

Investigation of planer laser induced fluorescence as an instantaneous field measuring technique
in water

by

Hatim Hamid Alrifaai

B.S., King Abdulaziz University, 2010
M.S., Kansas State University, 2018

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Alan Levin Department of Mechanical and Nuclear Engineering
Carl R. Ice College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2023

Abstract

This dissertation aims to study the use of the Planar Laser Induced Fluorescence (PLIF) technique to measure the instantaneous temperature field of water flowing through a duct. An experimental facility was developed specifically for PLIF visualization in water flow. In the duct, the bottom side is changeable and heated by an electrical heater. Rhodamine B and Nd:YAG laser (532 nm) were used to create the fluorescence in the experiment. The study presents techniques for making a temperature calibration curve. In addition, the research seeks to determine the best experimental conditions to enhance the accuracy and precision of the results. The primary focus of the study was the application of these techniques to determine an instantaneous field temperature in the flowing water duct. Several experimental factors were investigated to find their impact on the results' accuracy and precision. The temperature field and temperature distribution curve were measured for the isothermal and heating cases. Smooth and finned surfaces were examined. The investigation focused on the area close to the bottom surface of the duct. The experimental results were compared with computational results obtained by the FLUENT software. The study concluded that PLIF can be used for instantaneous field, but that high temperature gradients confound the usefulness of the results.

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Chapter 1 - Introduction

Experimental investigation of heat transfer associated with a turbulent flow is an important field of research. One important factor that is difficult to measure is the temperature field, which shows the temperature distribution through a plane.

Measuring the temperature field of a flowing fluid needs a nonintrusive method to avoid disturbing the flow. To accomplish this, nonintrusive measuring techniques are required, because the traditional single-point probes will interrupt the flow and cannot achieve the field's measurements without a massive number of probes [1]. Several nonintrusive measurement techniques are used in measuring the temperature field of flowing water, like planar laser-induced fluorescence (PLIF), thermographic liquid crystal (TLC), and tagging measurement techniques [2].

PLIF is one of the nonintrusive techniques of temperature field measurement. In this method, a temperature-sensitive dye is inserted into the fluid. When the solution of the fluid and dye receives a laser pulse, the dye will emit photons with an intensity correlated to the fluid temperature. A camera is required to catch the emitted photons. The variation of intensity is shown as the variation of grayscale level in the images. This research uses the PLIF method to measure the temperature field of flowing liquid water. The water flows turbulently through a square duct. To apply PLIF, Rhodamine B was used as a fluorescent dye. In addition, A Nd:YAG laser with a wavelength of 532 nm was used as the laser illumination source.

The research aimed to apply PLIF to measure the temperature field of a duct with a flat surface and a finned surface, and then to find the temperature distribution curve of a line within the duct. Temperature structure visualization was another goal of this research. More investigation was made for the results of the zone close to the surface. The study tried to estimate

the error of each pixel to find a relationship between the error and the position. In addition, the research sought to determine the best experimental conditions for enhancing the accuracy of the results. Several experimental factors were investigated to find their impact on the accuracy and precision of results. Camera aperture, laser energy, and laser plane thickness were examined.

To the researcher's knowledge, PLIF has not previously been used for measuring the temperature field or visualizing the temperature structure of the finned surface duct. In addition, the errors of the results of the zone close to the surface were presented in a way that was not similar to previous analyses in the literature.

To accomplish the aims, a test section was designed and built for this research. It has a duct where the water flows through, and it has a changeable surface. This research described the process of calibrating a thermometry system of flowing water in a duct. It used Matlab software to process the images and find a relationship between the image grayscale and the temperature. The dye photobleaching was examined. Besides, the study aimed to estimate the uncertainty of measuring the temperature field using PLIF. The experimental results were compared with computational results that were obtained using the FLUENT software.

Experiments were conducted to measure the field temperature of the flowing water in the isothermal case for temperatures from 25°C to 39°C. The resultant images were used in creating the temperature calibration curve and in estimating the errors. Then, images were taken for the heating case with four flow rates. For each flow rate, images were taken for two surface temperatures.

This dissertation has seven chapters. The first chapter is the introduction, which includes the topic's significance and the research goals. The second chapter is the literature review. In this chapter, the PLIF technique is explained, and the previous research that used PLIF in measuring

the temperature field of liquid water is presented. In chapter three, the experimental setup is explained. The apparatus, the laser instrumentation, and the optical instrumentation are presented in this chapter. In addition, the test section is explained. In the fourth chapter, the preparation for the computational solution is presented, including the simulated domain, mesh, and solved equations. The fifth chapter is about measuring the temperature field of isothermal water flow. In this case, there is no temperature gradient within the duct, and the whole water volume is at the same temperature. In this chapter, the process of calibrating a thermometry system is described. In addition, the experimental conditions for enhancing the results' accuracy are presented, and the PLIF measurement error is discussed. The sixth chapter is about using PLIF to measure the temperature field of the flowing water through a duct with smooth and finned surfaces. The seventh chapter contains the dissertation summary and recommendations for future works.

Chapter 2 - Literature Review

2.1 Introduction

This chapter presents a literature review. The PLIF technique is presented and discussed, and then the dye selection determinants are also discussed. After that, the PLIF configurations are explained. For each configuration, some experiments that used it are presented. The error sources are discussed.

2.2 Planar laser induced fluorescence

Measuring the temperature field of heated flowing water is beneficial when investigating heat transfer performance. To accomplish this, nonintrusive measuring techniques are required, because the traditional single-point probes will interrupt the flow and cannot achieve the field's measurement without a massive number of probes [1]. Several nonintrusive measurement techniques can be used to measure the temperature field of flowing water, like planar laser-induced fluorescence (PLIF), thermographic liquid crystal (TLC), and tagging measurement techniques [2].

The PLIF technique measures the temperature field by using a solution of temperature-sensitive dyes and a base fluid. The solution is exposed to an exciting laser connected to sheet-forming optics that project a laser sheet within the flow [3]. A suitable camera measures the light intensity and, thus, the fluid temperature. Laser-induced fluorescence (LIF) is similar and in general can be used to measure the fluid temperature at a point, line, 2D plane (PLIF), and 3D volumes [3]. The method is used in measuring several scalar quantities, like temperature, concentration, and pH.

The PLIF technique depends on the fluorescence phenomenon, which happens when the dye's atoms absorb energy from the incident light. Because of that energy, the electrons will

move from the ground state to the excited state. The electrons will return to the ground state and release photons during that transition [4]. Because of the energy losses at the excited state, the released photons have a longer wavelength than the absorbed laser wavelength [5]. In temperature-sensitive dyes, the released light intensity is proportional to the dye temperature [6]. Equation (2.1) is for the fluorescence intensity (F) [7].

$$F = \beta Q I_0 \varepsilon b C \quad (2.1)$$

Equation 1 depends on six factors: collection efficiency (β), quantum efficiency (Q), incident exciting light intensity (I_0), molar absorption (ε), absorption path length (b), and dye concentration (C). Collection efficiency (β) (unitless) is the fraction of the collected light by the camera to the total available light. This factor is controlled by the optical setup. Quantum efficiency (Q) (unitless) is the ratio of the dye-emitted light to the dye-absorbed light. This factor is temperature dependent. Incident exciting light intensity (I_0) (power/area) (W/m^2) is the intensity of the emitted laser. Molar absorption (ε) (L/mol cm) is a measure of the dye molar absorptivity. Absorption path length (b) (cm) is the distance that is traveled by the laser in the solution. Dye concentration (C) (mole/liter) is the fraction of the number of moles of the dye to the water volume [7] [25].

To use the PLIF technique in temperature measurement, all factors in equation 2.1 need to be constant during the experiment except the quantum efficiency, which is a function of temperature in the temperature-sensitive dyes. The effect of uncontrolled variation—like incident exciting light intensity variation—needs to be eliminated or estimated.

2.3 Dye selection

Selecting the proper dye is a crucial issue, because it should be suitable for the fluid type, the measured quantity, and the experimental circumstances. Several factors affect the selection process of a suitable dye for measuring the temperature field of water by using PLIF. They are summarized in Table 2-1.

Table 2-1 Constraints of selecting the dye and its quantity

#	constraints of selecting the dye and its quantity
1	dye water solubility
2	the laser wavelength is within the fluorescent absorption band
3	overlapping size of the absorption and emission spectra
4	dye quantum efficiency
5	dye's tendency to photobleach
6	dye temperature sensitivity
7	dye concentration

To measure the temperature field of water by PLIF, the dye needs to be water-soluble or slightly water-soluble. In addition, the dye should be compatible with the available laser. This suitability happens when the laser emission wavelength is within the dye absorption band [3]. The overlapping size of the absorption and emission spectra is a significant determinant in dye selection because of the need for separation between the absorption and emission spectra [3]. Without that separation, the dye will reabsorb the emitted light, then emit it, and so on.

The dye selection also depends on the dye quantum efficiency. It is the ratio of the dye-emitted light to the dye-absorbed light [3]. Quantum efficiency is called quantum yield in some references [8]. Kubin and Fletcher [8] investigated the quantum efficiency of some dyes. The quantum efficiency of any dye depends on the dye specifications, the used fluid, and the temperature.

The fluorescent dye's tendency to photobleach is a factor that affects dye selection, because the photobleaching causes errors in the results. "Photobleaching occurs when a fluorophore permanently loses the ability to fluoresce due to photon-induced chemical damage and covalent modification" [9]. Making a temperature calibration at the beginning of each experiment can eliminate or decrease the effect of the photobleaching.

The dye temperature sensitivity should be matched to the experiment. Smart and Laidlaw [6] investigated the temperature sensitivity of some fluorescent dyes. Equation (2.2) [6] shows the relationship between fluorescence intensity and the temperature, where F is the fluorescence intensity at a certain temperature, F_0 is the fluorescence intensity at 0°C , t is the temperature, and n is the dye exponent. The inverse relationship between the temperature and the fluorescent intensity is a result of the dye quantum yield decreasing when the temperature increases [5]. The exponent of several dyes is presented in Table 2-2 [6].

$$F = F_0 e^{n t} \quad (2.2)$$

Low solution concentration is preferred to get a linear relationship between the fluorescence and incident exciting light intensity. At high concentrations, more molecules collide, and the absorbed energy is dissipated in several ways, in addition to emitting the fluorescence light [11]. Then, getting a clear proportionality between the fluorescence intensity and the temperature is difficult.

Table 2-2 Exponent of several dyes

Dye	Temperature Exponent ($^{\circ}\text{C}^{-1}$)
Amino G acid	-0.0019
Photine CU	-0.012
Fluorescein	-0.0036
Lissamine FF	-0.0020
Pyranine	-0.0019
Rhodamine B	-0.027
Rhodamine WT	-0.027
Sulpho Rhodamine B	-0.029

2.4 PLIF configurations for measuring temperature field

PLIF is used for measuring the temperature field of a 2D plane with four configurations. It is used with one dye/one color, one dye/two colors, one dye/three colors, or two dyes/two colors. These cases are presented in figure 2-1. Each case is explained in this section.

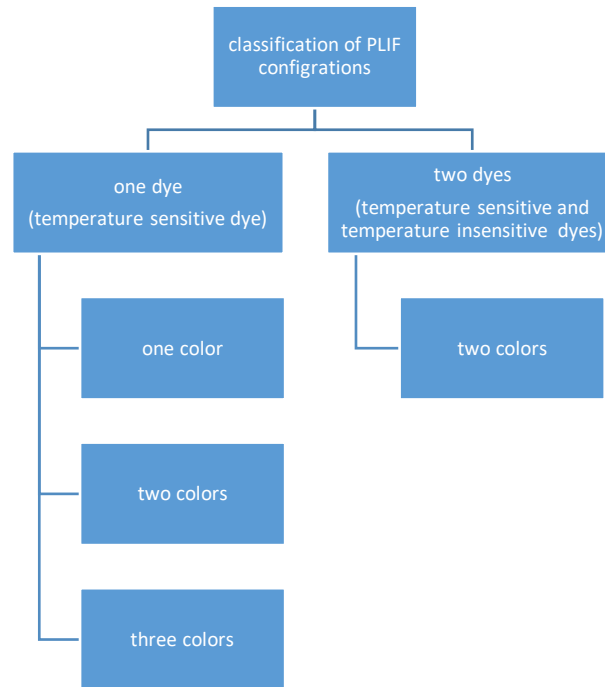


Figure 2-1 Classification of PLIF configurations

2.4.1 One dye/one color

In this case, there is a direct relationship between the fluorescence intensity and the temperature. The dye should be sensitive to temperature. Figure 2-2 shows the absorption and emission spectra of Rhodamine B. A certain band in the emission spectrum is selected. The light intensity at that band is measured for different temperatures. This method needs one camera. For this case, pulse-to-pulse energy variation, concentration variation, and nonuniformity energy within the laser sheet are the keys to accuracy.

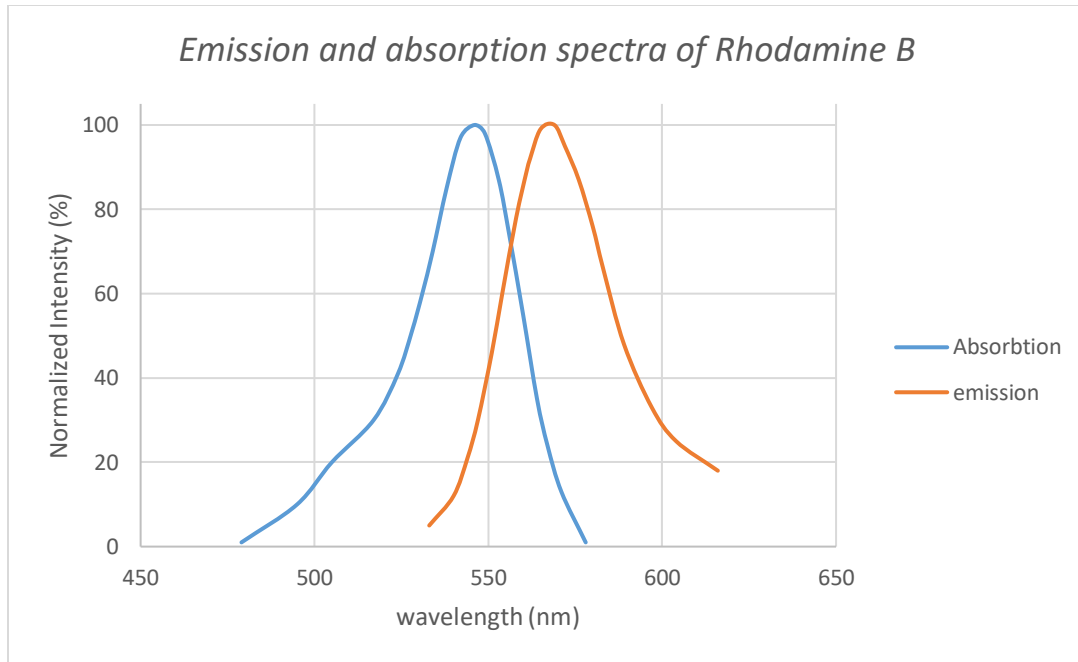


Figure 2-2 Emission and absorption spectra of Rhodamine B

Coolen et al. [5] used PLIF with a one dye/one color configuration to measure the temperature field of the water, and the fluorescent dye was Rhodamine B. The temperature calibration curve used water from 20°C to 60°C. The uncertainty was reported as $\pm 1.7^\circ\text{C}$. The technique was used to measure the temperature field of water in a closed cavity exposed to natural convection from surrounding heat exchangers.

In this experiment, for two reasons, they used an Nd:YAG laser instead of a CW Ar⁺, which was preferred because of its continuous light (constant intensity). The first reason was the higher power output of Nd:YAG compared to CW Ar⁺. That higher power allowed them to investigate a larger flow field. The second reason was that the wavelength of the Nd: YAG (532 nm) is closer to the absorption spectrum peak of Rhodamine B than the wavelength of the CW Ar⁺ (514 nm). They mentioned that using demineralized water is important, because the “non-fluorescent tracers can act as quenchers.” From the literature, they found that the expected laser

pulse-to-pulse variation is about 3%. To minimize it, they average 30 images to make the error due to pulse-to-pulse variation 0.55%. For the problem of pixel-to-pixel variation, they averaged every six adjacent pixels.

They stated that the temperature results' errors are from photobleaching, laser pulse to pulse variation, pH, reabsorption, and shadowgraph. Photobleaching affected the results when the solution was subject to a long excitation time (more than 40 s). The pH does not affect the accuracy of the results if it is between 5 and 12. The shadowgraph affected the accuracy of the results for the temperature gradient areas because the intensity in these areas is affected by density variation, which causes a variation in the refractive index.

Bogild et al. [18] used PLIF to validate a correlation of the heat transfer coefficient of laminar flowing through mini channels. PLIF was applied with a configuration of one dye/one color, where Rhodamine B was the fluorescent dye and an argon ion laser (532 nm) was the excitation source. The hydraulic diameter of the channel was 889 μm . To reduce pixel-to-pixel noise, they averaged every five surrounding pixels for the area close to the wall and every eight surrounding pixels for the rest. They ignored the areas that have poor quality results, so they just examined 11.5% of the image. In addition, they assumed the channel was symmetric. Thus, they investigated half of the channel. To account for the impact of the photobleaching in the results, they made a temperature calibration curve at the beginning of the experiment and another at the end, and then they took the average of these results to make a corrected linear temperature calibration curve with respect to photobleaching. For the shadowgraph effect, they stated it could affect the results significantly when the temperature gradient in a certain area within the laser sheet is more than $1^\circ\text{C}/\text{mm}$.

Sharaborin et al. [13] investigated the flow dynamics and the temperature field of water jet-swirled flow, which impinged on a flat heated surface. The investigation was conducted by particle image velocimetry (PIV) and PLIF techniques. For PLIF, they used a one dye/one color configuration, and the fluorescent dye was Rhodamine B. A 560 nm long-pass filter was installed. The temperature calibration curve was conducted for the temperatures between 24°C and 30°C.

The PLIF instantaneous results were filtered to overcome the bright and dark stripes shown in the resultant pictures because of the light refraction due to the nonuniform temperature gradient close to the surface. Then, they found the time average temperature field. Close to the surface, the difference between water temperature and surface temperature measured by IR is 1°C. Because of this small temperature gradient, the shadowgraph did not affect the results.

Grafsrønningen and Jensen [23] studied the transitional buoyant plume above a horizontal cylinder in water using PIV and PLIF to measure velocity and temperature fields simultaneously. Two monochrome cameras were used in the experiments; one is for PIV, and the other for PLIF. For PLIF, they used Rhodamine B as a fluorescent dye and a temperature calibration curve from the literature. The selected calibration curve matches the normalized fluorescence intensity with the temperature. The researchers examined the calibration curve with a well-known temperature case and found good correspondence. Reflection from tracer particles causes improper results in some pixels. In that case, they discarded the results of these pixels and got new data for them from the surrounding pixels. The resulting images have been processed to remove streaks and to solve the variation of pulse-to-pulse intensity. For PLIF, the pixel size is large (0.12 mm*0.12 mm), which might be suitable for an experiment that does not contain significant changes within a tiny area.

2.4.2 One dye/two colors

Another way of eliminating the impact of laser power variation and solution concentration variation is by applying a one dye/two colors configuration. In this method, a ratio of the intensity of two bands in the emission spectrum is calculated to estimate the temperature. As in equation 2.3, the ratio is just a function of the quantum efficiency of each band. Figure 2-3 shows the absorption and emission spectra of Rhodamine B, and an example of two bands might be selected to conduct this method.

$$\text{fluorescence ratio of two bands} = \frac{\beta Q_1 I_0 \varepsilon b C}{\beta Q_2 I_0 \varepsilon b C} = \frac{Q_1}{Q_2} \quad (2.3)$$

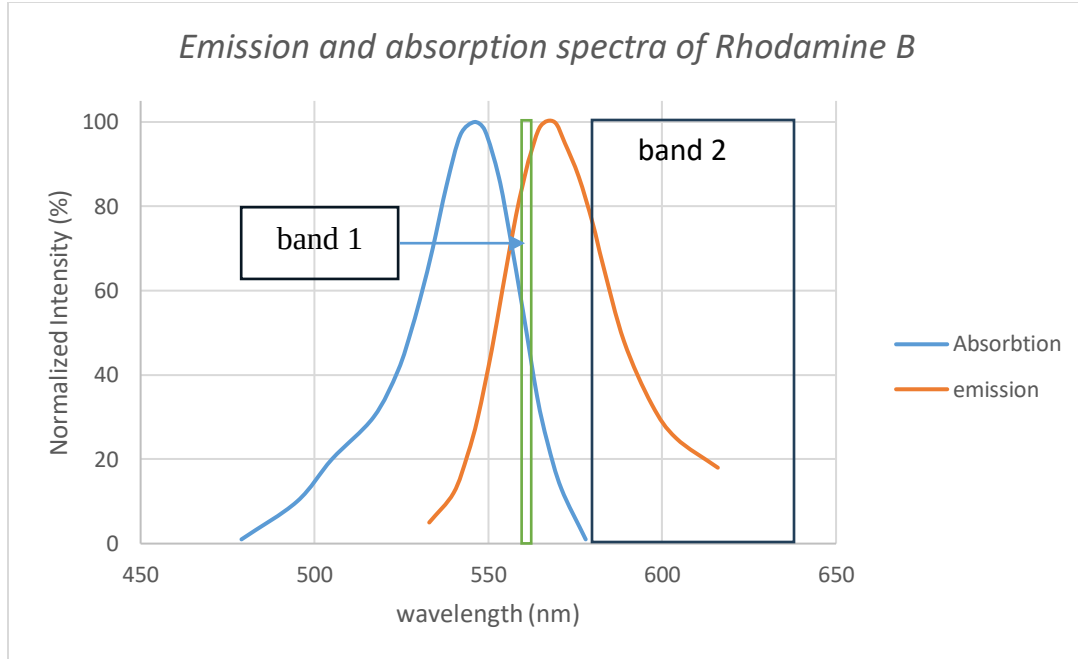


Figure 2-3 Emission and absorption spectra of Rhodamine B with two selected bands in the emission spectrum

Xu and Cai [11] applied a one dye/two colors configuration to measure water temperature by PLIF. The water temperature was controlled by a water bath. In the experiments, Rhodamine B was used as the fluorescent dye with a concentration of 10^{-5} M, while a 532 nm semiconductor laser was used as the excitation source. The water temperature was in the range of 293 K to 363 K. A second-degree temperature calibration curve was made in this research. The results uncertainty was 1 K. They mentioned that applying a one dye/two colors configuration requires the selection of two bands in the emission spectrum when the first band has a high temperature dependency and the second band has a relatively low temperature dependency. Then, the ratio of the fluorescence is found at two different spectral bands.

To clarify the difference in the temperature dependency in different bands, they found the emission spectra of Rhodamine B for several temperatures. In a certain band, the spectra curves are almost identical. Then, they assumed this band has a low temperature dependency. At

another band in the emission spectra, they found a difference between the spectra curves of the different temperatures; then, they assumed this band has a high temperature dependency.

Bruchhausen et al. [14] used the configuration of one dye/two colors of the PLIF technique by finding a ratio of the intensity of two different spectral bands. Rhodamine B used a fluorescent dye with a concentration of 10^{-6} mol/L. An Nd:YAG laser (532 nm) was the excitation source. The experiment was conducted to find the temperature field of a heated water turbulent jet (50°C), which was injected into cold flowing water (20°C). To apply the one dye/two colors configuration, they selected two bands in the emission spectrum of Rhodamine B and allocated a camera to each band by installing a suitable optical filter in each camera. For the shadowgraph effect, they said:

“The one-color technique requires the determination of the distribution of the laser intensity by a reference measurement prior to the actual temperature measurement, which makes it sensitive to shadowgraph effects. The two-color technique, in contrast, is independent of the local distribution of the laser intensity.” It might be because this configuration eliminates the effect of molar absorptivity.

2.4.3 One dye/three colors

This configuration was also made to eliminate the effects of pulse-to-pulse variation, concentration variation, and volume size. Three bands should be selected in the fluorescence spectrum of the temperature-sensitive dye. The first band has low sensitivity to temperature but is sensitive to absorption. The second band is sensitive to temperature and absorption. The third band is sensitive to temperature but has a low sensitivity to absorption. To determine the temperature, find the fluorescence ratio of band 1 to band 3 and of band 2 to band 3. Three

cameras are required in this case [16]. Figure 2-4 presents emission and absorption spectra of Rhodamine B with two selected bands in the emission spectrum. Lavieille et al. [16] used the configuration to measure the temperature field of a heated liquid jet. They mentioned that the reabsorption problem can be corrected.

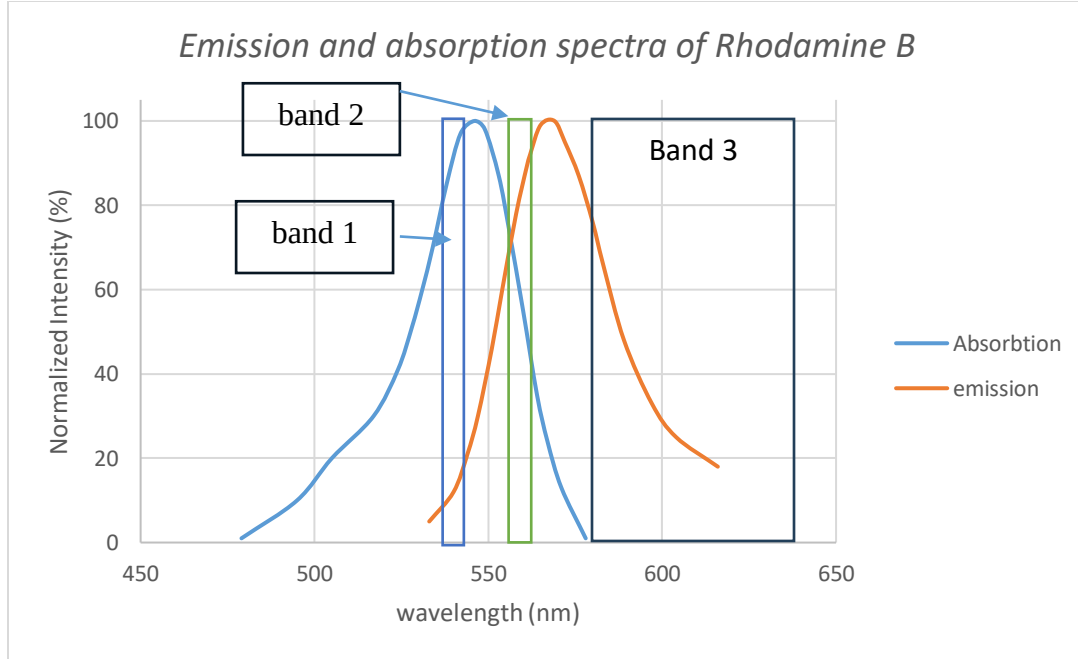


Figure 2-4 Emission and absorption spectra of Rhodamine B with three selected bands in the emission spectrum

2.4.4 Two dyes/two colors

This configuration is used to overcome the problem of pulse-to-pulse variation. In this case, two dyes are used in the experiment; one is temperature-sensitive, and the other is non-temperature-sensitive. The ratio of the fluorescence intensity of the two dyes will eliminate the impact of incident pulse intensity and the path length on finding the fluorescence intensity. To clarify that idea, recall equation 2.1.

$$F = \beta Q I_0 \varepsilon b C \quad (2.1)$$

Equation 2.4 is the ratio of the fluorescence intensity of two dyes.

$$\frac{F_1}{F_2} = \frac{\beta_1 Q_1 I_0 \varepsilon_1 b C_1}{\beta_2 Q_2 I_0 \varepsilon_2 b C_2} \quad (2.4)$$

This method depends on the assumption that β , ε , and C of both dyes are constant.

For selecting the combination of two dyes, they should satisfy three conditions:

- 1- One is temperature-sensitive, and the other is non-temperature-sensitive.
- 2- The laser wavelength is within the absorption spectrum of both dyes.
- 3- The overlap in the emission spectra of the two dyes needs to be reduced to minimize capturing signals of one dye in the camera of the other dye.

Two cameras are required in this case: one for each absorption band. The cameras' setup should contain optical filters to control what each camera sees.

This method has some challenges:

- 1- The two cameras have optical filters to control what each camera sees, because one camera is to capture the signals of the temperature-sensitive dye, while the other camera is to capture the signals of temperature-insensitive dye. Practically, some signal from the temperature-sensitive dye might be shown in the images of the temperature-insensitive dye and vice versa.
- 2- The concentration of the two dyes should be constant.
- 3- The dye assumed as temperature-insensitive might be affected by temperature changes.

Robinson et al. [7] used PLIF with a two dyes/two colors configuration to measure the temperature field of water. Temperature-sensitive Rhodamine 560 and temperature-insensitive Sulforhodamine 640 were used in the experiment. They selected this combination to reduce the overlap of the emission spectra of the two dyes, which reduces the capturing signals of a dye in the other camera. A cuvette heater heated the water from 20°C to 40°C with a 2°C increasing

step to get pictures of the water at a uniform temperature. To get the temperature calibration curve, they found the ratio of each dye signal for each temperature then normalized the result by dividing it by the ratio of the two dyes' signals at 20°C. The uncertainty was $\pm 1.4^\circ\text{C}$. In addition, the experiment was conducted to capture pictures of mixing hot water with relatively colder water.

Heronemus and Eckels [22] applied PLIF with a configuration of two dyes/two colors to measure the temperature field of tank-contained water, which was moving due to a temperature gradient. They selected Rhodamine B as a temperature-sensitive dye and Rhodamine 110 as a non-temperature-sensitive dye. Nd:YAG laser (532 nm) was the excitation source. They got raw images with vertical banding and masked the banding by averaging each eight adjusted pixels. To overcome the problem of any optical features or spots in the results, they normalized the results by dividing them by a reference temperature result. Then, they created the linear temperature calibration curve with an R square of 0.985. The standard deviation of the results was calculated to estimate the error. The results' error depends on the picture resolution. It was $\pm 2.4^\circ\text{C}$ when the resolution was $10 \times 10 \mu\text{m}$, while it was 1.3°C when the resolution was $104 \times 102 \mu\text{m}$.

Sakakibara and Adrian [20] measured the temperature field of Rayleigh-Benard convection using the PLIF technique with a configuration of two dyes/two colors. They used Rhodamine B as a temperature-sensitive dye and Rhodamine 110 as a non-temperature-sensitive dye. An argon-ion laser (488 nm) was used as the excitation source. They selected the laser wavelength as 488 nm instead of 514.5 nm to keep the laser wavelength out of the emission spectra of both dyes. The experiment was applied to the Rayleigh-Benard cell, which is an enclosed water container with adiabatic sidewalls, a hot base, and a cold top wall [2]. They stated that the naked

eye could not recognize the intensity variation of the temperature gradient case images for the raw images of the temperature-sensitive dye. They obtained accurate mean results of the temperature distribution in the Rayleigh-Benard convection even close to the walls with steep temperature deviation slopes. The instantaneous results showed the structures of the buoyant plumes.

Rochlitz and Scholz [24] applied PLIF for duct flow with one heated wall. They investigated near-wall results. They could measure the thermal boundary layer by using the combination of Rhodamine B as a temperature-sensitive dye and Rhodamine 110 as a non-temperature-sensitive dye. An Nd:YAG 532 nm laser was the excitation source in this experiment.

2.5 Summary

This chapter presented a literature review of using PLIF in measuring the temperature field of water. The technique idea and the dye selection constraints were presented. The experimental investigation research conducted to measure the temperature field of water was presented with respect to the selected PLIF configuration in each presented study.

Chapter 3 - The Experimental Setup

3.1 Introduction

This chapter describes the experimental facility and clarifies how the PLIF experiment was performed. At the beginning, the test section is explained in detail. Then, the water system that circulates the water through the test section is described. The instrumentation in the PLIF system is presented next. Finally, the uncertainty and experimental procedures are discussed.

3.2 Test section

Conducting the experiment requires the design and construction of a test section. In the current experimental investigation, the test section has a duct where water flows. The bottom heated surface of the duct needs to be changeable to use this test section for testing different designs of finned surfaces. To apply the PLIF technique, two visualization slots should be added to the duct: one for the laser and one for the camera. These two slots are covered with glass and sealed by a gasket. An electrical heater placed underneath the changeable surface provides heat. Holes for thermocouples in the lower surface are necessary for estimating the temperature of the changeable surface. The test section needed to connect to the apparatus in a flexible way and must also seal to prevent water leakage. The design and debugging of the test section was a significant part of my dissertation research.

The test section has nine parts, and each one of them is explained in detail below. Starting from the bottom, the first part is the heater cover, which is presented in Figure 3-1. It is made of 6061 aluminum alloy and has a length of 16 inches. It has a groove with a radius of 0.25 inches for inserting the electrical heaters. Two electrical heaters are installed in the groove of the heater cover. Each of the heaters has a length of 8 inches and a radius of 0.25 inches. The assembly of

the heater cover and the electrical heaters is presented in Figure 3-2. Above them, an aluminum block is installed. The heat is transferred from the electrical heater to the changeable surface through this aluminum block, which is made with 6061 aluminum alloy. There are two thermocouple holes to investigate the heat transfer through the block. The changeable surface is made with 2024 aluminum alloy. Two holes for thermocouples in this part allow estimation of surface temperature and heat flux. The test section has this changeable surface to examine different designs of fins. Figure 3-3 shows the assembly of the heater cover, heaters, and aluminum block. Figure 3-4 shows the assembly of the heater cover, heaters, aluminum block, and changeable surface. Figure 3-5 shows the section view of the assembly of the heater cover, heaters, aluminum block, and changeable surface.

A one-inch square cross-sectional duct with a length of 24 inches is installed on top of the assembly described above. The duct is made with 6061 aluminum alloy. There is a slot in the bottom of the duct into which to insert the changeable surface. The section view of the assembly is presented in Figure 3-6. Red RTV silicon is applied to seal the contacting surface of the aluminum block and square duct. Aluminum sticks clamp these parts together: four on the top and four on the bottom. Each top stick is connected to the bottom one with screws and nuts.

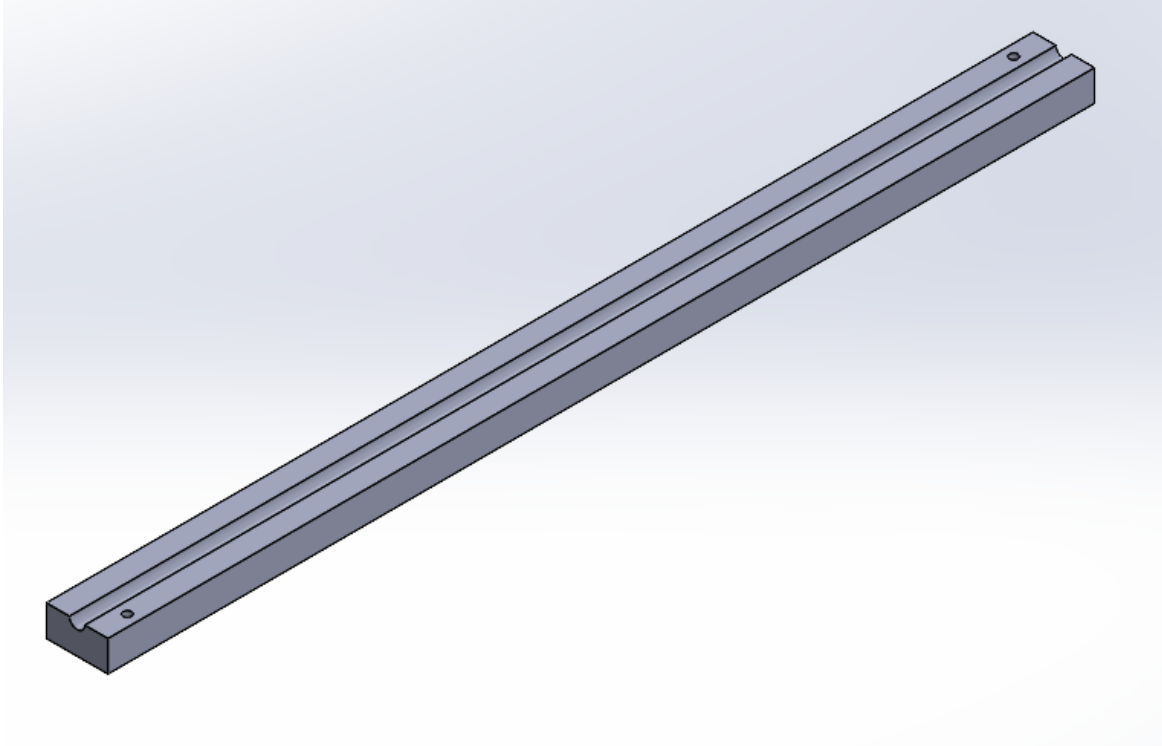


Figure 3-1 Heater cover

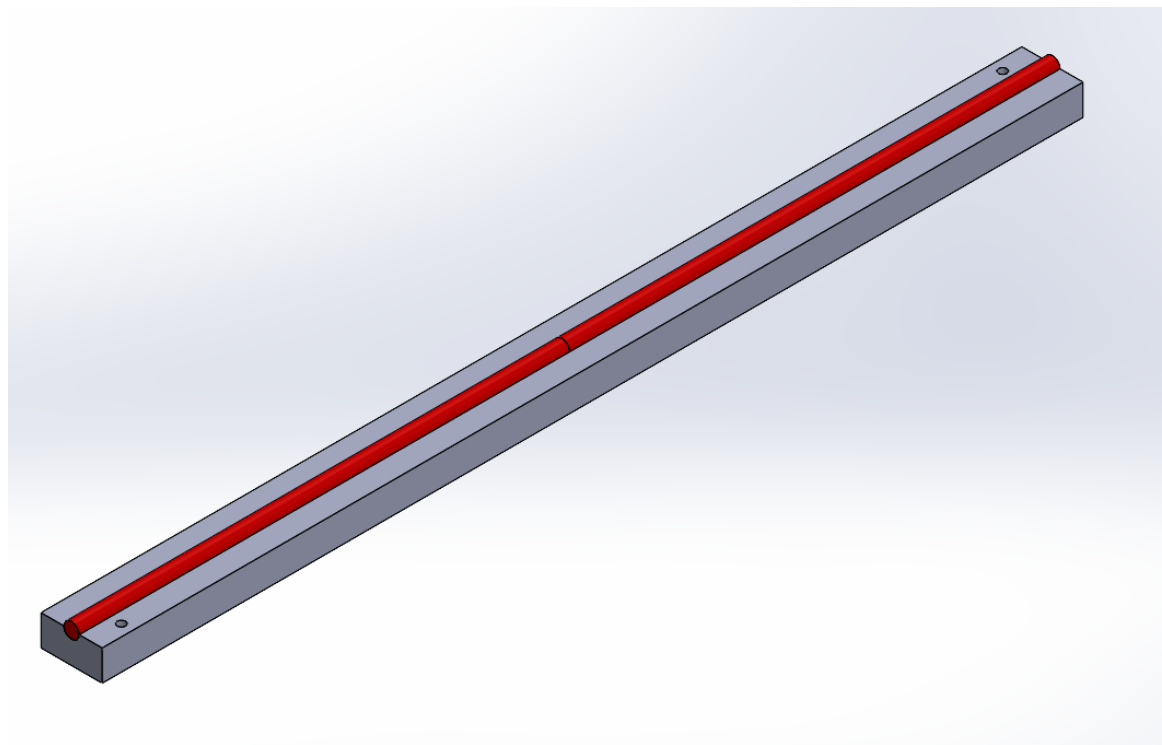


Figure 3-2 Assembly of the heater cover and electrical heaters

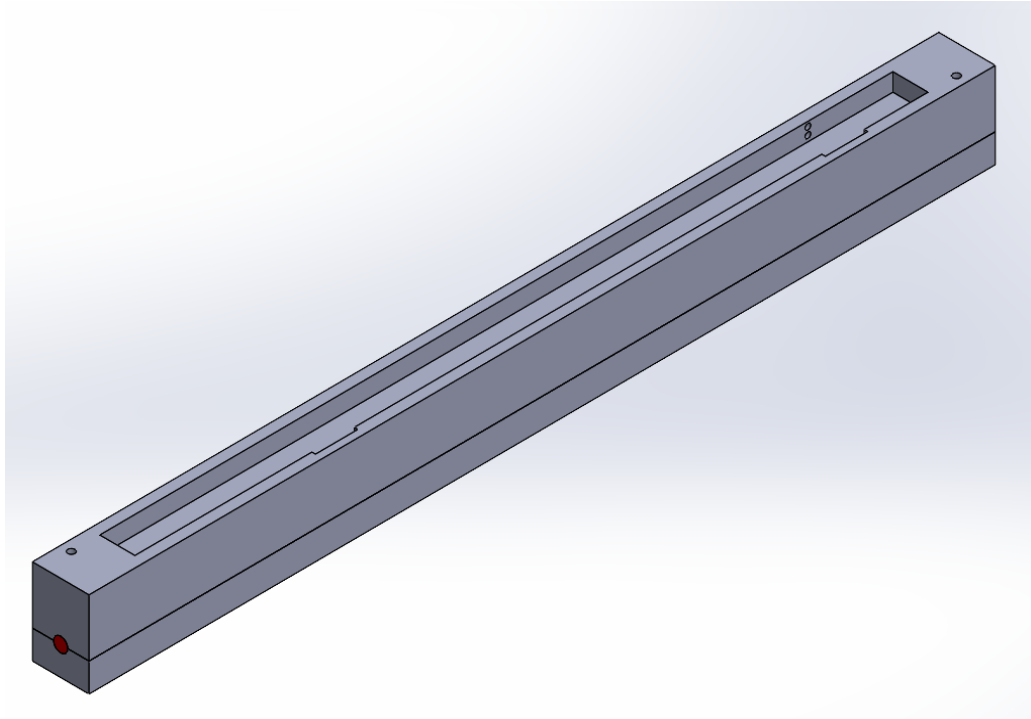


Figure 3-3 Assembly of the heater cover, heaters, and aluminum block

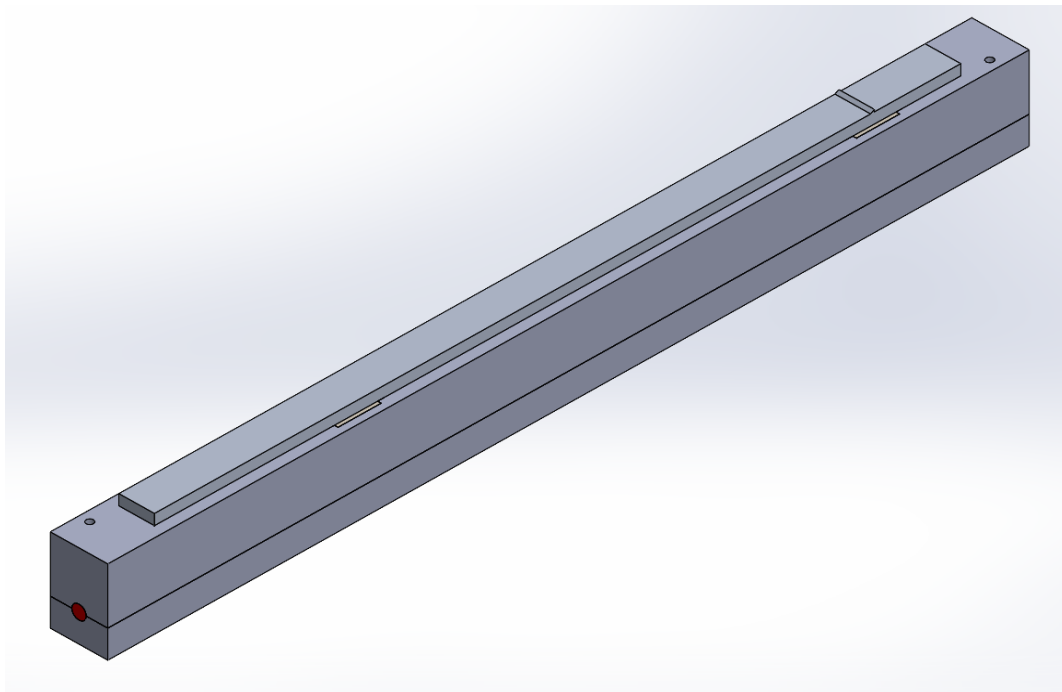


Figure 3-4 Assembly of the heater cover, heaters, aluminum block, and changeable surface

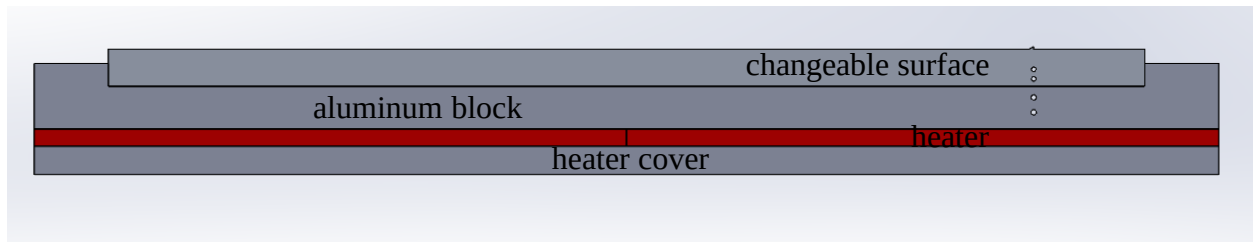


Figure 3-5 Section view of the assembly of the heater cover, heaters, aluminum block, and changeable surface

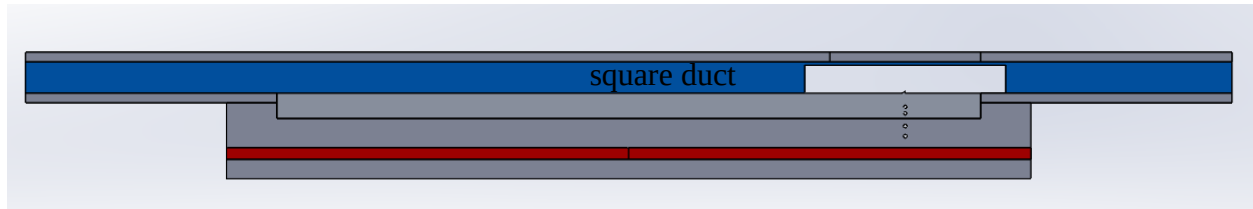


Figure 3-6 Section view of the assembly of the heater cover, heaters, aluminum block, changeable surface, and square duct

Three visualization slots are made on the upper square duct. A slot was created on the front side of the square duct to allow the camera to capture a view of the flowing water. On the top side, a slot was made to enable the laser light to enter. On the back side, a slot was made to avoid the influence of the duct's back surface topography. These three slots are covered with glass. A gasket seals the contact surfaces between the glass and the duct. The glass is clamped by aluminum bars, which are connected with screws and nuts.

