Development of Two-Color Laser Induced Fluorescence Fluid Temperature Imaging for Free Convection Heat Transfer Applications

by
Rachel McAfee

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Mechanical Engineering
(Honors Scholar)

Presented February 10, 2021
Commencement June 2021

AN ABSTRACT OF THE THESIS OF

Rachel McAfee for the degree of Honors Baccalaureate of Science in Mechanical Engineering presented on February 10, 2021. Title: Development of Two-Color Laser Induced Fluorescence Fluid Temperature Imaging for Free Convection Heat Transfer Applications

Abstract approved:____

Joshua Gess

The development of a continuous and reliable cooling method for computer chips is an evolving subject requiring continuous research in both computer science and thermal management. Two-dye laser induced fluorescence (LIF) provides a minimally invasive way to investigate electronics cooling fluid behavior. Dielectric fluids are of particular interest as they allow full contact with the electronics and have low boiling points, opening the door to two-phase cooling applications.

To validate the non-intrusive properties and viability of the application to dielectric fluid, two-dye planar laser induced fluorescence was used to experimentally capture the temperature profile above a horizontal copper surface using PF-5060 as the dielectric working fluid. Natural convection was examined at heat fluxes ranging from 0.16 to 0.76 W/cm^2 and ambient temperatures of 20-45°C. A two-color LIF technique with an Nd:YAG laser was used in order to implement an in situ calibration standard. Sulforhodamine 101 is used as the calibration standard as its fluorescent intensity profile is independent of fluid temperature. Rhodamine B, which has a fluorescent intensity profile that does vary with respect to temperature, is compared to that of the in-situ calibration standard. Since the attenuation experienced by the fluorescing light from both dyes is the same as they travel through the same path to reach the camera's CCD, the ratio of these intensities produced a reliable calibration standard for experimental measurements. A repeatable and unobtrusive method for measuring temperature profiles have been established in the single phase. This validated technique can be carried over to future two-phase and/or heterogeneous mixture studies.

Key Words: Laser induced fluorescence, Natural convection, Dielectric fluid

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I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

Rachel McAfee, Author

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NOMENCLATURE

Roman symbols

B Thickness of laser sheet, m
C Dye concentration, mol/m^3
I Fluorescence emitted energy, W/m^2
I_0 Laser emitted energy, W/m^2
m Correlation coefficient
n Correlation exponent
Nu Nusselt number
Ra Rayleigh number

Greek symbols

ϕ Particle quantum yield
ε Molar extinction coefficient m^2/mol

Subscripts

r Rhodamine B dye
s Sulforhodamine 101 dye
1 Temperature dependent dye
2 Temperature independent dye

Chapter 1: Introduction

The development of a continuous and reliable cooling method for computer chips is an evolving subject requiring continuous research in both computer science and thermal management. As consumer and private electronics shrink in size every year, they are becoming limited by their cooling methods. Natural convection heat transfer through liquid immersion is an effective cooling method for electronics provided that accurate models and testing methods are developed [1]. Dielectric (non-conductive) fluids are of particular interest as they allow full contact with the electronics and have low boiling points, opening the door to two-phase cooling applications [2,3,4]. The study aims to develop a dye recipe and method for determining fluid temperature without disrupting the natural fluid movement or heat transfer phenomenon.

1.1 Motivation and Objectives

The primary motivation of this research is the exploration of basic fluid phenomena with the goal to establish two-color laser induced fluorescence as a viable experimental technique for more advanced fluid phenomenon.

Liquid immersion, including two-phase cooling, is increasingly common. Dielectric fluids are particularly appealing due to their low boiling points, allowing the thermal management solution to take advantage of high heat transfer coefficients. When researching these applications, measuring temperature is critical in evaluating the cooling performance of possible solutions. A variety of temperature measurement techniques can be used to obtain this information, but many of them are intrusive and influence the actual performance of the system. Laser-Induced Fluorescence (LIF) is a non-intrusive technique that can provide temperature measurement of the coolant in many applications without interfering with the system being tested [5, 6].

To further expand on past research and the motivations that drove it, the current project had the following objectives:

- Determine a recipe of two fluorescing dyes that does not disrupt the natural fluid and heat transfer phenomenon for use in two-dye LIF.
- Develop a calibration procedure and experimental set-up for a natural convection study.
- Process data and compare to computational models to determine the success of the experimental method.

PF-5060, a commercial dielectric fluid, was selected as the working fluid due to its pervasive use in industry and easy access. The dielectric fluid is suitable for electronics cooling applications in both pool boiling and single-phase convection.

The data provided is expected to meet the following research goals:

- Develop a repeatable and unobtrusive method for calibration and measuring temperature profiles.
- Generate results that support the viability of two-dye LIF as an experimental technique for dielectric fluids.
- Provide a dye recipe such that future two-dye LIF experiments can better investigate more complex fluid and heat transfer phenomenon.

1.2 Structure of Thesis

This thesis consists of five chapters. Chapter 1 will briefly introduce the background of the research, including the motivation and project objectives. Chapter 2 consists of background studies in LIF and related research including viable dyes. Chapter 3 presents initial work conducted before LIF testing including the recipe development, proof of concept for the selected dyes, experimental setup, and calibration technique. Chapter 4 discusses the results of the natural convection study. Chapter 5 summarizes the goals and future studies that may be done to improve on this research.

