of heating a 3000 mL syringe full of air to 48.8 °C, and releasing the air out through a circular nozzle onto liquid crystal thermography film. As the air hits the film, a video is taken and using digital image processing, the temperature distribution of the film found from the crystal's color change. Using this data, the heat flux can be estimated. Necessary calculations, such as the Nusselt number and the Reynold's number in the stagnation area, are found using formulas from previous literature and experiments. The area directly below the jet turns red then green then blue as the temperature increases. The area surrounding outside the stagnation region is cooler as the air spreads.

Nomenclature

A = area
c = specific heat
D = outlet diameter
h = convective coefficient
k = thermal conductivity
Nu = Nusselt number
Re_D = Reynold's number
RGB = red (R), green (G), blue (B)
r_{stag} = radius of stagnation region
Q = volumetric flow rate
T = film temperature
T_{air} = heater air temperature
T_0 = initial film temperature
z = distance from nozzle outlet to film
μ = viscosity
ρ = density

I. Introduction

There are several types of impinging jets are used in many different industries, such as aerospace and the medical field. However, there is no general CFD code for all of the different types due to the complicated multiscale physics within the jet. Thus this work seeks a quick, visual, experimental way to qualitatively and quantitatively describe the heat transfer from a heated impinging jet. The experiment performed for this paper was created to simulate the respiration of the human body. When a person breathes out, the jet of air creates a distinct temperature profile. This experiment imitates the process of breathing out of a nostril onto a solid wall. The idea to do this builds on work from a paper on the quantification of breathing by Johnson[2]. In order to do this, a pump was heated and the jet of air was shot onto a film of liquid crystal.

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According to a paper by Stasiek[4], thermochromic liquid crystals are increasing being in heat transfer and fluid flow experimental research. The liquid crystals can be painted on a surface or suspended in a liquid to determine a temperature profile. When painted on a piece of film, the film changes color as the temperature increases. As the temperature goes up, the color of the film goes from colorless to red, green, blue, and violet before turning colorless again at the higher temperature. Stasiek wrote about a set of experiments that were performed using liquid crystals, including heat transfer coefficient distributions over a rough surface and the de Vahl Davis experiment. Each composite of liquid crystal has a different color-temperature play interval. The interval of the film that we used was 29 to 35 °C.

This experiment involves using the liquid crystal thermography to determine the stagnation area of a jet of heated air hitting a solid wall. The stagnation area is the area of highest temperature and the thermal boundary layer is constant in the stagnation zone. Therefore, the Nusselt number or convective coefficient is constant. The Nusselt number is taken from the Beitelmal[1] paper on the analysis of a 2-D jet and from this, the Reynold's number can be calculated. The main purpose is to show the different regions of impingement on a film of liquid crystal, using the appropriate Nusselt number and finding the Reynold's number for the stagnation region and to prove that using liquid crystal thermography can be used in further similar experiments. It is believed that the stagnation region should be the region directly below the jet of air. This area will have the highest temperature and as the flow spreads over the surface of the film, the colors of the liquid crystal will show that the temperature will decrease.

II. Experimental Setup

The setup consisted of heating a 3000 mL pump in an oven to the temperature of the human body, 37 °C. Unfortunately, the oven at our disposal would not stay at a temperature this low. We used two different temperatures, 48.8 °C and 62.2 °C. A piece of 3”x6” film painted with the liquid crystals is placed on a box with a whole cut out of it to show the colored side of the film. A digital camera was placed under the box to film the profile distribution. The air is then pumped out of the nozzle onto the liquid crystal. The pump is used to simulate the lungs, using a capacity that is approximately the capacity of human lungs, and the exit nozzle imitates the nostril. Our nozzle was a circular exit with a diameter of 0.5 in. The nozzle is placed a distance of 3.75 in above the film. As the air flows over the liquid crystal covered film, the film changes color depending on the temperature as previously mentioned. The video of the process is then analyzed by Matlab and the calculations of the Reynold's number and other data found. Also, as mentioned before, the data gained from this particular process is just to prove that it can be used in the future with more sophisticated methods. Necessary assumptions made during the calculations and experiment were that the air flow was incompressible and inviscid with constant properties. Entrainment was also neglected.