The test section is connected to the water system through two aluminum flanges that are welded to both ends of the square duct. Each aluminum flange is connected to a plastic flange and sealed by a gasket. Each plastic flange is connected to the water system by a plastic hose. Figure 3-7 shows the assembly of the test section, while Figure 3-8 presents the section view of the test section. The orange rectangle is the interrogation region in the experiment; its height is 9.52 mm, while its width is 15.8 mm. Figure 3-9 shows the arrangement of the test section, the laser head, and the camera.

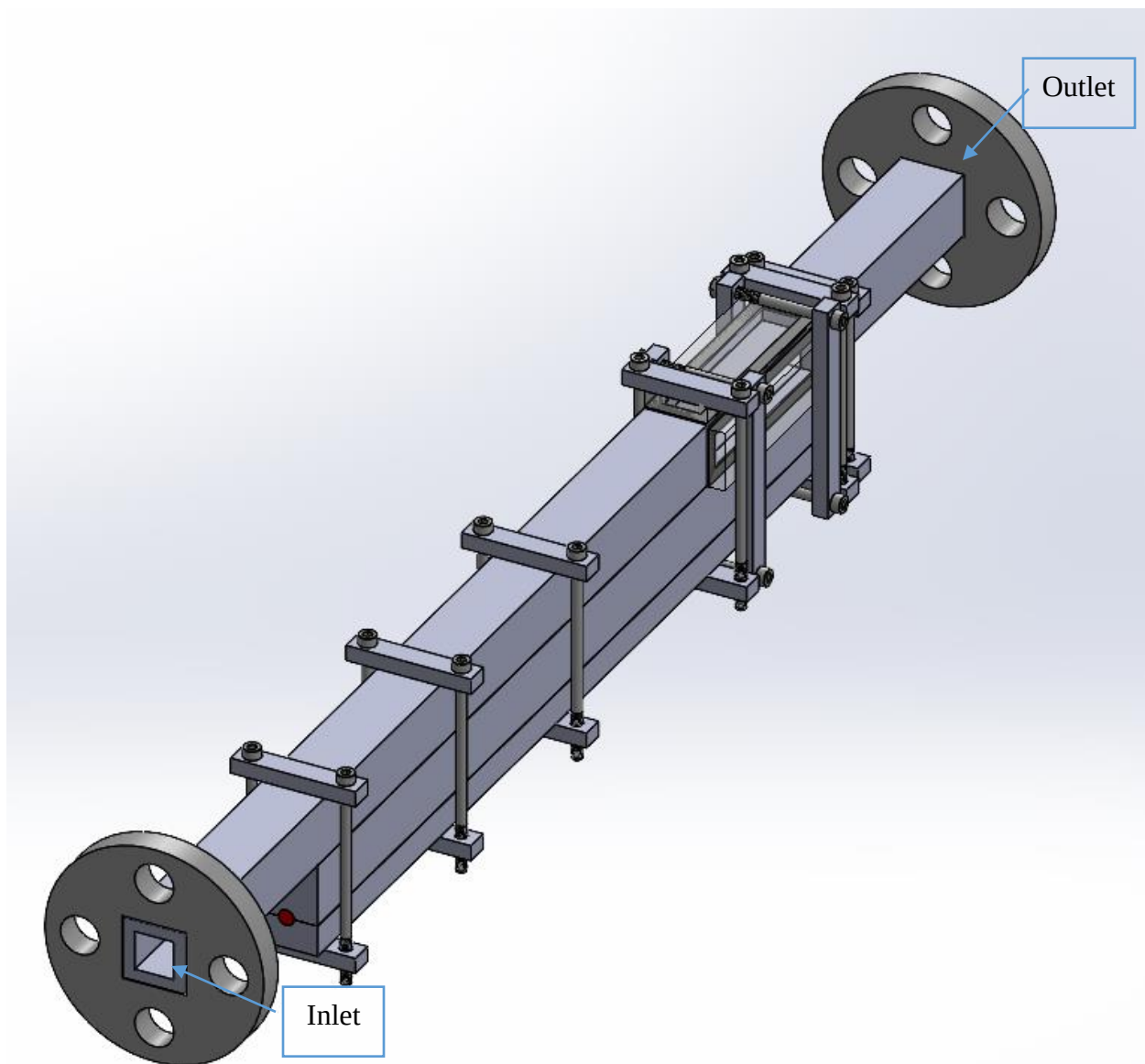


Figure 3-7 Assembly of the test section

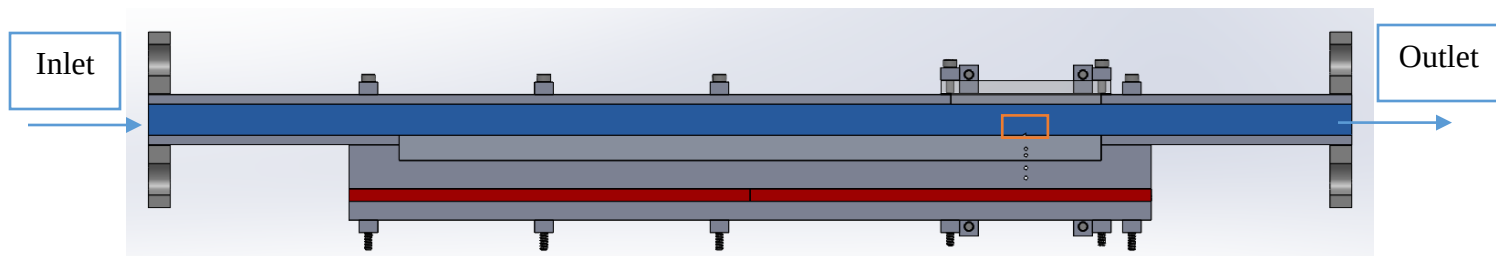


Figure 3-8 Section view of the test section

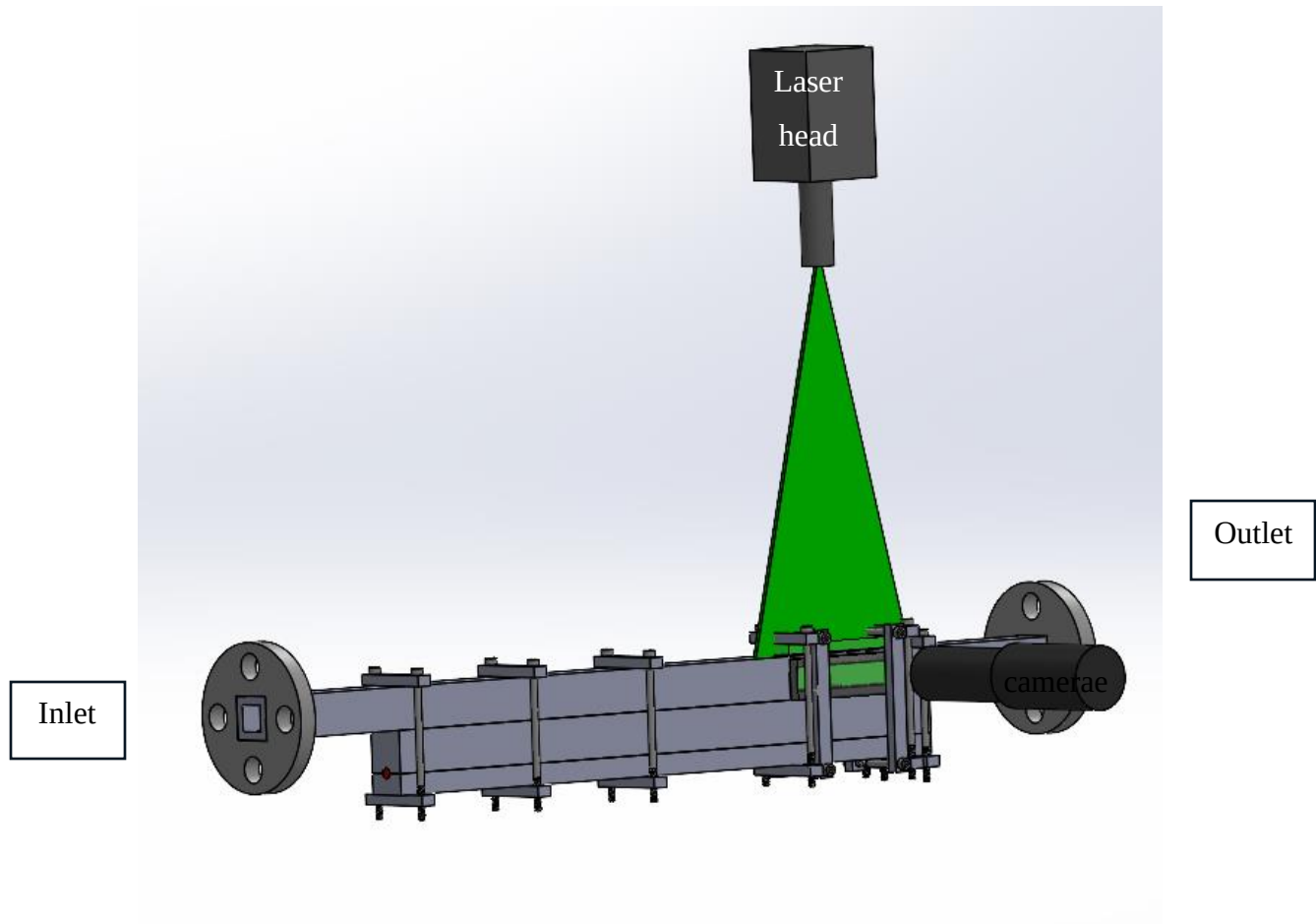


Figure 3-9 Arrangement of the test section, the laser head, and the camera.

3.3 Surface temperature estimation

Below the investigation area in the test section, there are four thermocouples. Two of these thermocouples are installed in the lower aluminum block, which transfers the heat from the heater to the changeable aluminum surface. These two thermocouples measure the heat transfer through the aluminum block. The changeable upper aluminum surface is flat or finned. Two more thermocouples are installed in the changeable aluminum surface. These two thermocouples document the heat transfer through the changeable aluminum surface and estimate the surface temperature. In Figure 3-10, the two blue points are the measured temperature by the two thermocouples in the aluminum block. The two orange points in Figure 3-10 are the measured

temperatures by the two thermocouples in the aluminum parts. Surface temperature is estimated by extrapolation of the two orange points. Figure 3-11 presents the thermocouple spots.

In the case shown in Figure 3-10, the results of the two thermocouples at the changeable aluminum part were 43.9°C and 41.9°C. The distances of these two points are 0.66 inch and 0.79 inch, where the heater's edge is the zero point.

Physically, the temperature varies in three dimensions (x,y,z). Still, it might be assumed as it changes in one dimension and ignore the minor variety in the other dimensions. Then, the surface temperature is estimated by using an equation in the form of:

$$T(x,y,z) \approx T(x) = mx + b \quad (3.1)$$

Where:

$$m \equiv \text{slop} = \frac{dT}{dx} = \frac{T_1 - T_2}{x_1 - x_2}$$

$$b \equiv y \text{ intercept}$$

Equation 3.2 is applied to find the one-dimensional heat flux through the surface.

$$q_x'' = -k \frac{dT}{dx} \quad (3.2)$$

Where k is the thermal conductivity.

Equation 3.3 were used to calculate the Biot number (Bi) [32] for the heat transfer in the aluminum block which transfers the heat from the electrical heater to the changeable surface.

The heat is also transferred by natural convection to the ambient air with assumed heat transfer coefficient (h) of $5 \frac{W}{m^2K}$. The thermal conductivity (k) of the 6061 aluminum is $155 \frac{W}{mK}$ at 27°C [33]. The width of the aluminum block (L) is 1 inch = 0.0254 m. Then the Biot number in this case is 0.00082.

$$Bi = \frac{hL}{k} \quad (3.3)$$

The heat transfer in the changeable surface is assumed as one-dimensional heat transfer because of four things. First, there is no heat generation in it. Second, the properties are assumed to be constant. Third, the temperatures are respected as the steady state case. Fourth, the Biot number is $\ll 1$.

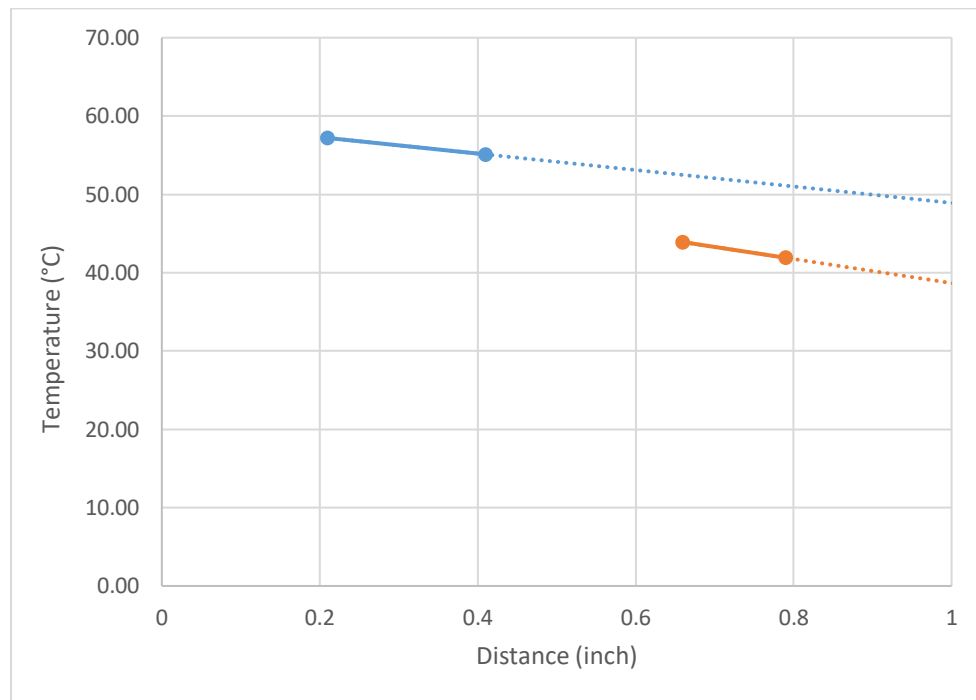


Figure 3-10 Results of the four thermocouples

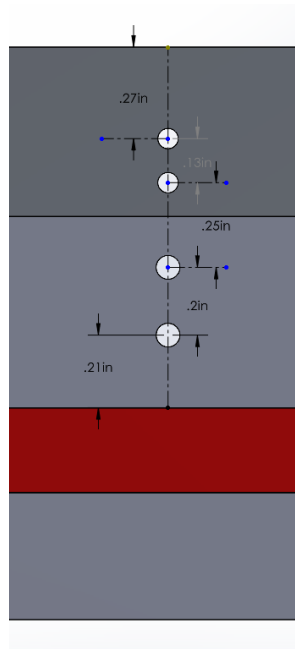


Figure 3-11 Thermocouples spots in the test section

3.4 The water system

The water system circulates the water through the test section, controls the flow rate, measures the flow rate, measures the water temperatures at the inlet and outlet of the test section, can release the added heat, and can evacuate the water from the system. The water system layout is in Figure 3-12. A $\frac{1}{3}$ hp centrifugal pump circulates the water through the test section. Gate valve 1 and gate valve 2 control the flow rate. A Micro Motion CFM050 flowmeter measures the flow rate. Type K thermocouples were used to measure the water temperature at the inlet and the outlet of the test section. The inlet water temperature is measured at about three feet away from the test section inlet, while the outlet water temperature is measured at about four feet away. A heat exchanger was installed to cool the water, which was heated by the heater of the test section. To control the cooling process, gate valve 3 was installed to control the heated water flow rate through the heat exchanger.

LabView was used to collect, record, and present the results of the measured quantities in the water system. Figure 3-13 presents the front panel of the LabView file. For the current experimental investigation, eight measured and predicted quantities were collected, recorded, and presented by LabView. The water temperature at the inlet and the outlet of the test section are shown in LabView, along with the mass flow rate and Reynolds number. In addition, LabView showed the results of four thermocouples used for measuring the aluminum block temperatures.

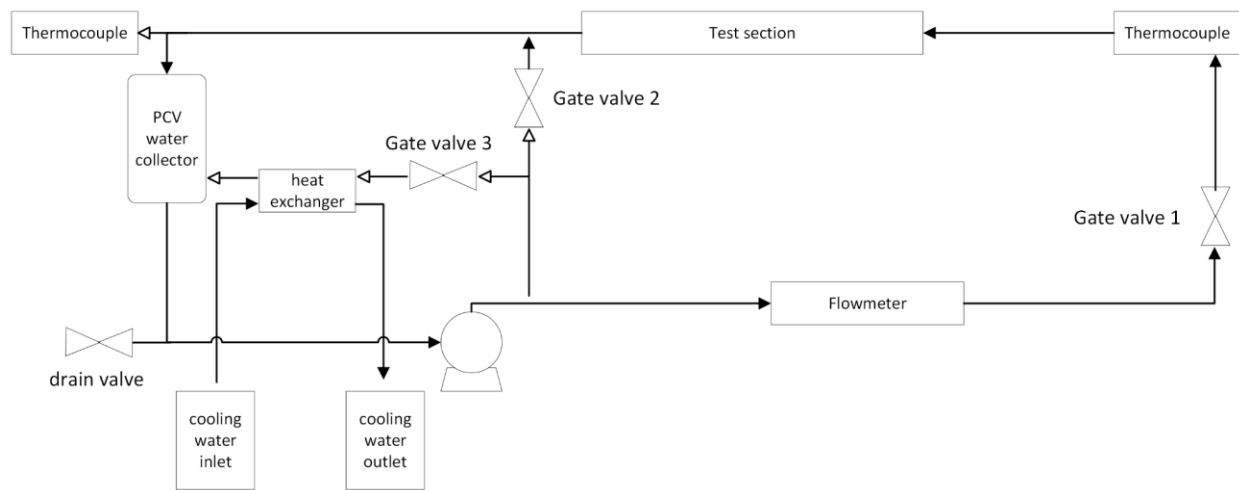


Figure 3-12 Water system layout

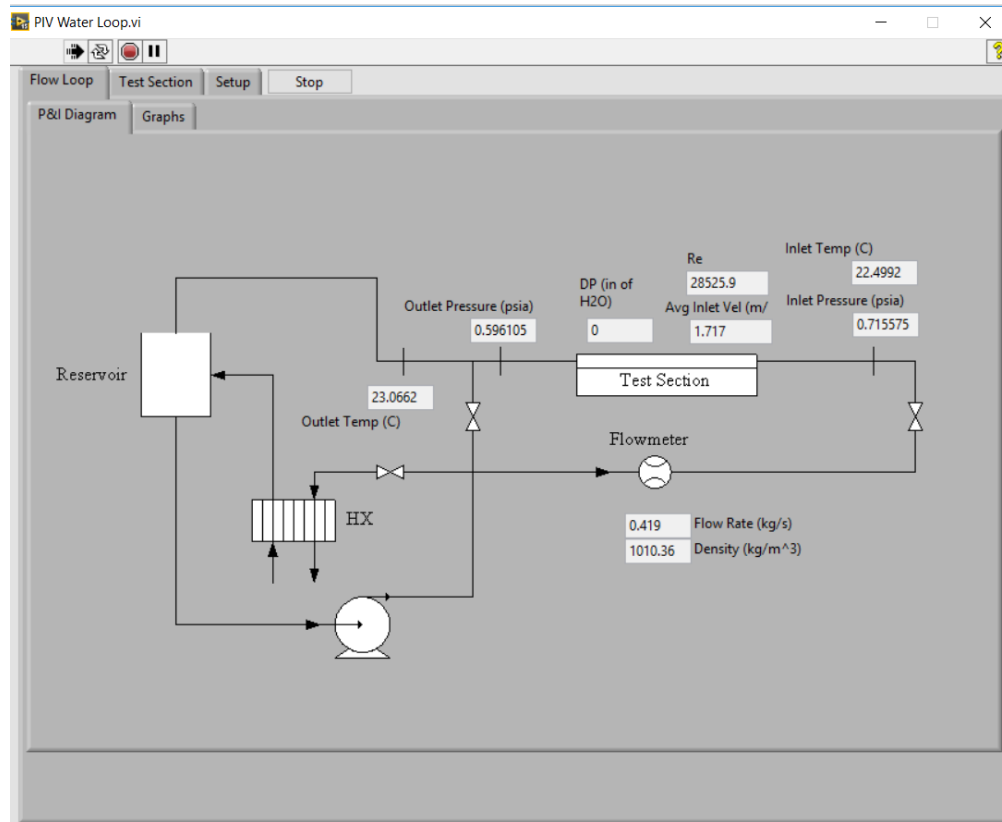


Figure 3-13 Front panel of the LabView file

3.5 Planer laser induced fluorescence

The PLIF technique used in the study was configured with one dye/one color. Rhodamine B was chosen as the fluorescent dye. Rhodamine B is a temperature-sensitive, water-soluble, organic polymer with a formula of $C_{28}H_{31}ClN_2O_3$ and a molar mass of 479. The solution of distilled water and Rhodamine B was made with a concentration of 0.5 mg/L. The pH of the solution is 7.1, so the solution is neutral. The illumination source in the experiment is an Nd:YAG laser with a wavelength of 532 nm. Figure 3-14 presents the emission and absorption spectra of Rhodamine B. In the figure, the blue curve is the absorption spectrum of Rhodamine

B, while the orange curve is the emission spectrum of Rhodamine B. The green line represents the laser pulse. The blue rectangle in the figure is the data collected by the camera when the 580 nm long-pass optical filter is installed. The figure shows that the emission and absorption spectra are overlapped between the wavelengths 530 to 580 nm. Then, the emitted light will be reabsorbed in this area. To avoid the reabsorption effect, a 580 nm long-pass optical filter is installed on the camera.

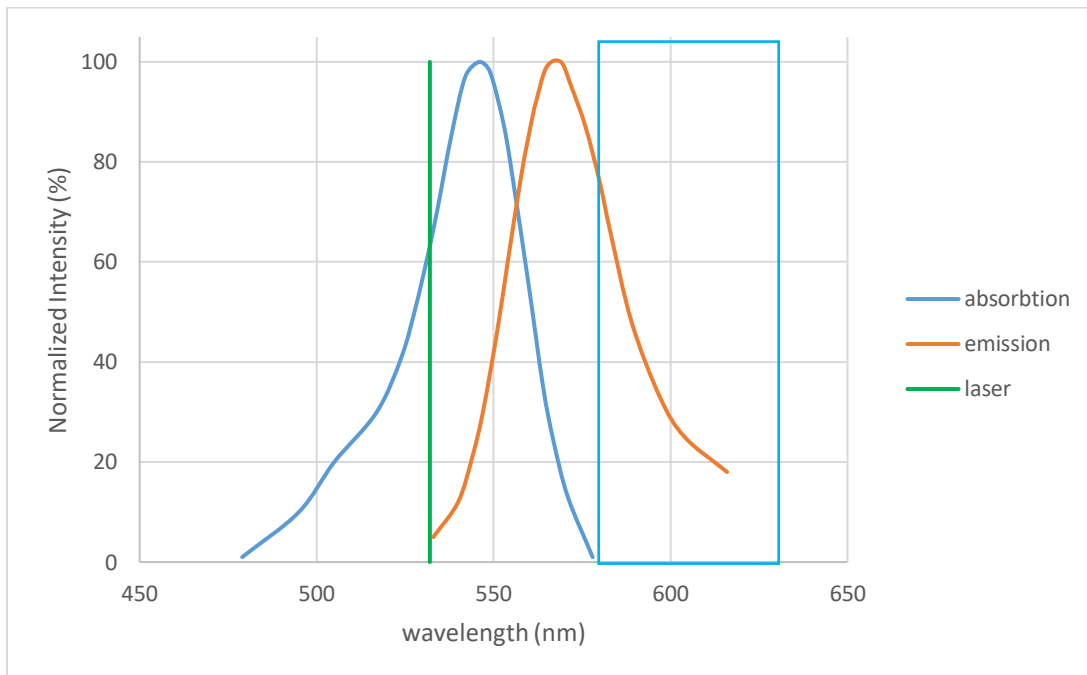


Figure 3-14 Emission and absorption spectra of Rhodamine B

To perform the experiment, an optical system was selected and installed. The optical system is presented in Figure 3-15. A TSI camera (model 630092) was used to investigate the flow. The camera sensor type is CCD (charge-coupled device) with a resolution of 3320 pixels x 2496 pixels. The images were taken with a pixel size of 4.76 μm , and they were gray with a grayscale range of 1 to 4095. In addition, a 580 nm long-pass optical filter was installed. The captured pictures were presented and processed by 4G Insight software. The timing system of the

experiment is shown in Figure 3-16. It shows that the camera captures five images per second. An optical calibration was performed to decide the acceptable distance between the camera and the test section, and the suitable camera zoom to clarify an object was immersed inside the test section. In addition, the focal depth was set by an optical calibration. The optical calibration is explained in detail in the next section.

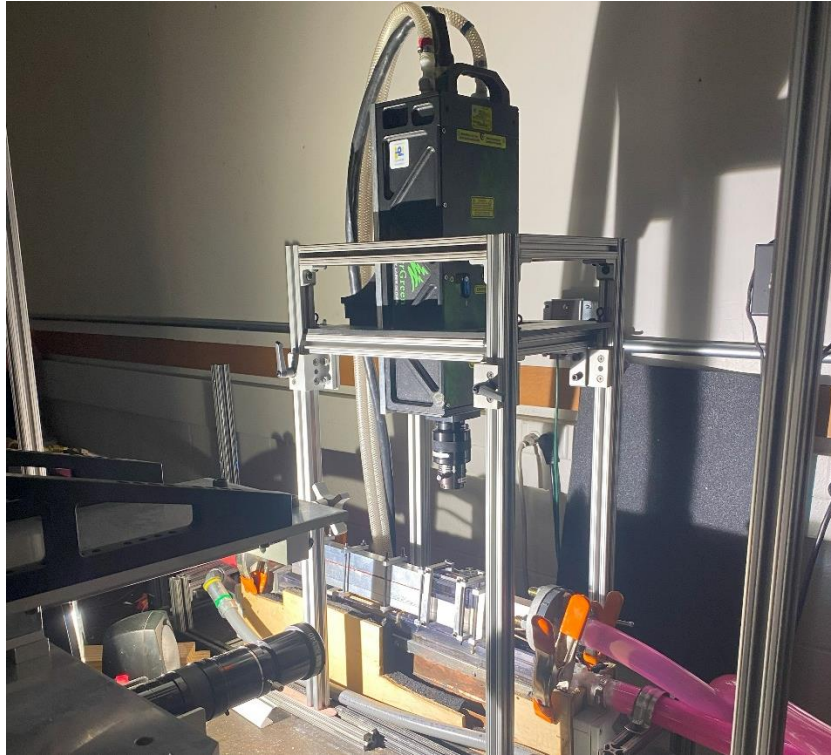


Figure 3-15 The optical system and the test section

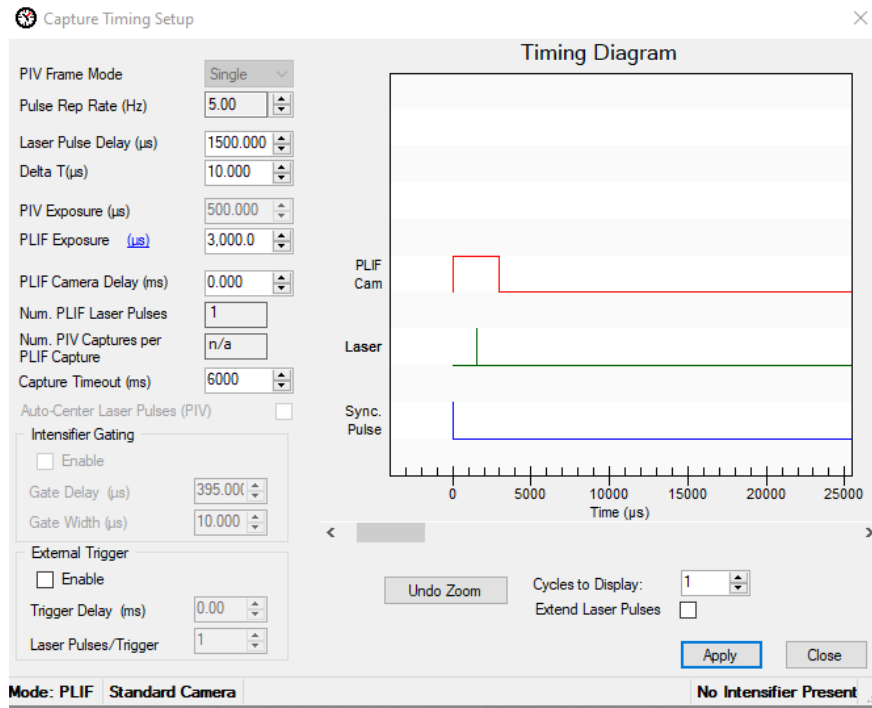


Figure 3-16 Experiment timing setup

3.6 Experimental procedure

The experiment followed a specific procedure. First, the test section needs to be assembled following the steps in Table 3-1. Next, the leakage of the test section is checked. If sealed, the system is flushed three times. Each time, the system is filled with six liters of water and the pump switched on to circulate the water for a couple of minutes. Water is then evacuated from the system.

On the other side, the optical system needs to be ready. The camera is installed. The optical objective is selected depending on the required dimensions of the captured images. For small images (3 mm*4 mm), use the objective of CF-4, but use the objective of CF-1 to capture large images (12 mm*16 mm). The selected optical filter is installed on the objective.

Optical calibration is required at this stage to determine the camera distance and zoom to make the laser plane spot within the focal depth. The calibration is performed by putting a

calibration grid target above the spot of the laser plane or by immersing the dotted target in the duct at the spot of the laser plane. Applying the calibration by immersing the target is more accurate, but it requires evacuating the water from the system then removing the top glass and closing gate valve 1. After that, pour water slowly from the slot in the top glass until the duct is full. Then, immerse the object. Figure 3-17 shows how to immerse the target in the water. Figure 3-18 shows putting the target above the duct.

After adjusting the target at the required spot, change the camera distance and the zoom until a clear image is present. That means the target is in focus, which means it is within the focal depth. If the image is fuzzy, it is out of focus. Figure 3-19 shows a fuzzy image, while Figure 3-20 shows a focused image. To determine the image dimensions, use the calibration tool in the Insight 4G software. Figures 3-21 and 3-22 are for the calibration tool. The distance between each two points in the target is 0.5 mm. According to that, press the measure button, which is shown in Figure 3-21, next press a point, then press another point, and then determine the distance between them. Depending on that, the image dimensions are shown as in Figure 3-22.

Table 3-1 Test section assembly steps

#	Steps
1	Add a gasket between the plastic flange and the aluminum flange, which is welded with the square duct. Then, bolt them together.
2	Put the heater cover on.
3	Put the heater in the groove of the heater cover.

4	Put the aluminum block on the heater and the heater cover.
5	Put the changeable surface in the top groove of the aluminum block.
6	Apply the RTV silicon around the changeable surface.
7	Put the square duct on the aluminum block. The changeable surface should be inserted in the bottom slot of the square duct.
8	After one hour, clamp these parts by using the aluminum sticks, bolts, and nuts.
9	Put on the three glass pieces and their gaskets. Then, clamp them together by using the aluminum sticks, bolts, and nuts.
10	Insert the thermocouples and seal them with 732 multipurpose silicon.

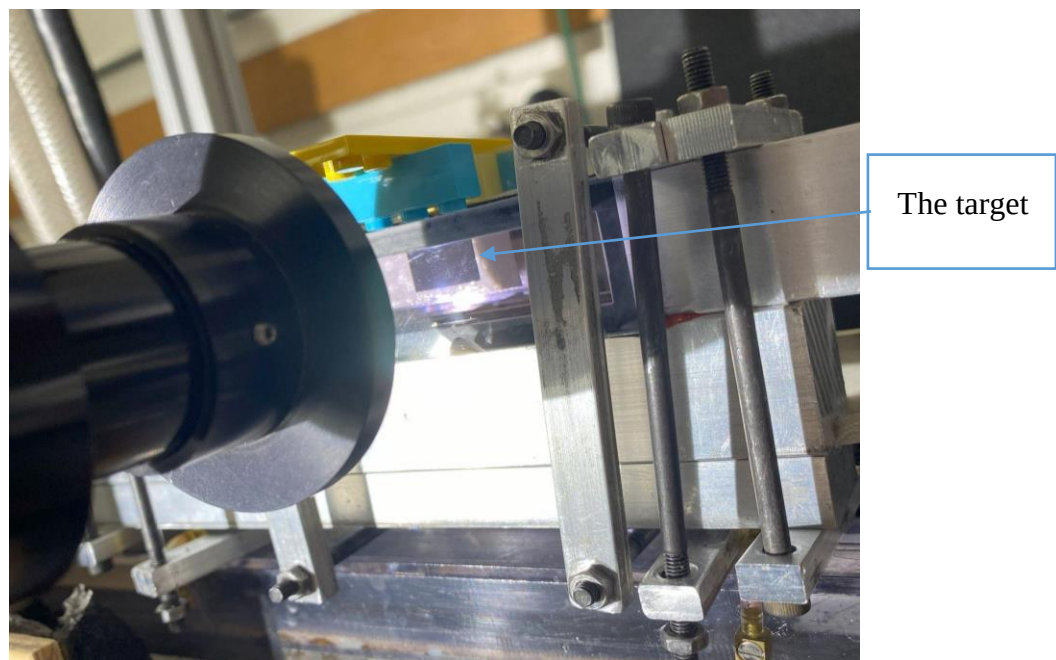


Figure 3-17 How to immerse the target in the water

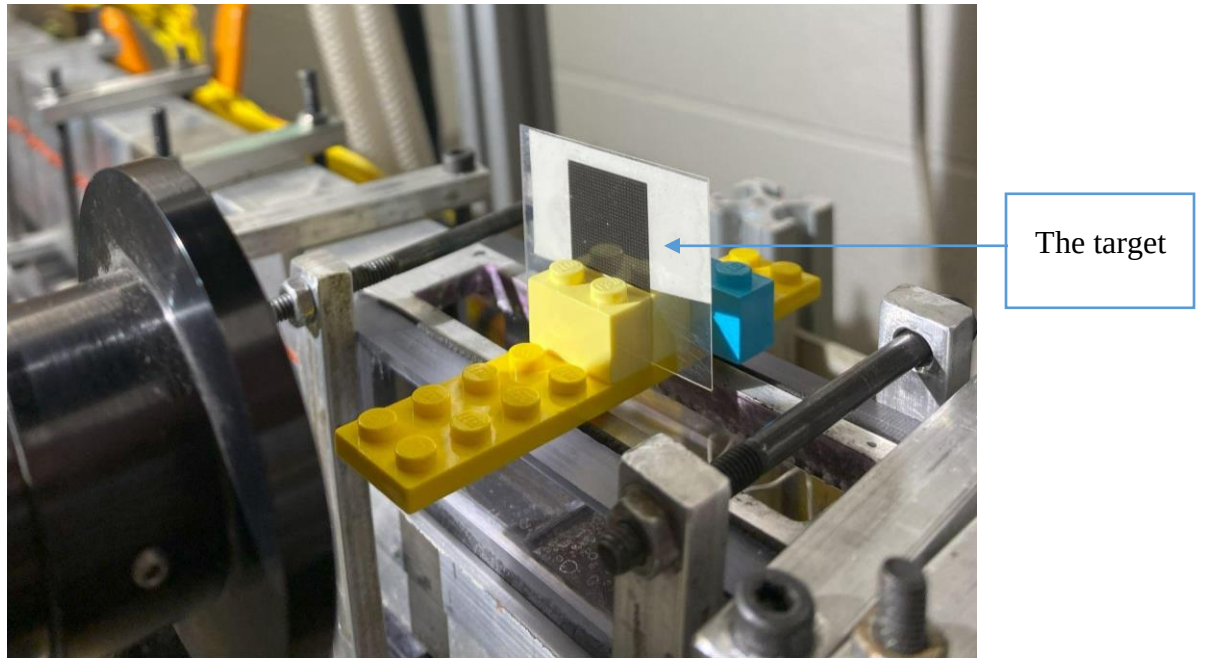


Figure 3-18 How to put the target above the duct

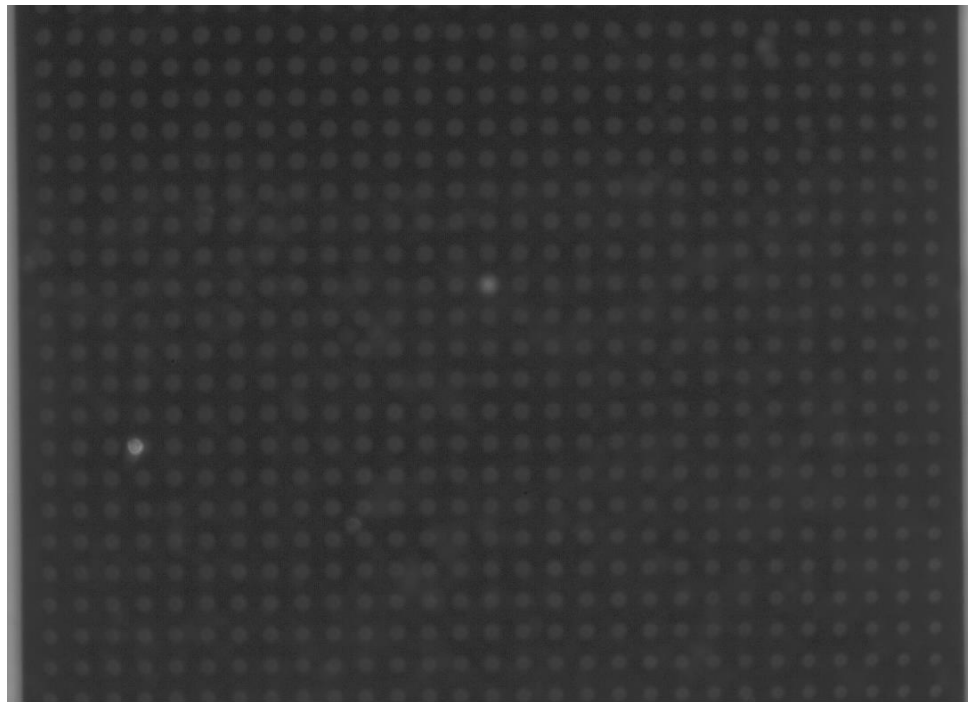


Figure 3-19 A fuzzy image



Figure 3-20 A focused image

2D Spatial Calibration

Camera:

Image Dimensions

Width (pixels)

Height (pixels)

Calibration

X ($\mu\text{m}/\text{pixel}$)

Y ($\mu\text{m}/\text{pixel}$)

Origin

X (pixel)

Y (pixel)

Field Of View Measured Manual

Object Size (mm)

Object Size (pixels)

Measure

1) Enter size in mm.
2) Click Measure button.
Click start point on image.
Click end point on image.

OK Cancel

Figure 3-21 Calibration tool - where to measure the distance between two points

2D Spatial Calibration

Camera: 1

Image Dimensions

Width (pixels) 3312

Height (pixels) 2488

Origin

UpperLeft

X (pixel) 0.00

Y (pixel) 2488.00

Calibration

X (μm/pixel) 4.76

Y (μm/pixel) 4.76

Field Of View Measured Manual

Enter either Width or Height and click Apply.