Chapter 2: Literature Review

2.1 Two-Dye Laser Induced Thermometry

LIF is used to obtain a map of varying temperature in a fluid by taking advantage of the unique abilities of fluorescing dyes. When a molecule of fluorescent dye is exposed to light within its absorbing wavelength range, it will absorb that energy, and the molecule will then be in a state of elevated energy. The molecule will then emit energy to return to the base energy state. The energy is emitted as light at a higher wavelength than what was absorbed, due to energy losses in the process. This difference in the absorbed and emitted wavelength is known as the Stokes shift, which is unique for each dye. The intensity of emitted light from the fluorescent dye can be expressed with the following equation [7]:

$$I = I_0 C \phi \varepsilon \mathrm{B} \tag{1}$$

I is the energy emitted as fluorescence (W/m^2), I_0 is the energy emitted by the laser (W/m^2), C is the concentration of dye in the fluid (mol/m^3), ϕ is the quantum yield, B is the thickness of the laser sheet (m), and ε is the molar extinction coefficient (m^2/mol). The quantum yield, ϕ, of a fluorescing dye is the ratio of the number of photons it fluoresces to the number of photons it absorbs. The molar extinction coefficient, ε, is the percentage of photons that a dye will absorb for a given wavelength of light. The properties ϕ and ε can both be temperature dependent. LIF uses this temperature dependency to extract temperature data from measurements of the emitted intensity, I.

When using LIF at the macro scale, multiple difficulties present themselves. First, due to scattering in the working fluid, the energy emitted by the laser that reaches the dye molecules will be different for every location within the laser sheet. Additionally, each point's fluorescence will have to travel a different path to get to the camera.

These difficulties are addressed by using a second dye and performing calibration for each measurement point, or camera pixel. Using a second dye allows for temperature data to be obtained by examining the ratio of emitted intensities, as shown in Equation 2. The numerator, I_1, is the measured intensity of the temperature dependent dye. The denominator, I_2, is the measured intensity of the temperature independent dye. Calibrating for each camera pixel accounts for issues in laser light path length.

$$\frac{I_1}{I_2} = \frac{I_0 C_1 \phi_1 \varepsilon_1}{I_0 C_2 \phi_2 \varepsilon_2} \quad (2)$$

Using the ratio of intensities allows for the measurement results to be independent of the magnitude of the laser emissions received by each molecule, making the measurement path independent. This greatly simplifies the calibration.

Further simplification can be achieved by using one dye that is temperature sensitive, and one that is temperature insensitive. Emissions of either dye from a given point will follow the same path and experience the same attenuation along their path to the camera. Using the ratio of emission intensities allows for path independent calibration for each measurement point, since the difference in the measured intensities will then primarily be due to the different temperature sensitivities of each dye. With one dye being temperature sensitive, and one dye being temperature independent, changes in the ratio of measured intensities, $\frac{I_1}{I_2}$, will correlate to the temperature of the fluid, allowing for temperature measurements.

2.2 Dye Selection

One of the main purposes of this study is to validate the use of LIF in studying dielectric fluid flow paths in convective heat transfer applications with PF-5060 used as the working fluid. Multiple studies have been done using Rhodamine B (RhB) as a temperature dependent dye in LIF temperature measurements, establishing it as an effective fluorescent dye for this type of application with non-dielectric working fluids. [8,9,10]. The light source for this study was a 532 nm Nd:YAG laser, which has an emission wavelength within range of RhB. For these reasons, it was used as the temperature dependent dye for this study.

There are far fewer LIF studies available in literature that include temperature independent dyes with excitation ranges that overlap with a laser emission wavelength of 532 nm. Sulfurhodamine 101 (SR101) has been used in academic studies for over 15 years, particularly in biological studies [11,12,13]. Lamouche et al examined the emissive power of SR101 in solutions of varying dielectric permittivity [14]. They showed that SR101 worked as a fluorescing dye in a dielectric solution as part of a non-LIF medical research application, as they measured optical data with a varying magnetic field and varying dielectric strength of the fluid. While SR101 has been used as a fluorescent dye in many types of research, there is no published data on SR101 being used as a dye in LIF for temperature measurements with a dielectric as the working fluid. There is data that shows SR101 has been used successfully with an Nd:YAG laser when it is dissolved in an ethanol/water mixture [7]. These studies suggest that SR101 will work for LIF temperature measurements in a dielectric fluid, but this must be carefully validated through calibration and corroboration of measured results to those expected by theory and modelling. This study intends to be a proof of concept for using LIF in convective heat transfer applications using a dielectric fluid with RhB and SR101 as the two-color dye combination.

Chapter 3: Development of LIF Methodology

3.1 Natural Convection Experimental Setup

Figure 1 shows a model of the mounted testing chamber with a portion of the oven removed for clarity. In order to develop a LIF calibration for this system, the entire dielectric chamber was placed inside a lab grade oven with a spatial temperature uniformity of +/- 0.25°C, measured using four thermocouples at different locations in the oven. The Nd:YAG laser produces a planar sheet that is delivered through a clear window installed on the front door of the oven. A cylindrical lens (-15 mm focal length) is used to create a laser line on the mirror, forming a vertical laser sheet in the dielectric fluid. An angled mirror fixed to the top of the test chamber housing the heated element and dielectric fluid is used to reflect the sheet perpendicular to the free convecting surface. Image capture of the fluorescing intensity profile is concurrent to the laser sheet illumination of the dye. The laser is mounted on a stand that can translate in the z-direction (up and down on Figure 1) to shift the laser sheet illumination in the fore and aft direction on the heated element. The result is a full temperature profile of heated fluid around the free convecting surface.