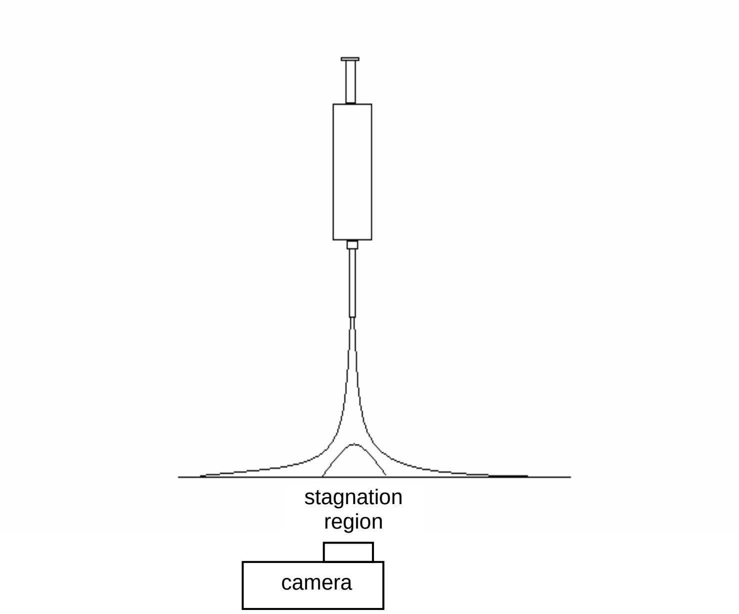


Figure 1. Experimental Setup. *3000 cc syringe filled with heated air is released onto liquid crystal thermography film over a period of approximately two seconds. A camera is position below to capture images of the film’s color change.*

III. Image Processing

The videos of the process captured the heating of the film during discharge of heated air from the pump (approximately two seconds) and the following cool down period. These videos are parsed into individual images with 28 images per second and cropped to the area of interest with a resolution of 203 pixels per inch. The stagnation point is located at the center of the circular color profile and the stagnation region identified as a radius

$$r_{stag} = 1.2\frac{D}{2} \tag{1}$$

as defined by Beitelmal[1]. This stagnation zone circle is plotted on top of the image seen in Fig. 2. The RGB information about each image is extracted from the image data and each set of color data is plotted separately, Fig. 3. Finally the hue is computed for each pixel using the color hexagon described by Preucil[3] where red is at 0°, green at 120° and blue at 240° using

$$hue = \operatorname{atan2}(\sqrt{3}(G - B), 2R - G - B) \tag{2}$$

Ultimately the hue can be calibrated to the temperature using a nonlinear calibration curve. For this initial work however, it suffices to simply look at the red, geen and blue progression of the temperature to determine if the color play interval is sufficient for the temperature of the heated air and geometry of the experimental setup.