Width (mm) 15.77

Height (mm) 11.84

Apply

OK Cancel

Figure 3-22 Calibration tool - where to present the image dimensions

After that, the solution of distilled water and Rhodamine B is prepared at the required concentration, considering that the total quantity of the solution is six liters. After pouring the solution into the system, the pump is run to circulate the solution in the system until the bubbles disappear. At this stage, the system is ready for the experiment.

Creating the temperature calibration curve is next. The pump circulates the water in the system. The heater is off, and the cooling water inlet valve is closed. Because of the friction in the pumping processes, the water temperature increases. Then, the water temperature will increase gradually from room temperature to more than 40°C. This behavior is used to make the temperature calibration curve. When the inlet water temperature is 25°C, capture ten images. Do the same thing when the water temperature is 27°C, 29°C, 31°C, 33°C, 35°C, 37°C, and 39°C. In Chapter 5, more details are presented on how these images are used to get the temperature calibration curve and how to analyze the results' accuracy using MATLAB.

To capture images of the heating case, turn the heater on and open the cooling water inlet valve. Select the heater power depending on the required surface temperature. When the surface temperature and the inlet water stay almost constant for more than ten minutes, capture the desired quantity of images for the heated case. Repeat this step when the user wants to examine different water flow rates.

3.7 Uncertainty

In the experiment, The Micro Motion CFM050 flowmeter and type K thermocouples are used to measure the flow rate and the temperature, respectively. For the flowmeter, the uncertainty was concluded from the manufacturer data. It is $\pm 0.1\%$ of the reading [26]. To find the uncertainty of the thermocouples, they were calibrated using a temperature calibration bath. The uncertainty was calculated with 95% confidence. Table 3-2 presents the uncertainty of the thermocouples, while Table 3-3 presents the calibration data for the thermocouples. Equation 3.4 was used to calculate the uncertainty of the thermocouples [34] when b_1 is the random error, b_2 is the systematic error, and s_x is the system error.

$$\text{uncertainty} = (b_1^2 + b_2^2 + s_x^2)^{1/2} \quad (3.4)$$

The random error is for the random variation of the measurement data about its average, while systematic error is the difference between the average of the measurement data and the true value [31]. The system error is informed by the instrument manufacturer.

Table 3-2 Thermocouples uncertainty

	Inlet thermocouple	Outlet thermocouple	First thermocouple in the test section	Second thermocouple in the test section	Third thermocouple in the test section	Fourth thermocouple in the test section
random error	0.05	0.02	0.07	0.02	0.06	0.09
systematic error	0.18	0.72	0.20	0.04	0.06	0.03
system error	0.10	0.10	0.10	0.10	0.10	0.10
uncertainty	0.22	0.72	0.24	0.11	0.13	0.14

Table 3-3 Thermocouples calibration data

Instrument	Slope	Offset
Inlet thermocouple	1.02	-0.071
Outlet thermocouple	1.02	0.201
First thermocouple in the test section	1.01	0.031
Second thermocouple in the test section	1.01	-0.048
Third thermocouple in the test section	1.02	-0.100
Fourth thermocouple in the test section	1.02	-0.193

3.8 Summary

The experimental setup was explained in this chapter. The test section, water system, optical instrumentation, and experimental procedure were presented. The optical calibration and temperature calibration procedures were explained.

Chapter 4 - Computational Fluid Simulation by FLUENT

4.1 Introduction

This chapter presents the method for simulating the flow through smooth and finned ducts using the commercial software FLUENT. The geometry, mesh, boundary conditions, assumptions, and solved equations are presented in this chapter. The experimental results will be compared with numerical results that were obtained from the FLUENT software. This comparison helps gain insight into the potential strengths and weaknesses of PLIF.

4.2 Geometry

To solve the problem computationally, two 3D models were created: one for the smooth surface duct and the other for the finned surface duct. The smooth surface duct contains three zones: inlet zone, heating zone, and outlet zone. The finned surface duct has one zone, which is the heating zone. Figure 4-1 shows the smooth surface duct, and Figure 4-2 shows the right view of the finned surface duct. For both ducts, the height and width are 0.625 inches. This is equal to the dimensions of the square duct used in the experiment.

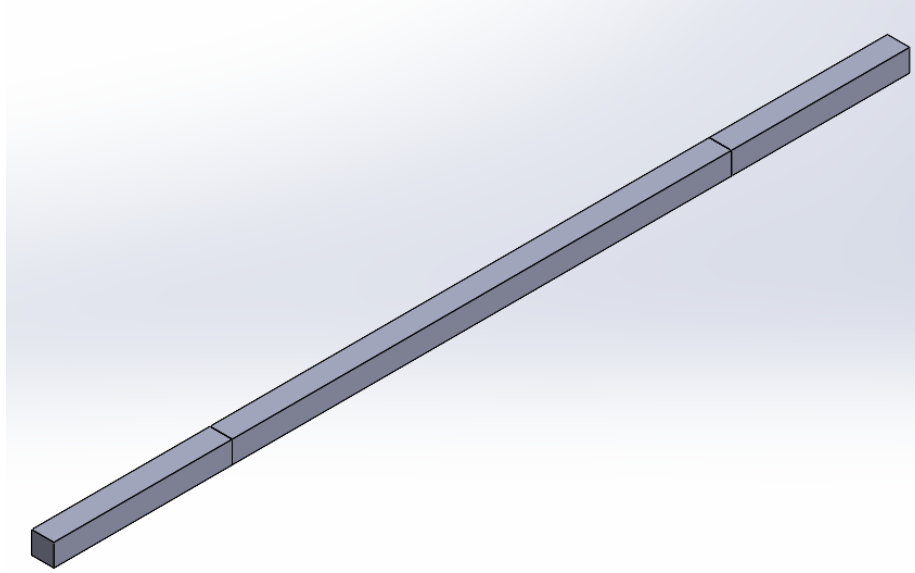


Figure 4-1 The smooth surface duct



Figure 4-2 The right side view of the finned surface duct

4.3 Mesh

After making the solid model, dividing the model into small cells—where the flow variables are calculated for the whole model—is required for solving any CFD problem. Figure 4-3 shows the generated mesh for the smooth surface duct. The figure shows the inflation layers at the walls where the boundary layer produces high velocity and temperature gradients: fifteen layers in the inflation zone with a growth of 1.2. The selected mesh element size is 1 mm in the center of the duct. The mesh size independence was checked by selecting four mesh sizes and solving the problem for each size. Then, the temperature distribution curve for a line was compared for the results of the four sizes and presented in Figure 4-4. It shows that the results of mesh sizes 2 mm, 1 mm, and 0.5 mm are almost equal. The results of the 5 mm mesh size are different from the others. To determine how the cells are close to the ideal cells, skewness is

calculated. The average of the skewness on the mesh is 0.23, while the standard deviation is 0.15. That indicates the mesh quality is good [27].

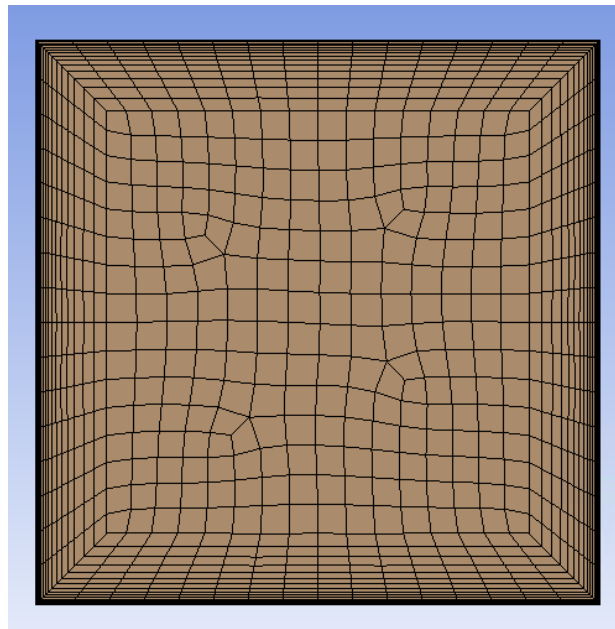


Figure 4-3 Mesh for the smooth surface duct

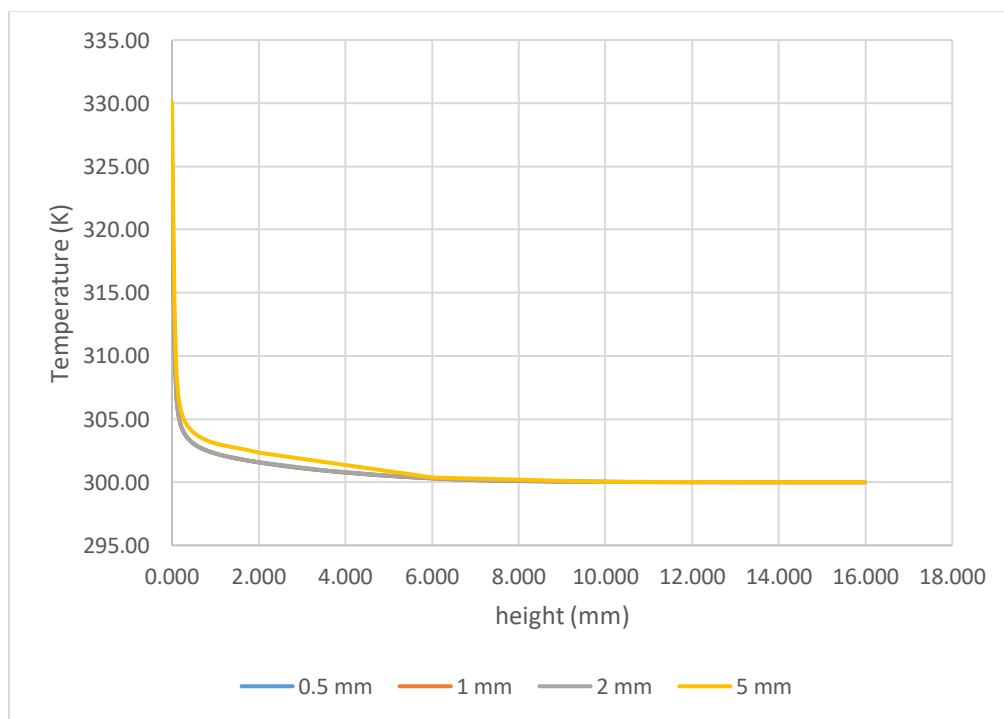


Figure 4-4 Mesh sensitivity analysis

For the finned surface duct, the mesh was created with a general size of 1 mm. The choice of face size was selected for the top and bottom surfaces with a size of 0.01 mm. This choice is used to inflate the mesh close to the surface. The average of the skewness on the mesh is 0.23, while the standard deviation is 0.014. This indicates the mesh quality is excellent, because the cells are very close to the ideal cell. Figure 4-5 shows the generated mesh for the finned surface duct at the inlet surface. Figure 4-6 shows a zoomed view of the section view for the fin area.

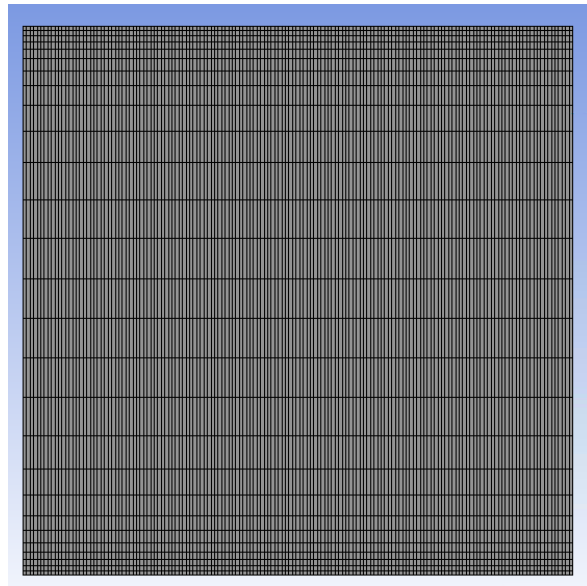


Figure 4-5 Generated mesh for the finned surface duct at the inlet surface

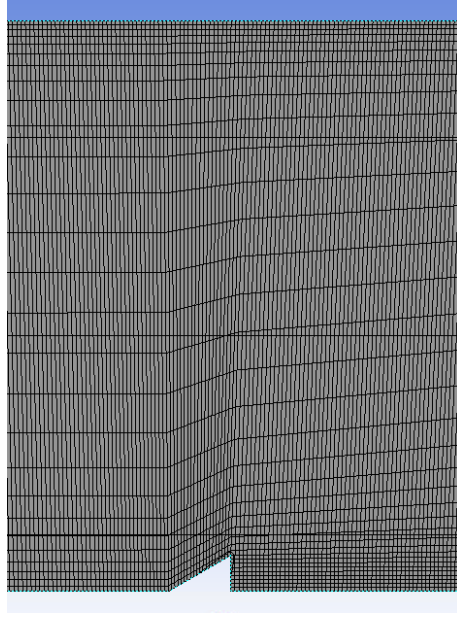


Figure 4-6 Zoomed view of the section view for the fin area

4.4 Boundary conditions and assumptions

The problem was solved for several cases to compare CFD results with PLIF results. The boundary conditions of the solved cases are presented in Table 4-1. They are set to be similar to the experimental cases. The problem was solved for the steady state case when the properties were assumed as constant.

Table 4-1 Boundary conditions of CDF simulation

cases	Average velocity (m/s)	Surface temperature (°C)	Inlet Temperature (°C)
1	1.80	31.78	25.80
2	1.80	36.41	27.40
3	1.45	31.67	25.20
4	1.45	36.02	26.10
5	1.05	31.20	25.30
6	1.05	38.25	26.90
7	0.44	32.14	25.90
8	0.44	37.92	27.40

4.5 Equations

4.5.1 Continuity and momentum equations

Computational fluid dynamics depend on numerical simultaneous solutions of continuity, momentum, transport, and energy equations. Equation 4.1 is the continuity equation for single-phase flow, while equation 4.2 is the momentum conservation equation [28].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \quad (4.1)$$

$$\frac{\partial}{\partial t} (\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \otimes \vec{u}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \quad (4.2)$$

Where:

ρ is the fluid density.

$\vec{u}$ is the fluid velocity.

p is the static pressure.

$\bar{\bar{\tau}}$ is the stress tensor.

$\rho \vec{g}$ is the gravitational body force.

$\vec{F}$ is the external body force.

4.5.2 Energy equations

Equation 4.3 is the energy equation solved by FLUENT when the problem does not contain heat generation. E and h in the equation are defined in equations 4.4 and 4.5, respectively [29].

$$\frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot (k_{eff} \nabla T - \sum_j h_j \vec{J}_j + (\bar{\bar{\tau}}_{eff} \cdot \vec{v})) \quad (4.3)$$

$$E = h - \frac{p}{\rho} + \frac{v^2}{2} \quad (4.4)$$

$$h = \sum_j Y_j h_j + \frac{p}{\rho} \quad (4.5)$$

$$h_j = \int_{T_{ref}}^T c_{p,j} dT \quad (4.6)$$

where:

k_{eff} is the effective conductivity, which is the summation of conductivity and turbulent thermal conductivity.

$\vec{J}_j$ is the diffusion flux of species j.

$k_{eff} \nabla T$ is for energy transfer by conduction.

$\sum_j h_j \vec{J}_j$ is for energy transfer by species diffusion.

$\overline{\tau_{eff}} \cdot \vec{v}$ is for energy transfer by viscous dissipation.

Y_j is the mass fraction of species j.

4.5.3 Viscous models

For the transport equations, the k- ϵ model is the turbulence model that was selected.

Equations 4.7 and 4.8 are the two transport equations, while equation 4.9 is for the turbulent viscosity. Table 4-2 shows the default values of transport equations constants [30].

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M \quad (4.7)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_k + C_{3\epsilon} G_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} \quad (4.8)$$

$$\mu_t = \rho C_\pi \frac{k^2}{\epsilon} \quad (4.9)$$

where:

k is turbulent kinetic energy.

ϵ is turbulent dissipation rate.

G_k is the turbulent kinetic energy from the mean velocity gradient.

G_b is the turbulent kinetic energy from the buoyancy.

σ_k is the Prandtl number for k .

σ_ϵ is the Prandtl number for ϵ .

Y_M is the ratio of the fluctuating dilation in compressible turbulence to overall dissipation rate.

$C_{1\epsilon}$, $C_{2\epsilon}$, $C_{3\epsilon}$ and C_π are constants.

Table 4-2 Default values of transport equations constants [30]

Constants	Default values
$C_{1\epsilon}$	1.44
$C_{2\epsilon}$	1.92
C_π	0.09
σ_k	1.0
σ_ϵ	1.3

4.6 Converging criteria

After making all terms of the solved equations on the left side, the solution gets converted when the right side equals the selected residual criteria. Figure 4-7 shows the selected residual

criteria. The results are not accepted if the solution does not converge within the chosen number of iteration.

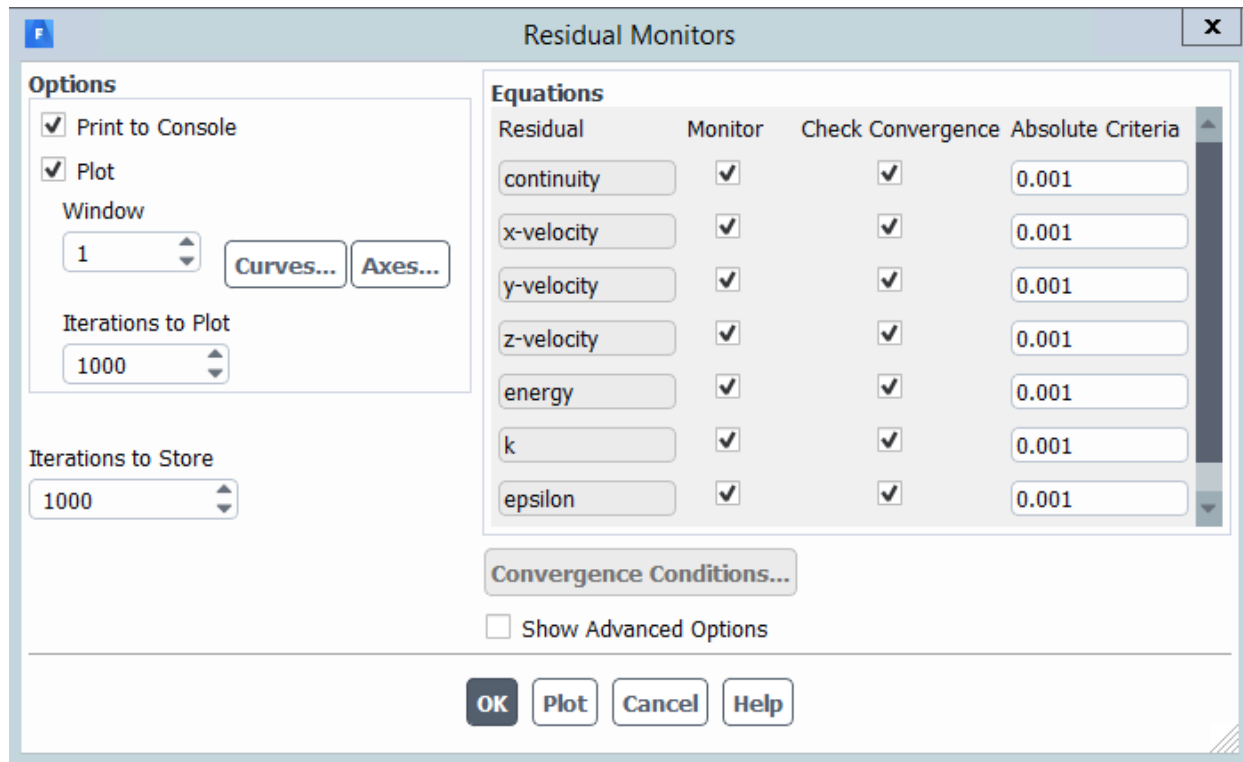


Figure 4-7 The selected residual criteria

4.7 Summary

This chapter presented how the computational solution was performed. The geometry, mesh, boundary conditions, assumptions, and solved equations were presented in this chapter. The results of the numerical solution are presented in Chapter 6. They will be compared with the experimental results.

Chapter 5 - Using PLIF in Temperature Field Measurement for Isothermal Water Flows

5.1 Introduction

The PLIF technique was used to measure the temperature field of isothermal water flows. The measurement was conducted for several temperatures while the temperature increase was obtained from the pump energy. In this case, the heater is off, because the temperature gradient in the duct is unwanted. These experiments are required to make the temperature calibration curves and to investigate the accuracy and precision of the results. The effects of changing the laser energy, camera aperture, and laser sheet thickness are also discussed.

5.2 Edge offset

The images that were taken contain a small portion of the solid side to allow investigation of the area right above the surface. When the images were examined, the edge of the surface was at a different height as the temperature increased. It is speculated that this is due to thermal expansion. Figures 5-1 to 5-10 are for the grayscale of the images of temperatures 25°C, 27°C, 29°C, 31°C, 33°C, 35°C, 37°C, and 39°C, in addition to two images for the heating case that is explained in Chapter 6. The figures were originally gray but were colored by MATLAB according to the colormap. In each image, a portion of the solid is shown. The surface edge was determined for each image, and the pointer shows the edge position in each image. Table 5-1 shows the pixel number of the edge for each image depending on the number shown in the figures. Because of this difference in the edge position, the surface edge should be determined at

the beginning. Then, any data below the edge should be cut and the edge respected as the starting point.