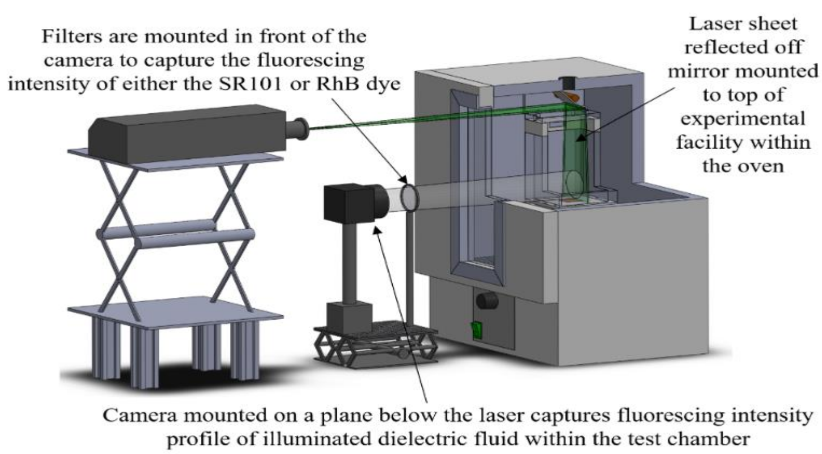

Fig. 1 Model showing the test chamber and clear viewing panel installed in the lab oven.

Figure 2 shows a model of the test chamber removed from the temperature-controlled oven. The bottom section of the main testing chamber consists of a copper heating block surrounded by Delrin ™ insulation on the sides. The top of the copper heating block is exposed to the working fluid. A polyimide electric resistance heater with thermal paste applied is placed under the copper block to serve as the heating source during natural convection testing.

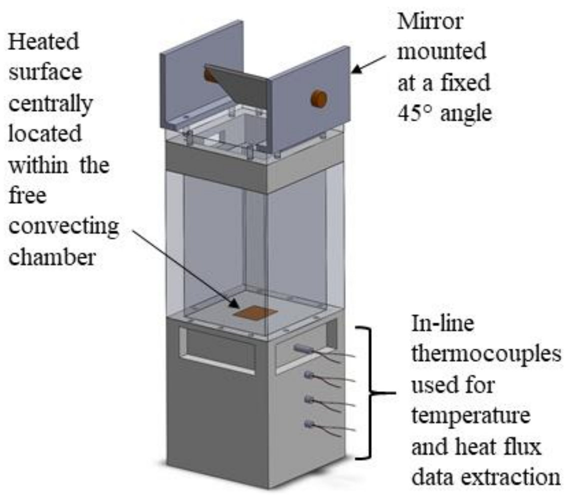

Fig. 2 Free convection experimental test chamber model.

Four thermocouples, also with thermal paste applied, are spaced as shown in Figure 3 within the copper block to measure temperature and heat flux. The fluid chamber has transparent polycarbonate sides, the top of the chamber is also clear polycarbonate. Four thermoelectric coolers are placed in a Delrin ™ ring near the top of the chamber to remove heat from the working fluid chamber, injecting it into the thermally controlled oven.

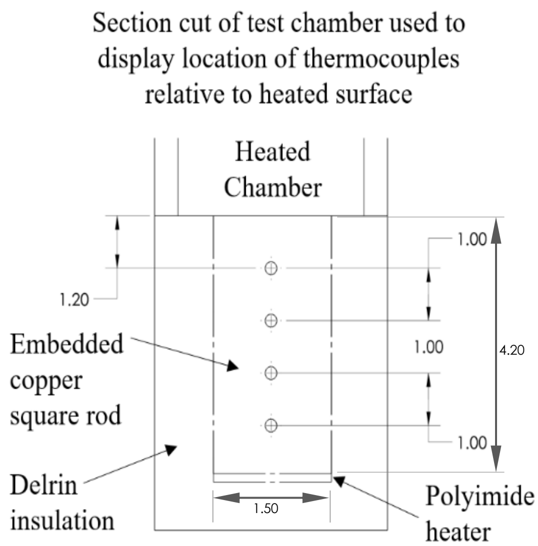

Fig. 3 Section cut showing location of thermocouples along embedded copper rod. Dimensions shown in figure are in inches.

3.2 Two-Dye Recipe Development

Both dyes were selected based on the limitations of the available Nd:YAG laser with an excitation wavelength of 532 nm. To calculate the ratio of intensities of the dyes in Equation 2 it is necessary to obtain measurements of the emissions for each dye independently. Figure 4 shows the emission spectra of the two dyes [15, 16]. Two filters were used to separate the emissions. An external filter mount, shown in front of the camera on Figure 5, is used to house either a band-pass filter to capture the intensity profile of the fluorescing RhB dye or a long-pass filter to capture the intensity profile of the fluorescing SR101 dye. The two filter bands are also shown on Figure 4. To acquire the two intensity values used for calibration and subsequent temperature measurement, these filters are manually changed out during steady-state conditions for the current experimental facility.