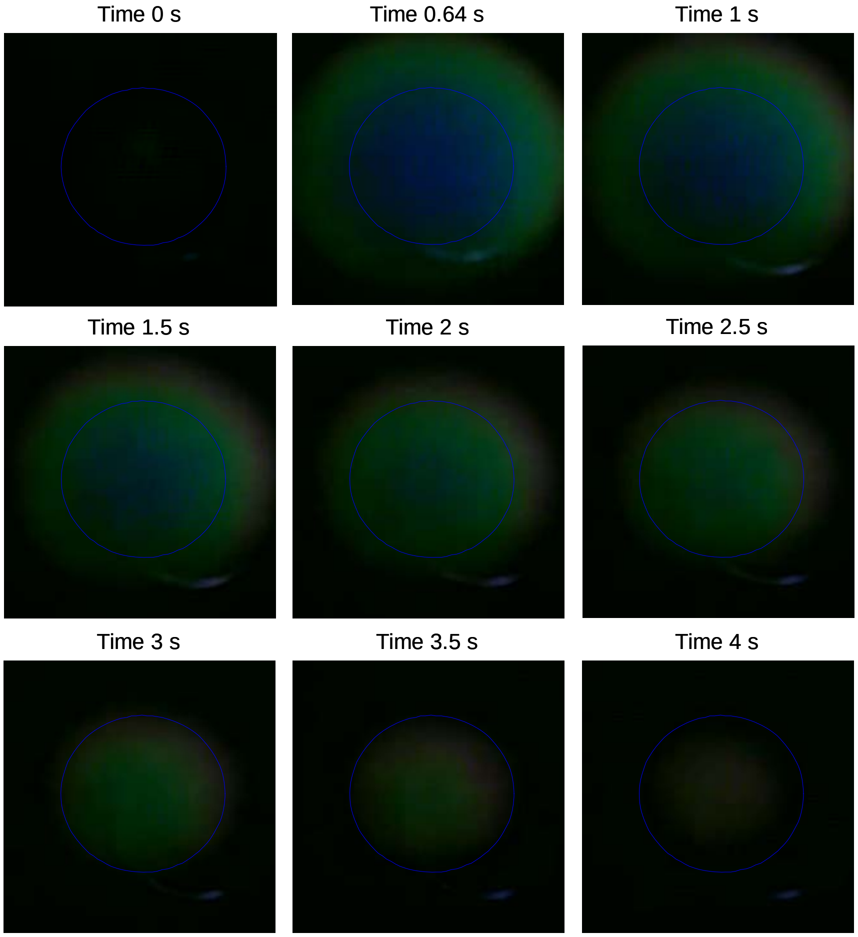

Time 0 s
Time 0.64 s
Time 1 s
Time 1.5 s
Time 2 s
Time 2.5 s
Time 3 s
Time 3.5 s
Time 4 s

Figure 4. Nine images parsed from a video of the liquid crystal thermography film with ~0.5 s time lapse between images. *The 48.8 °C air is released from the syringe over a two second time period. The film heats to a maximum at a time of 0.64 seconds (it takes just over a seconds for the film to heat up to the color change interval of 29-35 °C). The cool down period takes approximately 2.5 seconds. The blue circle in the figure represents the 0.6 inch stagnation region where the convective coefficient is constant.*

IV. Results

The experimental procedure was repeated several times with the syringe heated to either 48.8 °C or 62.2 °C. The 62.2 °C results exceeded the color play interval for this liquid crystal thermography. Figure 2 shows nine images parsed from a video of the film where the initial hot air temperature was 48.8 °C. The nine images show the time evolution of the color profile as the film heats up to a maxium (t = 0.68 s) then cools down. The air is discharged over a period of two seconds but it takes the film just more than a second to heat up to within the color play interval of 29-35 °C. The blue circle is the stagnation region found from Equation (1). Within this region the convective coefficient is constant as given by the Beitelmal's[1] Nusselt number, Equation (3)

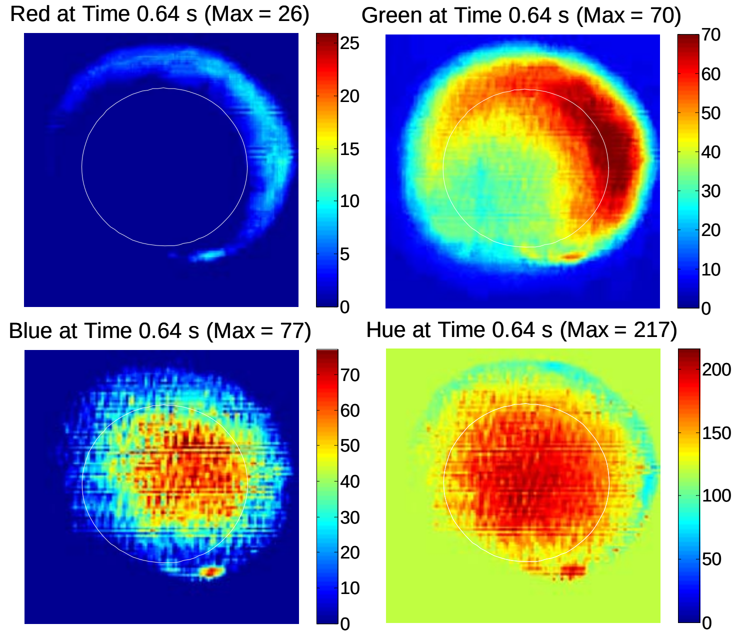
$$Nu = \frac{hD}{k} = 0.824(\mathrm{Re}_D)^{\frac{1}{2}}\left(\frac{z - r_{stag}}{D}\right)^{-\frac{1}{4}} \tag{3}$$