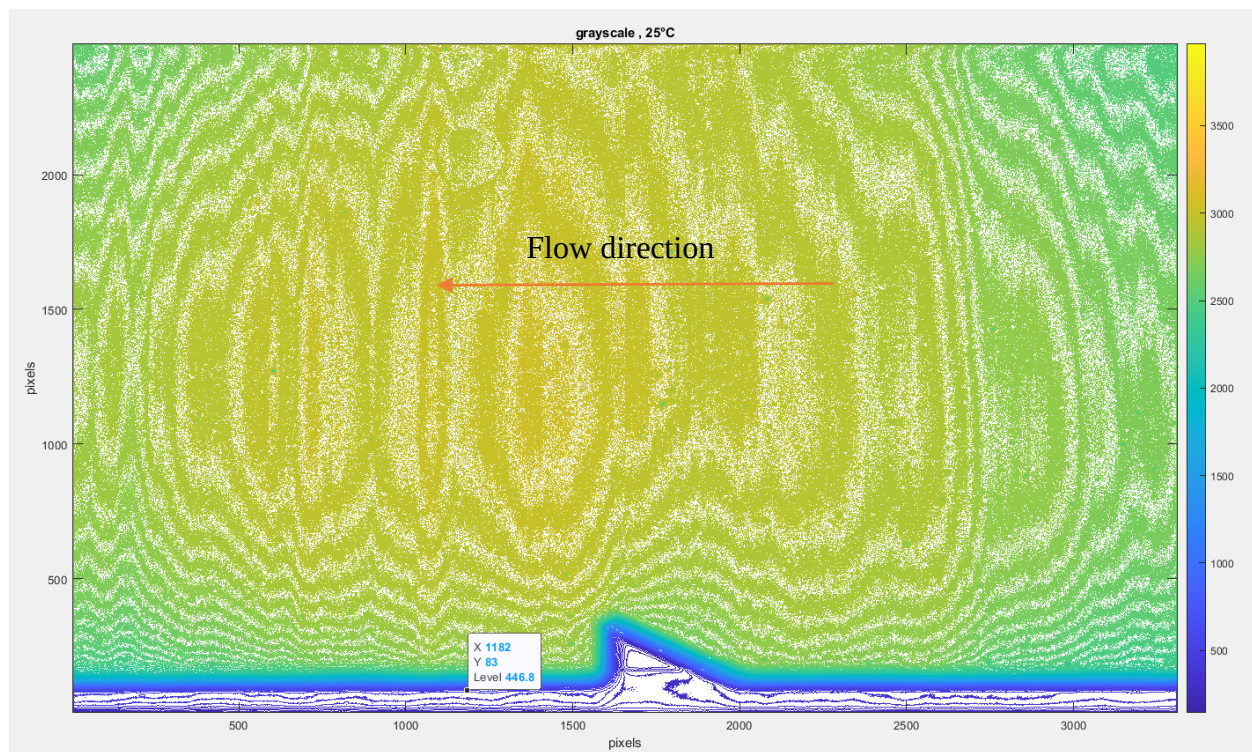


Figure 5-1 Grayscale at temperature 25°C

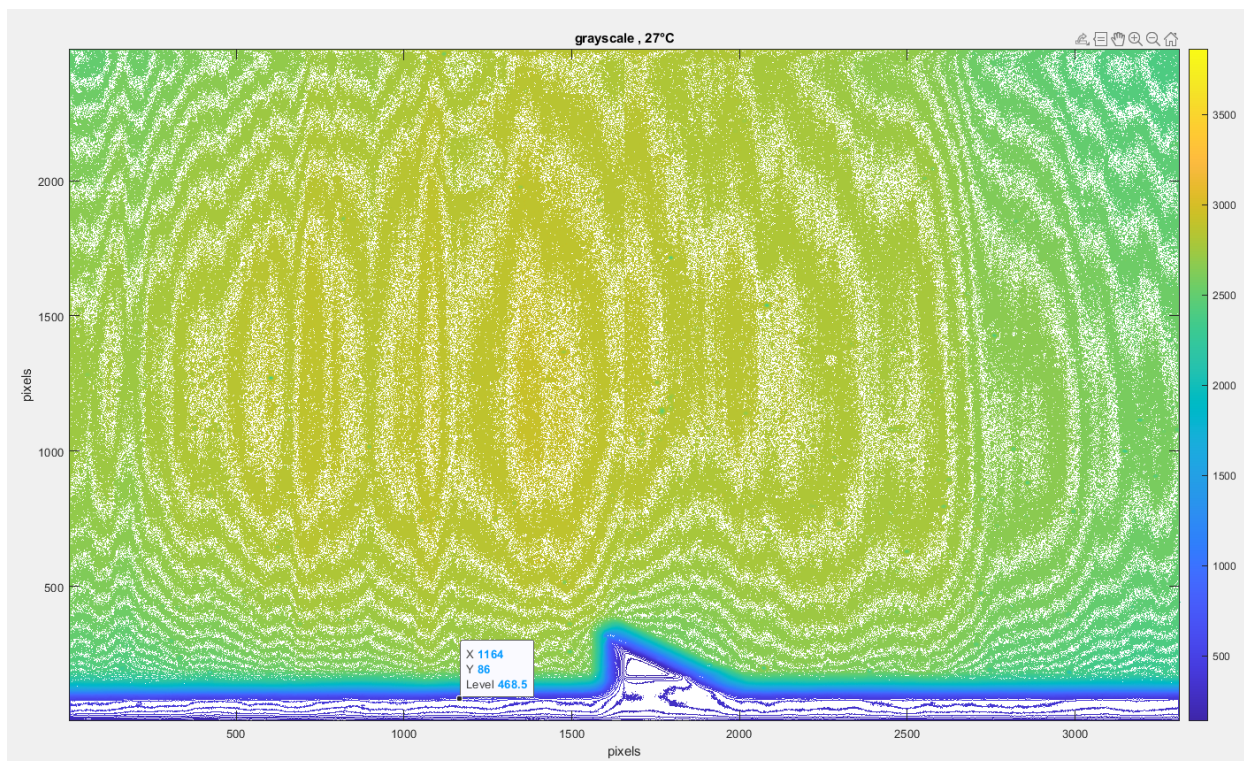


Figure 5-2 Grayscale at temperature 27°C

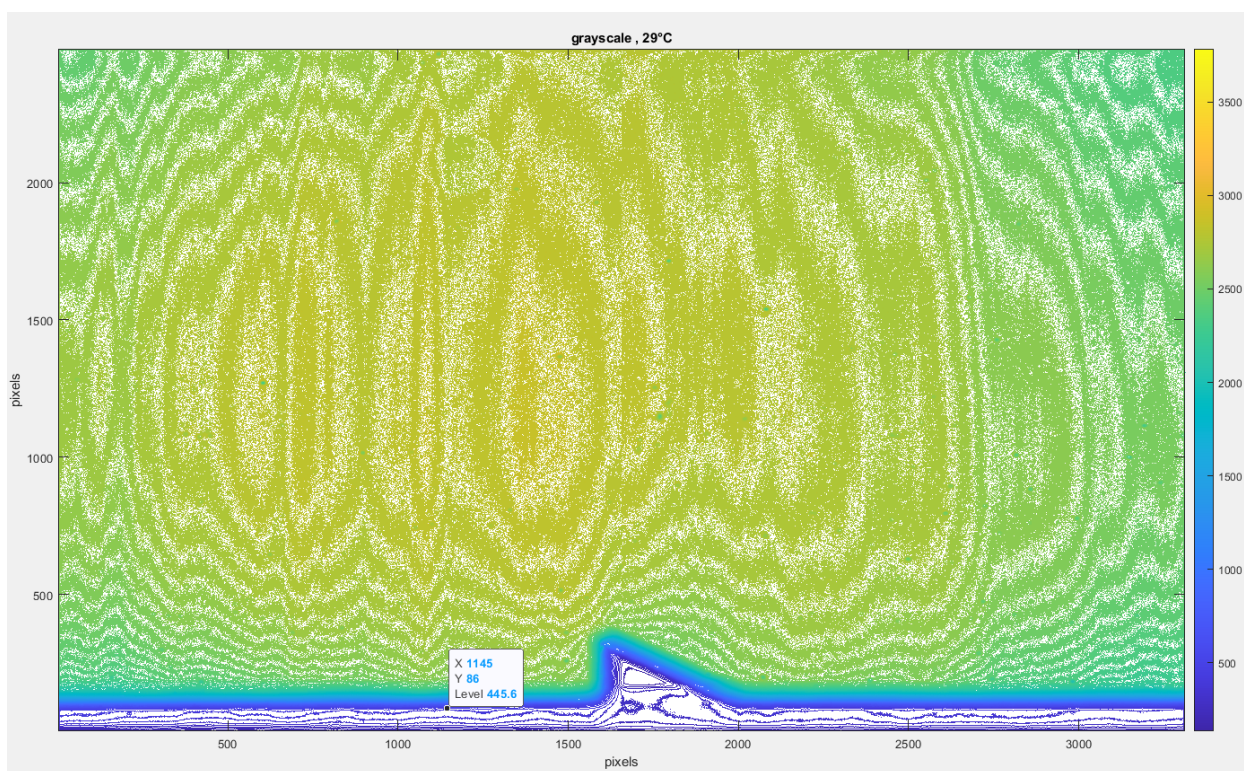


Figure 5-3 Grayscale at temperature 29°C

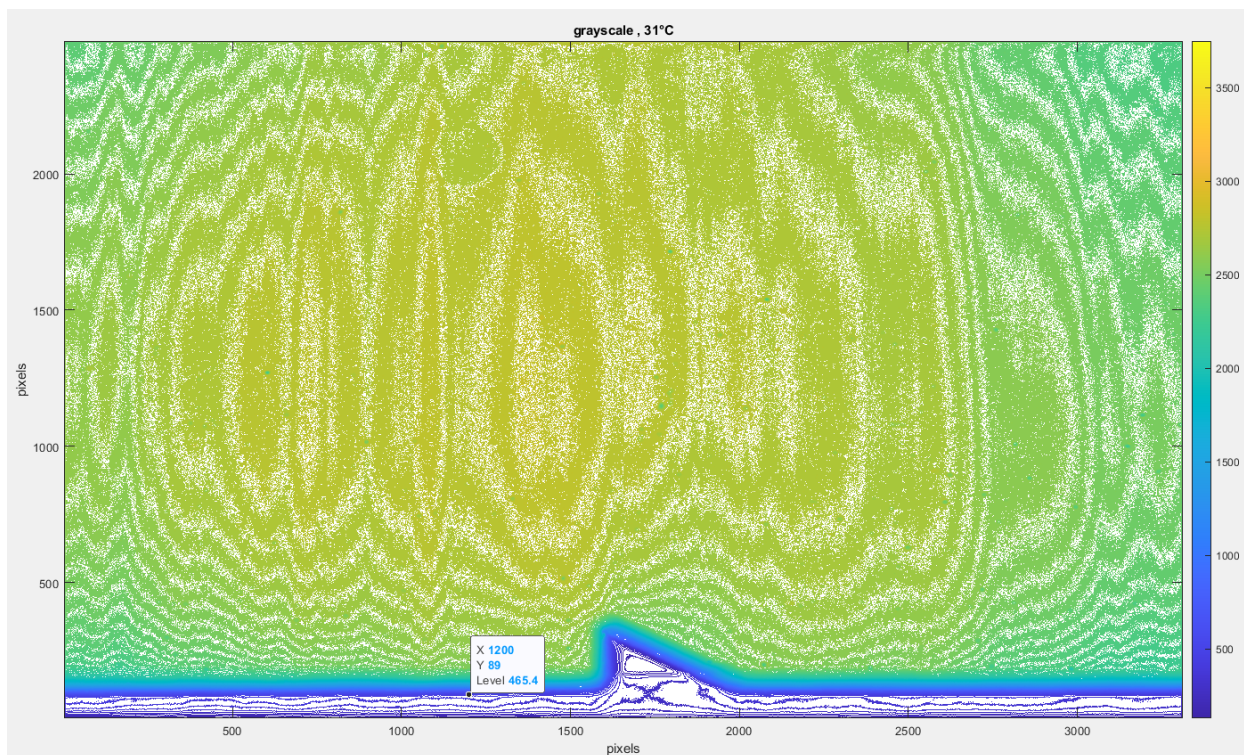


Figure 5-4 Grayscale at temperature 31°C

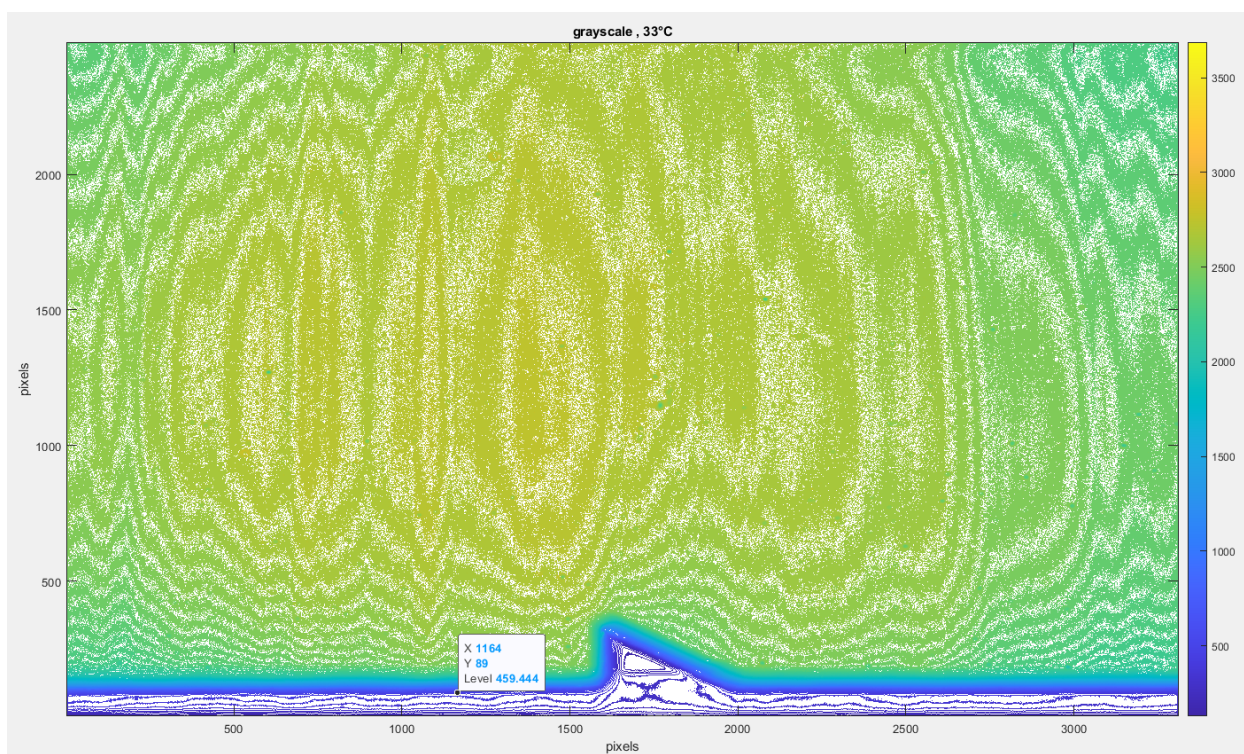


Figure 5-5 Grayscale at temperature 33°C

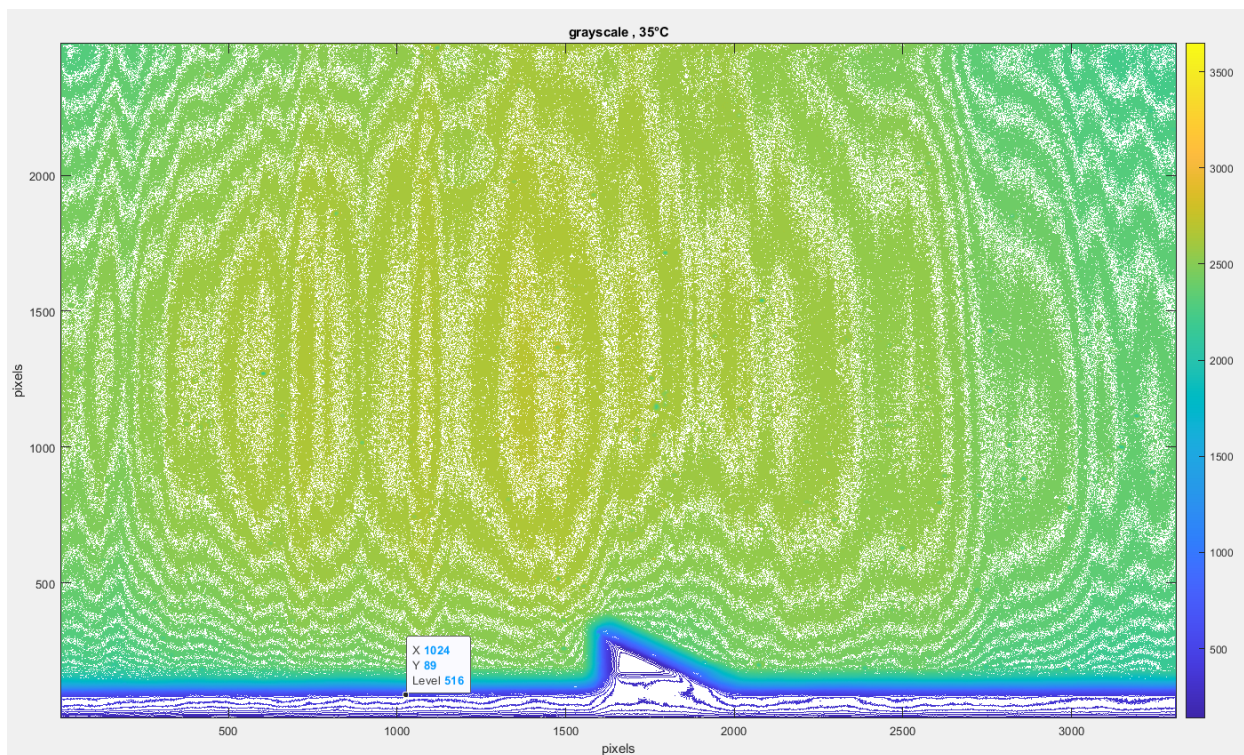


Figure 5-6 Grayscale at temperature 35°C

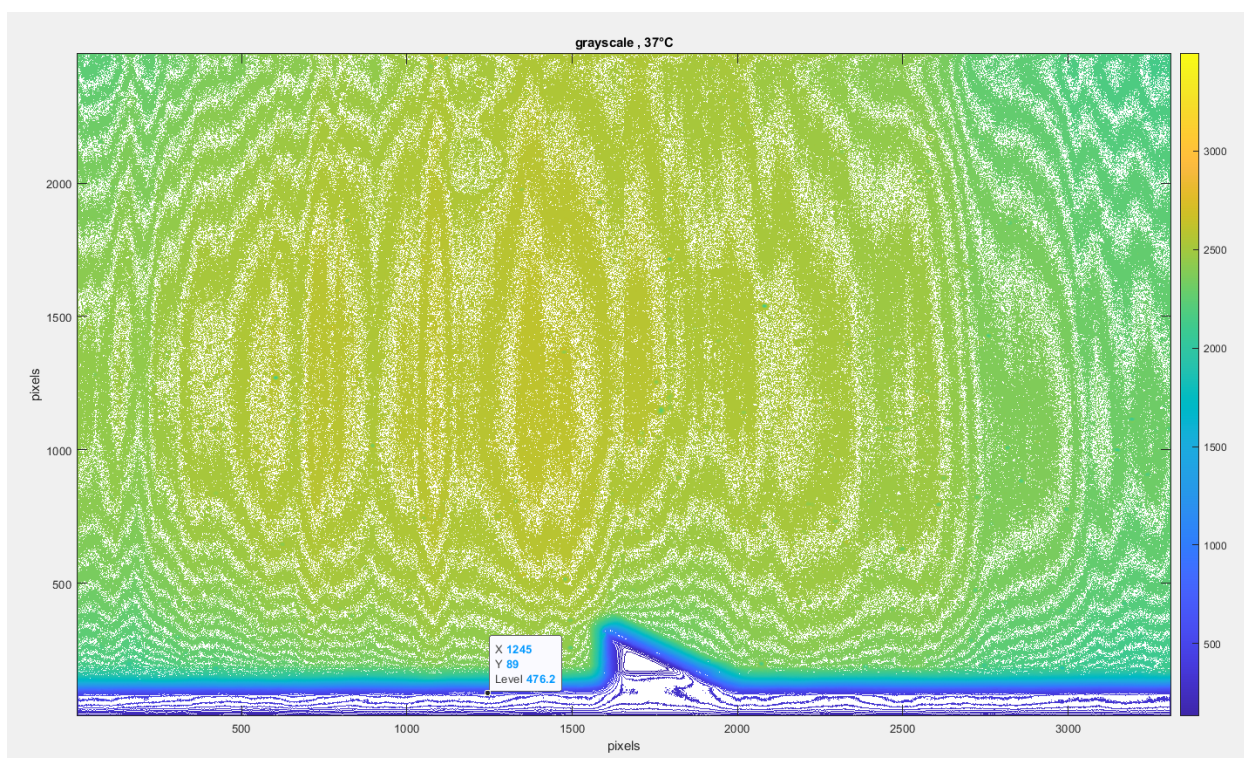


Figure 5-7 Grayscale at temperature 37°C

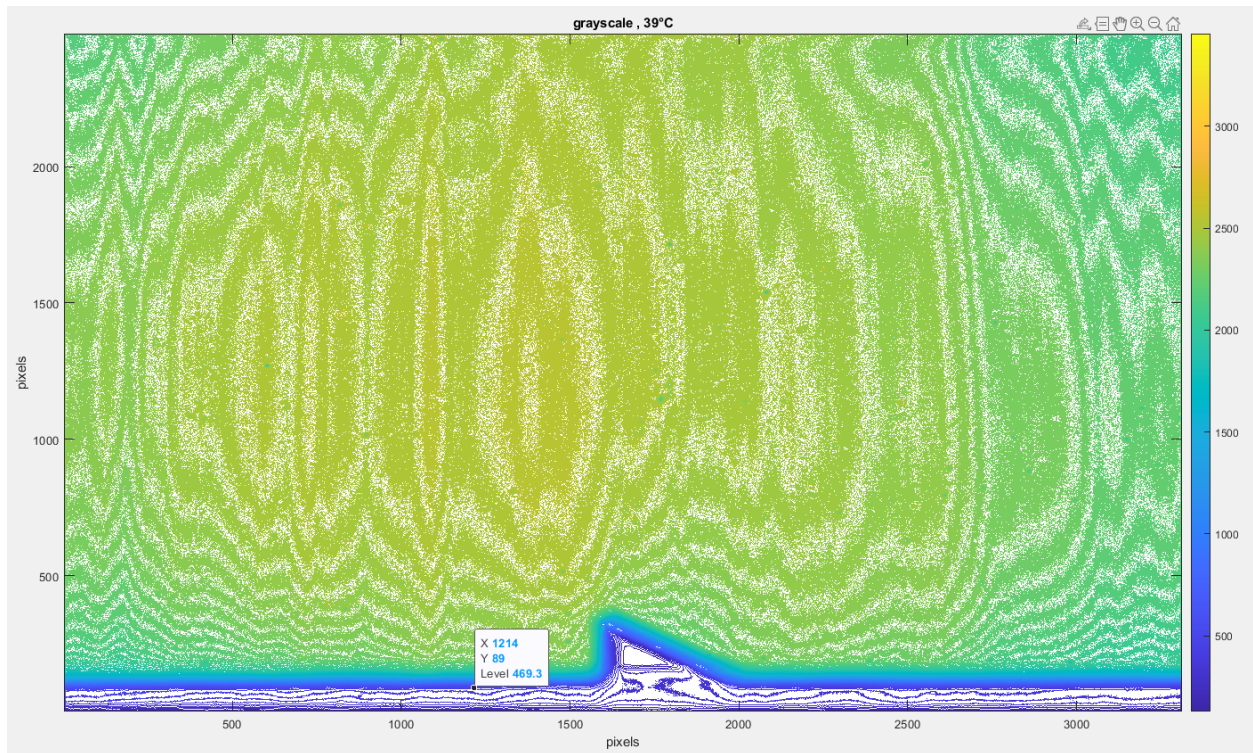


Figure 5-8 Grayscale at temperature 39°C

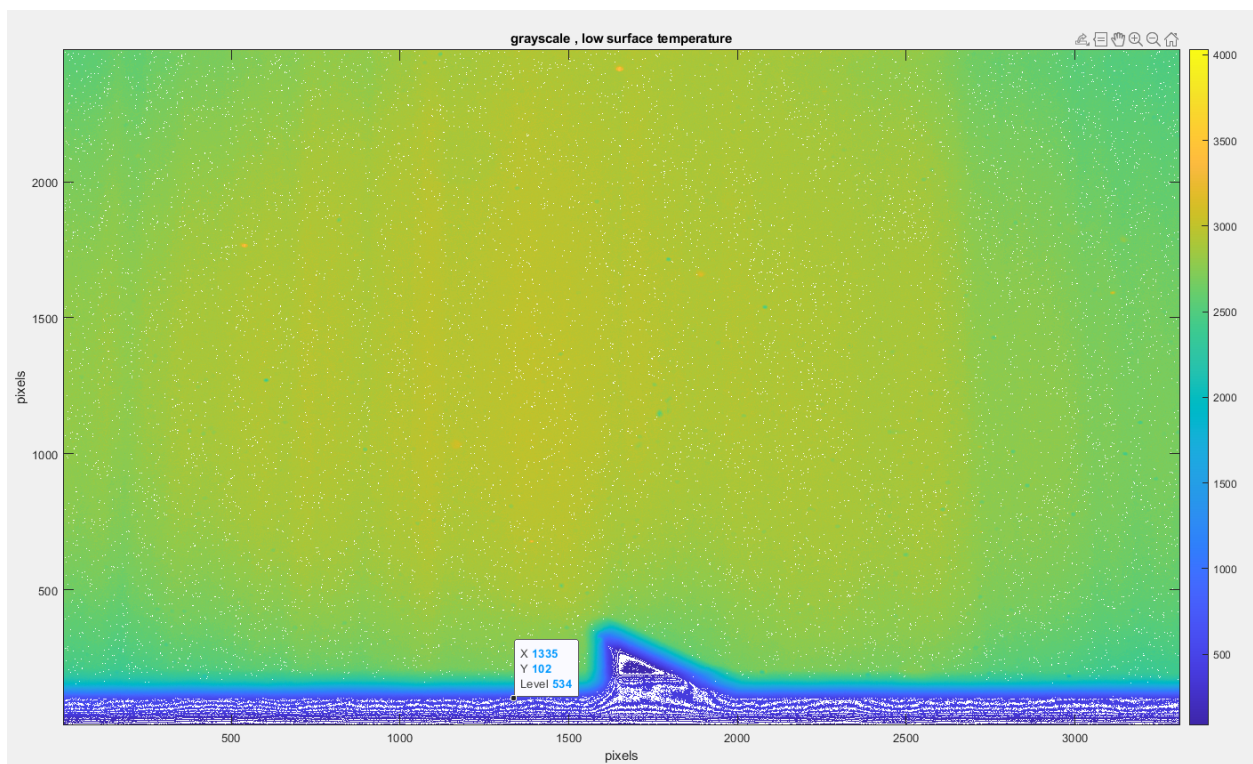


Figure 5-9 Grayscale of the heating case when the surface temperature is 31.78°C

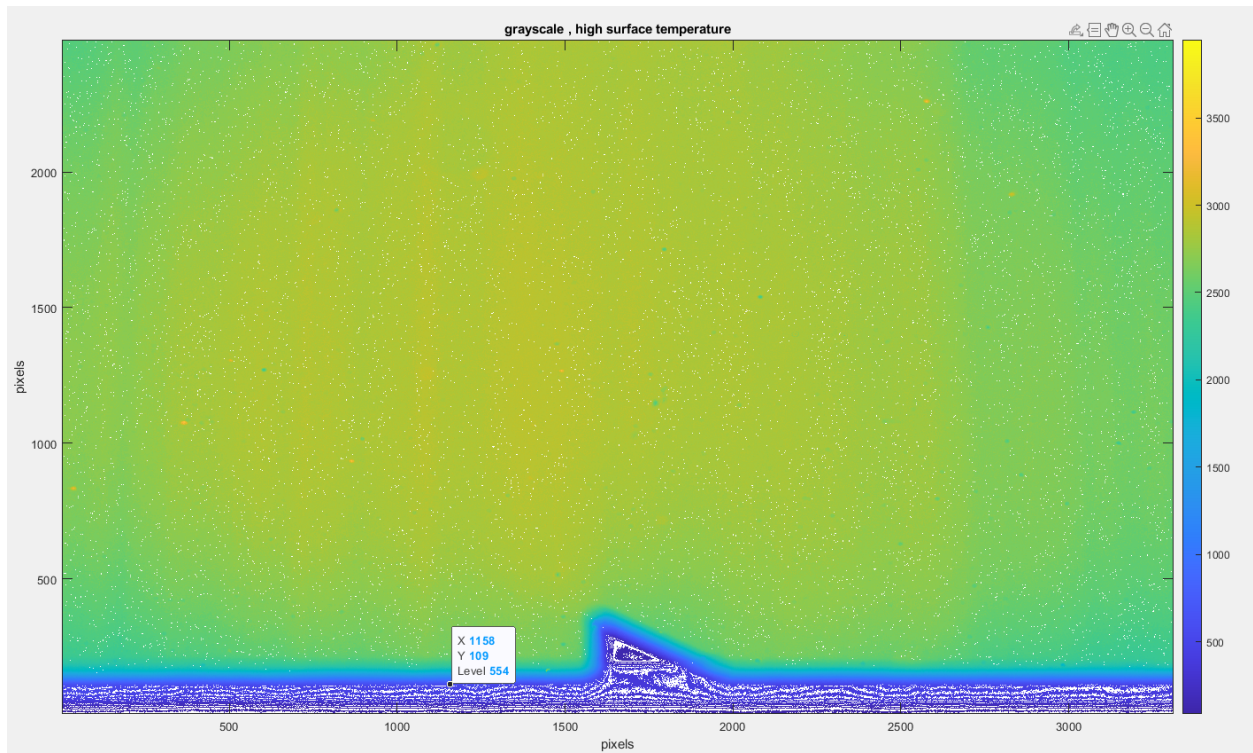


Figure 5-10 Grayscale of the heating case when the surface temperature is 36.4°C

Table 5-1 Pixel number of the edge for a certain run

Where the edge is	Y value
25°C	83
27°C	86
29°C	86
31°C	89
33°C	89
35°C	89
37°C	89
39°C	89
heating case with surface temperature of 31.87°C	102
heating case with surface temperature of 36.41°C	109

5.3 Temperature calibration curve

Creating a temperature calibration curve in PLIF means finding a relationship between a temperature and the fluorescence intensity, which might be demonstrated as grayscale. To create a temperature calibration curve, select certain temperatures for the calibration. Then, control the fluid temperature to arrive at the selected temperatures and capture images at each one.

In the current experiment, the pump recirculates the water through the test section. Because of the added heat from the pumping energy, the water temperature increases over time. The images were captured at temperatures of 25°C, 27°C, 29°C, 31°C, 33°C, 35°C, 37°C, and

39°C. For each temperature, ten images were taken. The resultant grayscale images were loaded into MATLAB. Figure 5-11 shows an image of water at 25°C after removing the solid portion. It shows the grayscale of each pixel. The camera does not collect the same amount of light at each pixel, causing a variation in the grayscale within the image. Because of that, each pixel should have its own temperature calibration curve.

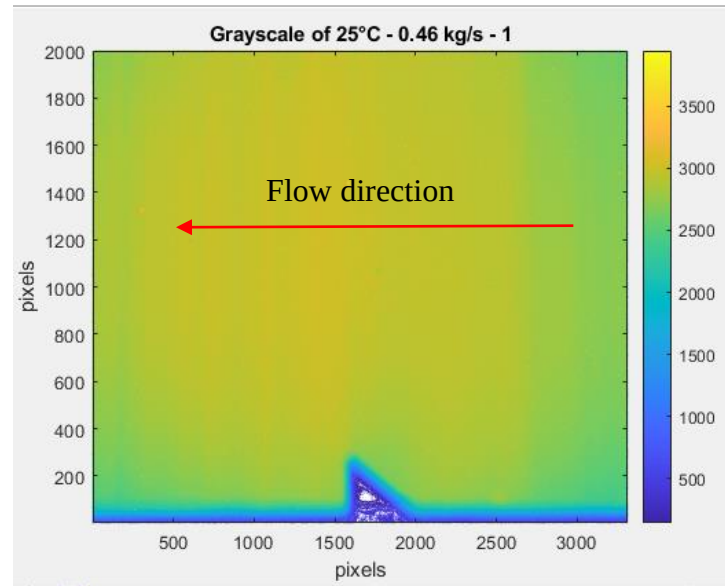


Figure 5-11 Grayscale at temperature 25 after removing the solid portion

After capturing the isothermal images, MATLAB creates the temperature calibration curve for each pixel by following several steps. First, MATLAB deduces the grayscale of each pixel of the ten images of each temperature. Then, for each pixel, it finds the average grayscale of the ten images of each temperature. Because the images were taken for eight temperatures (25°C, 27°C, 29°C, 31°C, 33°C, 35°C, 37°C, and 39°C), there are eight matrices. Each matrix is the average grayscale of the ten images of a certain temperature. Then, a third-degree polynomial curve fit is performed for each pixel. This method of curve fitting will find four constants to create equation 5.1.

$$T = ax^3 + bx^2 + cx + d \quad (5.1)$$

Where a, b, c, and d are curve fitting constants deduced from MATLAB, and x is the grayscale value. Figure 5-12 shows the grayscale of the temperatures 25°C, 27°C, 29°C, 31°C, 33°C, 35°C, 37°C, and 39°C at point (1000,1000), while Figure 5-13 is for point (1000,2000). In these two figures, horizontal and vertical error bars are shown. The horizontal bar is the estimated error of the grayscale for each temperature, with a confidence of 95%. The vertical bar is the estimated error of the temperature measurement for each temperature, with a confidence of 95%. In figure 5-12, the temperature uncertainty at 39°C is $\pm 0.9^\circ\text{C}$, while the temperature uncertainty at 29°C is $\pm 2.2^\circ\text{C}$. The average uncertainty in the eight temperatures is 1.7°C .

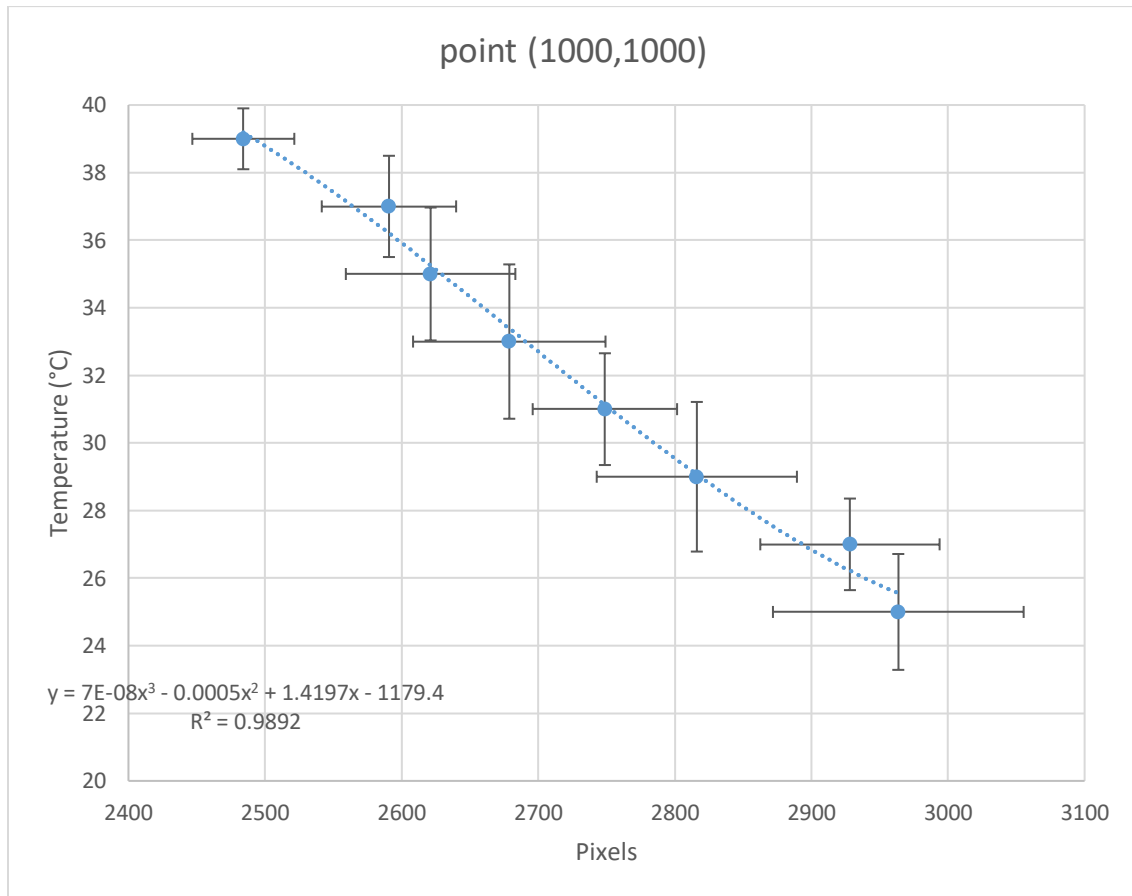


Figure 5-12 Grayscale of the temperatures 25°C, 27°C, 29°C, 31°C, 33°C, 35°C, 37°C, and 39°C at point (1000,1000)

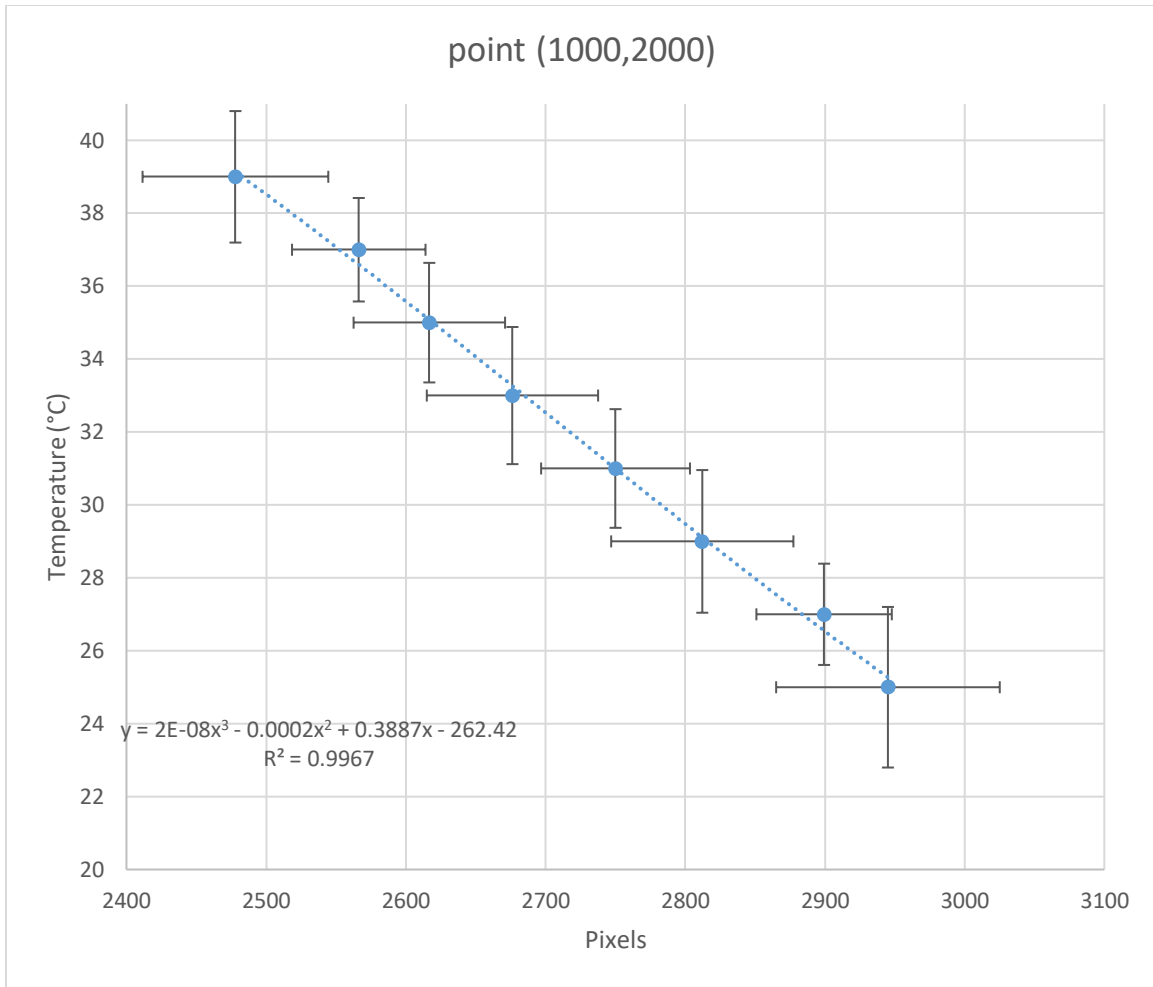


Figure 5-13 Grayscale of the temperatures 25°C, 27°C, 29°C, 31°C, 33°C, 35°C, 37°C, and 39°C at point (1000,2000)

Using the temperature calibration curves, the temperature fields of individual isothermal images are constructed. Figures 5-14 to 5-25 are examples of the isothermal resultant temperature fields.

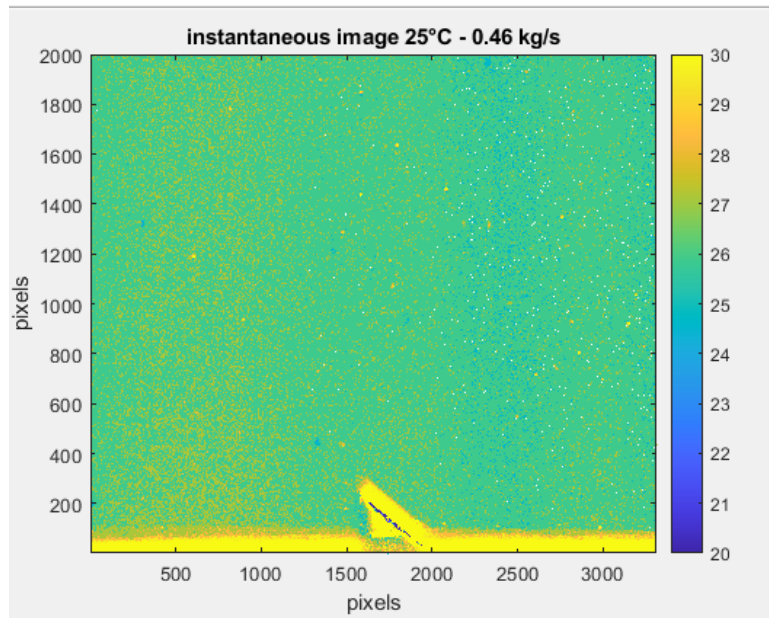


Figure 5-14 Instantaneous image when the water temperature is 25°C

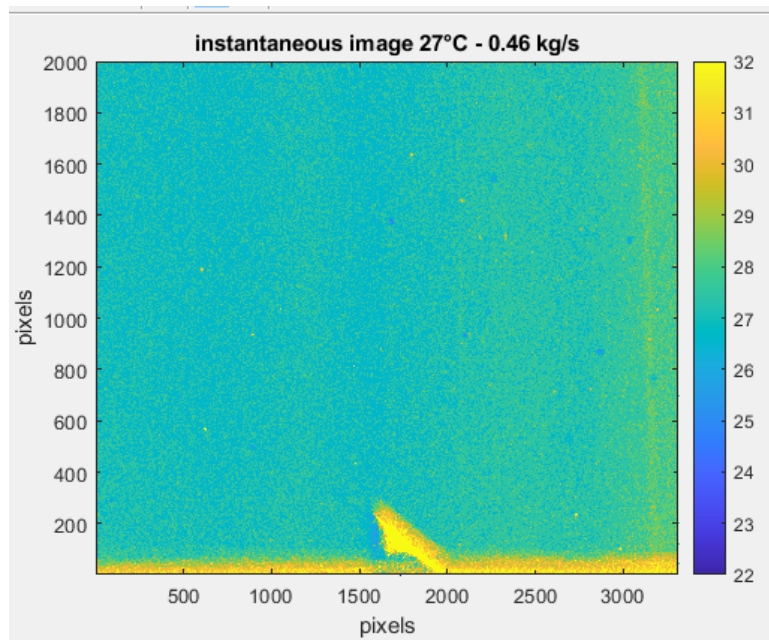


Figure 5-15 Instantaneous image when the water temperature is 27°C

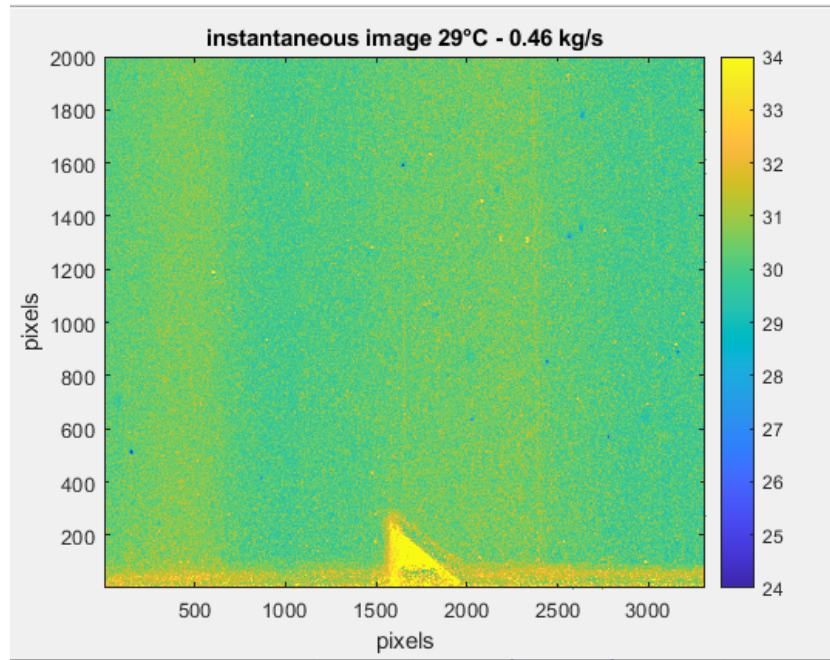


Figure 5-16 Instantaneous image when the water temperature is 29°C

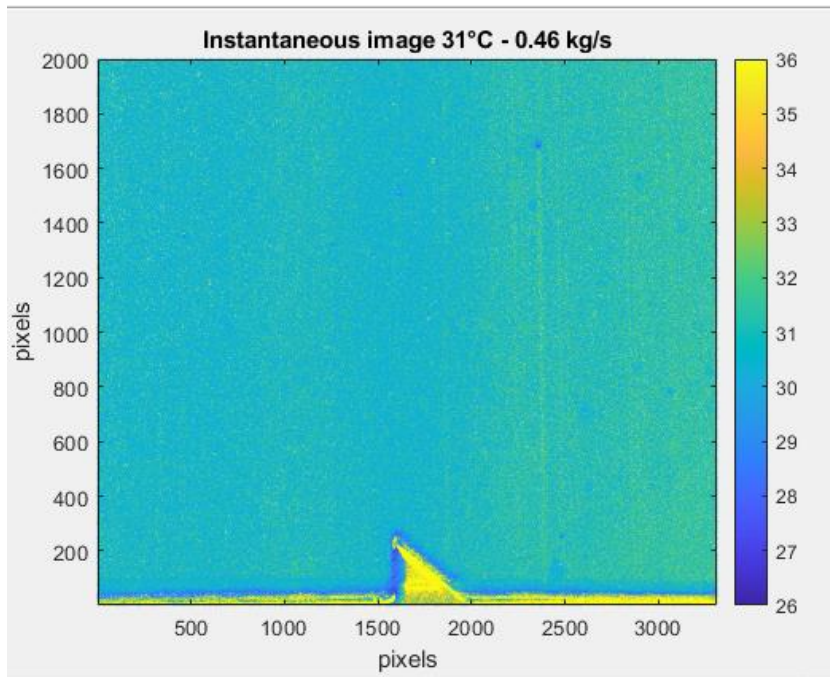


Figure 5-17 Instantaneous image when the water temperature is 31°C

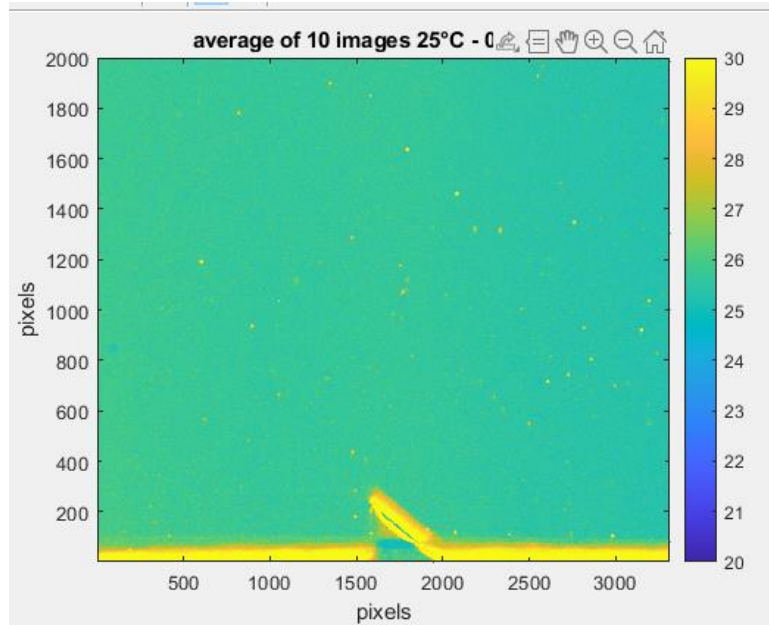


Figure 5-18 Average of ten images when the water temperature is 25°C

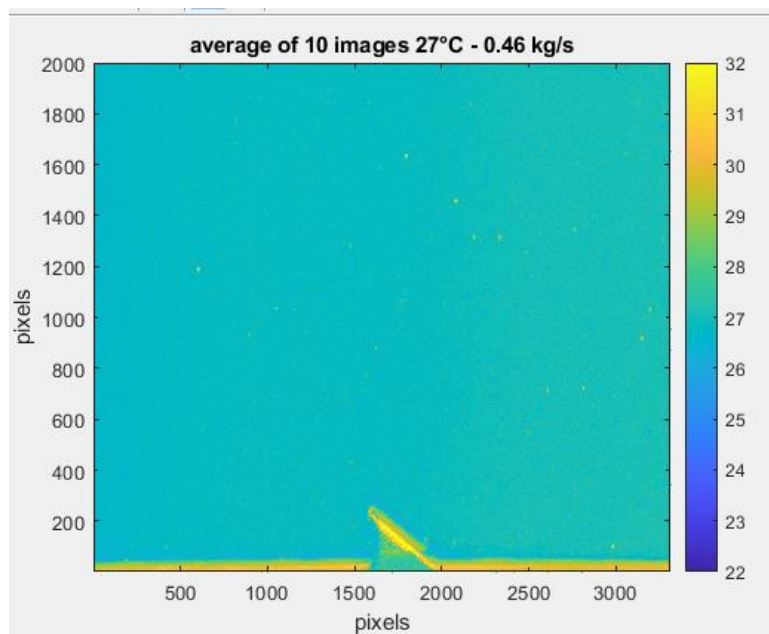


Figure 5-19 Average of ten images when the water temperature is 27°C

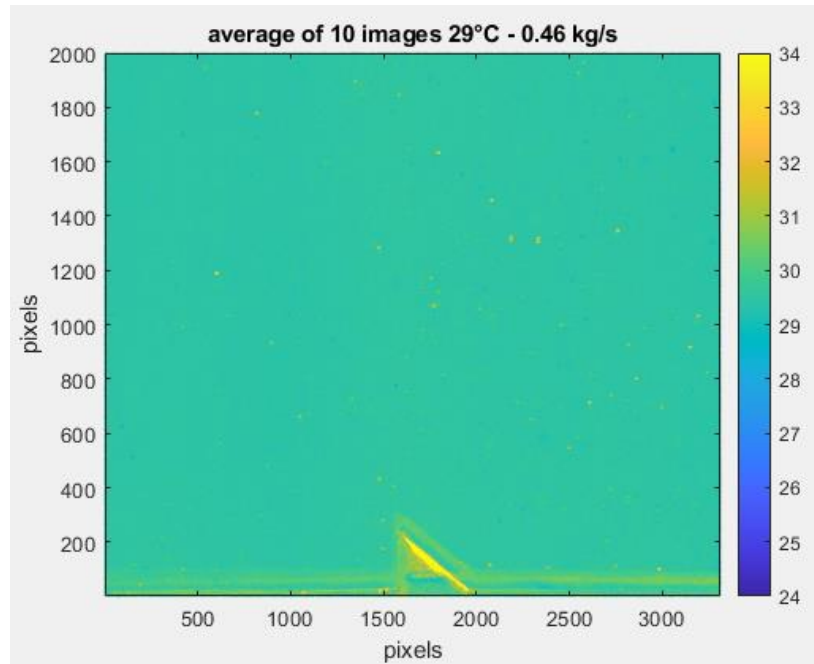


Figure 5-20 Average of ten images when the water temperature is 29°C

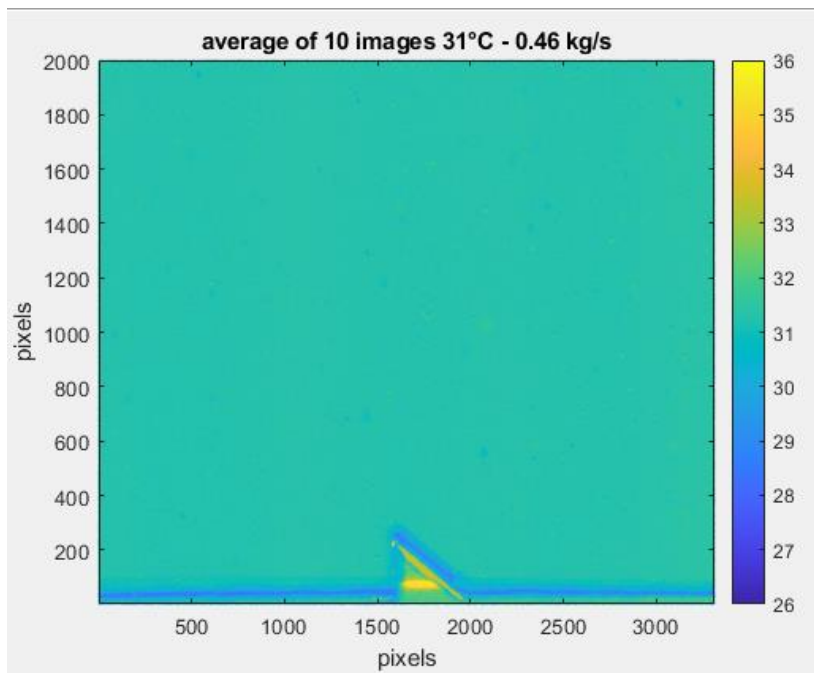


Figure 5-21 Average of ten images when the water temperature is 31°C

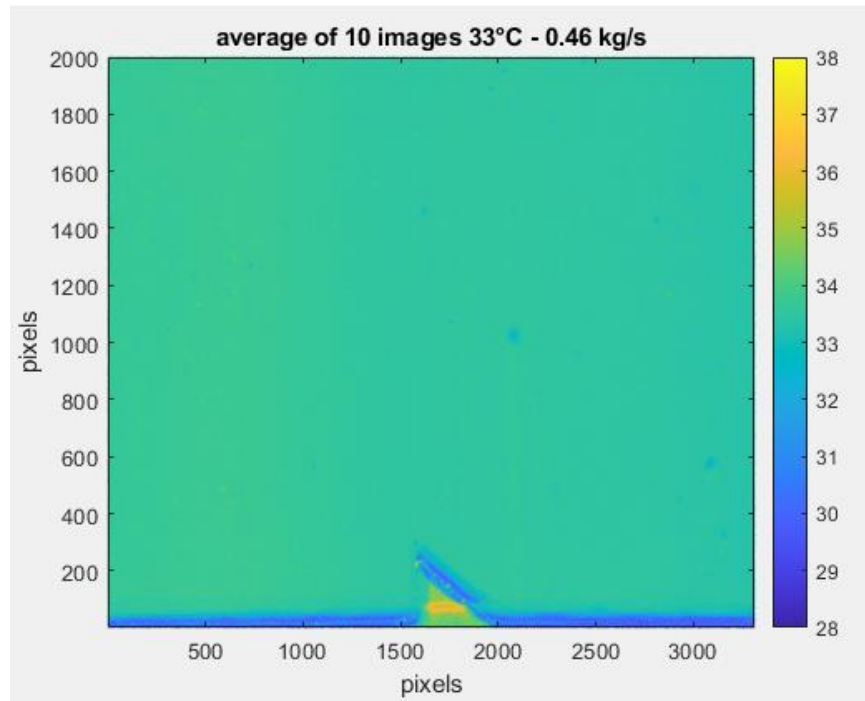


Figure 5-22 Average of ten images when the water temperature is 33°C

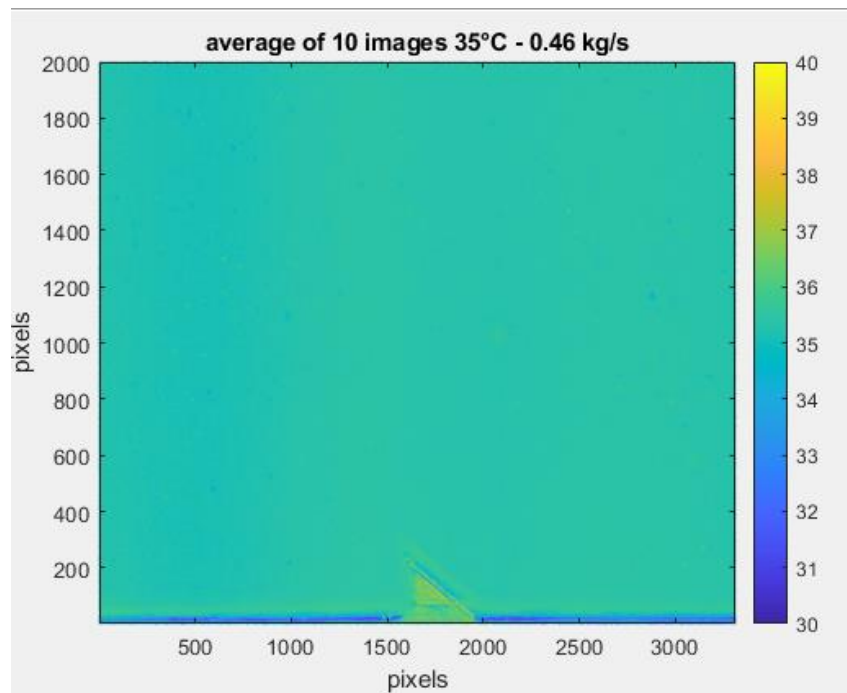


Figure 5-23 Average of ten images when the water temperature is 35°C

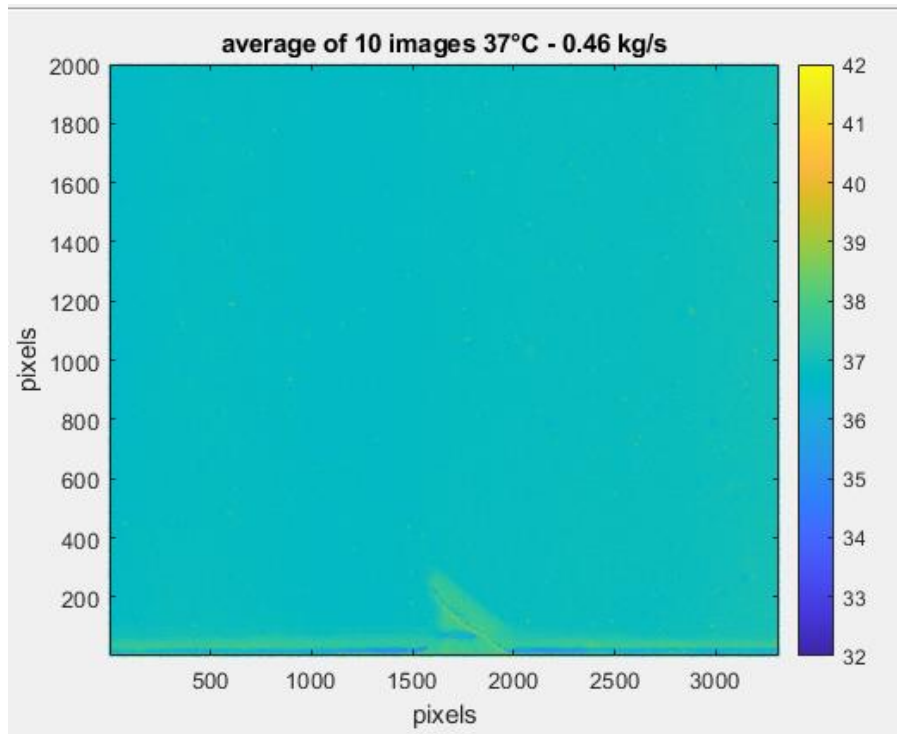


Figure 5-24 Average of ten images when the water temperature is 37°C

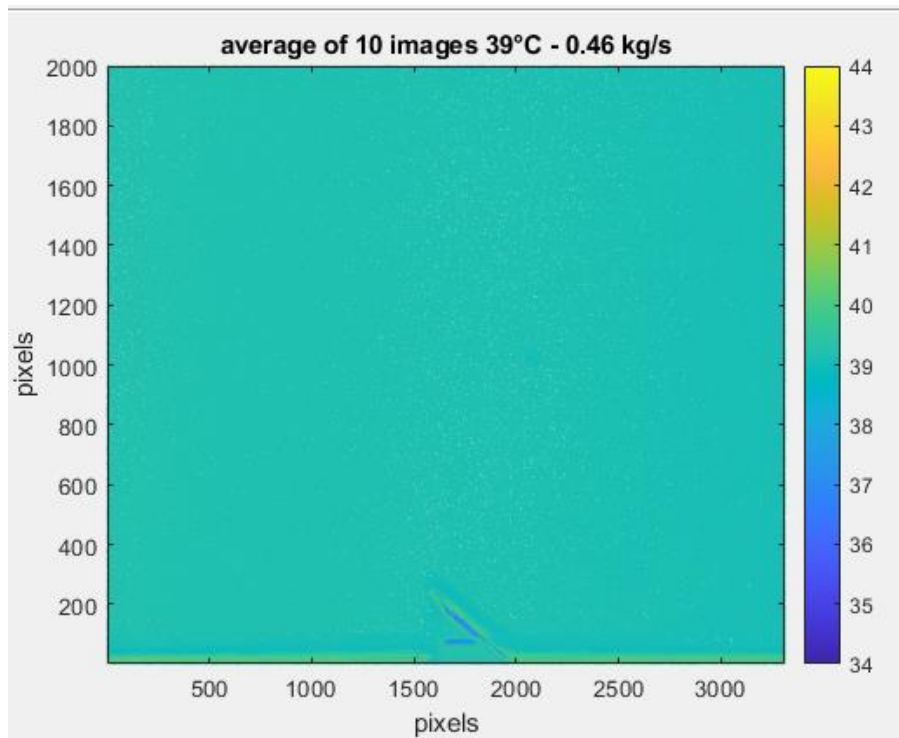


Figure 5-25 Average of ten images when the water temperature is 39°C

5.4 Photobleaching

To investigate the impact of photobleaching on the results, the isothermal images were taken twice. The first time, the images were captured for the eight temperatures. Next, the test section was heated to capture 20 images for the heating case. Then, after cooling the water, the images were captured for the eight temperatures for the second time, with about one hour between the first isothermal images and the second ones. Figure 5-26 shows the grayscale of a certain vertical line for temperature 25°C. It presents the results of the first and second runs. The two curves are almost identical, which means photobleaching did not affect the results.