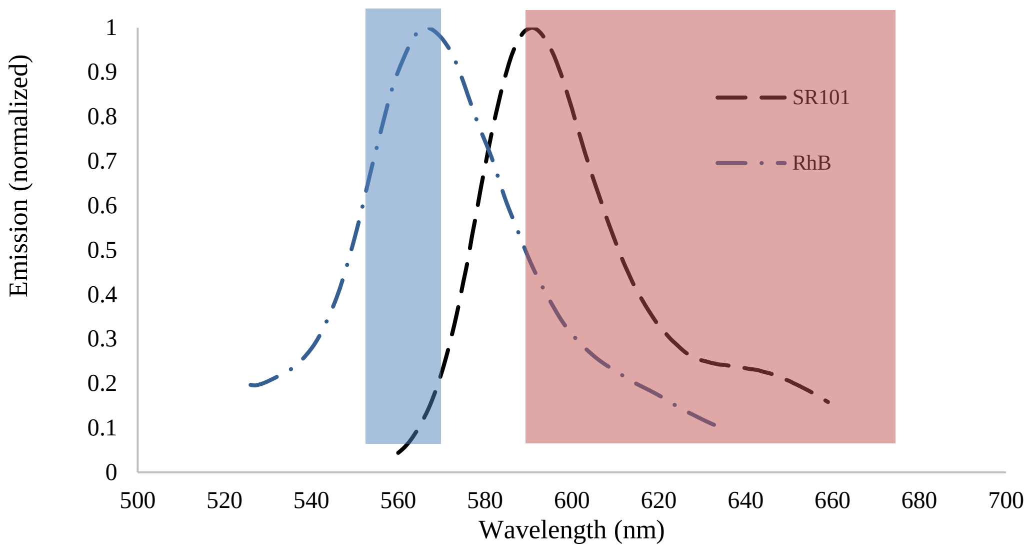

Fig. 4 Emission spectra of the fourescent dyes. Band pass filter range is shown in blue, high-pass filter is shown in red.

Due to a lack of literature availible on two-dye LIF, multiple tests were performed to select a viable dye recipe. Rather than use the significantly larger test chamber (see Figure 2) a smaller test facility consisting of three fluid chambers was constructed of polycarbonate to allow for simultaneous testing of various ratios at a lower cost. The small sample test facility is depicted in Figure 5. The polycarbonate was the same material and thickness as the actual test chamber and was positioned similarly to the experimental setup to mimic the path of travel for the fluorescent points during normal testing. Each of the small chambers were filled with dielectric with the appropriate dye recipe then sealed shut. The sample test facility was ramped through six temperatures, ranging from 20 °C to 45 °C. Images were captured with both the RhB and SR101 filter and the intensity ratio was calculated for each fluid chamber. The relationship between calculated intensity ratio and temperature was examined for each of the six potential recipes. At a point, increasing the temperature dependant dye, RhB, did not have a significant effect on the slope of the intensity ratio plot.

Once this point of diminishing returns was reached, that recipe was selected as the best Rhodamine B and Sulfurhodamine 101 combination for all of the tests moving forward.

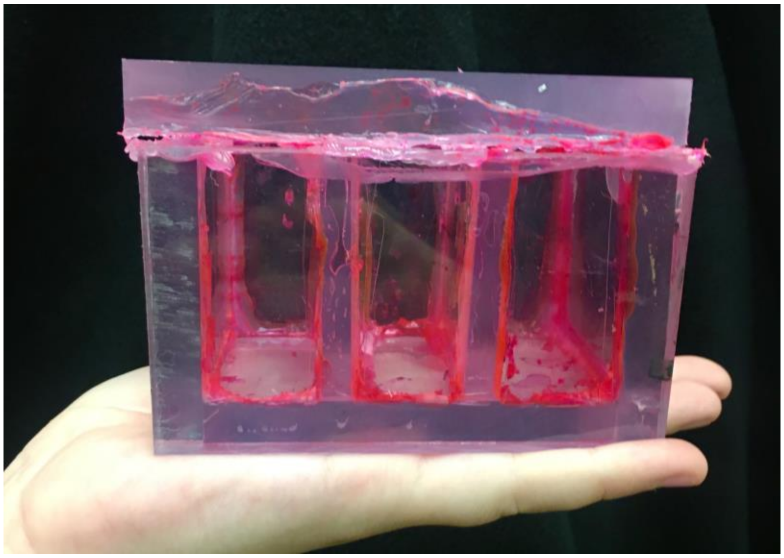

Fig. 5 Small sample test facility for simultaneous recipe testing.

3.3 Calibration

To take temperature measurements during natural convection, where the temperature in the fluid will be varied, calibration is needed to correlate the ratio of measured intensities to a specific temperature. The experiment was designed so that the temperature of the entire setup could be regulated in the lab oven. Steady state is reached when the entirety of the experimental facility is saturated at a constant prescribed temperature within the lab oven.

The temperature was measured at four locations around the oven and one in the fluid to verify uniformity. Steady state was determined to be achieved when the temperatures varied less than 0.5 °C over a span of at least 30 minutes across all the thermocouples. When steady state was reached, fifty images were taken with each filter. For each pixel, the ratio of the measured intensities was averaged over the images, and this was correlated to the steady state temperature. The intensity ratio for a given temperature was unique for each pixel, as the intensity of the laser sheet interacting with the dye and the intensity attenuation of the emitted light both vary with location. This was repeated three times to develop three averaged images per temperature.