Where the Reynold's number based on diameter is

$$\mathrm{Re}_D = \frac{\rho UD}{\mu} = \frac{4\rho Q}{\pi\mu D} \tag{4}$$

Figure 3 shows the RGB and hue data at time = 0.64 s, the time when the maximum temperature is reached. This figure shows no red within the stagnation region (the white circle). There is a considerable amount of green inside and outside the stagnation region and the peak blue values are inside the stagnation region. The maximum blue value is 77 out of 255 indicating that the temperature profile has not exceeded the temperature play interval. Hue is a function of the red, green and blue data (Equation (2)) and can be calibrated against temperature. Here the max hue is 217 °. Pure blue, RGB = (0,0,255) occurs at hue equal to 240. This RGB to hue maping is shown in Fig. 4. It should be noted that the temperature profile is skewed higher toward the right. This would indicate that the outlet was not perfectly normal to the film.

Figure 5 plots the sum of the red, green and blue data within the stagnation region as a function of time. This serves as a way to identify the time at which the maximum temperature occurs. Notice that the blue peaks at a time of about 0.64 s and then sharply tapers off from there. The green is present throughout, tapering off gradually at the end when red begins to appear.


Red at Time 0.64 s (Max = 26)

Green at Time 0.64 s (Max = 70)

Blue at Time 0.64 s (Max = 77)

Hue at Time 0.64 s (Max = 217)

Figure 3. RGB and Hue data at time = 0.64 s, when the maximum temperature distribution occurs. *These images show that the color play interval seems appropriate with the maximum temperature occurring at blue = 77 (out of 255). There is no red within the stagnation region; within the white circle. Red corresponds to the lower end of the color play interval. The lower left image displays hue and this can be calibrated to temperature.*