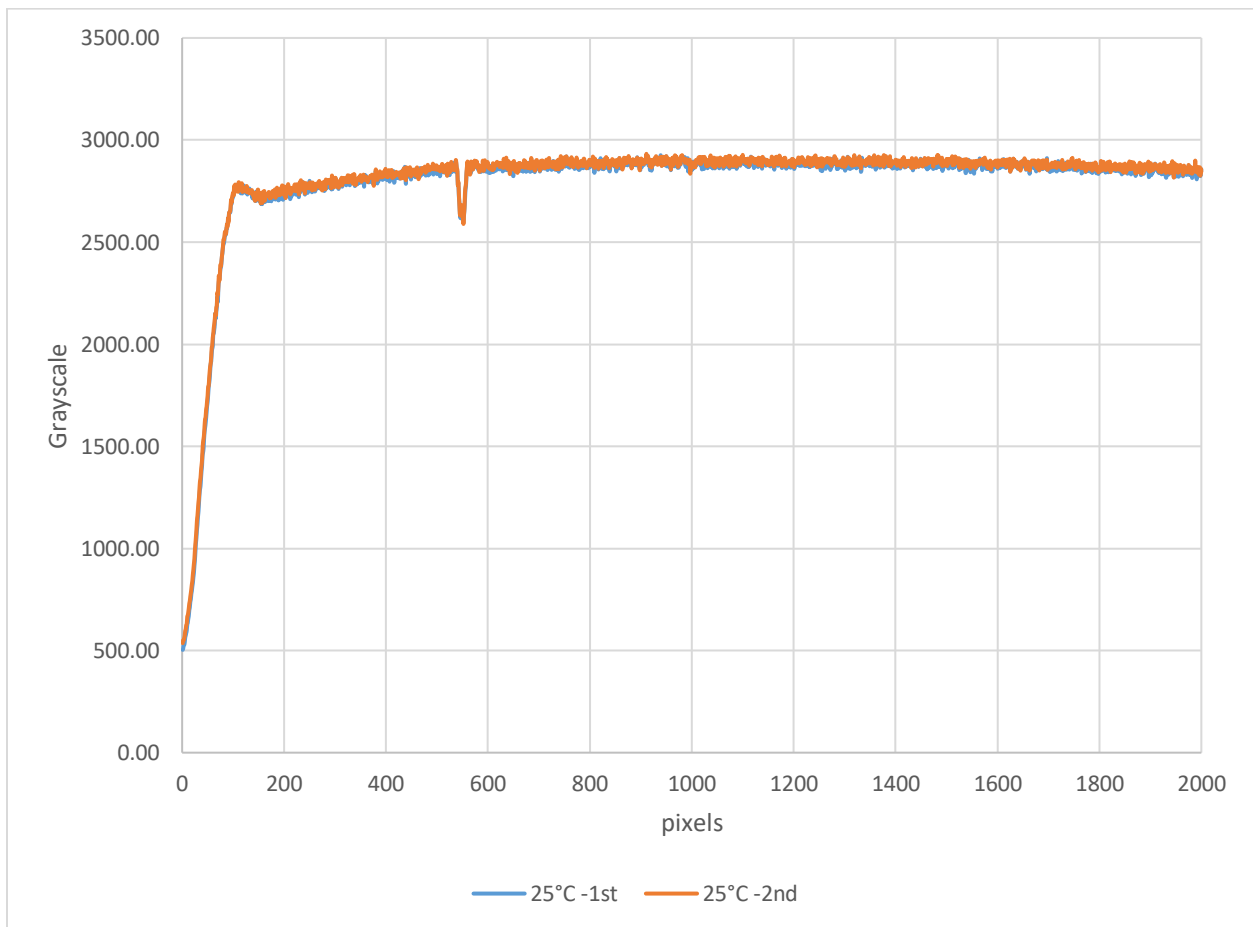


Figure 5-26 Grayscale of a certain vertical line for temperature 25°C from two runs

5.5 Estimate the error of measuring the temperature field using PLIF

To estimate the error, random error and systematic error were calculated. As illustrated in Figure 5-27, random error is for the random variation of the measurement data about its average, while systematic error is the difference between the average of the measurement data and the true value [31]. After measuring the field temperature of ten images at a certain temperature, random error was calculated by finding the standard deviation of the ten images' results at each pixel. Then, that standard deviation of each pixel was multiplied by two to get the random error with a confidence of 95%. To calculate the systematic error, the average of the field temperature of ten images at a certain temperature was calculated for each pixel. Then, the difference between the average of the temperature field of each pixel and the temperature measured by the thermocouple was calculated. Figures 5-28 and 5-29 show the random error and the systematic error at 25°C, respectively. Figures 5-30 and 5-31 show the random error and the systematic error at 27°C, respectively.

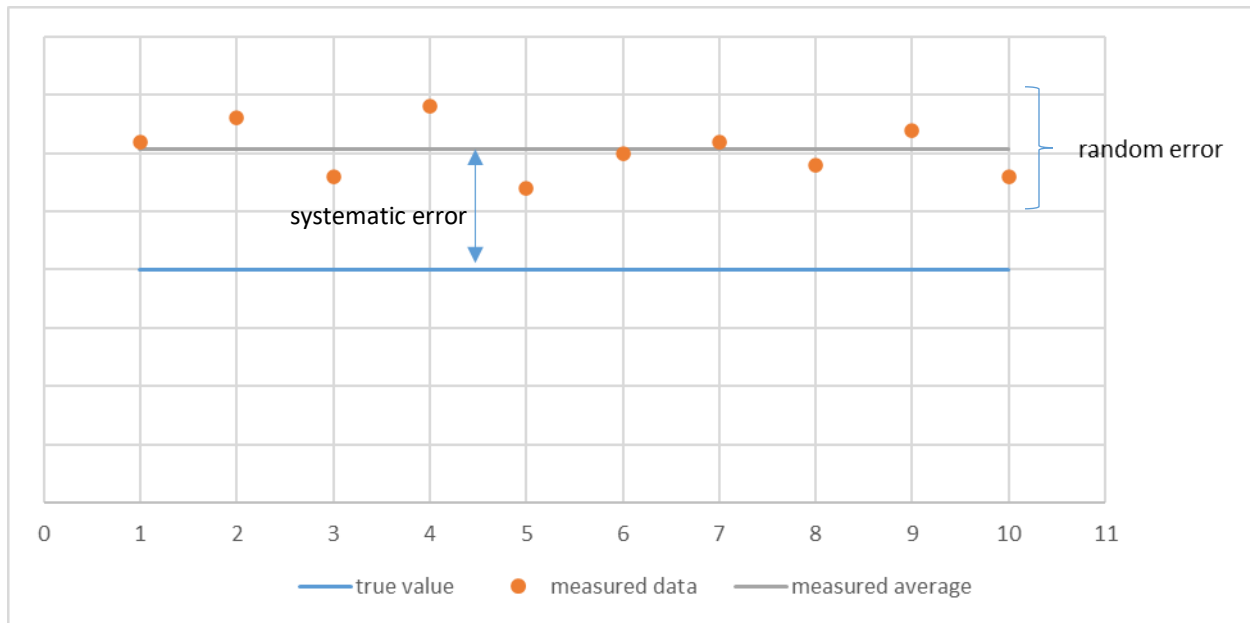


Figure 5-27 Illustration of systematic error and random error

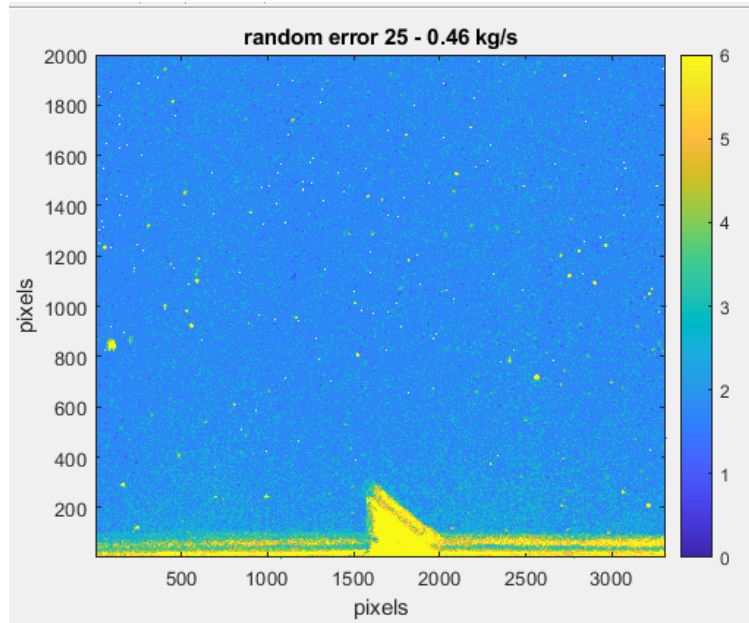


Figure 5-28 Random error at 25°C

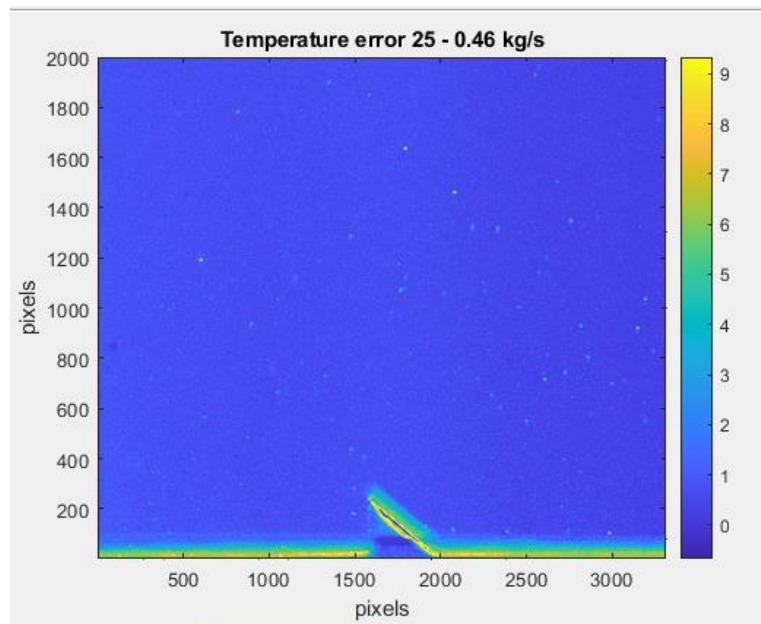


Figure 5-29 Systematic error at 25°C

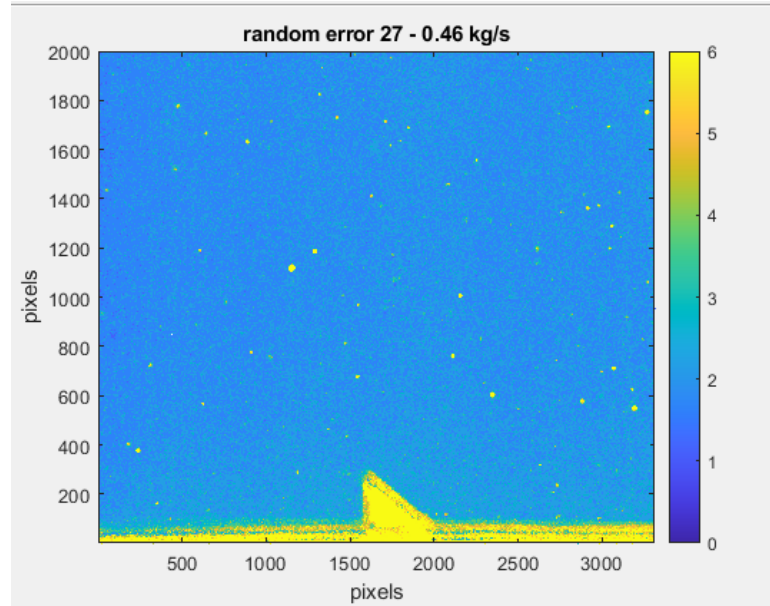


Figure 5-30 Random error at 27°C

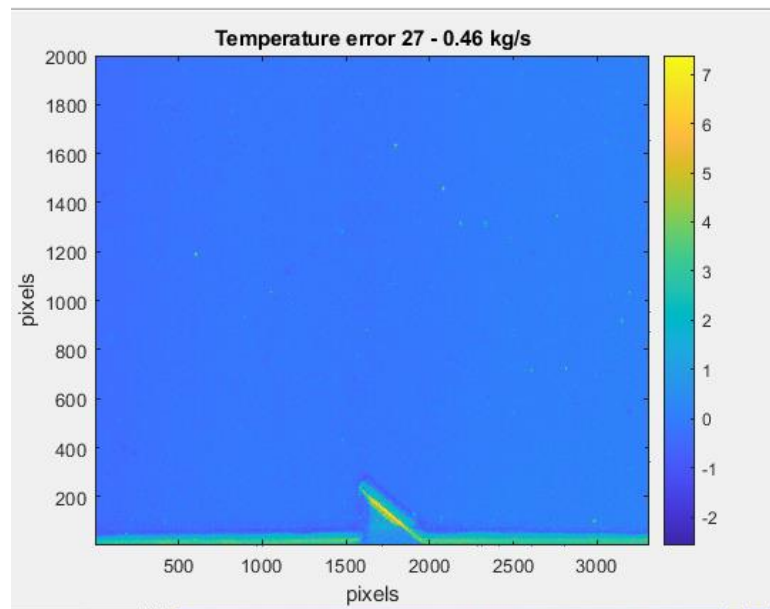


Figure 5-31 Systematic error at 27°C

The estimated error was high at the zone close to the surface. More investigation for the zone close to the surface showed that there is no proportionality between the temperature and the grayscale at that zone. The proportionality appears after 50 pixels from the surface. Figures 5-32 to 5-35 show the grayscale results at temperatures 25°C, 27°C, 29°C, 31°C, 33°C, 35°C, 37°C,

and 39°C of points (10,2500), (20,2500), (50,2500) and (100,2500), respectively. In points (10,2500) and (20,2500), there is no proportionality anyhow. A kind of proportionality appears at point (50,2500), but is not useful in temperature prediction. At point (100,2500), there is a clear proportionality between the grayscale and the temperature. This phenomenon prevents accurate temperature measurements close to the surface. It is speculated that this is due to the random laser reflection at the surface. R square was calculated for each pixel to estimate the accuracy of the deduced temperature calibration curves. The R square is shown in Figure 5-36.

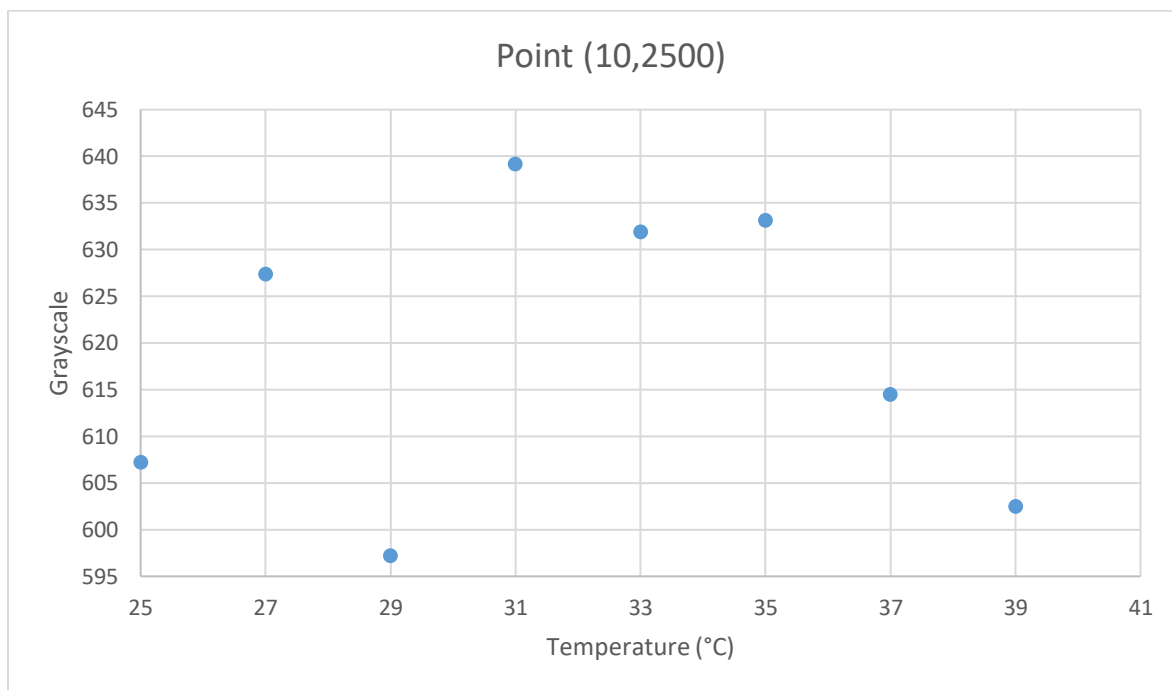


Figure 5-32 Grayscale at point (10,2500)

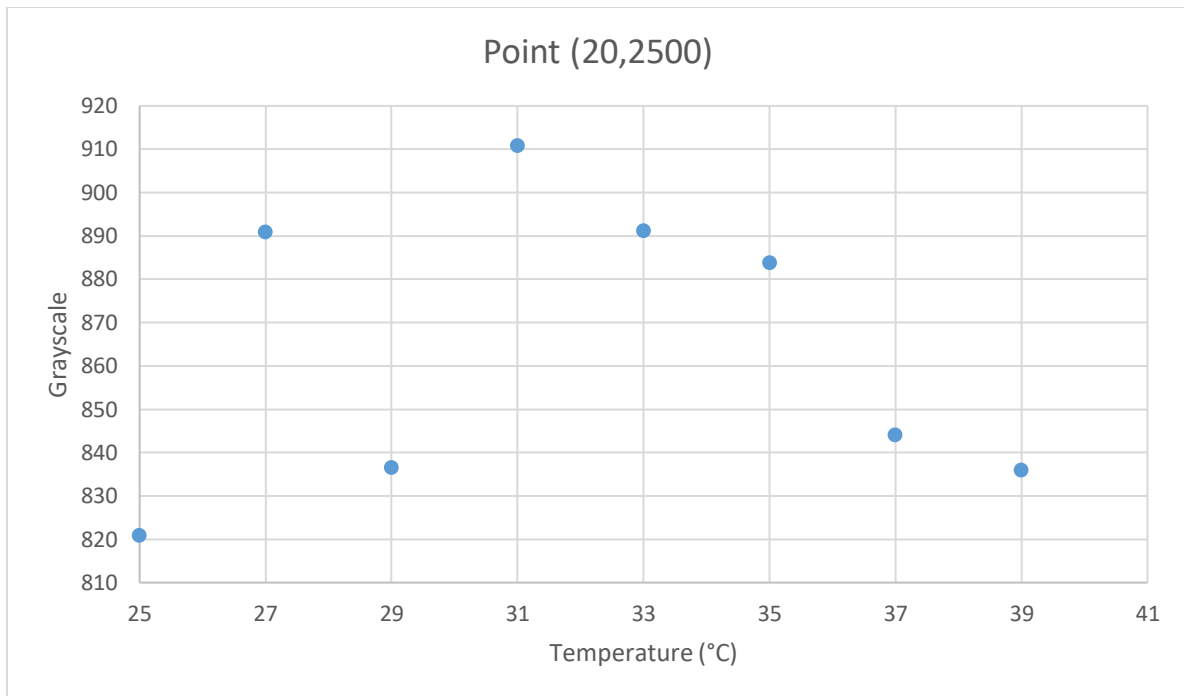


Figure 5-33 Grayscale at point (20,2500)

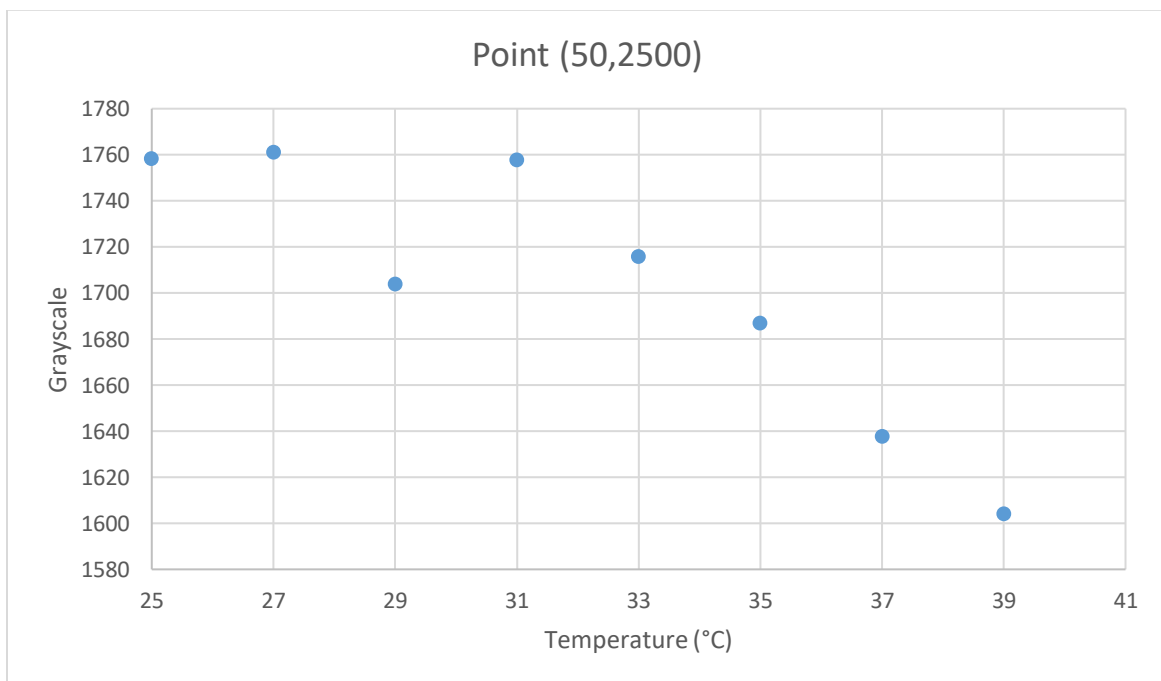


Figure 5-34 Grayscale at point (50,2500)

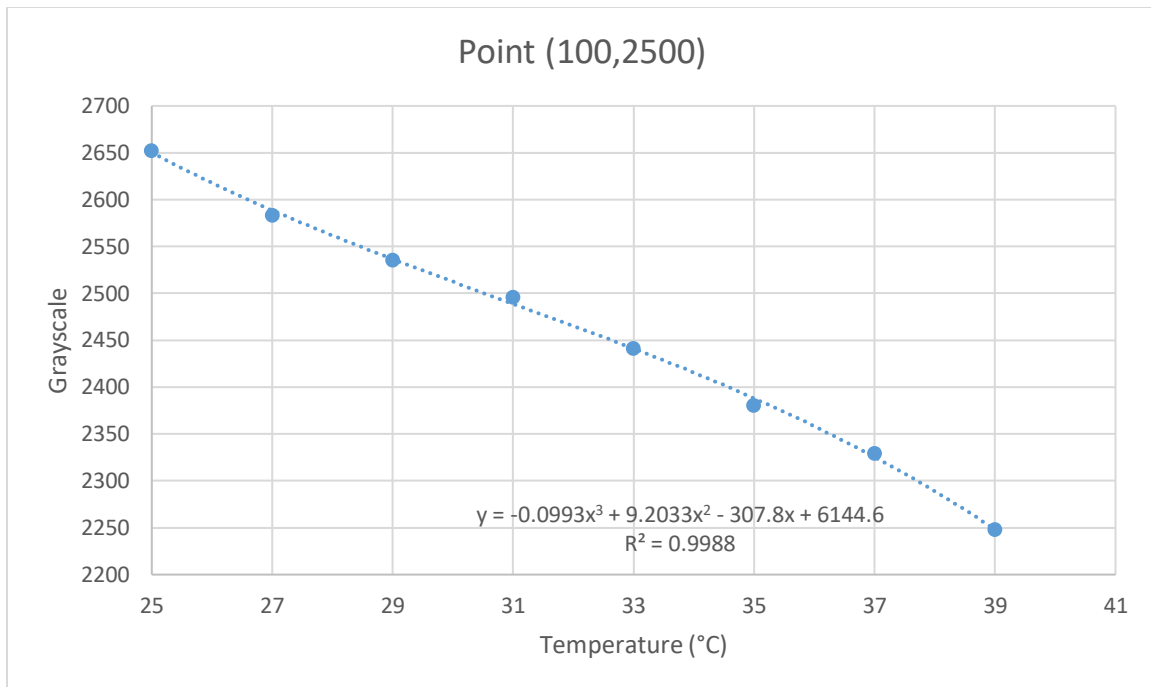


Figure 5-35 Grayscale at point (100,2500)

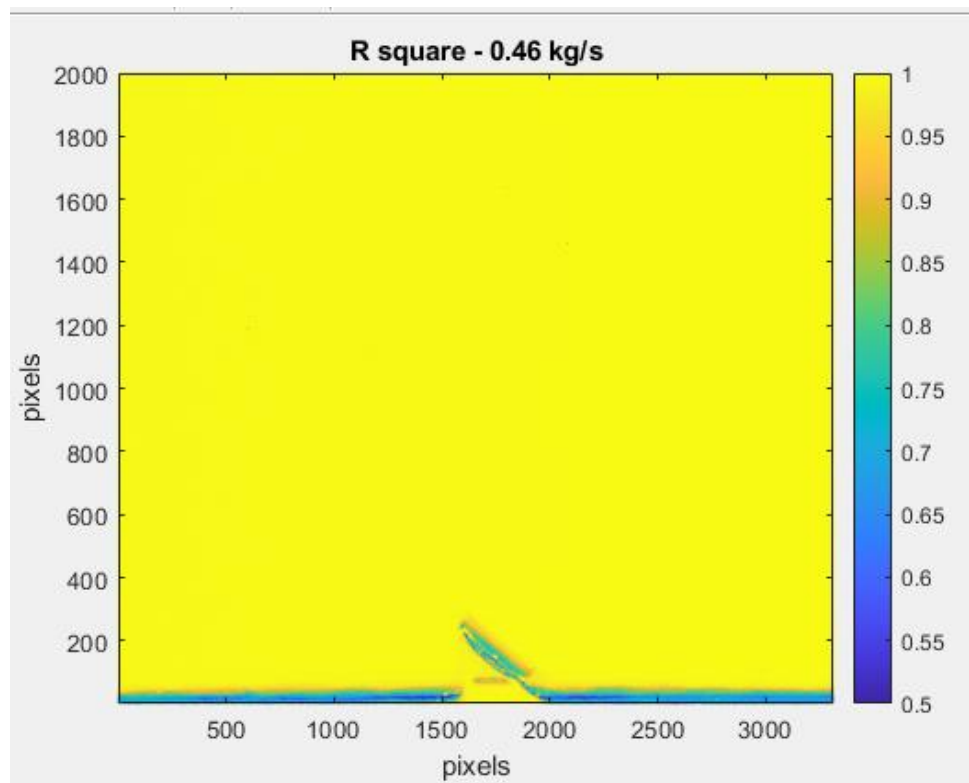


Figure 5-36 R square

5.6 The effect of changing the laser energy, camera aperture, and laser sheet thickness

5.6.1 The effect of the aperture

The camera aperture controls the light quantity that gets into the camera sensor. The camera aperture affects the focal depth. The smallest focal depth is with the largest aperture, while the largest focal depth is with the smallest aperture. Three apertures were examined to check which one produced better results in PLIF experiments. The three examined apertures are small (F/16), medium (F/4), and large (F/1.4). For each aperture, ten images were captured for three temperatures: 25°C, 30°C, and 35°C. The average grayscale and standard deviation of each image were calculated. Then, the percentage ratio of the standard deviation to the average of each image was calculated. The results are presented in Table 5-2.

In Table 5-2, the orange zone shows the average grayscale of each image of temperatures 25°C, 30°C, and 35°C at the three tested apertures. The purple zone shows the standard deviation of the grayscale of each image of temperatures 25°C, 30°C, and 35°C at the three tested apertures. The green zone shows the percentage ratio of the standard deviation to the average of the grayscale of each image of temperatures 25°C, 30°C, and 35°C at the three tested apertures.

The table shows that the percentage ratio of the standard deviation to the average of each image in the small aperture case is almost 8%, while it is about 4% in the medium and large aperture cases. The results show that conducting PLIF with a medium aperture or large aperture will give less pixel-to-pixel variation. Increasing the pixel-to-pixel variation will not affect the results' error if a temperature calibration curve was made for each pixel. However, it could increase the results' error if one temperature calibration curve was made with respect to the average grayscale of all pixels of the images.

Table 5-2 Comparison of grayscale value of three camera apertures

	Small aperture			medium aperture			large aperture		
	Average grayscale			Average grayscale			Average grayscale		
	25 °C	30 °C	35 °C	25 °C	30 °C	35 °C	25 °C	30 °C	35 °C
1	58.73	55.15	51.85	1089.48	1025.81	947.15	1912.48	1953.25	1877.65
2	58.62	55.68	52.22	1085.02	1028.45	953.06	2023.98	1966.50	1848.49
3	59.05	55.30	52.20	1091.10	1017.10	963.99	2059.97	1971.20	1837.27
4	58.65	55.09	52.12	1088.18	1029.78	955.17	2091.52	1980.37	1841.05
5	58.89	55.82	51.61	1078.52	1029.80	954.30	2133.33	1965.75	1834.77
6	58.39	55.11	52.34	1085.59	1033.32	963.29	2142.59	1993.57	1860.26
7	58.38	55.33	51.96	1087.96	1023.74	956.74	2148.63	1975.14	1837.90
8	58.55	55.18	52.26	1076.37	1021.91	960.19	2163.32	1967.46	1851.18
9	58.90	55.30	52.31	1080.57	1029.01	953.71	2158.58	1957.74	1855.49
10	58.65	55.74	52.00	1088.28	1027.16	960.33	2160.41	1968.80	1847.06
	standard deviation			standard deviation			standard deviation		
1	4.91	4.76	4.60	44.81	42.26	41.44	75.99	92.30	84.23
2	4.86	4.81	4.67	44.82	43.73	41.83	89.42	92.39	82.33
3	4.89	4.73	4.64	45.99	39.51	41.46	81.71	91.45	85.52
4	4.88	4.74	4.59	43.47	41.29	40.07	85.52	98.36	79.72
5	4.97	4.80	4.61	44.04	43.12	38.88	80.83	93.02	87.03
6	4.89	4.73	4.62	44.09	42.59	41.59	89.70	92.82	88.23
7	4.89	4.80	4.61	46.10	41.10	43.12	91.46	88.24	87.01
8	4.89	4.75	4.59	44.65	40.04	40.95	95.71	89.18	76.45
9	4.97	4.73	4.64	46.10	43.31	39.55	98.12	94.60	89.82
10	4.86	4.75	4.62	50.36	43.87	38.08	106.19	89.56	87.70
	standard deviation/ average			standard deviation/ average			standard deviation/ average		
1	8.4%	8.6%	8.9%	4.1%	4.1%	4.4%	4.0%	4.7%	4.5%
2	8.3%	8.6%	8.9%	4.1%	4.3%	4.4%	4.4%	4.7%	4.5%
3	8.3%	8.5%	8.9%	4.2%	3.9%	4.3%	4.0%	4.6%	4.7%
4	8.3%	8.6%	8.8%	4.0%	4.0%	4.2%	4.1%	5.0%	4.3%

5	8.4%	8.6%	8.9%	4.1%	4.2%	4.1%	3.8%	4.7%	4.7%
6	8.4%	8.6%	8.8%	4.1%	4.1%	4.3%	4.2%	4.7%	4.7%
7	8.4%	8.7%	8.9%	4.2%	4.0%	4.5%	4.3%	4.5%	4.7%
8	8.3%	8.6%	8.8%	4.1%	3.9%	4.3%	4.4%	4.5%	4.1%
9	8.4%	8.6%	8.9%	4.3%	4.2%	4.1%	4.5%	4.8%	4.8%
10	8.3%	8.5%	8.9%	4.6%	4.3%	4.0%	4.9%	4.5%	4.7%

5.6.2 The effect of changing the laser energy

The experiment was conducted with low-, medium-, and high-energy lasers to capture ten images of temperatures 25°C, 30°C, and 35°C. The goal was to decide which case has better results. The grayscale results are in Table 5-3.

In the low-energy laser case, there is no proportionality between the temperature and the grayscale. The table below shows that the average grayscale of 30°C is 57.37, while the average grayscale of 35°C is 57.02. In addition, the pulse-to-pulse variation is high, as shown in the high percentage ratio of the standard deviation to the average grayscales.

In the medium and high laser energy cases, there is proportionality between the temperature and the grayscale. For the pulse-to-pulse variation, the high-energy laser is better than the medium-energy laser, because the high-energy laser has a lower percentage ratio of the standard deviation to the average grayscales than the medium-energy laser.

Table 5-3 Comparison of grayscale value of low, medium, and high laser energy

	Low energy laser			Medium energy laser			High energy laser		
	Average grayscale			Average grayscale			Average grayscale		
	25 °C	30 °C	35 °C	25 °C	30 °C	35 °C	25 °C	30 °C	35 °C
1	68.79	59.26	53.88	1648.69	1549.93	1420.29	2046.18	1907.17	1785.42
2	60.89	60.57	52.08	1646.00	1566.77	1412.82	2032.70	1923.49	1785.51
3	67.93	58.52	60.84	1626.38	1526.68	1439.61	2029.51	1917.31	1792.14
4	69.56	48.87	56.83	1669.76	1538.00	1435.76	2028.27	1925.86	1793.73
5	52.57	65.54	54.39	1675.27	1566.45	1432.12	2038.21	1915.42	1795.39
6	63.82	55.30	62.59	1643.89	1547.89	1425.94	2047.10	1914.37	1797.89
7	63.70	63.69	54.06	1653.36	1534.31	1436.95	2020.41	1921.17	1790.60
8	67.02	58.64	60.92	1660.84	1563.45	1429.89	2040.74	1918.44	1796.39
9	72.62	58.07	53.69	1667.81	1544.16	1446.36	2039.29	1924.80	1789.47
10	67.94	45.26	60.93	1647.61	1544.57	1436.45	2038.89	1917.73	1797.10
average	65.48	57.37	57.02	1653.96	1548.22	1431.62	2036.13	1918.58	1792.36
standard deviation									
deviation	5.35	5.89	3.70	13.92	13.05	9.31	7.93	5.32	4.32
percentage ratio	8.2%	10.3%	6.5%	0.8%	0.8%	0.7%	0.4%	0.3%	0.2%

5.6.3 The effect of changing the laser sheet thickness

The experiment was conducted with a thick and thin laser sheet to capture ten images of temperatures 25°C, 30°C, and 35°C. The goal was to decide which thickness has better results.

The grayscale results of the thick laser sheet and thin laser sheet are in Table 5-4.

The results show that the thick laser sheet has less pulse-to-pulse variation, because the thick laser sheet has a lower percentage ratio of the standard deviation to the average grayscales than the thin laser sheet. In the case of the thick laser, the whole focal depth is within the laser sheet. On the other hand, the thickness of the thin laser sheet is less than the focal depth.

Table 5-4 Comparison of thick laser sheet and thin laser sheet

	Thick laser			Thin laser		
	Average grayscale			Average grayscale		
	25 °C	30 °C	35 °C	25 °C	30 °C	35 °C
	2046.18	1907.17	1785.42	1168.248	1109.818	1047.494
	2032.70	1923.49	1785.51	1186.547	1118.763	1045.932
	2029.51	1917.31	1792.14	1184.332	1110.444	1052.806
	2028.27	1925.86	1793.73	1187.23	1114.942	1044.687
	2038.21	1915.42	1795.39	1176.009	1116.219	1048.546
	2047.10	1914.37	1797.89	1185.448	1127.55	1048.166
	2020.41	1921.17	1790.60	1178.85	1113.563	1047.123
	2040.74	1918.44	1796.39	1181.149	1112.496	1035.616
	2039.29	1924.80	1789.47	1196.544	1105.408	1043.359
	2038.89	1917.73	1797.10	1184.817	1118.581	1050.128
average	2036.13	1918.58	1792.36	1182.92	1114.78	1046.39
standard deviation	7.93	5.32	4.32	7.16	5.77	4.39
percentage ratio	0.4%	0.3%	0.2%	0.6%	0.5%	0.4%

5.7 Summary

This chapter presented field temperature measurements of isothermal water by PLIF. The creation of the temperature calibration curve was explained. The photobleaching effect was investigated. The temperature sensitivity was calculated for each pixel. The temperature error was estimated. The effect of changing the camera aperture, laser energy, and laser sheet thickness on the PLIF results was examined.

Chapter 6 - PLIF Temperature Field Measurement for the Heated Cases

6.1 Introduction

The PLIF technique was used to measure the temperature field of a heated water flow. The measurements were conducted for several velocities and surface temperatures. The heat is from the electrical heater underneath the test section. The temperature was measured using the temperature calibration curves that were explained in Chapter 5. The results close to the surface were investigated. The PLIF results were compared to the CFD results. The temperature fields and temperature distribution curves are presented.

6.2 CFD Results

As explained in Chapter 4, the smooth and finned ducts were simulated by the FLUENT software. The goal of this simulation was to compare its results with the experimental results. For the temperature distribution curve of the smooth surface duct, temperatures along the red line shown in Figure 6-1 and located 440 mm from the inlet are used to find the temperature distribution curve for the smooth surface case. Figure 6-2 presents the two lines selected to collect data to estimate the temperature distribution curve of the finned duct. The red line before the fin is located 313.3 mm from the inlet, while the yellow line after the fin is located 320.4 mm from the inlet.

Figure 6-3 presents the temperature distribution curve in the smooth duct for four velocities when the surface temperature is 40°C, while Figure 4 is a zoom-in of Figure 6-3 to present the temperature distribution in the 2 mm height right above the surface. The figure shows that the difference between the temperature distribution curves of the four different velocities

just appears within 1 mm above the surface. After that, the curves are identical. This indicates that PLIF will not produce different temperature distribution curves for different velocities unless it can get accurate results at 1 mm right above the surface. Figure 6-5 shows the computational results of the temperature field for the case of 1.8 m/s velocity and 40°C surface temperature.

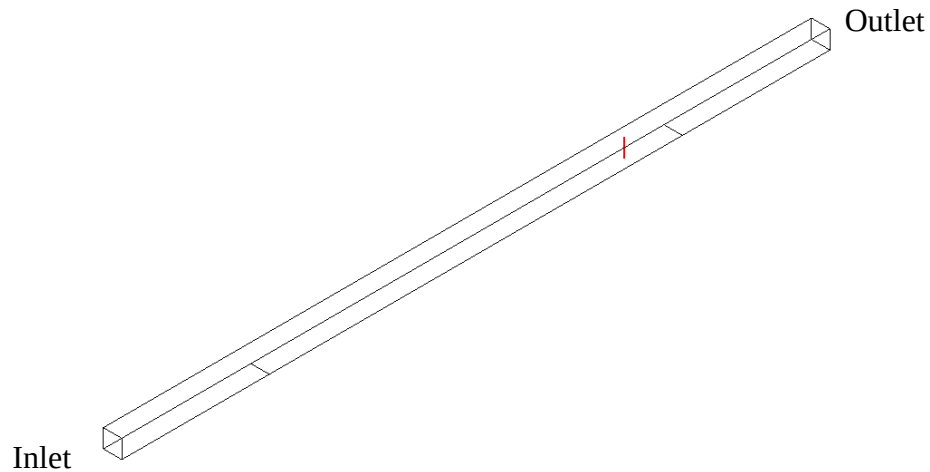


Figure 6-1 The line used to collect the data of the temperature distribution curve of the smooth surface



Figure 6-2 The lines used to collect the data of the temperature distribution curves of the finned surface

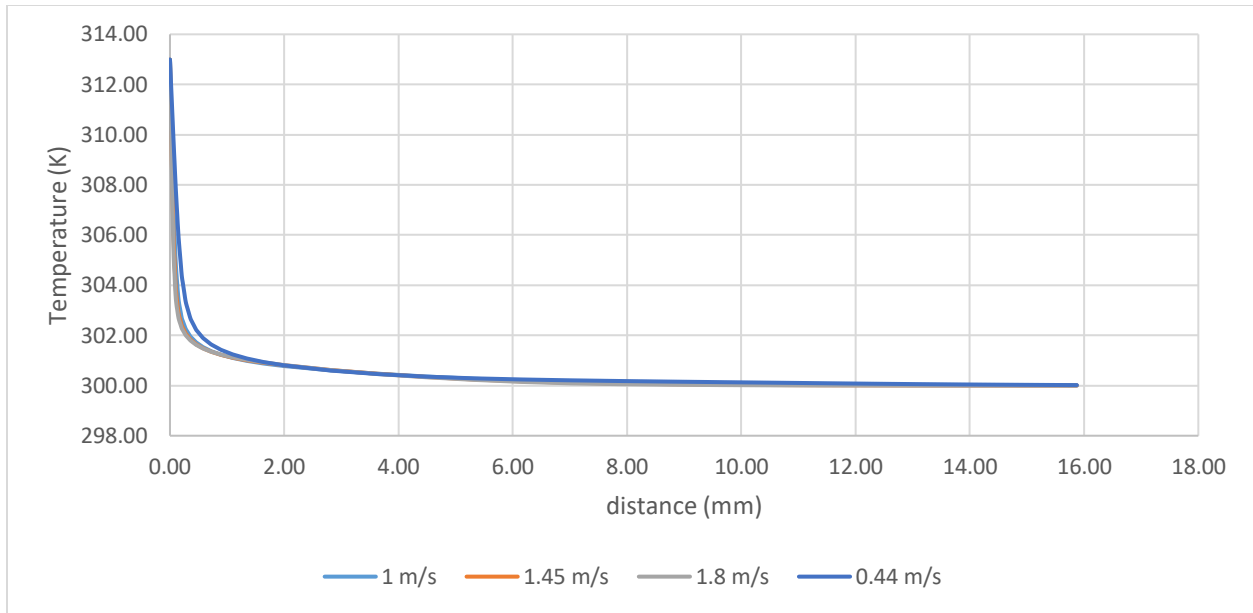


Figure 6-3 Temperature distribution curves for four velocities

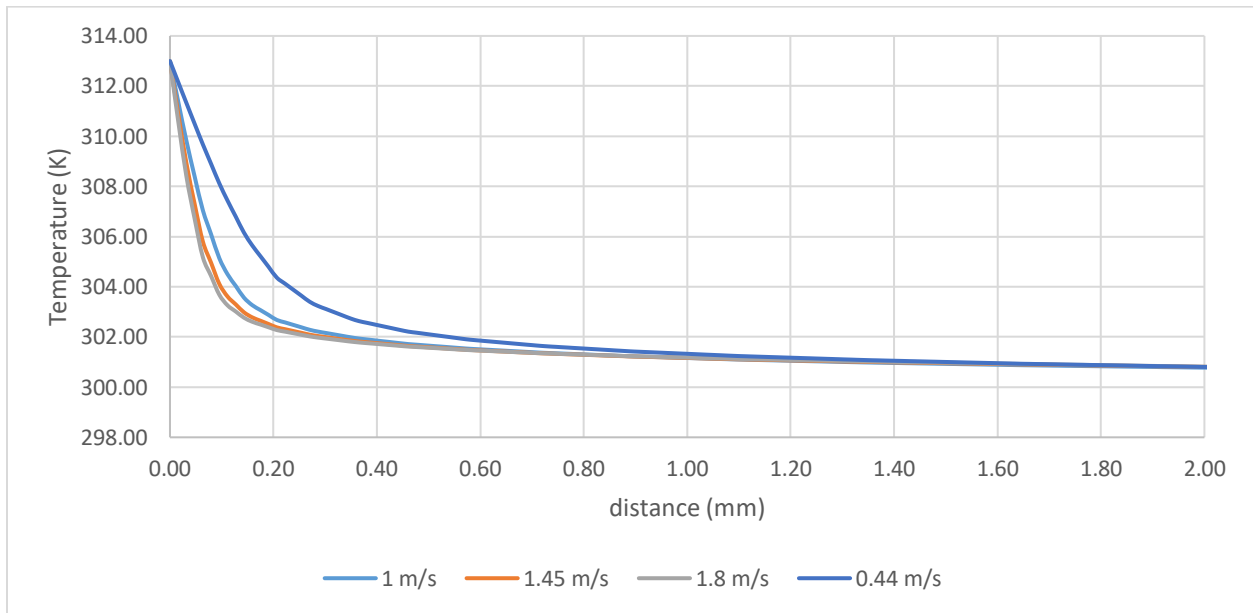


Figure 6-4 Zoom-in of the temperature distribution curves for four velocities

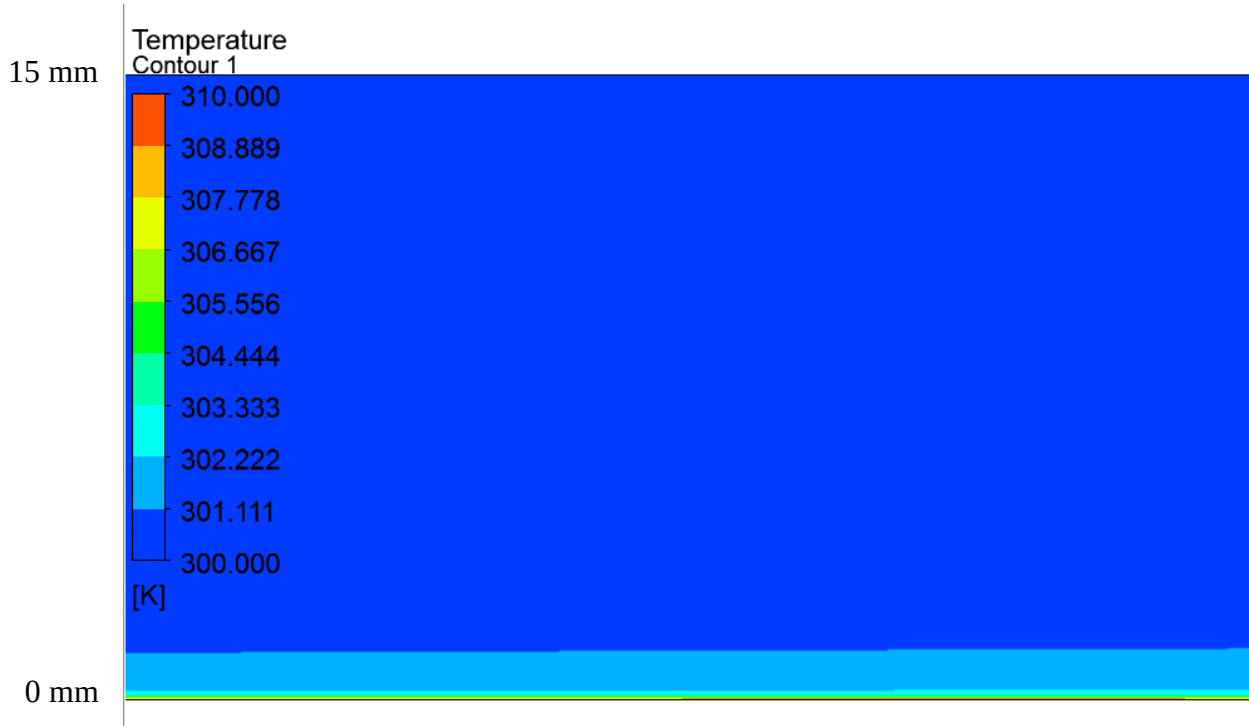


Figure 6-5 The computational results of the temperature field for the case of 1.8 m/s velocity and 40°C surface temperature

6.3 Shadowgraph effect

The supposed grayscale of a point in the heating case might be estimated depending on the estimated surface temperature and measured inlet and outlet temperatures. At point (100,2500), proportionality exists between the grayscale and the temperature, as presented in Figure 6-6. When the water velocity is 1.8 m/s, the surface temperature is 31.8°C and the inlet temperature is 25.8°C, and the grayscale at the point is 2697, which is higher than the grayscale of 25°C, meaning the temperature there is less than 25°C, which is physically impossible. For the same point and velocity, when the surface temperature is 36.41°C and the inlet temperature is 27.4, the grayscale is 2601, which is for a temperature of 26°C.