Figure 6 shows a sample calibration curve for a single pixel that was obtained when varying the oven temperature in the range of 20 to 45°C. The data follows the general trend given in Natrajan and Christensen, who used the same two dyes with a different working fluid [7].

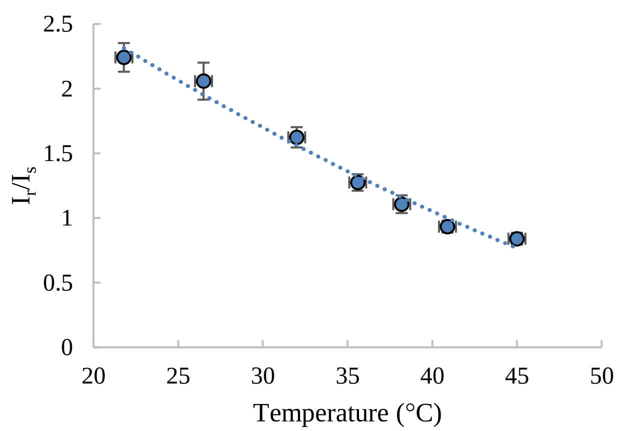

Fig. 6 Calibration curve showing change in intensity ratio with varying fluid temperature with second order polynomial trend line shown.

3.4 Non-Intrusive Testing

A major motivation for this experiment is that this is a non-intrusive means of temperature measurement. Many temperature measurement techniques rely on physical disruption of flow, such as the use of thermocouples or thermistors. LIF removes this obstacle, but still has the potential to affect the heat transfer due to the dye added to the working fluid. Multiple tests were performed to determine if the dye had any impact on the heat transfer in the fluid.

A thermistor was placed in the heated chamber to measure the bulk fluid temperature. As heat flux was applied to the bottom of the copper block, thermocouples in the block were used to estimate the temperature of the heated surface through Fourier's Law of linear extrapolation. Surface thermocouples were placed on the outside of the Delrin ™ to estimate the heat losses from the sides to accurately estimate the heat flux from the heated surface to the fluid, shown in Figure 3. The tests were repeated both with and without dye added to the working fluid.

The dye was found to have negligible influence on the heat transfer performance. Free convection testing between $7.5 \times 10^6 < Ra < 4.2 \times 10^7$ showed that the dye only decreased the Nusselt number by an average of 1.3%. The data was used to create a correlation for Nusselt number based on the Rayleigh number, $Nu = m(Ra)^n$, where m = 1.7959 and n = 0.2239. Data is shown in Figure 7.

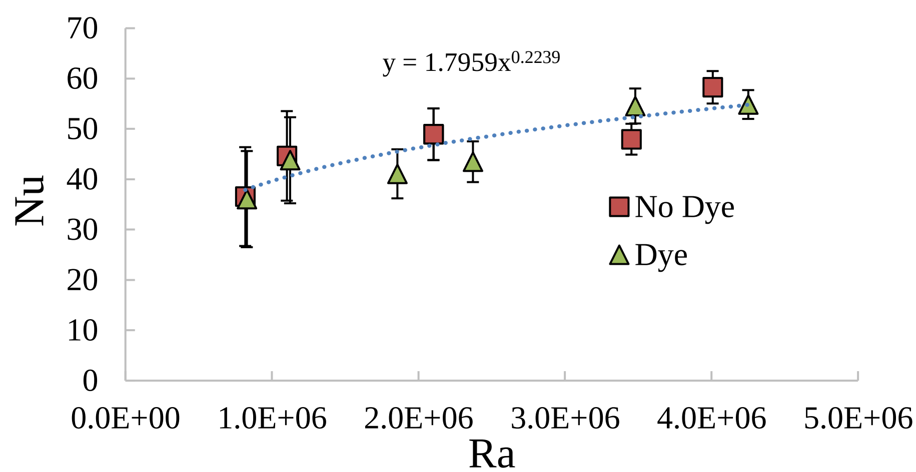

Fig. 7 Rayleigh number versus Nusselt number for the dye/no-dye comparison.

Chapter 4: Analysis of Natural Convection

4.1 Natural Convection Numerical Model

To validate the findings of the experiment in this proof-of-concept study, an ANSYS Fluent CFD model was created using version 19.1. Fluent is not able to perform steady state calculations of natural convection when there are appreciable temperature differences in the fluid. The Fluent model was run as a transient model until it reached steady state.

The model used a laminar viscous model for the fluid and included the energy equation with buoyancy effects. A time step of 0.25 seconds was used, and steady state was reached after 3,570 iterations. The same heat flux values from the experiment were used as the thermal boundary condition for the heater at the bottom of the chamber. The top surface had a negative heat flux applied to approximate the cooling provided by the thermoelectric coolers. This value was set equal to the overall heat transfer coming in from the heat source. All other surfaces were assumed to have minimal heat losses. The initial fluid velocity was set to zero. A mesh independence study was performed that showed with a finer mesh the calculated temperature varied by less than 0.02 °C when compared to the results with the initial mesh. This indicated that the initial mesh was sufficient.

4.2 Experimental Method

After calibration data has been obtained for each pixel, a temperature map of the fluid can be obtained for condition of non-uniform temperature in the fluid. For this experiment, measurements were taken in natural convection at three heat flux settings, 0.16, 0.40, and 0.76 W/cm^2. Thermoelectric coolers are used to remove the same amount of heat from the air just above the dielectric fluid. The system was allowed to come to steady state for each measurement.