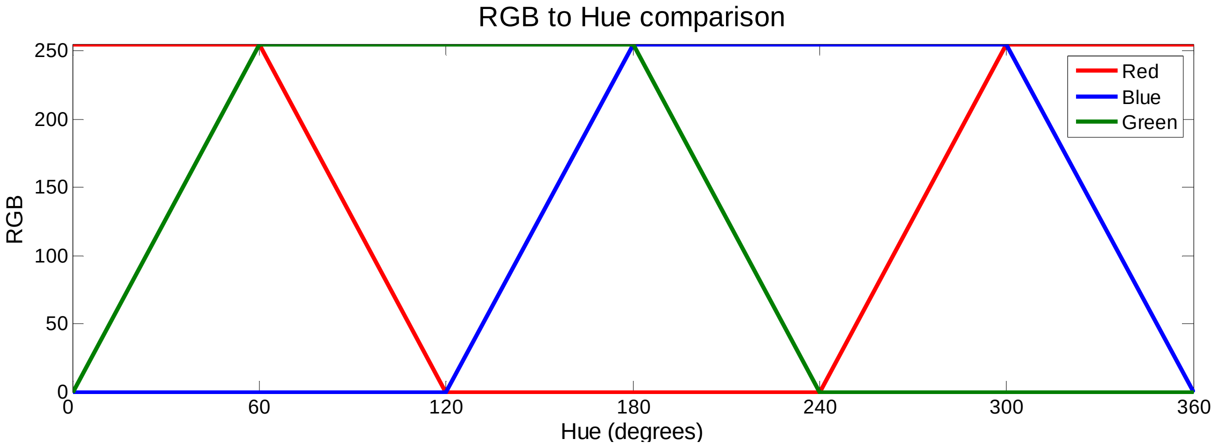


Figure 4. Comparison of RGB to Hue values. *This figure shows the mapping of RGB values to Preucil's formula for hue value as given by Equation (2). The maximum temperature measured in the experimental results occurred at a hue value of 217 degrees and the maximum possible blue hue occurs at 240 ° which indicate that this experiment has not exceeded the color play interval.*

Clearly the temperature ramp up and cool down is captured with the liquid crystal thermography film. The next step is to quantify the temperature this will be undertaken as future work. Stasiek[4] includes Equation (5) for the heat transfer in the film when the film is mounted to PVC backing of sufficient thickness where the transient temperature is given as

$$\frac{T - T_0}{T_{air} - T_0} = 1 - erf(\beta); \qquad \beta = h\left(\frac{t}{\rho c k}\right) \tag{5}$$

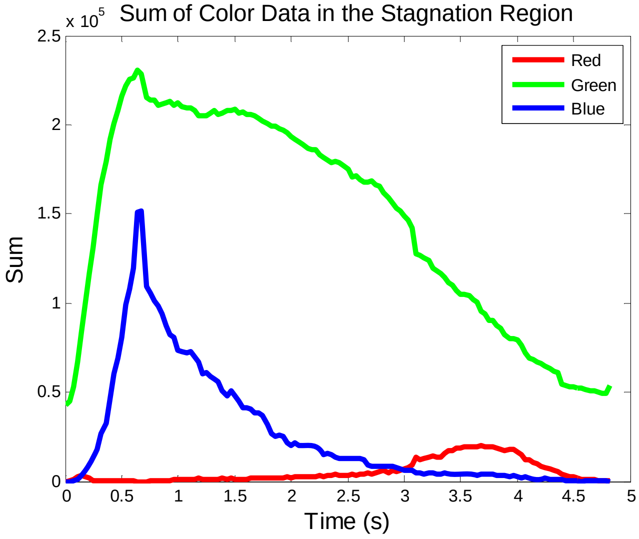


Figure 5. Magnetization as a function of applied field. *Figure captions should be bold and justified, with a period and a single tab (no hyphen or other character) between the figure number and the figure description.*

V. Future Work

The process of using liquid crystal thermography to determine the stagnation region of a flow of air can be reproduced in the future using more sophisticated methods than the ones used here. Better equipment would prove better results. In this instance, a box was used to hold the film, and unfortunately, it blocked the necessary light needed to produce a good quality video or picture. If a plexiglass box was used instead, more light could be seen. Another problem for our process was the limiting temperatures of the oven. The oven that we were able to use was limited to temperatures higher than 48 °C, and even at that state, it fluctuated. A better oven would be ideal for this setup. Also, when the air was pumped out of the nozzle, the nozzle was being held by a hand. This made it virtually impossible to keep the jet at the correct angle and height. If the nozzle was placed in a clamp to hold it in place, it would guarantee the repeatability of the experiment. Regardless, our setup did prove that the liquid crystal painted film is very acceptable in this type of research.

References

[1] Beitelmal, A.H., Shah, A.J., and Saad, M.A., "Analysis of an Impinging Two-Dimensional Jet," *Journal of Heat Transfer*, March 2006, Vol. 128, pp307-310.

[2] Johnson, M.L., Price, P.A., and Jovanov, E., "A New Method for the Quantification of Breathing," *IEEE EMBS Annual International Conference Proceeding*, 2007.

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[4] Stasiek, J.A., and Kowalewski, T.A., "Thermochromic Liquied Crystals Applied for Heat Transfer Research," *Optop-Electronics Review*, Vol. 10, No. 1, 2002.