In point (500,2500), this problem disappears. Figure 6-7 shows the grayscale of temperatures 25°C, 27°C, 29°C, 31°C, 33°C, 35°C, 37°C, and 39°C. When the water velocity is

1.8 m/s, the surface temperature is 31.8°C and the inlet temperature is 25.8°C, and the grayscale at the point is 2813, which is for a temperature of 25.9°C: almost the inlet temperature and the expected temperature at this point.

At the same point, when the surface temperature is 36.41°C and the inlet temperature is 27.4, the grayscale is 2722, which is for a temperature of 28.4°C: higher than the inlet temperature by just 1°C, which is within the expected error.

It is speculated that this is due to the shadowgraph effect, which affects the accuracy of the results when the temperature gradient is higher than 1°C in 1 mm. The shadowgraph affected the accuracy of the results for the temperature gradient areas, because the intensity in these areas is affected by density variation, which causes a variation in the refractive index [5].

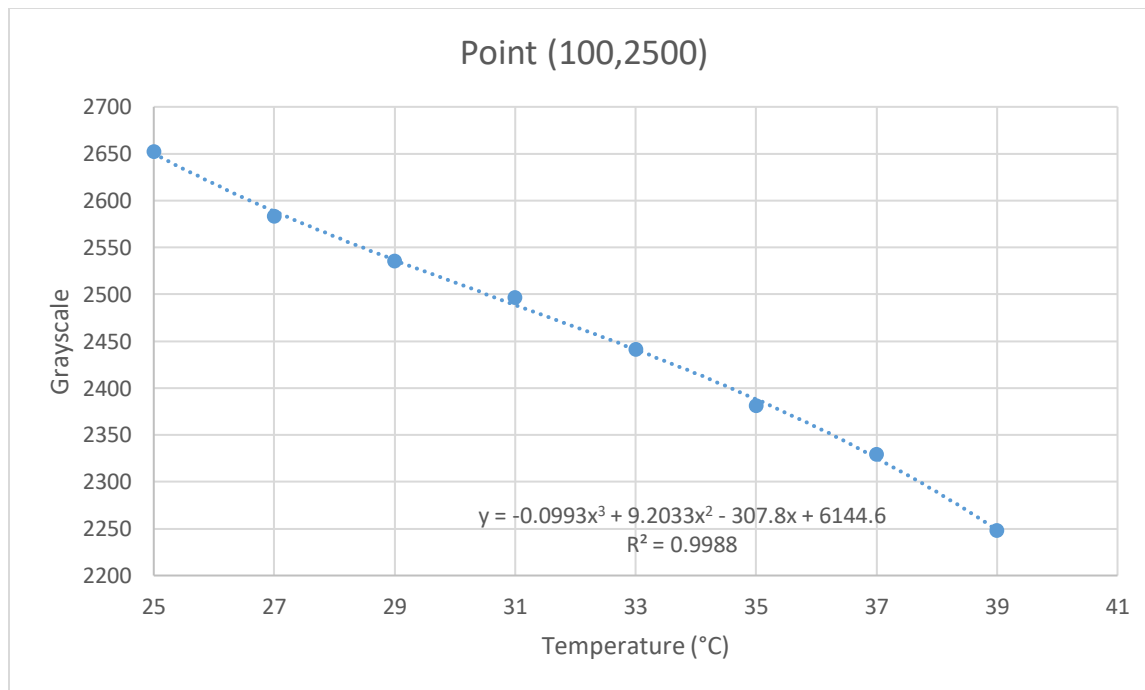


Figure 6-6 Grayscale at point (100,2500)

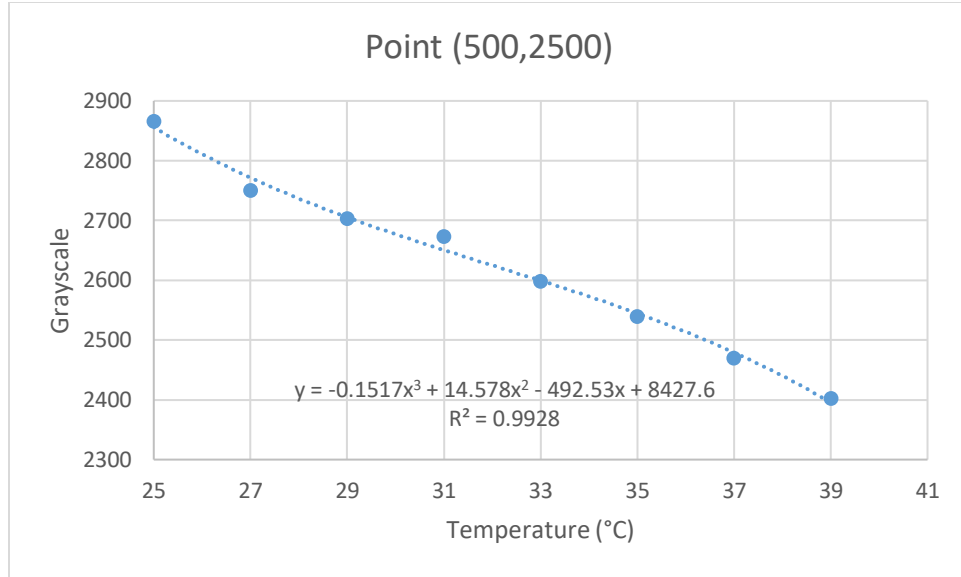


Figure 6-7 Grayscale at point (500,2500)

6.4 Heating experiment cases

After capturing the required images for the isothermal case to create the temperature calibration curve, the apparatus needs to be prepared for the heating case. In this case, the heater is on, and the inlet valve of the cooling water inlet is open. The heater power was adjusted to accommodate the required surface temperature.

The experiment was conducted for four different flow rates. For each flow rate, two surface temperatures were examined. Then, PLIF was used to measure the temperature field of eight cases of heating, which are listed in Table 6-1. All cases are in turbulent flow.

Table 6-1 Experimental heating cases

cases	flow rate (kg/s)	velocity (m/s)	Reynolds number	Surface temperature (°C)	Inlet Temperature (°C)	outlet Temperature (°C)
1	0.46	1.80	28301	31.78	25.80	26.50
2	0.46	1.80	28301	36.41	27.40	28.20
3	0.36	1.45	22823	31.67	25.20	26.00
4	0.36	1.45	22823	36.02	26.10	27.10
5	0.26	1.05	16483	31.20	25.30	26.10
6	0.26	1.05	16483	38.25	26.90	27.90
7	0.11	0.44	6973	32.14	25.90	26.90
8	0.11	0.44	6973	37.92	27.40	28.60

6.5 Experimental results of temperature field

Figures 6-8 to 6-16 show the instantaneous temperature field results of different flow rates. Each is for one case, as listed in Table 6-1. In all of them, the significant temperature gradient is within the yellow zone. As explained before, the results in this zone are not accurate. In the results of velocities of 1 m/s and 0.44 m/s, the temperature field contains temperature structure after the fin. The results show that a temperature gradient can be captured by PLIF in the cases of low velocities and low surface temperatures.

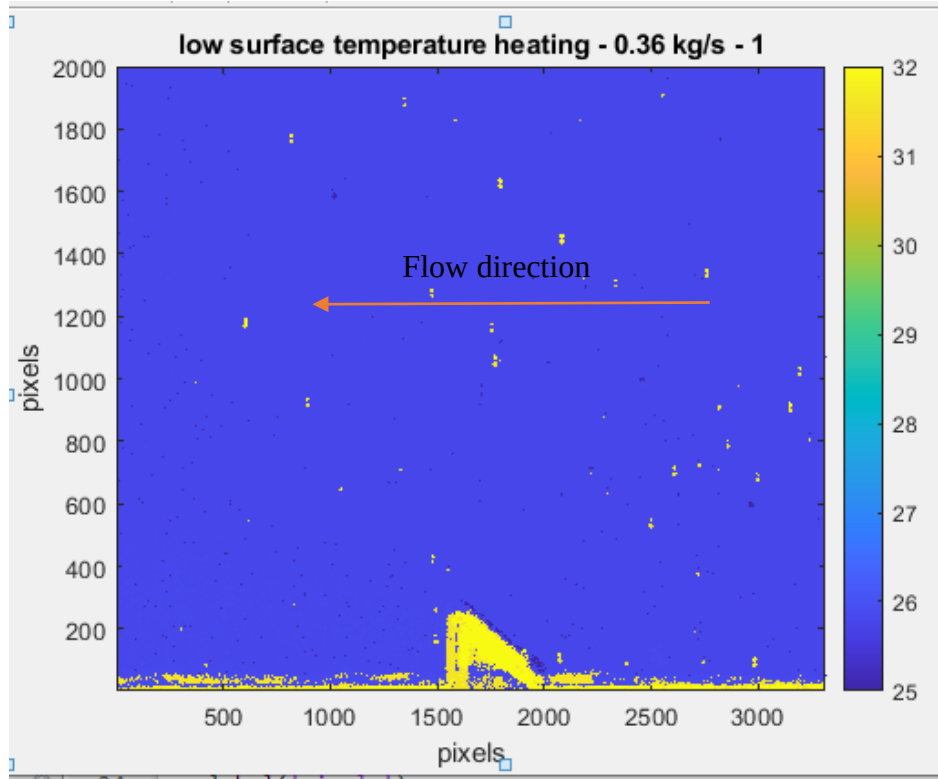


Figure 6-8 An instantaneous temperature field of the third case

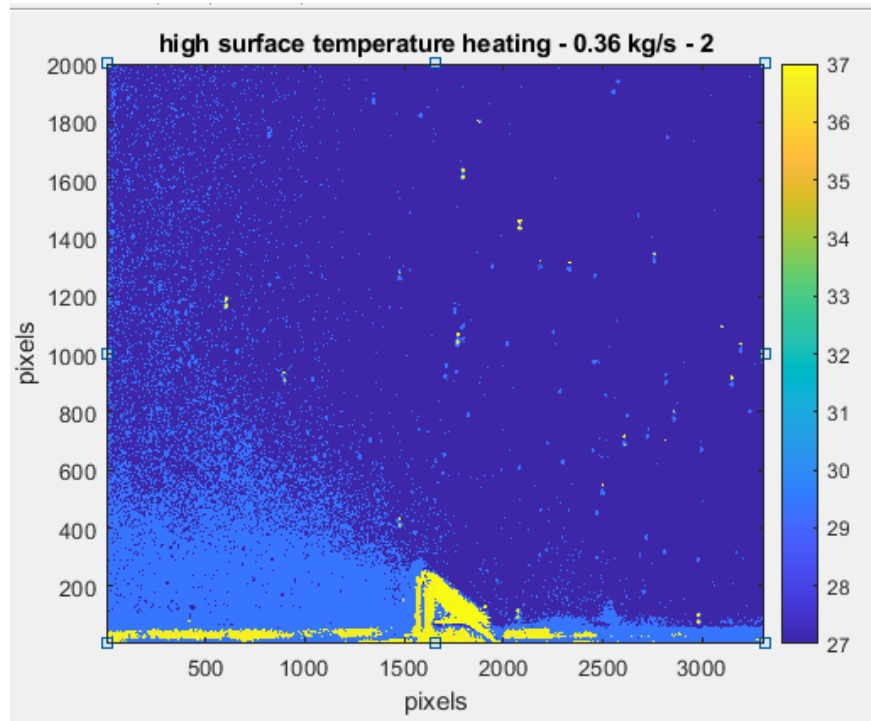


Figure 6-9 An instantaneous temperature field of the fourth case

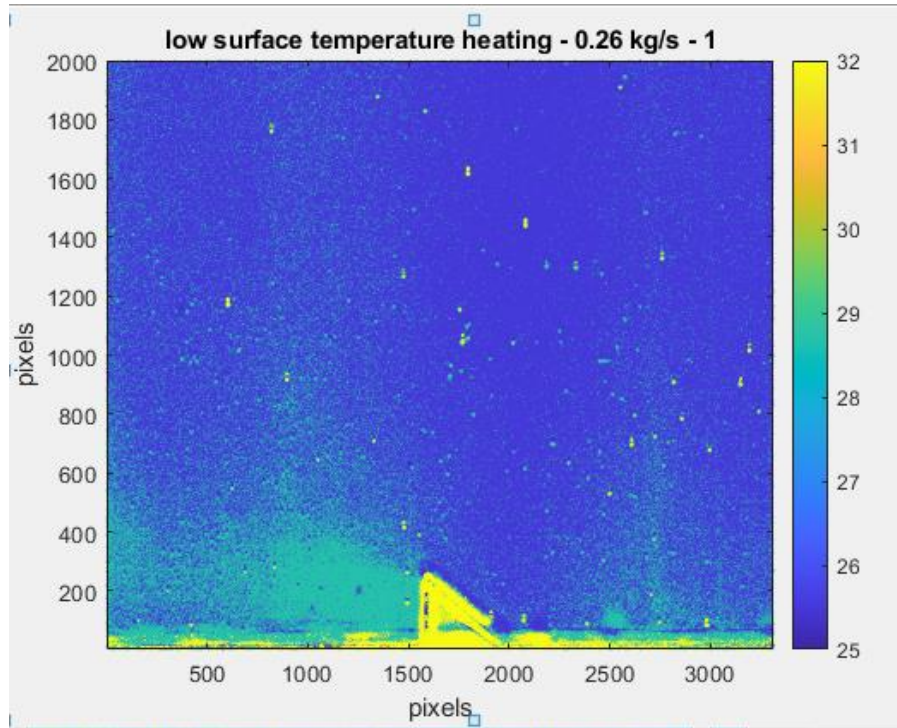


Figure 6-10 An instantaneous temperature field of the fifth case

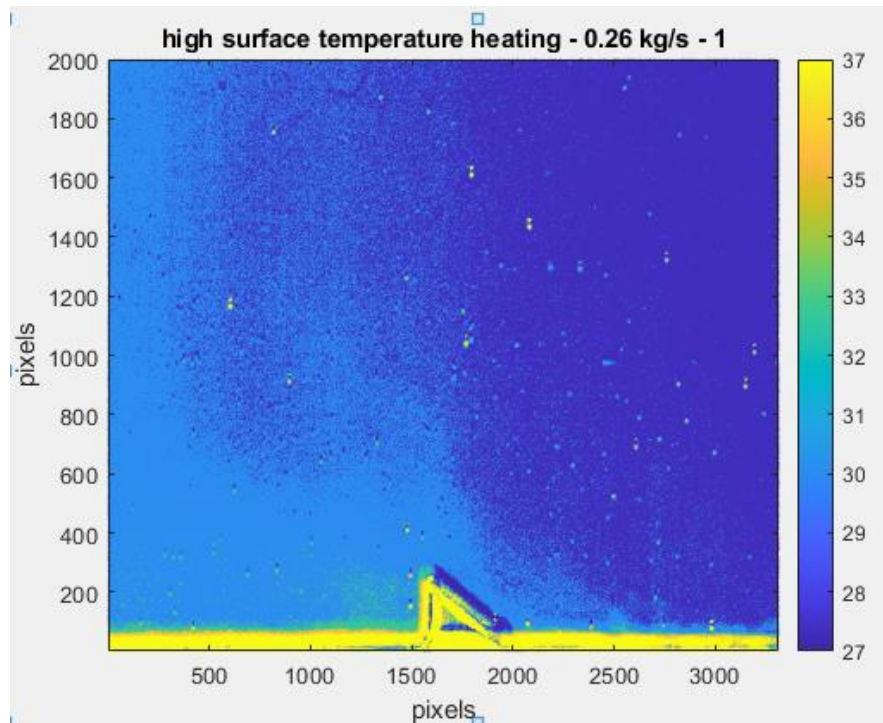


Figure 6-11 An instantaneous temperature field of the sixth case

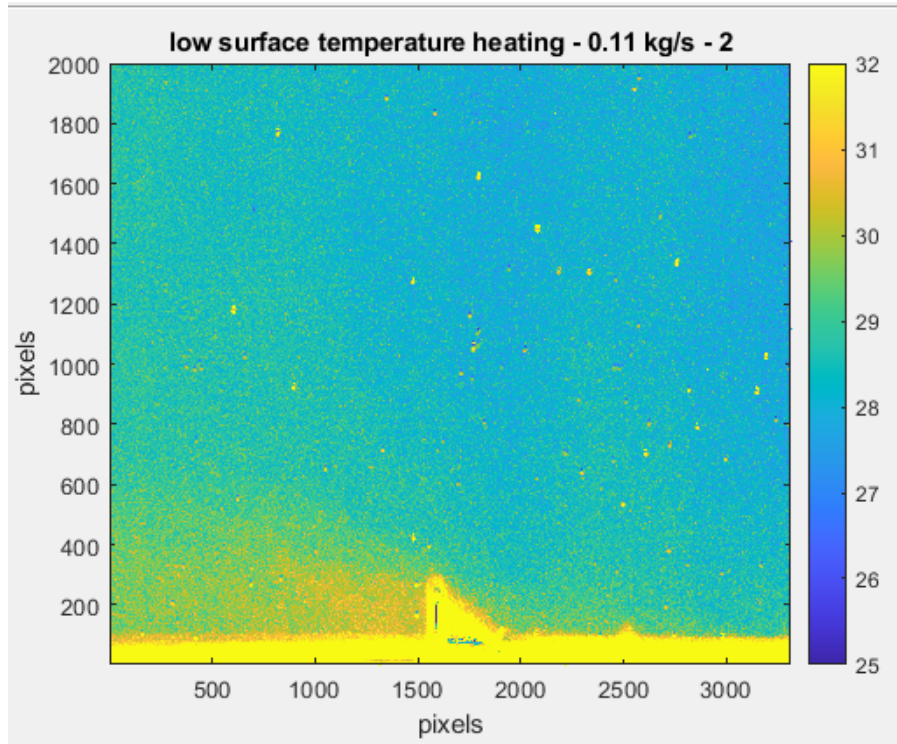


Figure 6-12 An instantaneous temperature field of the seventh case

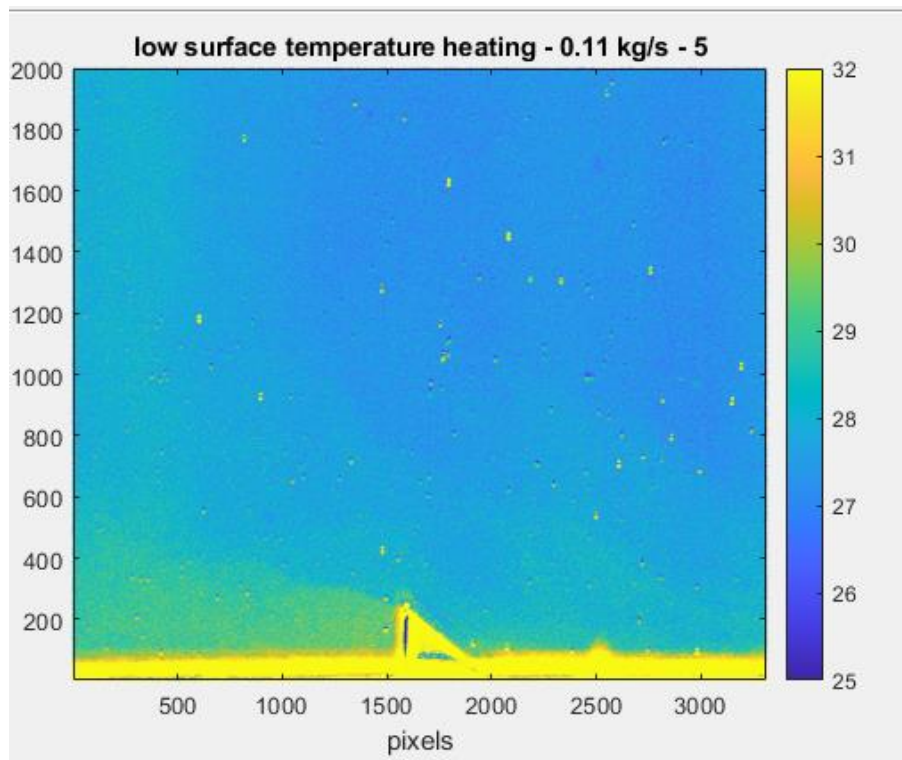


Figure 6-13 An instantaneous temperature field of the seventh case

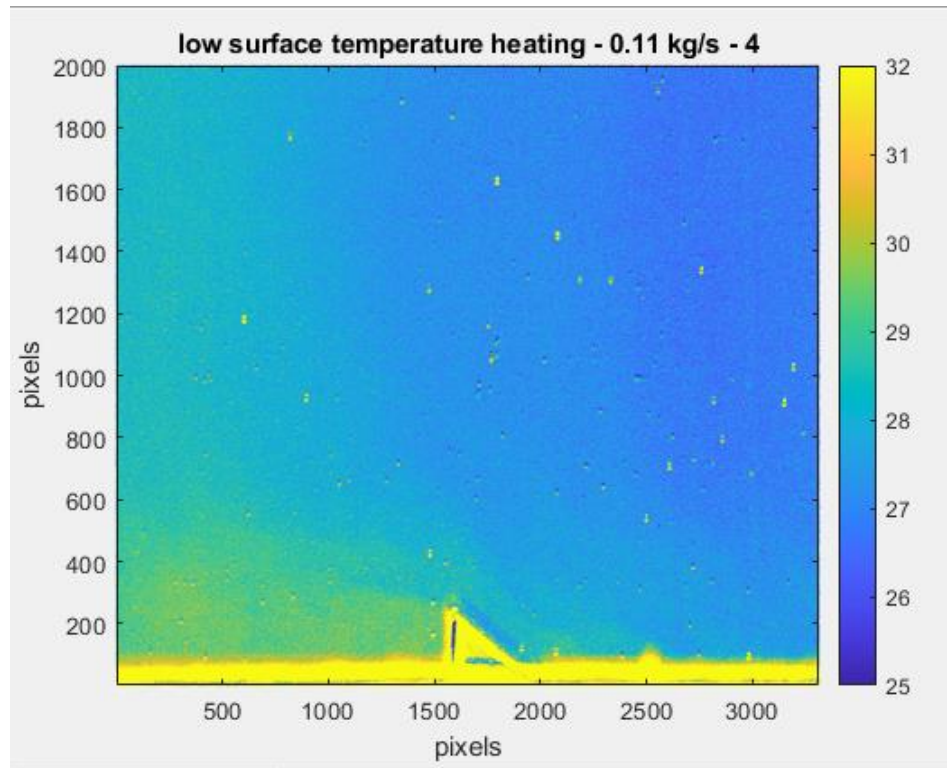


Figure 6-14 An instantaneous temperature field of the seventh case

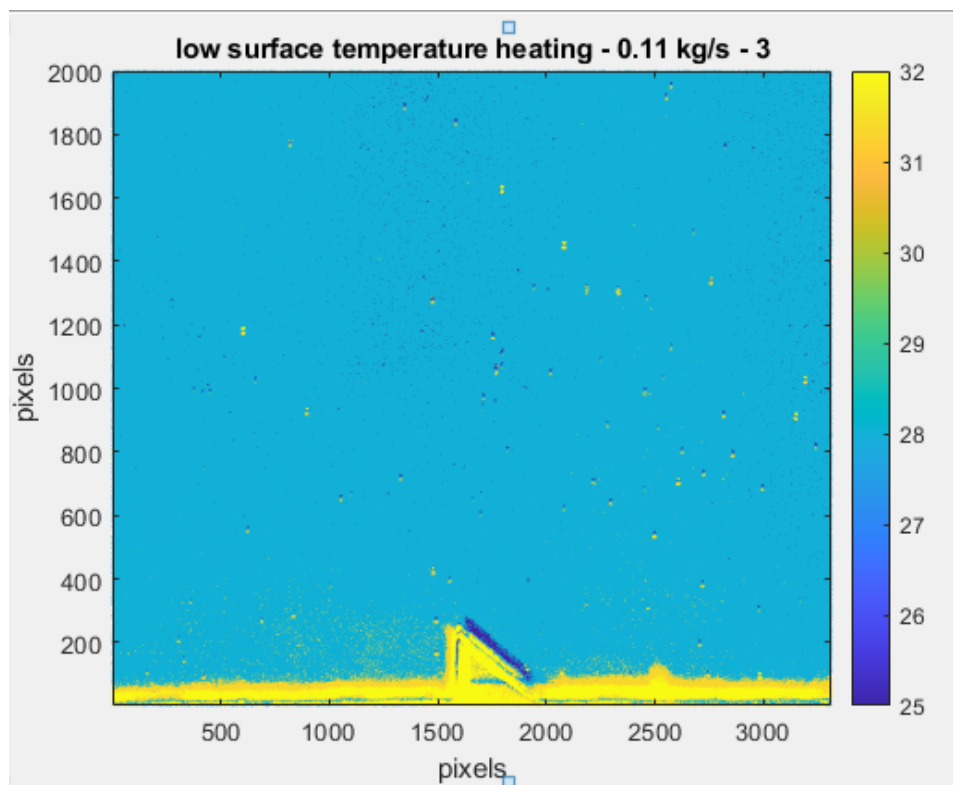


Figure 6-15 An instantaneous temperature field of the seventh case

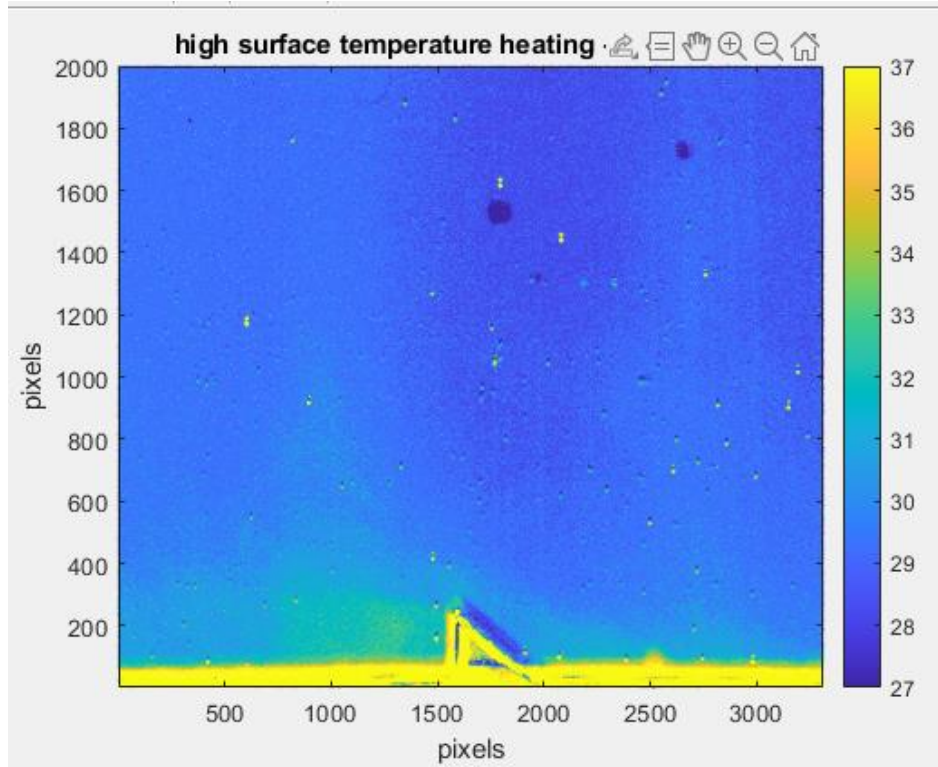


Figure 6-16 An instantaneous temperature field of the eighth case

6.6 Experimental results of the temperature distribution curves

Figures 6-17 to 6-24 show the experimental and computational results of the temperature distribution at the column of pixel 2500, which is before the fin. For the CFD, the results at this spot are taken from the simulation of the smooth duct. Each Figure is for a certain one of the cases shown in Table 6-1. In all these figures, the temperature axis limits were selected to be 20°C to 40°C because, close to the surface, there are some unreasonable results that might arrive in the hundreds. At 2.5 mm height, the results increase suddenly for all cases. The reason is not clear, but it is likely related to the glass. As the velocity decreases, the shape of the temperature distribution curve close to the surface is more similar to the CFD curve, but the measured temperatures at the surface are still higher than the surface temperature. That indicates that the shadowgraph effect decreases with the velocity decreasing. Figure 6-25 shows the experimental

and computational results of the temperature distribution of the eighth case at the column of pixel 1000, which is before the fin. By comparing Figures 6-24 and 6-25, the thermal boundary layer thickness after the fin can be seen to be more than the thermal boundary layer thickness before the fin.

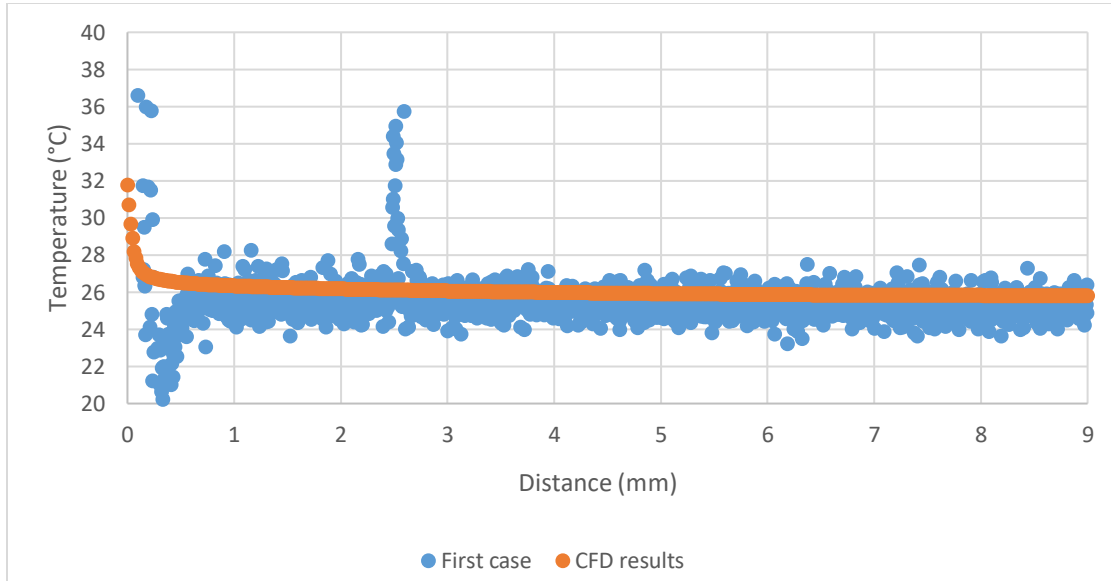


Figure 6-17 Temperature distribution curve before the fin from PLIF results and CFD results for the first case

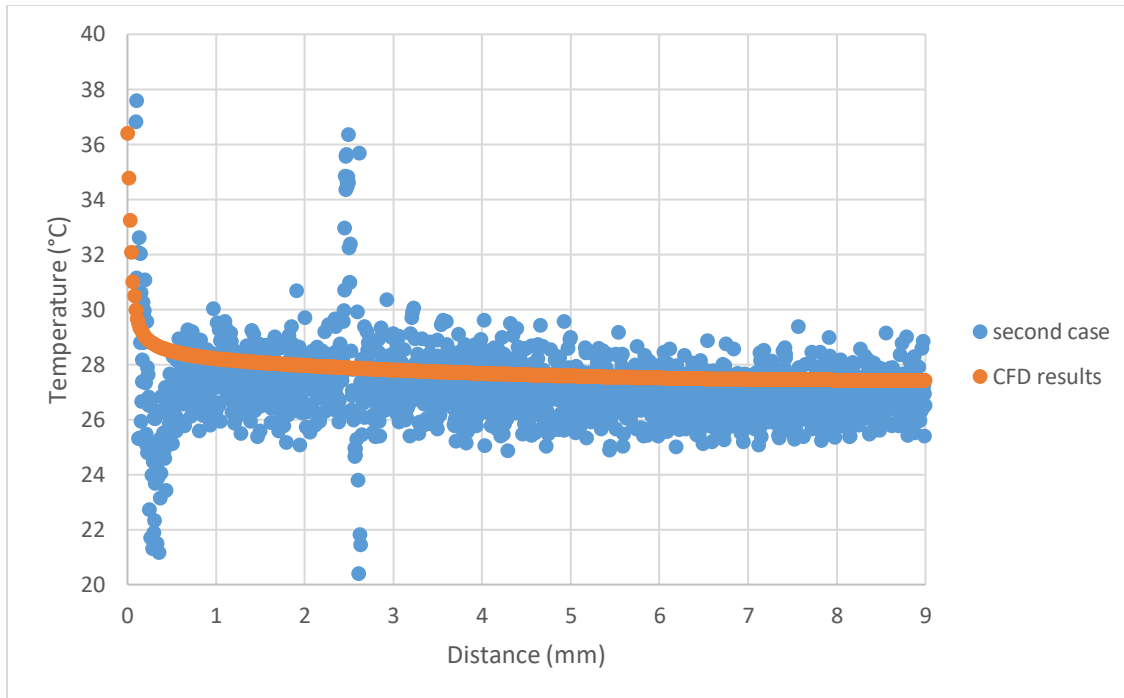


Figure 6-18 Temperature distribution curve before the fin from PLIF results and CFD results for the second case

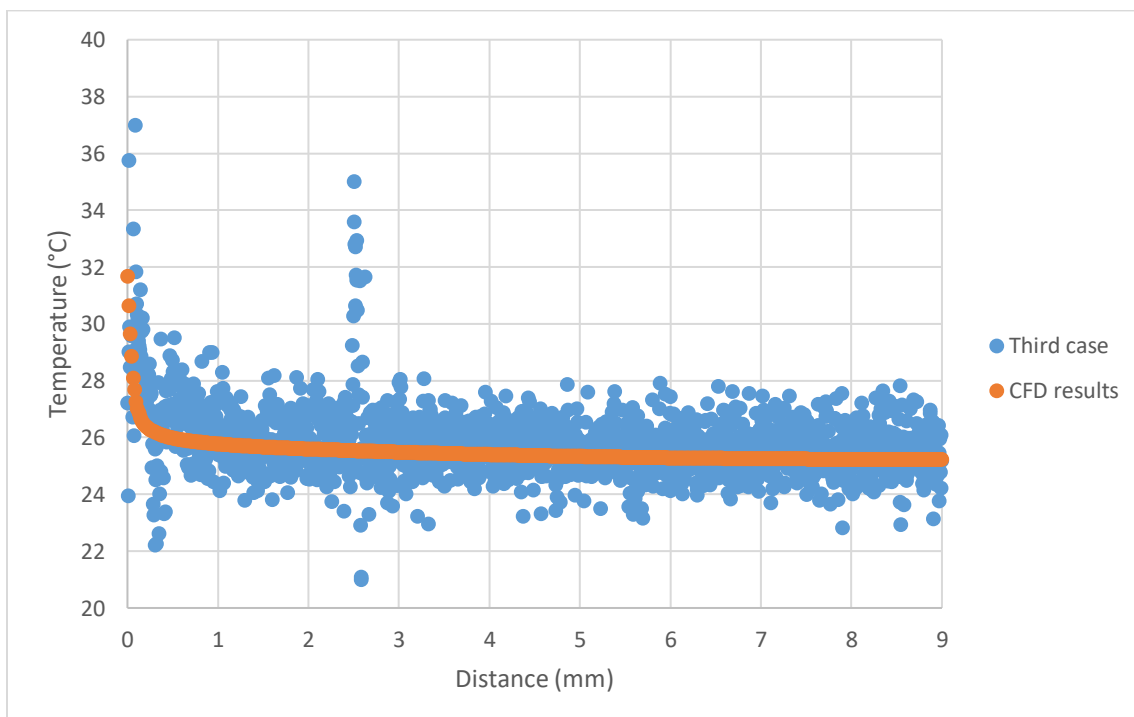


Figure 6-19 Temperature distribution curve before the fin from PLIF results and CFD results for the third case

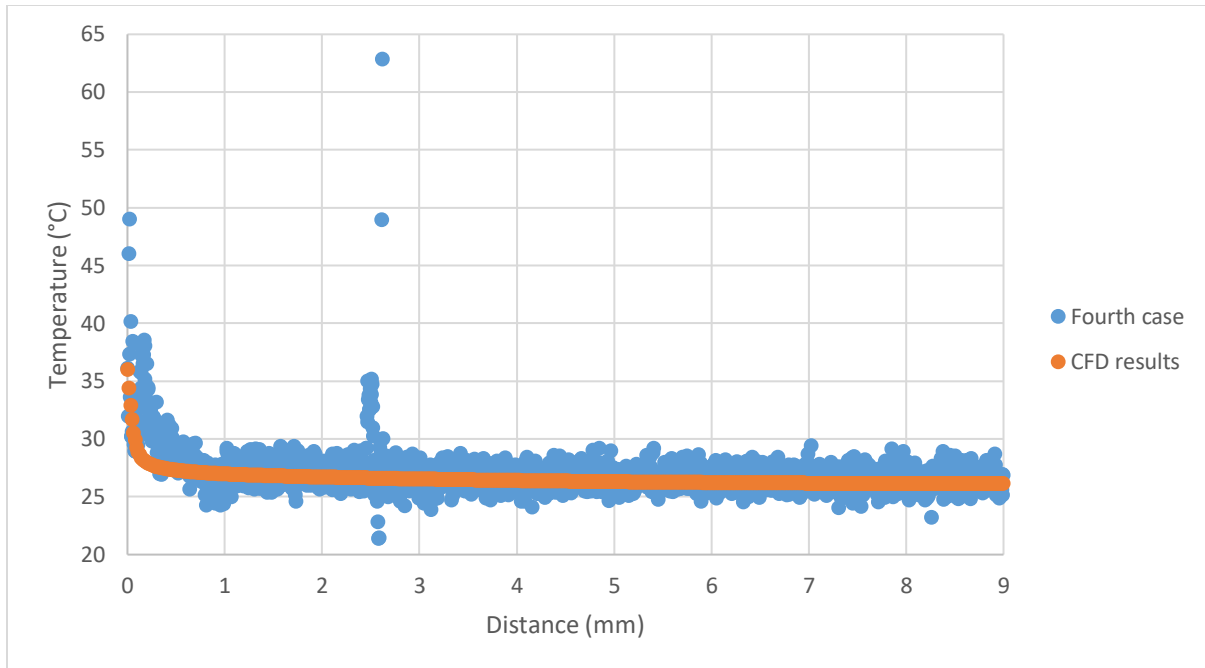


Figure 6-20 Temperature distribution curve before the fin from PLIF results and CFD results for the fourth case