Like the calibration, fifty images were taken using each filter. The intensities were then analyzed using Matlab and correlated to a temperature for each point, and a map of temperature for the fluid was created for each heat flux. The images created from the LIF measurements were compared pixel by pixel to the results from Fluent.

4.3 Results

Figure 8 shows the results of the Fluent model after reaching steady state for the case of 0.4 W/cm^2. The figure shows the calculated temperature at all points in a vertical slice in the fluid volume, taken at the midpoint of the test chamber. Figure 9 shows the image obtained using LIF, also for a heat flux of 0.4 W/cm^2. The two images are shown using the same temperature range and similar color scales.

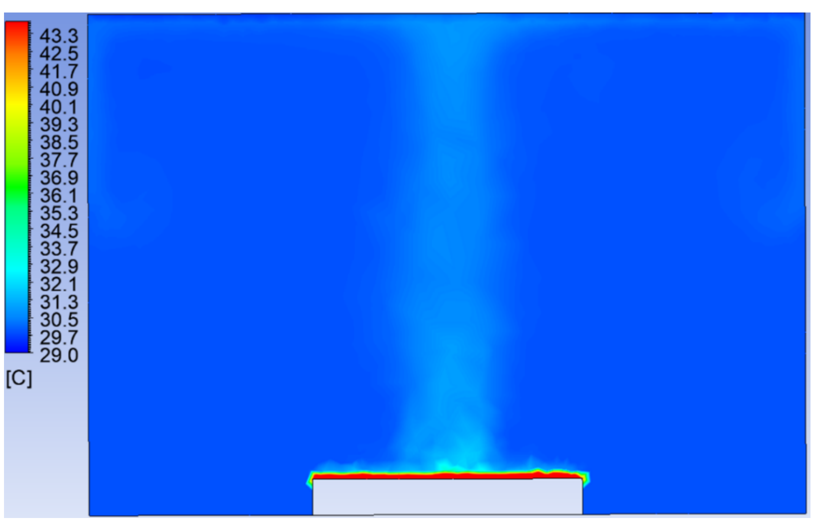

Fig. 8 Temperature map from Fluent simulation showing a natural convection plume.

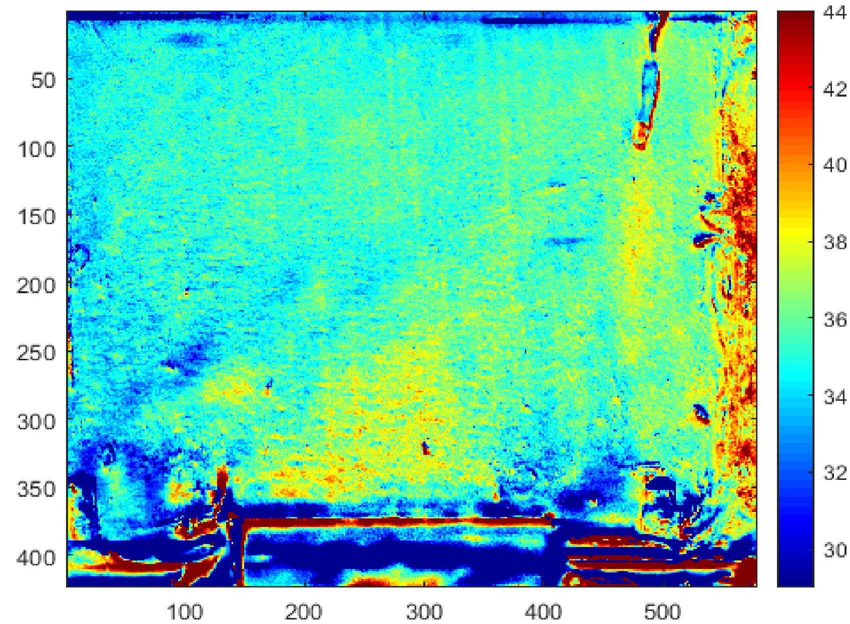

Fig. 9 Temperature map from LIF simulation showing a natural convection plume.

The LIF measurements allow for the calculating of the overall average fluid temperature for a vertical slice. This is very useful in convection as it allows for measuring of the ambient temperature used in calculating the heat transfer coefficient. A thermistor was in the fluid, but not in the LIF measurement plane, and was used to estimate the ambient fluid temperature.

The LIF measurements of average fluid temperature surrounding the heated plate were compared to the thermistor measurements and the average temperature results from the Fluent model, shown in Table 1. The results show that the thermistor reading is within 10% of the overall average temperature, which could be used as an approximation for the ambient temperature. Using LIF may provide a more accurate physical representation of the ambient temperature particularly in the generation of empirical convection correlations that are highly dependent on the definition of a free stream temperature.

Table 1. Average in-plane temperature

Overall Average Temperature (°C)			
W/cm^2	LIF	Thermistor	Model
0.16	33.3	32.1	32.1
0.4	33.9	30.4	30.29
0.76	42.5	44.6	42.6

Using the temperature data from LIF, heat transfer coefficients were calculated for the three measurements. The surface temperature was calculated as the average temperature from the LIF measurements very near the heated surface. The ambient temperature was calculated by taking the average of all the temperature measurements in the plane. The heat flux was calculated using the power delivered to the heater and estimated losses. These were then used to calculate the heat transfer coefficients. The results are tabulated in Table 2. Heat transfer coefficients were also calculated for the three test cases using the correlation developed from the dye-no dye testing discussed earlier. The LIF measurements fall within 15% of the developed correlation for all tested fluxes.