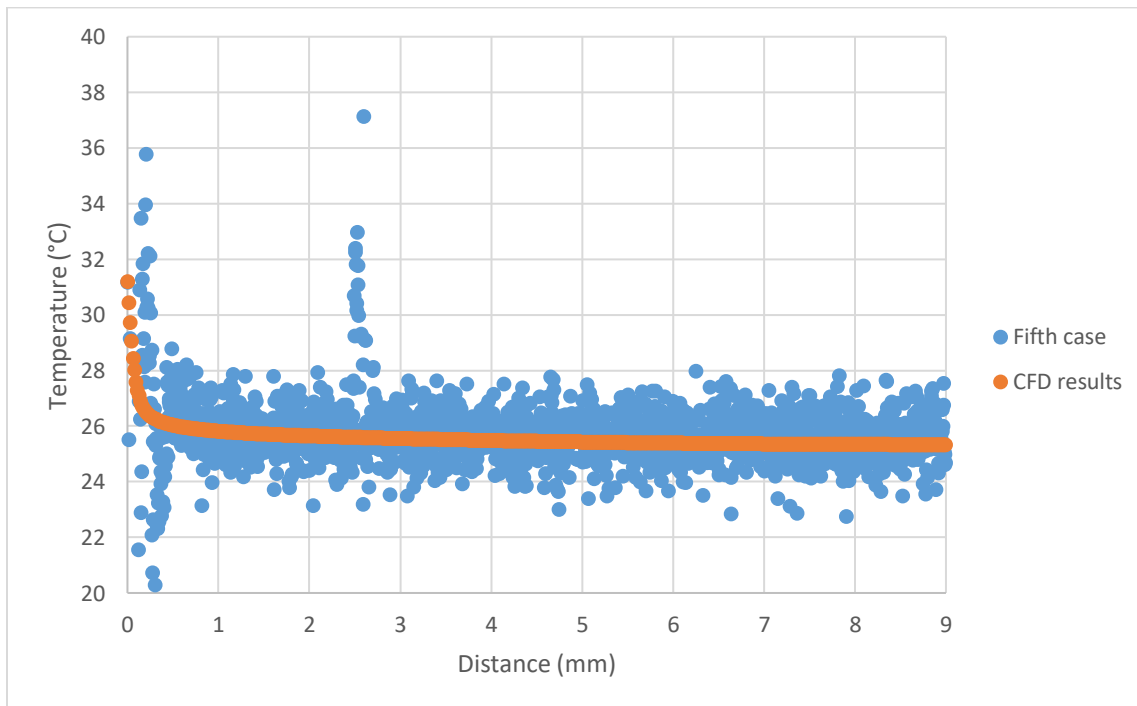


Figure 6-21 Temperature distribution curve before the fin from PLIF results and CFD results for the fifth case

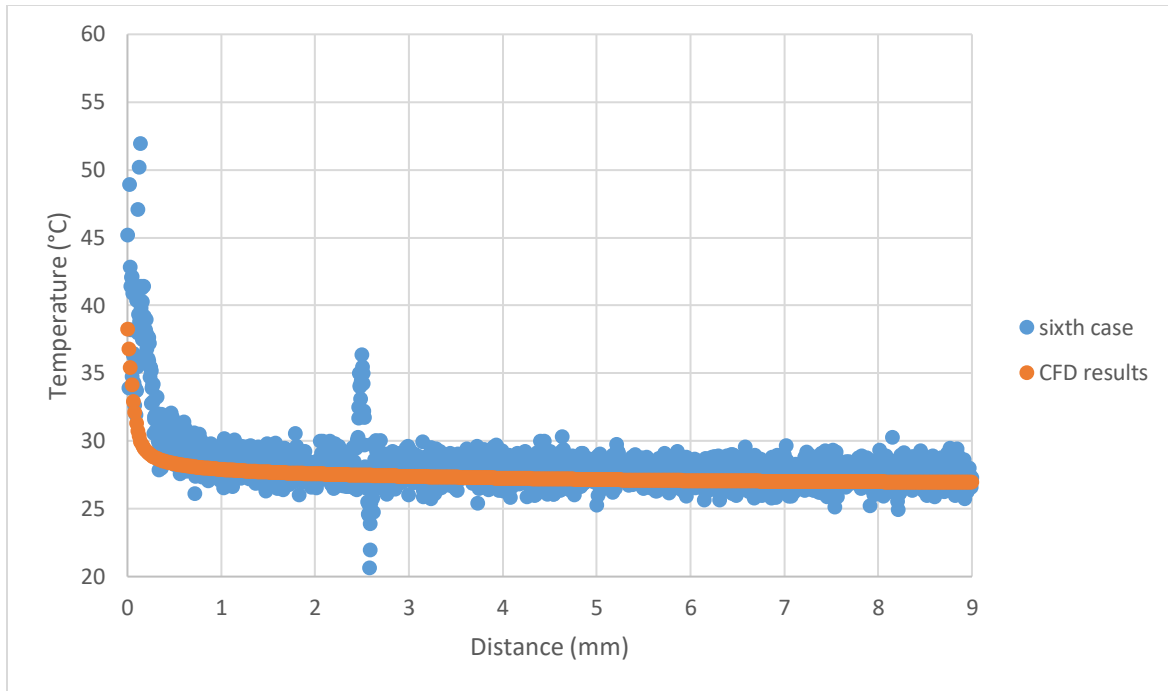


Figure 6-22 Temperature distribution curve before the fin from PLIF results and CFD results for the sixth case

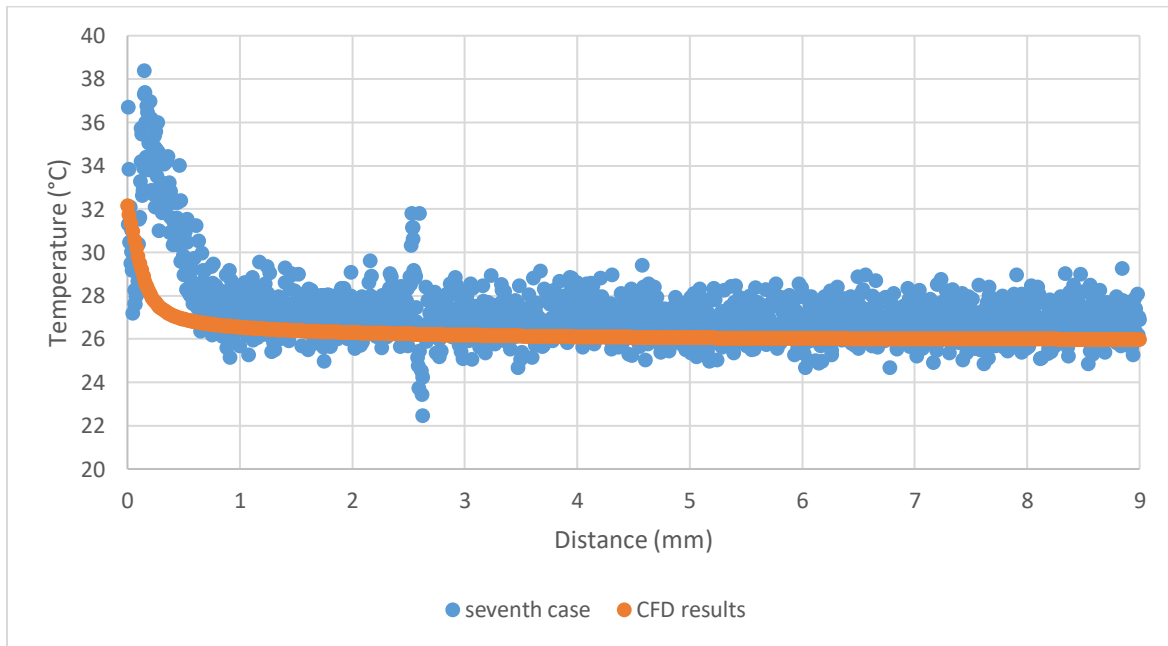


Figure 6-23 Temperature distribution curve before the fin from PLIF results and CFD results for the seventh case

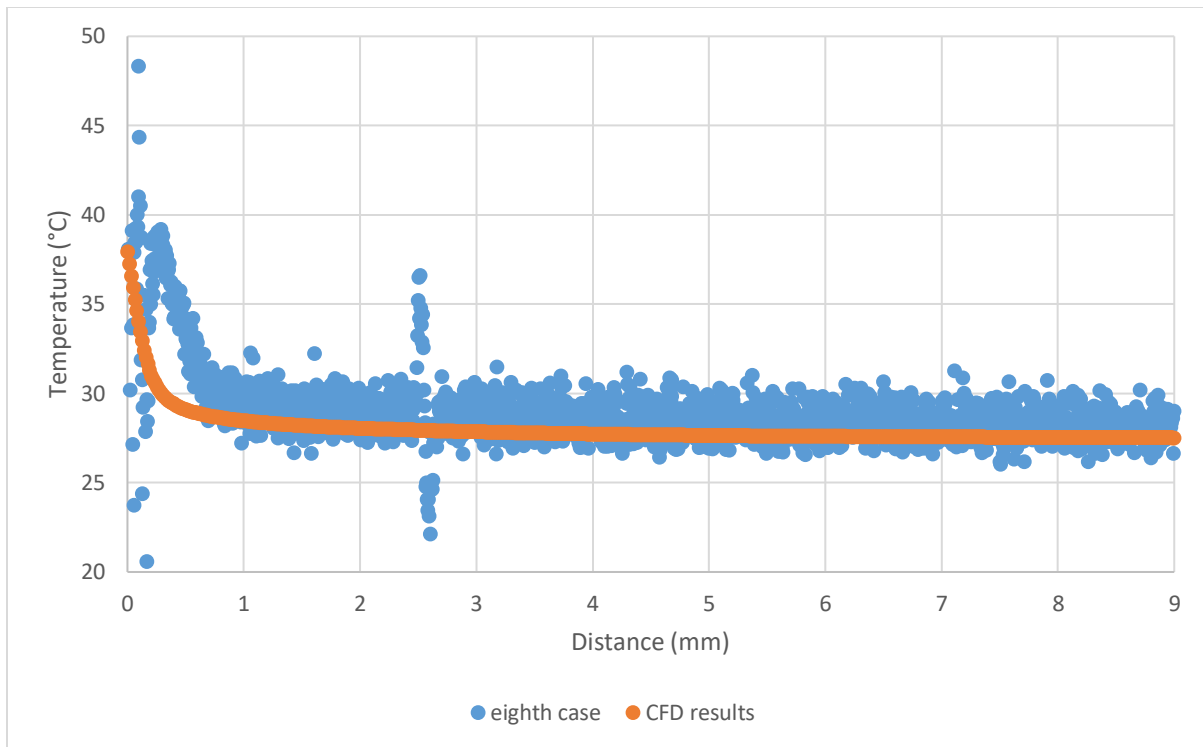


Figure 6-24 Temperature distribution curve before the fin from PLIF results and CFD results for the eighth case

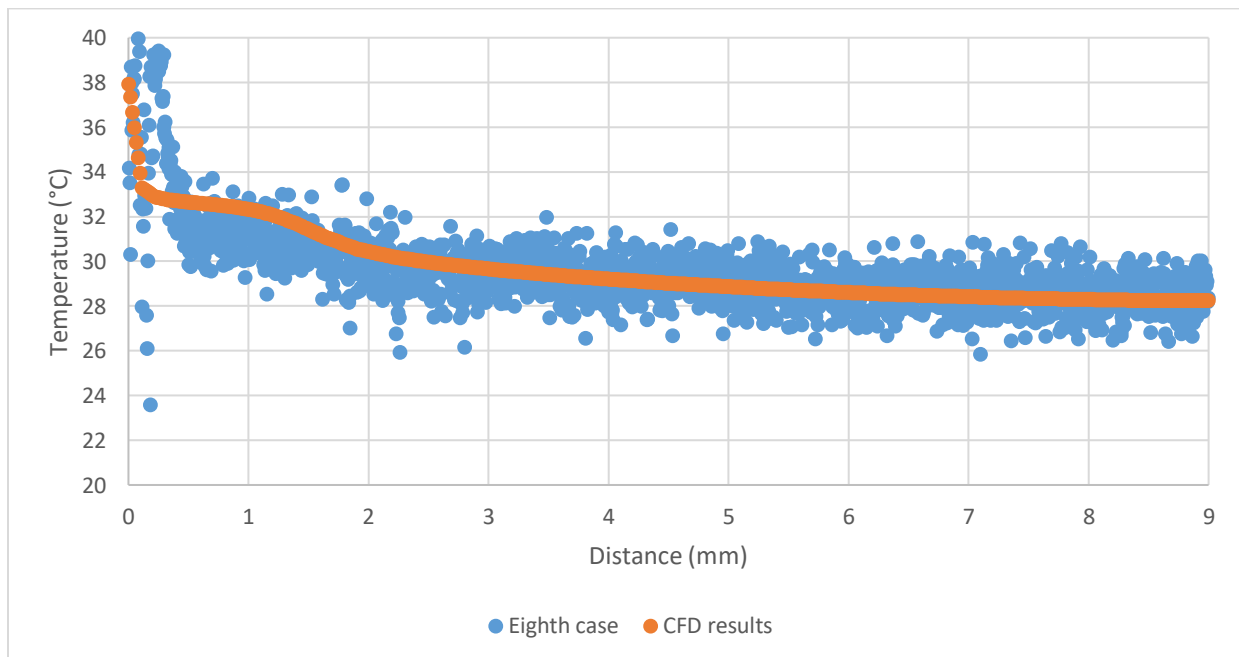


Figure 6-25 Temperature distribution curve after the fin from PLIF results and CFD results for the eighth case

6.7 Summary

This chapter was for the PLIF and CFD results for the heating case. The temperature field and the temperature distribution curve were presented for several cases. The inaccuracy of the results close to the surface was discussed.

Chapter 7 - Summary and Recommendations

In summary, this study investigated using the planar laser induced fluorescence technique to measure the temperature field of flowing liquid water through a square duct.

The dissertation was introduced by talking about the importance of the topic and the dissertation goals. Then a literature review was presented in Chapter 2 to discuss the planar laser induced fluorescence technique and show some significant published research efforts in using PLIF for measuring the temperature field of water. Chapter 3 was about the experimental setup. The designed test section was explained in detail, and the instrumentations related to PLIF were presented. In Chapter 4, the introductory steps of the simulation by CFD were presented. The simulation was done by FLUENT software. The solved equations in the simulation were shown. Chapter 5 was about using PLIF to measure the temperature field of isothermal flowing water. The temperature calibration curve was created, and the error was estimated for each pixel. Some experimental conditions were tested to check their impact on the accuracy of the results. They were the camera aperture, laser energy, and laser sheet thickness. Chapter 6 was about using PLIF to measure the temperature field of flowing water when the temperature gradient exists through the water because of an electrical heater underneath the test section. More investigation was done for the results of the zone right above the surface. The temperature field and temperature distribution curve were presented for several cases. The resultant temperature distribution curves were compared with CFD results. Good compatibility between the PLIF results and CFD results in the zone far of the surface.

The research showed that PLIF with the configuration of one dye/one color is applicable for the measuring temperature field of isothermal cases with respecting the high expected error close to the surface. The temperature field in the heating case is applicable in the cases of low

velocity where the PLIF technique can capture the temperature structure. The research estimated the random error and systematic error of each pixel and found that the error is high close to the surface. In the isothermal cases, it is speculated that the error is due to the random laser reflection at the surface. In the heating cases, the error is due to the shadowgraph in addition to the random laser reflection. The investigation of the effect of the experimental conditions showed that using a large camera aperture, high laser energy, and thick laser sheet will enhance the accuracy of the results.

In the future, it's recommended to find a way to enhance the results of the zone close to the surface. The configuration of two dyes/two colors has the potential to solve the problem, but it needs more investigation. After that, testing different designs of finned surfaces is the following step to find the optimal design of the finned surface. Associated planer laser induced fluorescence (PLIF) with particle image velocimetry (PIV) is recommended for future work to match the temperature analysis with the velocity analysis.

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Appendix A - MATLAB code

This MATLAB code is for analyzing the raw PLIF images. It is mainly for determining the grayscale in each pixel in each image, creating temperature calibration curves, estimating the results errors, and finding the temperature field of the heating cases.

```
grayImage_25_with_fin_0_46_flow_rate_2nd_1 = double(imread('20
July000101.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_25_with_fin_0_46_flow_rate_2nd_2 = double(imread('20
July000102.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_25_with_fin_0_46_flow_rate_2nd_3 = double(imread('20
July000103.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_25_with_fin_0_46_flow_rate_2nd_4 = double(imread('20
July000104.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_25_with_fin_0_46_flow_rate_2nd_5 = double(imread('20
July000105.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_25_with_fin_0_46_flow_rate_2nd_6 = double(imread('20
July000106.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_25_with_fin_0_46_flow_rate_2nd_7 = double(imread('20
July000107.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_25_with_fin_0_46_flow_rate_2nd_8 = double(imread('20
July000108.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_25_with_fin_0_46_flow_rate_2nd_9 = double(imread('20
July000109.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_25_with_fin_0_46_flow_rate_2nd_10 = double(imread('20
July000110.T000.D000.P000.H000.PLIF1.TIF'));

grayImage_25_with_fin_0_46_flow_rate_2nd=cat(3,grayImage_25_with_fin_0_46_flow_rate_2
nd_1,grayImage_25_with_fin_0_46_flow_rate_2nd_2,grayImage_25_with_fin_0_46_flow_rate_
2nd_3,grayImage_25_with_fin_0_46_flow_rate_2nd_4,grayImage_25_with_fin_0_46_flow_rate
_2nd_5,grayImage_25_with_fin_0_46_flow_rate_2nd_6,grayImage_25_with_fin_0_46_flow_ra
te_2nd_7,grayImage_25_with_fin_0_46_flow_rate_2nd_8,grayImage_25_with_fin_0_46_flow_ra
te_2nd_9,grayImage_25_with_fin_0_46_flow_rate_2nd_10);

grayImage_average_with_fin_0_46_flow_rate_2nd_25=mean(grayImage_25_with_fin_0_46_flow
_rate_2nd,3);

grayImage_27_with_fin_0_46_flow_rate_2nd_1 = double(imread('20
July000111.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_27_with_fin_0_46_flow_rate_2nd_2 = double(imread('20
July000112.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_27_with_fin_0_46_flow_rate_2nd_3 = double(imread('20
July000113.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_27_with_fin_0_46_flow_rate_2nd_4 = double(imread('20
July000114.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_27_with_fin_0_46_flow_rate_2nd_5 = double(imread('20
July000115.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_27_with_fin_0_46_flow_rate_2nd_6 = double(imread('20
July000116.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_27_with_fin_0_46_flow_rate_2nd_7 = double(imread('20
July000117.T000.D000.P000.H000.PLIF1.TIF'));
```

```

grayImage_27_with_fin_0_46_flow_rate_2nd_8 = double(imread('20
July000118.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_27_with_fin_0_46_flow_rate_2nd_9 = double(imread('20
July000119.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_27_with_fin_0_46_flow_rate_2nd_10 = double(imread('20
July000120.T000.D000.P000.H000.PLIF1.TIF'));

grayImage_27_with_fin_0_46_flow_rate_2nd=cat(3,grayImage_27_with_fin_0_46_flow_rate_2
nd_1,grayImage_27_with_fin_0_46_flow_rate_2nd_2,grayImage_27_with_fin_0_46_flow_rate_
2nd_3,grayImage_27_with_fin_0_46_flow_rate_2nd_4,grayImage_27_with_fin_0_46_flow_rate
_2nd_5,grayImage_27_with_fin_0_46_flow_rate_2nd_6,grayImage_27_with_fin_0_46_flow_rat
e_2nd_7,grayImage_27_with_fin_0_46_flow_rate_2nd_8,grayImage_27_with_fin_0_46_flow_ra
te_2nd_9,grayImage_27_with_fin_0_46_flow_rate_2nd_10);

grayImage_average_with_fin_0_46_flow_rate_2nd_27=mean(grayImage_27_with_fin_0_46_flow
_rate_2nd,3);

grayImage_29_with_fin_0_46_flow_rate_2nd_1 = double(imread('20
July000121.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_29_with_fin_0_46_flow_rate_2nd_2 = double(imread('20
July000122.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_29_with_fin_0_46_flow_rate_2nd_3 = double(imread('20
July000123.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_29_with_fin_0_46_flow_rate_2nd_4 = double(imread('20
July000124.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_29_with_fin_0_46_flow_rate_2nd_5 = double(imread('20
July000125.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_29_with_fin_0_46_flow_rate_2nd_6 = double(imread('20
July000126.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_29_with_fin_0_46_flow_rate_2nd_7 = double(imread('20
July000127.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_29_with_fin_0_46_flow_rate_2nd_8 = double(imread('20
July000128.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_29_with_fin_0_46_flow_rate_2nd_9 = double(imread('20
July000129.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_29_with_fin_0_46_flow_rate_2nd_10 = double(imread('20
July000130.T000.D000.P000.H000.PLIF1.TIF'));

grayImage_29_with_fin_0_46_flow_rate_2nd=cat(3,grayImage_29_with_fin_0_46_flow_rate_2
nd_1,grayImage_29_with_fin_0_46_flow_rate_2nd_2,grayImage_29_with_fin_0_46_flow_rate_
2nd_3,grayImage_29_with_fin_0_46_flow_rate_2nd_4,grayImage_29_with_fin_0_46_flow_rate
_2nd_5,grayImage_29_with_fin_0_46_flow_rate_2nd_6,grayImage_29_with_fin_0_46_flow_rat
e_2nd_7,grayImage_29_with_fin_0_46_flow_rate_2nd_8,grayImage_29_with_fin_0_46_flow_ra
te_2nd_9,grayImage_29_with_fin_0_46_flow_rate_2nd_10);

grayImage_average_with_fin_0_46_flow_rate_2nd_29=mean(grayImage_29_with_fin_0_46_flow
_rate_2nd,3);

grayImage_31_with_fin_0_46_flow_rate_2nd_1 = double(imread('20
July000131.T000.D000.P000.H000.PLIF1.TIF'));

```

```

grayImage_31_with_fin_0_46_flow_rate_2nd_2 = double(imread('20
July000132.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_31_with_fin_0_46_flow_rate_2nd_3 = double(imread('20
July000133.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_31_with_fin_0_46_flow_rate_2nd_4 = double(imread('20
July000134.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_31_with_fin_0_46_flow_rate_2nd_5 = double(imread('20
July000135.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_31_with_fin_0_46_flow_rate_2nd_6 = double(imread('20
July000136.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_31_with_fin_0_46_flow_rate_2nd_7 = double(imread('20
July000137.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_31_with_fin_0_46_flow_rate_2nd_8 = double(imread('20
July000138.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_31_with_fin_0_46_flow_rate_2nd_9 = double(imread('20
July000139.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_31_with_fin_0_46_flow_rate_2nd_10 = double(imread('20
July000140.T000.D000.P000.H000.PLIF1.TIF'));

```

```

grayImage_31_with_fin_0_46_flow_rate_2nd=cat(3,grayImage_31_with_fin_0_46_flow_rate_2
nd_1,grayImage_31_with_fin_0_46_flow_rate_2nd_2,grayImage_31_with_fin_0_46_flow_rate_
2nd_3,grayImage_31_with_fin_0_46_flow_rate_2nd_4,grayImage_31_with_fin_0_46_flow_rate
_2nd_5,grayImage_31_with_fin_0_46_flow_rate_2nd_6,grayImage_31_with_fin_0_46_flow_rat
e_2nd_7,grayImage_31_with_fin_0_46_flow_rate_2nd_8,grayImage_31_with_fin_0_46_flow_ra
te_2nd_9,grayImage_31_with_fin_0_46_flow_rate_2nd_10);

```

```

grayImage_average_with_fin_0_46_flow_rate_2nd_31=mean(grayImage_31_with_fin_0_46_flow
_rate_2nd,3);

```

```

grayImage_33_with_fin_0_46_flow_rate_2nd_1 = double(imread('20
July000141.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_33_with_fin_0_46_flow_rate_2nd_2 = double(imread('20
July000142.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_33_with_fin_0_46_flow_rate_2nd_3 = double(imread('20
July000143.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_33_with_fin_0_46_flow_rate_2nd_4 = double(imread('20
July000144.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_33_with_fin_0_46_flow_rate_2nd_5 = double(imread('20
July000145.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_33_with_fin_0_46_flow_rate_2nd_6 = double(imread('20
July000146.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_33_with_fin_0_46_flow_rate_2nd_7 = double(imread('20
July000147.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_33_with_fin_0_46_flow_rate_2nd_8 = double(imread('20
July000148.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_33_with_fin_0_46_flow_rate_2nd_9 = double(imread('20
July000149.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_33_with_fin_0_46_flow_rate_2nd_10 = double(imread('20
July000150.T000.D000.P000.H000.PLIF1.TIF'));

```

```
grayImage_33_with_fin_0_46_flow_rate_2nd=cat(3,grayImage_33_with_fin_0_46_flow_rate_2nd_1,grayImage_33_with_fin_0_46_flow_rate_2nd_2,grayImage_33_with_fin_0_46_flow_rate_2nd_3,grayImage_33_with_fin_0_46_flow_rate_2nd_4,grayImage_33_with_fin_0_46_flow_rate_2nd_5,grayImage_33_with_fin_0_46_flow_rate_2nd_6,grayImage_33_with_fin_0_46_flow_rate_2nd_7,grayImage_33_with_fin_0_46_flow_rate_2nd_8,grayImage_33_with_fin_0_46_flow_rate_2nd_9,grayImage_33_with_fin_0_46_flow_rate_2nd_10);
```

```
grayImage_average_with_fin_0_46_flow_rate_2nd_33=mean(grayImage_33_with_fin_0_46_flow_rate_2nd,3);
```

```
grayImage_35_with_fin_0_46_flow_rate_2nd_1 = double(imread('20 July000151.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_35_with_fin_0_46_flow_rate_2nd_2 = double(imread('20 July000152.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_35_with_fin_0_46_flow_rate_2nd_3 = double(imread('20 July000153.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_35_with_fin_0_46_flow_rate_2nd_4 = double(imread('20 July000154.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_35_with_fin_0_46_flow_rate_2nd_5 = double(imread('20 July000155.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_35_with_fin_0_46_flow_rate_2nd_6 = double(imread('20 July000156.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_35_with_fin_0_46_flow_rate_2nd_7 = double(imread('20 July000157.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_35_with_fin_0_46_flow_rate_2nd_8 = double(imread('20 July000158.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_35_with_fin_0_46_flow_rate_2nd_9 = double(imread('20 July000159.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_35_with_fin_0_46_flow_rate_2nd_10 = double(imread('20 July000160.T000.D000.P000.H000.PLIF1.TIF'));
```

```
grayImage_35_with_fin_0_46_flow_rate_2nd=cat(3,grayImage_35_with_fin_0_46_flow_rate_2nd_1,grayImage_35_with_fin_0_46_flow_rate_2nd_2,grayImage_35_with_fin_0_46_flow_rate_2nd_3,grayImage_35_with_fin_0_46_flow_rate_2nd_4,grayImage_35_with_fin_0_46_flow_rate_2nd_5,grayImage_35_with_fin_0_46_flow_rate_2nd_6,grayImage_35_with_fin_0_46_flow_rate_2nd_7,grayImage_35_with_fin_0_46_flow_rate_2nd_8,grayImage_35_with_fin_0_46_flow_rate_2nd_9,grayImage_35_with_fin_0_46_flow_rate_2nd_10);
```

```
grayImage_average_with_fin_0_46_flow_rate_2nd_35=mean(grayImage_35_with_fin_0_46_flow_rate_2nd,3);
```

```
grayImage_37_with_fin_0_46_flow_rate_2nd_1 = double(imread('20 July000161.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_37_with_fin_0_46_flow_rate_2nd_2 = double(imread('20 July000162.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_37_with_fin_0_46_flow_rate_2nd_3 = double(imread('20 July000163.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_37_with_fin_0_46_flow_rate_2nd_4 = double(imread('20 July000164.T000.D000.P000.H000.PLIF1.TIF'));
```

```

grayImage_37_with_fin_0_46_flow_rate_2nd_5 = double(imread('20
July000165.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_37_with_fin_0_46_flow_rate_2nd_6 = double(imread('20
July000166.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_37_with_fin_0_46_flow_rate_2nd_7 = double(imread('20
July000167.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_37_with_fin_0_46_flow_rate_2nd_8 = double(imread('20
July000168.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_37_with_fin_0_46_flow_rate_2nd_9 = double(imread('20
July000169.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_37_with_fin_0_46_flow_rate_2nd_10 = double(imread('20
July000170.T000.D000.P000.H000.PLIF1.TIF'));

```

```

grayImage_37_with_fin_0_46_flow_rate_2nd=cat(3,grayImage_37_with_fin_0_46_flow_rate_2
nd_1,grayImage_37_with_fin_0_46_flow_rate_2nd_2,grayImage_37_with_fin_0_46_flow_rate_
2nd_3,grayImage_37_with_fin_0_46_flow_rate_2nd_4,grayImage_37_with_fin_0_46_flow_rate_
2nd_5,grayImage_37_with_fin_0_46_flow_rate_2nd_6,grayImage_37_with_fin_0_46_flow_rat
e_2nd_7,grayImage_37_with_fin_0_46_flow_rate_2nd_8,grayImage_37_with_fin_0_46_flow_ra
te_2nd_9,grayImage_37_with_fin_0_46_flow_rate_2nd_10);

```

```

grayImage_average_with_fin_0_46_flow_rate_2nd_37=mean(grayImage_37_with_fin_0_46_flow
_rate_2nd,3);

```

```

grayImage_39_with_fin_0_46_flow_rate_2nd_1 = double(imread('20
July000171.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_39_with_fin_0_46_flow_rate_2nd_2 = double(imread('20
July000172.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_39_with_fin_0_46_flow_rate_2nd_3 = double(imread('20
July000173.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_39_with_fin_0_46_flow_rate_2nd_4 = double(imread('20
July000174.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_39_with_fin_0_46_flow_rate_2nd_5 = double(imread('20
July000175.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_39_with_fin_0_46_flow_rate_2nd_6 = double(imread('20
July000176.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_39_with_fin_0_46_flow_rate_2nd_7 = double(imread('20
July000177.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_39_with_fin_0_46_flow_rate_2nd_8 = double(imread('20
July000178.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_39_with_fin_0_46_flow_rate_2nd_9 = double(imread('20
July000179.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_39_with_fin_0_46_flow_rate_2nd_10 = double(imread('20
July000180.T000.D000.P000.H000.PLIF1.TIF'));

```

```

grayImage_39_with_fin_0_46_flow_rate_2nd=cat(3,grayImage_39_with_fin_0_46_flow_rate_2
nd_1,grayImage_39_with_fin_0_46_flow_rate_2nd_2,grayImage_39_with_fin_0_46_flow_rate_
2nd_3,grayImage_39_with_fin_0_46_flow_rate_2nd_4,grayImage_39_with_fin_0_46_flow_rate_
2nd_5,grayImage_39_with_fin_0_46_flow_rate_2nd_6,grayImage_39_with_fin_0_46_flow_rat
e_2nd_7,grayImage_39_with_fin_0_46_flow_rate_2nd_8,grayImage_39_with_fin_0_46_flow_ra
te_2nd_9,grayImage_39_with_fin_0_46_flow_rate_2nd_10);

```

```
grayImage_average_with_fin_0_46_flow_rate_2nd_39=mean(grayImage_39_with_fin_0_46_flow_rate_2nd,3);
```

```
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_1 = double(imread('20
July000181.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_2 = double(imread('20
July000182.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_3 = double(imread('20
July000183.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_4 = double(imread('20
July000184.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_5 = double(imread('20
July000185.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_6 = double(imread('20
July000186.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_7 = double(imread('20
July000187.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_8 = double(imread('20
July000188.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_9 = double(imread('20
July000189.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_10 = double(imread('20
July000190.T000.D000.P000.H000.PLIF1.TIF'));
```

```
grayImage_low_surface_temperature_with_fin_0_36_flow_rate=cat(3,grayImage_low_surface
_temperature_with_fin_0_36_flow_rate_1,grayImage_low_surface_temperature_with_fin_0_3
6_flow_rate_2,grayImage_low_surface_temperature_with_fin_0_36_flow_rate_3,grayImage_l
ow_surface_temperature_with_fin_0_36_flow_rate_4,grayImage_low_surface_temperature_wi
th_fin_0_36_flow_rate_5,grayImage_low_surface_temperature_with_fin_0_36_flow_rate_6,g
rayImage_low_surface_temperature_with_fin_0_36_flow_rate_7,grayImage_low_surface_temp
erature_with_fin_0_36_flow_rate_8,grayImage_low_surface_temperature_with_fin_0_36_flo
w_rate_9,grayImage_low_surface_temperature_with_fin_0_36_flow_rate_10);
```

```
grayImage_av_with_fin_0_46_flow_rate_2nd_low_surface_temp=mean(grayImage_low_surface
_temperature_with_fin_0_36_flow_rate,3);
```

```
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_1 = double(imread('20
July000191.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_2 = double(imread('20
July000192.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_3 = double(imread('20
July000193.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_4 = double(imread('20
July000194.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_5 = double(imread('20
July000195.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_6 = double(imread('20
July000196.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_7 = double(imread('20
July000197.T000.D000.P000.H000.PLIF1.TIF'));
```

```

grayImage_high_surface_temperature_with_fin_0_36_flow_rate_8 = double(imread('20
July000198.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_9 = double(imread('20
July000199.T000.D000.P000.H000.PLIF1.TIF'));
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_10 = double(imread('20
July000200.T000.D000.P000.H000.PLIF1.TIF'));

```

```

grayImage_high_surface_temperature_with_fin_0_36_flow_rate=cat(3,grayImage_high_surfa
ce_temperature_with_fin_0_36_flow_rate_1,grayImage_high_surface_temperature_with_fin_
0_36_flow_rate_2,grayImage_high_surface_temperature_with_fin_0_36_flow_rate_3,grayIma
ge_high_surface_temperature_with_fin_0_36_flow_rate_4,grayImage_high_surface_temperat
ure_with_fin_0_36_flow_rate_5,grayImage_high_surface_temperature_with_fin_0_36_flow_r
ate_6,grayImage_high_surface_temperature_with_fin_0_36_flow_rate_7,grayImage_high_sur
face_temperature_with_fin_0_36_flow_rate_8,grayImage_high_surface_temperature_with_fi
n_0_36_flow_rate_9,grayImage_high_surface_temperature_with_fin_0_36_flow_rate_10);

```

```

grayImage_av_with_fin_0_46_flow_rate_2nd_high_surface_temp=mean(grayImage_high_surfac
e_temperature_with_fin_0_36_flow_rate,3);

```

%%%%%%%%%% To cut the solid side

```

grayImage_25_with_fin_0_46_flow_rate_2nd_cut_1 =
grayImage_25_with_fin_0_46_flow_rate_2nd_1(83:2082,:);
grayImage_25_with_fin_0_46_flow_rate_2nd_cut_2 =
grayImage_25_with_fin_0_46_flow_rate_2nd_2(83:2082,:);
grayImage_25_with_fin_0_46_flow_rate_2nd_cut_3 =
grayImage_25_with_fin_0_46_flow_rate_2nd_3(83:2082,:);
grayImage_25_with_fin_0_46_flow_rate_2nd_cut_4 =
grayImage_25_with_fin_0_46_flow_rate_2nd_4(83:2082,:);
grayImage_25_with_fin_0_46_flow_rate_2nd_cut_5 =
grayImage_25_with_fin_0_46_flow_rate_2nd_5(83:2082,:);
grayImage_25_with_fin_0_46_flow_rate_2nd_cut_6 =
grayImage_25_with_fin_0_46_flow_rate_2nd_6(83:2082,:);
grayImage_25_with_fin_0_46_flow_rate_2nd_cut_7 =
grayImage_25_with_fin_0_46_flow_rate_2nd_7(83:2082,:);
grayImage_25_with_fin_0_46_flow_rate_2nd_cut_8 =
grayImage_25_with_fin_0_46_flow_rate_2nd_8(83:2082,:);
grayImage_25_with_fin_0_46_flow_rate_2nd_cut_9 =
grayImage_25_with_fin_0_46_flow_rate_2nd_9(83:2082,:);
grayImage_25_with_fin_0_46_flow_rate_2nd_cut_10 =
grayImage_25_with_fin_0_46_flow_rate_2nd_10(83:2082,:);

```

```

grayImage_25_with_fin_0_46_flow_rate_2nd_cut=cat(3,grayImage_25_with_fin_0_46_flow_ra
te_2nd_cut_1,grayImage_25_with_fin_0_46_flow_rate_2nd_cut_2,grayImage_25_with_fin_0_4
6_flow_rate_2nd_cut_3,grayImage_25_with_fin_0_46_flow_rate_2nd_cut_4,grayImage_25_wit
h_fin_0_46_flow_rate_2nd_cut_5,grayImage_25_with_fin_0_46_flow_rate_2nd_cut_6,grayIma
ge_25_with_fin_0_46_flow_rate_2nd_cut_7,grayImage_25_with_fin_0_46_flow_rate_2nd_cut_
8,grayImage_25_with_fin_0_46_flow_rate_2nd_cut_9,grayImage_25_with_fin_0_46_flow_rate
_2nd_cut_10);

```

```

grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut=mean(grayImage_25_with_fin_0_46_
flow_rate_2nd_cut,3);
grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_25_cut=std(grayImage_25_with
_fin_0_46_flow_rate_2nd_cut,[],3);

```

```

grayImage_27_with_fin_0_46_flow_rate_2nd_cut_1 =
grayImage_27_with_fin_0_46_flow_rate_2nd_1(86:2085,:);
grayImage_27_with_fin_0_46_flow_rate_2nd_cut_2 =
grayImage_27_with_fin_0_46_flow_rate_2nd_2(86:2085,:);
grayImage_27_with_fin_0_46_flow_rate_2nd_cut_3 =
grayImage_27_with_fin_0_46_flow_rate_2nd_3(86:2085,:);
grayImage_27_with_fin_0_46_flow_rate_2nd_cut_4 =
grayImage_27_with_fin_0_46_flow_rate_2nd_4(86:2085,:);
grayImage_27_with_fin_0_46_flow_rate_2nd_cut_5 =
grayImage_27_with_fin_0_46_flow_rate_2nd_5(86:2085,:);
grayImage_27_with_fin_0_46_flow_rate_2nd_cut_6 =
grayImage_27_with_fin_0_46_flow_rate_2nd_6(86:2085,:);
grayImage_27_with_fin_0_46_flow_rate_2nd_cut_7 =
grayImage_27_with_fin_0_46_flow_rate_2nd_7(86:2085,:);
grayImage_27_with_fin_0_46_flow_rate_2nd_cut_8 =
grayImage_27_with_fin_0_46_flow_rate_2nd_8(86:2085,:);
grayImage_27_with_fin_0_46_flow_rate_2nd_cut_9 =
grayImage_27_with_fin_0_46_flow_rate_2nd_9(86:2085,:);
grayImage_27_with_fin_0_46_flow_rate_2nd_cut_10 =
grayImage_27_with_fin_0_46_flow_rate_2nd_10(86:2085,:);

```

```

grayImage_27_with_fin_0_46_flow_rate_2nd_cut=cat(3,grayImage_27_with_fin_0_46_flow_ra
te_2nd_cut_1,grayImage_27_with_fin_0_46_flow_rate_2nd_cut_2,grayImage_27_with_fin_0_4
6_flow_rate_2nd_cut_3,grayImage_27_with_fin_0_46_flow_rate_2nd_cut_4,grayImage_27_wit
h_fin_0_46_flow_rate_2nd_cut_5,grayImage_27_with_fin_0_46_flow_rate_2nd_cut_6,grayIma
ge_27_with_fin_0_46_flow_rate_2nd_cut_7,grayImage_27_with_fin_0_46_flow_rate_2nd_cut_
8,grayImage_27_with_fin_0_46_flow_rate_2nd_cut_9,grayImage_27_with_fin_0_46_flow_rate
_2nd_cut_10);

```

```

grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut=mean(grayImage_27_with_fin_0_46_
flow_rate_2nd_cut,3);
grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_27_cut=std(grayImage_27_with
_fin_0_46_flow_rate_2nd_cut,[],3);

```

```

grayImage_29_with_fin_0_46_flow_rate_2nd_cut_1 =
grayImage_29_with_fin_0_46_flow_rate_2nd_1(86:2085,:);
grayImage_29_with_fin_0_46_flow_rate_2nd_cut_2 =
grayImage_29_with_fin_0_46_flow_rate_2nd_2(86:2085,:);
grayImage_29_with_fin_0_46_flow_rate_2nd_cut_3 =
grayImage_29_with_fin_0_46_flow_rate_2nd_3(86:2085,:);
grayImage_29_with_fin_0_46_flow_rate_2nd_cut_4 =
grayImage_29_with_fin_0_46_flow_rate_2nd_4(86:2085,:);
grayImage_29_with_fin_0_46_flow_rate_2nd_cut_5 =
grayImage_29_with_fin_0_46_flow_rate_2nd_5(86:2085,:);
grayImage_29_with_fin_0_46_flow_rate_2nd_cut_6 =
grayImage_29_with_fin_0_46_flow_rate_2nd_6(86:2085,:);