Table 2. Heat transfer coefficient using multiple methods.

Heat Transfer Coefficients			
W/cm^2	LIF	Correlation	Difference
0.16	209.9	199.5	5.2%
0.4	229.0	240.9	4.9%
0.76	294.3	256.8	14.6%

4.4 Discussion

In comparing the images many differences can be seen. The fluent model predicts a much thinner plume than is seen in the LIF image. Also, from the image, it appears that the overall temperature in the LIF image is higher than that of the Fluent model, which was confirmed in later analysis shown in Table 1.

There are multiple regions noted in the LIF image where there are significant discrepancies from the model as indicated in Figure 10. Regions A and B both experienced noticeable glare when the images were taken, which disrupted the measurement technique in these areas, causing large swings in the light intensities measured. Region D is the location of the thermistor that was used to measure the fluid temperature. Dye tended to collect on the thermistor, and the increased dye density along with the physical interference of the thermistor affected the LIF measurements in this area. In Region C, the silicon sealant used in constructing the chamber collects dye like the thermistor, giving inappropriately high temperature measurements. During the analysis of the LIF data, a filter was applied to exclude these extreme high and low temperature results in these regions.

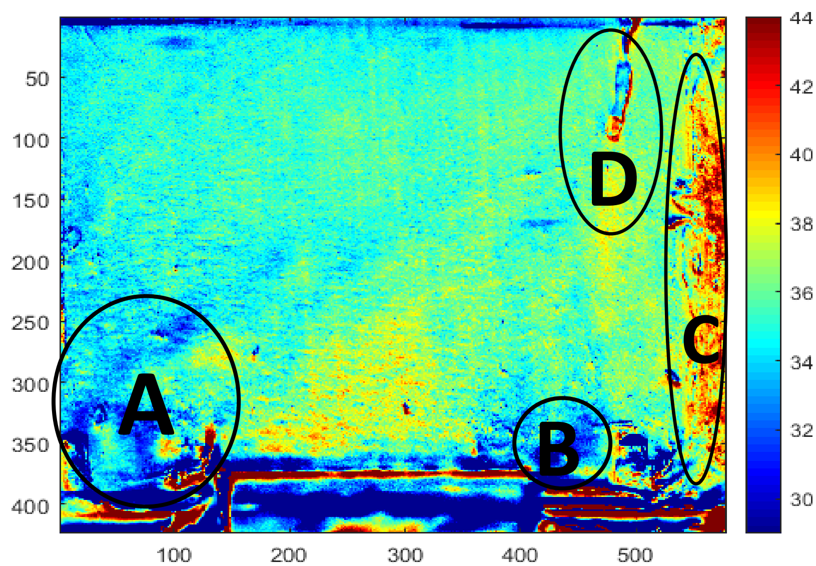

Fig. 10 Temperature map from LIF measurements showing natural convection plume. Regions of significant error are highlighted.

Table 3 lists the relative error of the LIF measurements compared to the model. During analysis, issues with systematic error were occurring on the left side of the LIF images. This was more than likely due to glare and reflections on the polycarbonate surfaces that will be corrected in future studies. As shown in Table 3, comparing only the right sides of the Fluent model and LIF images shows a significant reduction in error due to the elimination of glare problem areas from the analysis.

Table 3. Error of LIF measurements to model results

W/cm^2	Error - Total	Error - Right Side
0.16	8.1%	5.0%
0.4	18.0%	11.4%
0.76	35.7%	14.4%

Chapter 5: Conclusions and Recommendations for Future Work

Temperature profile measurement around immersion cooled surfaces will become more relevant to the electronics cooling community as devices become more energy dense. Smaller packaging means that ancillary components will be placed in greater proximity to higher heat flux devices, and two-dye laser-induced fluorescence could be used to understand and predict the impact of neighboring components to the overall heat transfer and coolant flow.

5.1 Conclusions

Data presented confirmed that LIF temperature measurement is a non-intrusive way to measure variant temperature profiles within confined free convection streams using a dielectric fluid. A calibration curve has been developed for the test setup that matches the trends published from similar studies. The calibration was used to obtain a temperature map in the dielectric fluid under natural convection conditions. An empirical correlation for PF-5060 natural convection heat transfer from an isoflux horizontal flat plate is provided. A Fluent model was created that shows the expected behavior of natural convection. The model was compared against experimental measurements to show that LIF with SR101 and Rhodamine B is an effective measurement technique for convective heat transfer characterization with a dielectric working fluid, producing comparative errors of less than 15% for several critical macroscale characteristics of free convection flow.

Ultimately, the thesis fulfills the project scope as it demonstrates:

- A repeatable and unobtrusive method for calibration and measuring temperature profiles using LIF.
- Results that support the viability of two-dye LIF as an experimental technique for dielectric fluids.
- A dye recipe such that future two-dye LIF experiments can better investigate more complex fluid and heat transfer phenomenon.

5.2 Future Work

Future work will seek to mitigate all of the systematic errors in the experimental facility, specifically glare from highly reflective surfaces within the oven and copper surface. Experimental methods will be expanded to transient heat transfer phenomenon by incorporating an image splitter. This would allow the camera to capture images using both filters simultaneously using an external filter mount, drastically improving accuracy.

Work has already commenced in capturing the collapse rate and temperature profile of a rising superheated vapor bubble using a new two-color LIF recipe and test facility. Proven in the single-phase, this technique will be extended to two-phase pool and flow boiling heat transfer studies at the macro and minichannel scales.

Appendices

Appendix A: Image Processing Code

```
#!C:\Users\mcafe\miniconda3 python

import os
import numpy as np
import matplotlib.pyplot as plt
from PIL import Image


def average_images(path_to_filter):
    """
    Take average intensity of all images in that directory, used to average
all
    :param path_to_filter: path to the folder of just one filter (aka just
Rhodamine or SH)
    :return: average intensity values for all inputted images
    """
    stacked_image = np.empty([822, 1000])
    for file in os.listdir(path_to_filter):
        greyimage = Image.open(os.path.join(path_to_filter,
file)).convert('LA')
        stacked_image = np.dstack((stacked_image, np.array(greyimage)[:, :,
0]))
    averaged_image = np.mean(stacked_image, axis=2)[2:774, 2:917]
    return averaged_image


def develop_point(path_to_temp):
    """
    Given a path to a particular temperature identifies the temperature and
develops a calibration point
    :param path_to_temp: path to the folder with the two filters, single
temperature
    :return: intensity ratio to make one calibration point
    """
    for filtertype in os.listdir(path_to_temp):
        if filtertype == 'R':
            R_avg = average_images(os.path.join(path_to_temp, filtertype))
        elif filtertype == 'S':
            S_avg = average_images(os.path.join(path_to_temp, filtertype))
    intensity_ratio_matrix = np.divide(R_avg, S_avg)
    return intensity_ratio_matrix


def develop_calibration_matrix(path_to_data):
    """
    Run the calibration point for all availible datasets to build a 3D
matrix
    :param path_to_data:
    :return:
    """
```

```
    temperatures = []
    firstrun = True
    for temp in os.listdir(path_to_data):
        temperatures.append(str(temp).split('_', 1)[0])
        if firstrun:
            calibration = develop_point(os.path.join(path_to_data, temp))
            firstrun = False
            secondrun = True
            print('Calibrated {} data'.format(temp))
        elif secondrun:
            np.expand_dims(calibration, axis=2)
            calibration = np.dstack((calibration,
develop_point(os.path.join(path_to_data, temp))))
            secondrun = False
            print('Calibrated {} data'.format(temp))
        else:
            calibration = np.dstack((calibration,
develop_point(os.path.join(path_to_data, temp))))
            print('Calibrated {} data'.format(temp))
    if calibration.shape[2] > 1:
        plt.plot(temperatures, np.average(calibration, axis=(0, 1)), 'o',
color='black')
        plt.xlabel('Temperature (C)')
        plt.ylabel('Average Intensity Ratio for Entire Image')
        plt.show()
    temperatures = np.array(temperatures)
    temperatures = temperatures.astype(np.float)
    return calibration, temperatures


def develop_fitted_relationship(calibration, temperatures):
    """
    Given a 3D numpy array of calibrations and all the corresponding
temperatures develops a calibration curve for
    each individual pixel
    :param calibration:
    :param temperatures:
    :return:
    """
    pixel_fit = np.empty((calibration.shape[0], calibration.shape[1], 2))
    for y in range(calibration.shape[0]):
        for x in range(calibration.shape[1]):
            intensity_ratios = calibration[y, x]
            pixel_fit[y, x] = np.polyfit(intensity_ratios, temperatures, 1)
    return pixel_fit


def final_image(filename):  # START CODE NOW
    """
    Finds calibration for all points, interprets the final image, saves as
a npy file for use in interpret functions
    :param filename: what to name the saved final data as (good to mark
different fluxes with)
    :return: final numpy array
    """
```

```
    path1 = input("Enter the path to data: ")
    path2 = input("Enter the path to final: ")
    final_intensity_matrix = develop_point(path2)
    calibration = develop_calibration_matrix(path1)
    pixel_fit = develop_fitted_relationship(calibration[0], calibration[1])
    final_temps = np.empty((final_intensity_matrix.shape[0],
final_intensity_matrix.shape[1]))
    for y in range(final_intensity_matrix.shape[0]):
        for x in range(final_intensity_matrix.shape[1]):
            calibration_for_point = np.poly1d(pixel_fit[y, x])
            final_temps[y, x] =
calibration_for_point(final_intensity_matrix[y, x])
    np.savetxt(os.path.join(path2, filename), final_temps, delimiter=',')
    return final_temps


def interpret_final_image(lowtemp, hightemp):
    """
    Take in the values of a final image, plot and show, save image, load in
fluent data
    :param lowtemp: setting for heatmap colorbar
    :param hightemp: setting for heatmap colorbar
    :return:
    """
    path1 = input("Enter the path to final image data: ")
    path2 = input("Enter path to where image should be saved: ")
    path3 = input("Enter path to model data: ")
    final_temps = np.loadtxt(path1, delimiter=',', dtype=float)
    fluent = np.loadtxt(path3, delimiter=',', dtype=float)  # read in
fluent image and store
    plt.imshow(final_temps, cmap='hot')
    plt.clim(lowtemp, hightemp)
    plt.colorbar()
    plt.savefig(os.path.join(path2, 'HeatMap.png'))
    plt.show()
    return final_temps
```

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