```

```

grayImage_29_with_fin_0_46_flow_rate_2nd_cut_7 =
grayImage_29_with_fin_0_46_flow_rate_2nd_7(86:2085,:);
grayImage_29_with_fin_0_46_flow_rate_2nd_cut_8 =
grayImage_29_with_fin_0_46_flow_rate_2nd_8(86:2085,:);
grayImage_29_with_fin_0_46_flow_rate_2nd_cut_9 =
grayImage_29_with_fin_0_46_flow_rate_2nd_9(86:2085,:);
grayImage_29_with_fin_0_46_flow_rate_2nd_cut_10 =
grayImage_29_with_fin_0_46_flow_rate_2nd_10(86:2085,:);

grayImage_29_with_fin_0_46_flow_rate_2nd_cut=cat(3,grayImage_29_with_fin_0_46_flow_ra
te_2nd_cut_1,grayImage_29_with_fin_0_46_flow_rate_2nd_cut_2,grayImage_29_with_fin_0_4
6_flow_rate_2nd_cut_3,grayImage_29_with_fin_0_46_flow_rate_2nd_cut_4,grayImage_29_wit
h_fin_0_46_flow_rate_2nd_cut_5,grayImage_29_with_fin_0_46_flow_rate_2nd_cut_6,grayIma
ge_29_with_fin_0_46_flow_rate_2nd_cut_7,grayImage_29_with_fin_0_46_flow_rate_2nd_cut_
8,grayImage_29_with_fin_0_46_flow_rate_2nd_cut_9,grayImage_29_with_fin_0_46_flow_rate
_2nd_cut_10);

grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut=mean(grayImage_29_with_fin_0_46_
flow_rate_2nd_cut,3);
grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_29_cut=std(grayImage_29_with
_fin_0_46_flow_rate_2nd_cut,[],3);

grayImage_31_with_fin_0_46_flow_rate_2nd_cut_1 =
grayImage_31_with_fin_0_46_flow_rate_2nd_1(89:2088,:);
grayImage_31_with_fin_0_46_flow_rate_2nd_cut_2 =
grayImage_31_with_fin_0_46_flow_rate_2nd_2(89:2088,:);
grayImage_31_with_fin_0_46_flow_rate_2nd_cut_3 =
grayImage_31_with_fin_0_46_flow_rate_2nd_3(89:2088,:);
grayImage_31_with_fin_0_46_flow_rate_2nd_cut_4 =
grayImage_31_with_fin_0_46_flow_rate_2nd_4(89:2088,:);
grayImage_31_with_fin_0_46_flow_rate_2nd_cut_5 =
grayImage_31_with_fin_0_46_flow_rate_2nd_5(89:2088,:);
grayImage_31_with_fin_0_46_flow_rate_2nd_cut_6 =
grayImage_31_with_fin_0_46_flow_rate_2nd_6(89:2088,:);
grayImage_31_with_fin_0_46_flow_rate_2nd_cut_7 =
grayImage_31_with_fin_0_46_flow_rate_2nd_7(89:2088,:);
grayImage_31_with_fin_0_46_flow_rate_2nd_cut_8 =
grayImage_31_with_fin_0_46_flow_rate_2nd_8(89:2088,:);
grayImage_31_with_fin_0_46_flow_rate_2nd_cut_9 =
grayImage_31_with_fin_0_46_flow_rate_2nd_9(89:2088,:);
grayImage_31_with_fin_0_46_flow_rate_2nd_cut_10 =
grayImage_31_with_fin_0_46_flow_rate_2nd_10(89:2088,:);

grayImage_31_with_fin_0_46_flow_rate_2nd_cut=cat(3,grayImage_31_with_fin_0_46_flow_ra
te_2nd_cut_1,grayImage_31_with_fin_0_46_flow_rate_2nd_cut_2,grayImage_31_with_fin_0_4
6_flow_rate_2nd_cut_3,grayImage_31_with_fin_0_46_flow_rate_2nd_cut_4,grayImage_31_wit
h_fin_0_46_flow_rate_2nd_cut_5,grayImage_31_with_fin_0_46_flow_rate_2nd_cut_6,grayIma
ge_31_with_fin_0_46_flow_rate_2nd_cut_7,grayImage_31_with_fin_0_46_flow_rate_2nd_cut_
8,grayImage_31_with_fin_0_46_flow_rate_2nd_cut_9,grayImage_31_with_fin_0_46_flow_rate
_2nd_cut_10);

grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut=mean(grayImage_31_with_fin_0_46_
flow_rate_2nd_cut,3);

```

```
grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_31_cut=std(grayImage_31_with  
_fin_0_46_flow_rate_2nd_cut,[],3);
```

```
grayImage_33_with_fin_0_46_flow_rate_2nd_cut_1 =  
grayImage_33_with_fin_0_46_flow_rate_2nd_1(89:2088,:);  
grayImage_33_with_fin_0_46_flow_rate_2nd_cut_2 =  
grayImage_33_with_fin_0_46_flow_rate_2nd_2(89:2088,:);  
grayImage_33_with_fin_0_46_flow_rate_2nd_cut_3 =  
grayImage_33_with_fin_0_46_flow_rate_2nd_3(89:2088,:);  
grayImage_33_with_fin_0_46_flow_rate_2nd_cut_4 =  
grayImage_33_with_fin_0_46_flow_rate_2nd_4(89:2088,:);  
grayImage_33_with_fin_0_46_flow_rate_2nd_cut_5 =  
grayImage_33_with_fin_0_46_flow_rate_2nd_5(89:2088,:);  
grayImage_33_with_fin_0_46_flow_rate_2nd_cut_6 =  
grayImage_33_with_fin_0_46_flow_rate_2nd_6(89:2088,:);  
grayImage_33_with_fin_0_46_flow_rate_2nd_cut_7 =  
grayImage_33_with_fin_0_46_flow_rate_2nd_7(89:2088,:);  
grayImage_33_with_fin_0_46_flow_rate_2nd_cut_8 =  
grayImage_33_with_fin_0_46_flow_rate_2nd_8(89:2088,:);  
grayImage_33_with_fin_0_46_flow_rate_2nd_cut_9 =  
grayImage_33_with_fin_0_46_flow_rate_2nd_9(89:2088,:);  
grayImage_33_with_fin_0_46_flow_rate_2nd_cut_10 =  
grayImage_33_with_fin_0_46_flow_rate_2nd_10(89:2088,:);
```

```
grayImage_33_with_fin_0_46_flow_rate_2nd_cut=cat(3,grayImage_33_with_fin_0_46_flow_ra  
te_2nd_cut_1,grayImage_33_with_fin_0_46_flow_rate_2nd_cut_2,grayImage_33_with_fin_0_4  
6_flow_rate_2nd_cut_3,grayImage_33_with_fin_0_46_flow_rate_2nd_cut_4,grayImage_33_wit  
h_fin_0_46_flow_rate_2nd_cut_5,grayImage_33_with_fin_0_46_flow_rate_2nd_cut_6,grayIma  
ge_33_with_fin_0_46_flow_rate_2nd_cut_7,grayImage_33_with_fin_0_46_flow_rate_2nd_cut_  
8,grayImage_33_with_fin_0_46_flow_rate_2nd_cut_9,grayImage_33_with_fin_0_46_flow_rate  
_2nd_cut_10);
```

```
grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut=mean(grayImage_33_with_fin_0_46_  
flow_rate_2nd_cut,3);
```

```
grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_33_cut=std(grayImage_33_with  
_fin_0_46_flow_rate_2nd_cut,[],3);
```

```
grayImage_35_with_fin_0_46_flow_rate_2nd_cut_1 =  
grayImage_35_with_fin_0_46_flow_rate_2nd_1(89:2088,:);  
grayImage_35_with_fin_0_46_flow_rate_2nd_cut_2 =  
grayImage_35_with_fin_0_46_flow_rate_2nd_2(89:2088,:);  
grayImage_35_with_fin_0_46_flow_rate_2nd_cut_3 =  
grayImage_35_with_fin_0_46_flow_rate_2nd_3(89:2088,:);  
grayImage_35_with_fin_0_46_flow_rate_2nd_cut_4 =  
grayImage_35_with_fin_0_46_flow_rate_2nd_4(89:2088,:);  
grayImage_35_with_fin_0_46_flow_rate_2nd_cut_5 =  
grayImage_35_with_fin_0_46_flow_rate_2nd_5(89:2088,:);  
grayImage_35_with_fin_0_46_flow_rate_2nd_cut_6 =  
grayImage_35_with_fin_0_46_flow_rate_2nd_6(89:2088,:);  
grayImage_35_with_fin_0_46_flow_rate_2nd_cut_7 =  
grayImage_35_with_fin_0_46_flow_rate_2nd_7(89:2088,:);  
grayImage_35_with_fin_0_46_flow_rate_2nd_cut_8 =  
grayImage_35_with_fin_0_46_flow_rate_2nd_8(89:2088,:);
```

```

grayImage_35_with_fin_0_46_flow_rate_2nd_cut_9 =
grayImage_35_with_fin_0_46_flow_rate_2nd_9(89:2088,:);
grayImage_35_with_fin_0_46_flow_rate_2nd_cut_10 =
grayImage_35_with_fin_0_46_flow_rate_2nd_10(89:2088,:);

grayImage_35_with_fin_0_46_flow_rate_2nd_cut=cat(3,grayImage_35_with_fin_0_46_flow_ra
te_2nd_cut_1,grayImage_35_with_fin_0_46_flow_rate_2nd_cut_2,grayImage_35_with_fin_0_4
6_flow_rate_2nd_cut_3,grayImage_35_with_fin_0_46_flow_rate_2nd_cut_4,grayImage_35_wit
h_fin_0_46_flow_rate_2nd_cut_5,grayImage_35_with_fin_0_46_flow_rate_2nd_cut_6,grayIma
ge_35_with_fin_0_46_flow_rate_2nd_cut_7,grayImage_35_with_fin_0_46_flow_rate_2nd_cut_
8,grayImage_35_with_fin_0_46_flow_rate_2nd_cut_9,grayImage_35_with_fin_0_46_flow_rate
_2nd_cut_10);

grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut=mean(grayImage_35_with_fin_0_46_
flow_rate_2nd_cut,3);
grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_35_cut=std(grayImage_35_with
_fin_0_46_flow_rate_2nd_cut,[],3);

grayImage_37_with_fin_0_46_flow_rate_2nd_cut_1 =
grayImage_37_with_fin_0_46_flow_rate_2nd_1(89:2088,:);
grayImage_37_with_fin_0_46_flow_rate_2nd_cut_2 =
grayImage_37_with_fin_0_46_flow_rate_2nd_2(89:2088,:);
grayImage_37_with_fin_0_46_flow_rate_2nd_cut_3 =
grayImage_37_with_fin_0_46_flow_rate_2nd_3(89:2088,:);
grayImage_37_with_fin_0_46_flow_rate_2nd_cut_4 =
grayImage_37_with_fin_0_46_flow_rate_2nd_4(89:2088,:);
grayImage_37_with_fin_0_46_flow_rate_2nd_cut_5 =
grayImage_37_with_fin_0_46_flow_rate_2nd_5(89:2088,:);
grayImage_37_with_fin_0_46_flow_rate_2nd_cut_6 =
grayImage_37_with_fin_0_46_flow_rate_2nd_6(89:2088,:);
grayImage_37_with_fin_0_46_flow_rate_2nd_cut_7 =
grayImage_37_with_fin_0_46_flow_rate_2nd_7(89:2088,:);
grayImage_37_with_fin_0_46_flow_rate_2nd_cut_8 =
grayImage_37_with_fin_0_46_flow_rate_2nd_8(89:2088,:);
grayImage_37_with_fin_0_46_flow_rate_2nd_cut_9 =
grayImage_37_with_fin_0_46_flow_rate_2nd_9(89:2088,:);
grayImage_37_with_fin_0_46_flow_rate_2nd_cut_10 =
grayImage_37_with_fin_0_46_flow_rate_2nd_10(89:2088,:);

grayImage_37_with_fin_0_46_flow_rate_2nd_cut=cat(3,grayImage_37_with_fin_0_46_flow_ra
te_2nd_cut_1,grayImage_37_with_fin_0_46_flow_rate_2nd_cut_2,grayImage_37_with_fin_0_4
6_flow_rate_2nd_cut_3,grayImage_37_with_fin_0_46_flow_rate_2nd_cut_4,grayImage_37_wit
h_fin_0_46_flow_rate_2nd_cut_5,grayImage_37_with_fin_0_46_flow_rate_2nd_cut_6,grayIma
ge_37_with_fin_0_46_flow_rate_2nd_cut_7,grayImage_37_with_fin_0_46_flow_rate_2nd_cut_
8,grayImage_37_with_fin_0_46_flow_rate_2nd_cut_9,grayImage_37_with_fin_0_46_flow_rate
_2nd_cut_10);

grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut=mean(grayImage_37_with_fin_0_46_
flow_rate_2nd_cut,3);
grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_37_cut=std(grayImage_37_with
_fin_0_46_flow_rate_2nd_cut,[],3);

```

```

grayImage_39_with_fin_0_46_flow_rate_2nd_cut_1 =
grayImage_39_with_fin_0_46_flow_rate_2nd_1(89:2088,:);
grayImage_39_with_fin_0_46_flow_rate_2nd_cut_2 =
grayImage_39_with_fin_0_46_flow_rate_2nd_2(89:2088,:);
grayImage_39_with_fin_0_46_flow_rate_2nd_cut_3 =
grayImage_39_with_fin_0_46_flow_rate_2nd_3(89:2088,:);
grayImage_39_with_fin_0_46_flow_rate_2nd_cut_4 =
grayImage_39_with_fin_0_46_flow_rate_2nd_4(89:2088,:);
grayImage_39_with_fin_0_46_flow_rate_2nd_cut_5 =
grayImage_39_with_fin_0_46_flow_rate_2nd_5(89:2088,:);
grayImage_39_with_fin_0_46_flow_rate_2nd_cut_6 =
grayImage_39_with_fin_0_46_flow_rate_2nd_6(89:2088,:);
grayImage_39_with_fin_0_46_flow_rate_2nd_cut_7 =
grayImage_39_with_fin_0_46_flow_rate_2nd_7(89:2088,:);
grayImage_39_with_fin_0_46_flow_rate_2nd_cut_8 =
grayImage_39_with_fin_0_46_flow_rate_2nd_8(89:2088,:);
grayImage_39_with_fin_0_46_flow_rate_2nd_cut_9 =
grayImage_39_with_fin_0_46_flow_rate_2nd_9(89:2088,:);
grayImage_39_with_fin_0_46_flow_rate_2nd_cut_10 =
grayImage_39_with_fin_0_46_flow_rate_2nd_10(89:2088,:);

```

```

grayImage_39_with_fin_0_46_flow_rate_2nd_cut=cat(3,grayImage_39_with_fin_0_46_flow_ra
te_2nd_cut_1,grayImage_39_with_fin_0_46_flow_rate_2nd_cut_2,grayImage_39_with_fin_0_4
6_flow_rate_2nd_cut_3,grayImage_39_with_fin_0_46_flow_rate_2nd_cut_4,grayImage_39_wit
h_fin_0_46_flow_rate_2nd_cut_5,grayImage_39_with_fin_0_46_flow_rate_2nd_cut_6,grayIma
ge_39_with_fin_0_46_flow_rate_2nd_cut_7,grayImage_39_with_fin_0_46_flow_rate_2nd_cut_
8,grayImage_39_with_fin_0_46_flow_rate_2nd_cut_9,grayImage_39_with_fin_0_46_flow_rate
_2nd_cut_10);

```

```

grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut=mean(grayImage_39_with_fin_0_46_
flow_rate_2nd_cut,3);
grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_39_cut=std(grayImage_39_with
_fin_0_46_flow_rate_2nd_cut,[],3);

```

```

grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_1 =
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_1(99:2098,:);
grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_2 =
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_2(99:2098,:);
grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_3 =
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_3(99:2098,:);
grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_4 =
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_4(99:2098,:);
grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_5 =
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_5(99:2098,:);
grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_6 =
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_6(99:2098,:);
grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_7 =
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_7(99:2098,:);
grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_8 =
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_8(99:2098,:);

```

```

grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_9 =
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_9(99:2098,:);
grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_10 =
grayImage_low_surface_temperature_with_fin_0_36_flow_rate_10(99:2098,:);

```

```

grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut=cat(3,grayImage_low_surface_t
mp_with_fin_0_36_flow_rate_cut_1,grayImage_low_surface_temp_with_fin_0_36_flow_rate_c
ut_2,grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_3,grayImage_low_surface_t
emp_with_fin_0_36_flow_rate_cut_4,grayImage_low_surface_temp_with_fin_0_36_flow_rate_
cut_5,grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_6,grayImage_low_surface_
temp_with_fin_0_36_flow_rate_cut_7,grayImage_low_surface_temp_with_fin_0_36_flow_rate
_cut_8,grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_9,grayImage_low_surface
_temp_with_fin_0_36_flow_rate_cut_10);

```

```

grayImage_av_with_fin_0_46_flow_rate_2nd_low_surface_temp_cut=mean(grayImage_low_surf
ace_temp_with_fin_0_36_flow_rate_cut,3);
grayImage_std_with_fin_0_46_flow_rate_2nd_low_surface_temp_cut=std(grayImage_low_surf
ace_temp_with_fin_0_36_flow_rate_cut,[],3);

```

```

grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_1 =
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_1(106:2105,:);
grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_2 =
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_2(106:2105,:);
grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_3 =
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_3(106:2105,:);
grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_4 =
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_4(106:2105,:);
grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_5 =
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_5(106:2105,:);
grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_6 =
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_6(106:2105,:);
grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_7 =
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_7(106:2105,:);
grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_8 =
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_8(106:2105,:);
grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_9 =
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_9(106:2105,:);
grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_10 =
grayImage_high_surface_temperature_with_fin_0_36_flow_rate_10(106:2105,:);

```

```

grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut=cat(3,grayImage_high_surface_
temp_with_fin_0_36_flow_rate_cut_1,grayImage_high_surface_temp_with_fin_0_36_flow_rat
e_cut_2,grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_3,grayImage_high_surf
ace_temp_with_fin_0_36_flow_rate_cut_4,grayImage_high_surface_temp_with_fin_0_36_flow
_rate_cut_5,grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_6,grayImage_high_
surface_temp_with_fin_0_36_flow_rate_cut_7,grayImage_high_surface_temp_with_fin_0_36_
flow_rate_cut_8,grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_9,grayImage_h
igh_surface_temp_with_fin_0_36_flow_rate_cut_10);

```

```

grayImage_av_with_fin_0_36_flow_rate_2nd_high_surface_temp_cut=mean(grayImage_high_su
rface_temp_with_fin_0_36_flow_rate_cut,3);

```

```
grayImage_std_with_fin_0_46_flow_rate_2nd_high_surface_temp_cut=std(grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut,[],3);
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% To find temperature sensitivity
```

```
grayscale_difference_25_39_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut-grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut;
temperature_sensitivity_2nd=(1/14).*grayscale_difference_25_39_2nd;
grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_cut=cat(3,grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_25_cut,grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_27_cut,grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_29_cut,grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_31_cut,grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_33_cut,grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_35_cut,grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_37_cut,grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_39_cut);
grayImage_standard_deviation_fin_0_46_flow_rate_2nd_cut_average=mean(grayImage_standard_deviation_with_fin_0_46_flow_rate_2nd_cut,3);
grayImage_std_fin_0_46_flow_rate_2nd_cut_max_95_confidence=2*grayImage_standard_deviation_fin_0_46_flow_rate_2nd_cut_average;
grayImage_error_fin_0_46_flow_rate_2nd_cut_max_95_confidence=grayImage_std_fin_0_46_flow_rate_2nd_cut_max_95_confidence./temperature_sensitivity_2nd;
```

```
%figure;
%contour( grayImage_error_fin_0_46_flow_rate_2nd_cut_max_95_confidence,5000);
%title('Temperature error - 0.46 kg/s')
%xlabel('pixels');
%ylabel('pixels');
%caxis([1 6]);
%colorbar;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% find average and standard deviation
```

```
average_25_2nd=[mean(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_1(:))
    mean(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_2(:))
    mean(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_3(:))
    mean(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_4(:))
    mean(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_5(:))
    mean(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_6(:))
    mean(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_7(:))
    mean(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_8(:))
    mean(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_9(:))
    mean(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_10(:))];
```

```
standard_deviation_25_2nd=[std(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_1(:))
    std(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_2(:))
    std(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_3(:))
    std(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_4(:))
    std(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_5(:))
    std(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_6(:))
    std(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_7(:))
    std(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_8(:))
    std(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_9(:))
    std(grayImage_25_with_fin_0_46_flow_rate_2nd_cut_10(:))];
```

```
average_of_averages_25_2nd=mean(average_25_2nd(:));
```

```

standard_deviation_of_averages_25_2nd=std(average_25_2nd(:));

average_27_2nd=[mean(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_1(:))
    mean(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_2(:))
    mean(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_3(:))
    mean(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_4(:))
    mean(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_5(:))
    mean(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_6(:))
    mean(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_7(:))
    mean(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_8(:))
    mean(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_9(:))
    mean(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_10(:))];

standard_deviation_27_2nd=[std(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_1(:))
    std(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_2(:))
    std(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_3(:))
    std(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_4(:))
    std(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_5(:))
    std(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_6(:))
    std(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_7(:))
    std(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_8(:))
    std(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_9(:))
    std(grayImage_27_with_fin_0_46_flow_rate_2nd_cut_10(:))];

everage_of_averages_27_2nd=mean(average_27_2nd(:));
standard_deviation_of_averages_27_2nd=std(average_27_2nd(:));

average_29_2nd=[mean(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_1(:))
    mean(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_2(:))
    mean(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_3(:))
    mean(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_4(:))
    mean(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_5(:))
    mean(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_6(:))
    mean(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_7(:))
    mean(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_8(:))
    mean(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_9(:))
    mean(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_10(:))];

standard_deviation_29_2nd=[std(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_1(:))
    std(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_2(:))
    std(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_3(:))
    std(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_4(:))
    std(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_5(:))
    std(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_6(:))
    std(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_7(:))
    std(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_8(:))
    std(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_9(:))
    std(grayImage_29_with_fin_0_46_flow_rate_2nd_cut_10(:))];

everage_of_averages_29_2nd=mean(average_29_2nd(:));
standard_deviation_of_averages_29_2nd=std(average_29_2nd(:));

average_31_2nd=[mean(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_1(:))
    mean(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_2(:))
    mean(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_3(:))

```

```

mean(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_4(:))
mean(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_5(:))
mean(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_6(:))
mean(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_7(:))
mean(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_8(:))
mean(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_9(:))
mean(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_10(:));

standard_deviation_31_2nd=[std(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_1(:))
std(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_2(:))
std(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_3(:))
std(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_4(:))
std(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_5(:))
std(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_6(:))
std(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_7(:))
std(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_8(:))
std(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_9(:))
std(grayImage_31_with_fin_0_46_flow_rate_2nd_cut_10(:))];

everage_of_averages_31_2nd=mean(average_31_2nd(:));
standard_deviation_of_averages_31_2nd=std(average_31_2nd(:));

average_33_2nd=[mean(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_1(:))
mean(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_2(:))
mean(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_3(:))
mean(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_4(:))
mean(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_5(:))
mean(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_6(:))
mean(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_7(:))
mean(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_8(:))
mean(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_9(:))
mean(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_10(:))];

standard_deviation_33_2nd=[std(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_1(:))
std(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_2(:))
std(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_3(:))
std(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_4(:))
std(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_5(:))
std(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_6(:))
std(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_7(:))
std(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_8(:))
std(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_9(:))
std(grayImage_33_with_fin_0_46_flow_rate_2nd_cut_10(:))];

everage_of_averages_33_2nd=mean(average_33_2nd(:));
standard_deviation_of_averages_33_2nd=std(average_33_2nd(:));

average_35_2nd=[mean(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_1(:))
mean(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_2(:))
mean(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_3(:))
mean(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_4(:))
mean(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_5(:))
mean(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_6(:))

```

```

mean(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_7(:))
mean(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_8(:))
mean(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_9(:))
mean(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_10(:));

standard_deviation_35_2nd=[std(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_1(:))
std(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_2(:))
std(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_3(:))
std(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_4(:))
std(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_5(:))
std(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_6(:))
std(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_7(:))
std(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_8(:))
std(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_9(:))
std(grayImage_35_with_fin_0_46_flow_rate_2nd_cut_10(:))];

everage_of_averages_35_2nd=mean(average_35_2nd(:));
standard_deviation_of_averages_35_2nd=std(average_35_2nd(:));

average_37_2nd=[mean(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_1(:))
mean(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_2(:))
mean(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_3(:))
mean(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_4(:))
mean(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_5(:))
mean(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_6(:))
mean(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_7(:))
mean(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_8(:))
mean(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_9(:))
mean(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_10(:))];

standard_deviation_37_2nd=[std(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_1(:))
std(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_2(:))
std(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_3(:))
std(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_4(:))
std(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_5(:))
std(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_6(:))
std(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_7(:))
std(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_8(:))
std(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_9(:))
std(grayImage_37_with_fin_0_46_flow_rate_2nd_cut_10(:))];

everage_of_averages_37_2nd=mean(average_37_2nd(:));
standard_deviation_of_averages_37_2nd=std(average_37_2nd(:));

average_39_2nd=[mean(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_1(:))
mean(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_2(:))
mean(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_3(:))
mean(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_4(:))
mean(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_5(:))
mean(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_6(:))
mean(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_7(:))
mean(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_8(:))
mean(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_9(:))
mean(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_10(:))];

```

```

standard_deviation_39_2nd=[std(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_1(:))
    std(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_2(:))
    std(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_3(:))
    std(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_4(:))
    std(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_5(:))
    std(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_6(:))
    std(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_7(:))
    std(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_8(:))
    std(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_9(:))
    std(grayImage_39_with_fin_0_46_flow_rate_2nd_cut_10(:))];

eaverage_of_averages_39_2nd=mean(average_39_2nd(:));
standard_deviation_of_averages_39_2nd=std(average_39_2nd(:));

average_2nd=[average_25_2nd average_27_2nd average_29_2nd average_31_2nd
average_33_2nd average_35_2nd average_37_2nd average_39_2nd];

grayscale_25_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_25(:,2500);
grayscale_27_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_27(:,2500);
grayscale_29_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_29(:,2500);
grayscale_31_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_31(:,2500);
grayscale_33_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_33(:,2500);
grayscale_35_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_35(:,2500);
grayscale_37_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_37(:,2500);
grayscale_39_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_39(:,2500);
grayscale_36_flow_low_heating=grayImage_low_surface_temperature_with_fin_0_36_flow_ra
te_1(:,2500);
grayscale_36_flow_high_heating=grayImage_high_surface_temperature_with_fin_0_36_flow_
rate_1(:,2500);

results_2nd_2500=[grayscale_25_2nd grayscale_27_2nd grayscale_29_2nd grayscale_31_2nd
grayscale_33_2nd grayscale_35_2nd grayscale_37_2nd grayscale_39_2nd
grayscale_36_flow_low_heating grayscale_36_flow_high_heating];

grayscale_25_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_25(20,:);
grayscale_27_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_27(20,:);
grayscale_29_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_29(20,:);
grayscale_31_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_31(20,:);
grayscale_33_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_33(20,:);
grayscale_35_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_35(20,:);
grayscale_37_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_37(20,:);
grayscale_39_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_39(20,:);
grayscale_36_flow_low_heating=grayImage_low_surface_temperature_with_fin_0_36_flow_ra
te_1(20,:);
grayscale_36_flow_high_heating=grayImage_high_surface_temperature_with_fin_0_36_flow_
rate_1(20,:);

results_2nd_20=[grayscale_25_2nd; grayscale_27_2nd; grayscale_29_2nd;
grayscale_31_2nd; grayscale_33_2nd; grayscale_35_2nd; grayscale_37_2nd;
grayscale_39_2nd; grayscale_36_flow_low_heating; grayscale_36_flow_high_heating];

```

%% near surface investigation

```
near_surface_investigation_25= grayImage_25_with_fin_0_46_flow_rate_2nd_cut(20,:);
near_surface_investigation_27= grayImage_27_with_fin_0_46_flow_rate_2nd_cut(1:100,:);
near_surface_investigation_29= grayImage_29_with_fin_0_46_flow_rate_2nd_cut(1:100,:);
near_surface_investigation_31= grayImage_31_with_fin_0_46_flow_rate_2nd_cut(1:100,:);
near_surface_investigation_33= grayImage_33_with_fin_0_46_flow_rate_2nd_cut(1:100,:);
near_surface_investigation_35= grayImage_35_with_fin_0_46_flow_rate_2nd_cut(1:100,:);
near_surface_investigation_37= grayImage_37_with_fin_0_46_flow_rate_2nd_cut(1:100,:);
near_surface_investigation_39= grayImage_39_with_fin_0_46_flow_rate_2nd_cut(1:100,:);
```

```
average_near_surface_2nd=[mean(near_surface_investigation_25(:))
    mean(near_surface_investigation_27(:))
    mean(near_surface_investigation_29(:))
    mean(near_surface_investigation_31(:))
    mean(near_surface_investigation_33(:))
    mean(near_surface_investigation_35(:))
    mean(near_surface_investigation_37(:))
    mean(near_surface_investigation_39(:))];
```

```
standard_deviation_near_surface_2nd=[std(near_surface_investigation_25(:))
    std(near_surface_investigation_27(:))
    std(near_surface_investigation_29(:))
    std(near_surface_investigation_31(:))
    std(near_surface_investigation_33(:))
    std(near_surface_investigation_35(:))
    std(near_surface_investigation_37(:))
    std(near_surface_investigation_39(:))];
```

%% to estimate temperature

```
g_2nd_1=grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut;
g_2nd_2=grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut;
g_2nd_3=grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut;
g_2nd_4=grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut;
g_2nd_5=grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut;
g_2nd_6=grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut;
g_2nd_7=grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut;
g_2nd_8=grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut;
```

```
G_2nd=zeros(2000,3312,8);
G_2nd(:,:,1)=g_2nd_1;
G_2nd(:,:,2)=g_2nd_2;
G_2nd(:,:,3)=g_2nd_3;
G_2nd(:,:,4)=g_2nd_4;
G_2nd(:,:,5)=g_2nd_5;
G_2nd(:,:,6)=g_2nd_6;
G_2nd(:,:,7)=g_2nd_7;
G_2nd(:,:,8)=g_2nd_8;
```

```
T_2nd = [25;27;29;31;33;35;37;39];
size_G_2nd = size(G_2nd);
```

```
%%%%%%%%%% Third degree
```

```
for i = 1:size_G_2nd(1);  
    for j = 1:size_G_2nd(2);  
        grayscale_2nd = squeeze(G_2nd(i,j,:));  
        fit_2nd_third_degree = polyfit(grayscale_2nd,T_2nd,3);  
        a_2nd_third_degree(i,j)=fit_2nd_third_degree(1);  
        b_2nd_third_degree(i,j)=fit_2nd_third_degree(2);  
        c_2nd_third_degree(i,j)=fit_2nd_third_degree(3);  
        d_2nd_third_degree(i,j)=fit_2nd_third_degree(4);  
    end  
end
```

```
for i = 1:size_G_2nd(1);  
    for j = 1:size_G_2nd(2);
```

```
        T_25_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut(i,j)^3+b_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut(i,j)^2+c_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut(i,j)+d_2nd_third_degree(i,j);
```

```
        T_27_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut(i,j)^3+b_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut(i,j)^2+c_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut(i,j)+d_2nd_third_degree(i,j);
```

```
        T_29_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut(i,j)^3+b_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut(i,j)^2+c_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut(i,j)+d_2nd_third_degree(i,j);
```

```
        T_31_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut(i,j)^3+b_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut(i,j)^2+c_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut(i,j)+d_2nd_third_degree(i,j);
```

```
        T_33_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut(i,j)^3+b_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut(i,j)^2+c_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut(i,j)+d_2nd_third_degree(i,j);
```

```
        T_35_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut(i,j)^3+b_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut(i,j)^2+c_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut(i,j)+d_2nd_third_degree(i,j);
```

```
        T_37_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut(i,j)^3+b_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut(i,j)^2+c_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut(i,j)+d_2nd_third_degree(i,j);
```

```
        T_39_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut(i,j)^3+b_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut(i,j)^2+c_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut(i,j)+d_2nd_third_degree(i,j);
```

```

w_rate_2nd_39_cut(i,j)^2+c_2nd_third_degree(i,j)*grayImage_average_with_fin_0_46_flow_
_rate_2nd_39_cut(i,j)+d_2nd_third_degree(i,j);
    end
end

```

```

T_2nd = [25;27;29;31;33;35;37;39];
average_T_2nd=mean([25 27 29 31 33 35 37 39]);
sum_square_2nd=[(25-average_T_2nd)^2;(27-average_T_2nd)^2;(29-average_T_2nd)^2;(31-
average_T_2nd)^2;(33-average_T_2nd)^2;(35-average_T_2nd)^2;(37-average_T_2nd)^2;(39-
average_T_2nd)^2];
sum_square_total_2nd=sum(sum_square_2nd);

```

```

Error_2nd_third_degree=zeros(2000,3312,8);
Error_2nd_third_degree(:,:,1)=T_25_2nd_third_degree-25;
Error_2nd_third_degree(:,:,2)=T_27_2nd_third_degree-27;
Error_2nd_third_degree(:,:,3)=T_29_2nd_third_degree-29;
Error_2nd_third_degree(:,:,4)=T_31_2nd_third_degree-31;
Error_2nd_third_degree(:,:,5)=T_33_2nd_third_degree-33;
Error_2nd_third_degree(:,:,6)=T_35_2nd_third_degree-35;
Error_2nd_third_degree(:,:,7)=T_37_2nd_third_degree-37;
Error_2nd_third_degree(:,:,8)=T_39_2nd_third_degree-39;

```

```

Error_square_2nd_third_degree=Error_2nd_third_degree.^2;

```

```

Total_Error_square_2nd_third_degree=sum(Error_square_2nd_third_degree,3);
R_Square_2nd_third_degree=1-
(Total_Error_square_2nd_third_degree./sum_square_total_2nd);

```

```

for i = 1:size_G_2nd(1);
    for j = 1:size_G_2nd(2);

```

```

T_25_1_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_
rate_2nd_cut_1(i,j)^3+b_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2n
d_cut_1(i,j)^2+c_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2nd_cut_1
(i,j)+d_2nd_third_degree(i,j);

```

```

T_25_2_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_
rate_2nd_cut_2(i,j)^3+b_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2n
d_cut_2(i,j)^2+c_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2nd_cut_2
(i,j)+d_2nd_third_degree(i,j);

```

```

T_25_3_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_
rate_2nd_cut_3(i,j)^3+b_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2n
d_cut_3(i,j)^2+c_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2nd_cut_3
(i,j)+d_2nd_third_degree(i,j);

```

```

T_25_4_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_
rate_2nd_cut_4(i,j)^3+b_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2n
d_cut_4(i,j)^2+c_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2nd_cut_4
(i,j)+d_2nd_third_degree(i,j);

```

```
T_25_5_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2nd_cut_5(i,j)^3+b_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2nd_cut_5(i,j)^2+c_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2nd_cut_5(i,j)+d_2nd_third_degree(i,j);
```

```
T_25_7_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2nd_cut_7(i,j)^3+b_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2nd_cut_7(i,j)^2+c_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2nd_cut_7(i,j)+d_2nd_third_degree(i,j);
```

```
T_25_9_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2nd_cut_9(i,j)^3+b_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2nd_cut_9(i,j)^2+c_2nd_third_degree(i,j)*grayImage_25_with_fin_0_46_flow_rate_2nd_cut_9(i,j)+d_2nd_third_degree(i,j);
```

```
T_27_1_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_1(i,j)^3+b_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_1(i,j)^2+c_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_1(i,j)+d_2nd_third_degree(i,j);
```

```
T_27_3_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_3(i,j)^3+b_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_3(i,j)^2+c_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_3(i,j)+d_2nd_third_degree(i,j);
```

```
T_27_6_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_6(i,j)^3+b_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_6(i,j)^2+c_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_6(i,j)+d_2nd_third_degree(i,j);
```

```
T_27_8_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_8(i,j)^3+b_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_8(i,j)^2+c_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_8(i,j)+d_2nd_third_degree(i,j);
```

```
T_27_10_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_10(i,j)^3+b_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_10(i,j)^2+c_2nd_third_degree(i,j)*grayImage_27_with_fin_0_46_flow_rate_2nd_cut_10(i,j)+d_2nd_third_degree(i,j);
```

```
T_29_2_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_2(i,j)^3+b_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_2(i,j)^2+c_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_2(i,j)+d_2nd_third_degree(i,j);
```

```
T_29_4_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_4(i,j)^3+b_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_4(i,j)^2+c_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_4(i,j)+d_2nd_third_degree(i,j);
```

```
T_29_6_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_6(i,j)^3+b_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_6(i,j)^2+c_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_6(i,j)+d_2nd_third_degree(i,j);
```

```
T_29_7_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_7(i,j)^3+b_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_7(i,j)^2+c_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_7(i,j)+d_2nd_third_degree(i,j);
```

```
T_29_9_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_9(i,j)^3+b_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_9(i,j)^2+c_2nd_third_degree(i,j)*grayImage_29_with_fin_0_46_flow_rate_2nd_cut_9(i,j)+d_2nd_third_degree(i,j);
```

```
T_31_1_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_1(i,j)^3+b_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_1(i,j)^2+c_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_1(i,j)+d_2nd_third_degree(i,j);
```

```
T_31_3_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_3(i,j)^3+b_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_3(i,j)^2+c_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_3(i,j)+d_2nd_third_degree(i,j);
```

```
T_31_5_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_5(i,j)^3+b_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_5(i,j)^2+c_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_5(i,j)+d_2nd_third_degree(i,j);
```

```
T_31_8_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_8(i,j)^3+b_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_8(i,j)^2+c_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_8(i,j)+d_2nd_third_degree(i,j);
```

```
T_31_10_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_10(i,j)^3+b_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_10(i,j)^2+c_2nd_third_degree(i,j)*grayImage_31_with_fin_0_46_flow_rate_2nd_cut_10(i,j)+d_2nd_third_degree(i,j);
```

```
T_33_2_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_33_with_fin_0_46_flow_rate_2nd_cut_2(i,j)^3+b_2nd_third_degree(i,j)*grayImage_33_with_fin_0_46_flow_rate_2nd_cut_2(i,j)^2+c_2nd_third_degree(i,j)*grayImage_33_with_fin_0_46_flow_rate_2nd_cut_2(i,j)+d_2nd_third_degree(i,j);
```

```
T_33_4_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_33_with_fin_0_46_flow_rate_2nd_cut_4(i,j)^3+b_2nd_third_degree(i,j)*grayImage_33_with_fin_0_46_flow_rate_2nd_cut_4(i,j)^2+c_2nd_third_degree(i,j)*grayImage_33_with_fin_0_46_flow_rate_2nd_cut_4(i,j)+d_2nd_third_degree(i,j);
```

```
T_33_6_2nd_third_degree(i,j)=a_2nd_third_degree(i,j)*grayImage_33_with_fin_0_46_flow_rate_2nd_cut_6(i,j)^3+b_2nd_third_degree(i,j)*grayImage_33_with_fin_0_46_flow_rate_2nd_cut_6(i,j)^2+c_2nd_third_degree(i,j)*grayImage_33_with_fin_0_46_flow_rate_2nd_cut_6(i,j)+d_2nd_third_degree(i,j);
```



```
rd_degree(i,j)*grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_8(i,j)+d_2nd_t  
hird_degree(i,j);
```

```
T_high_surface_temp_with_fin_0_36_flow_rate_9_2nd_third_degree(i,j)=a_2nd_third_degre  
e(i,j)*grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_9(i,j)^3+b_2nd_third_d  
egree(i,j)*grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_9(i,j)^2+c_2nd_thi  
rd_degree(i,j)*grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_9(i,j)+d_2nd_t  
hird_degree(i,j);
```

```
T_high_surface_temp_with_fin_0_36_flow_rate_10_2nd_third_degree(i,j)=a_2nd_third_degr  
ee(i,j)*grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_10(i,j)^3+b_2nd_third  
_degree(i,j)*grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_10(i,j)^2+c_2nd_  
third_degree(i,j)*grayImage_high_surface_temp_with_fin_0_36_flow_rate_cut_10(i,j)+d_2  
nd_third_degree(i,j);
```

```
end  
end
```

```
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_1=T_low_surface_temp_with_fin_0  
_36_flow_rate_1_2nd_third_degree(1:2000,2500);  
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_2=T_low_surface_temp_with_fin_0  
_36_flow_rate_2_2nd_third_degree(1:2000,2500);  
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_3=T_low_surface_temp_with_fin_0  
_36_flow_rate_3_2nd_third_degree(1:2000,2500);  
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_4=T_low_surface_temp_with_fin_0  
_36_flow_rate_4_2nd_third_degree(1:2000,2500);  
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_5=T_low_surface_temp_with_fin_0  
_36_flow_rate_5_2nd_third_degree(1:2000,2500);  
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_6=T_low_surface_temp_with_fin_0  
_36_flow_rate_6_2nd_third_degree(1:2000,2500);  
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_7=T_low_surface_temp_with_fin_0  
_36_flow_rate_7_2nd_third_degree(1:2000,2500);  
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_8=T_low_surface_temp_with_fin_0  
_36_flow_rate_8_2nd_third_degree(1:2000,2500);  
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_9=T_low_surface_temp_with_fin_0  
_36_flow_rate_9_2nd_third_degree(1:2000,2500);  
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_10=T_low_surface_temp_with_fin_  
0_36_flow_rate_10_2nd_third_degree(1:2000,2500);
```

```
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_1=T_low_surface_temp_with_fin_0_  
36_flow_rate_1_2nd_third_degree(1:2000,1000);  
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_2=T_low_surface_temp_with_fin_0_  
36_flow_rate_2_2nd_third_degree(1:2000,1000);  
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_3=T_low_surface_temp_with_fin_0_  
36_flow_rate_3_2nd_third_degree(1:2000,1000);  
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_4=T_low_surface_temp_with_fin_0_  
36_flow_rate_4_2nd_third_degree(1:2000,1000);  
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_5=T_low_surface_temp_with_fin_0_  
36_flow_rate_5_2nd_third_degree(1:2000,1000);  
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_6=T_low_surface_temp_with_fin_0_  
36_flow_rate_6_2nd_third_degree(1:2000,1000);
```

```

Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_7=T_low_surface_temp_with_fin_0_
36_flow_rate_7_2nd_third_degree(1:2000,1000);
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_8=T_low_surface_temp_with_fin_0_
36_flow_rate_8_2nd_third_degree(1:2000,1000);
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_9=T_low_surface_temp_with_fin_0_
36_flow_rate_9_2nd_third_degree(1:2000,1000);
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_10=T_low_surface_temp_with_fin_0_
36_flow_rate_10_2nd_third_degree(1:2000,1000);

```

```

Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_1=T_high_surface_temp_with_fin_
0_36_flow_rate_1_2nd_third_degree(1:2000,2500);
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_2=T_high_surface_temp_with_fin_
0_36_flow_rate_2_2nd_third_degree(1:2000,2500);
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_3=T_high_surface_temp_with_fin_
0_36_flow_rate_3_2nd_third_degree(1:2000,2500);
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_4=T_high_surface_temp_with_fin_
0_36_flow_rate_4_2nd_third_degree(1:2000,2500);
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_5=T_high_surface_temp_with_fin_
0_36_flow_rate_5_2nd_third_degree(1:2000,2500);
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_6=T_high_surface_temp_with_fin_
0_36_flow_rate_6_2nd_third_degree(1:2000,2500);
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_7=T_high_surface_temp_with_fin_
0_36_flow_rate_7_2nd_third_degree(1:2000,2500);
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_8=T_high_surface_temp_with_fin_
0_36_flow_rate_8_2nd_third_degree(1:2000,2500);
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_9=T_high_surface_temp_with_fin_
0_36_flow_rate_9_2nd_third_degree(1:2000,2500);
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_10=T_high_surface_temp_with_fi
n_0_36_flow_rate_10_2nd_third_degree(1:2000,2500);

```

```

Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_1=T_high_surface_temp_with_fin_
0_36_flow_rate_1_2nd_third_degree(1:2000,1000);
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_2=T_high_surface_temp_with_fin_
0_36_flow_rate_2_2nd_third_degree(1:2000,1000);
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_3=T_high_surface_temp_with_fin_
0_36_flow_rate_3_2nd_third_degree(1:2000,1000);
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_4=T_high_surface_temp_with_fin_
0_36_flow_rate_4_2nd_third_degree(1:2000,1000);
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_5=T_high_surface_temp_with_fin_
0_36_flow_rate_5_2nd_third_degree(1:2000,1000);
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_6=T_high_surface_temp_with_fin_
0_36_flow_rate_6_2nd_third_degree(1:2000,1000);
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_7=T_high_surface_temp_with_fin_
0_36_flow_rate_7_2nd_third_degree(1:2000,1000);
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_8=T_high_surface_temp_with_fin_
0_36_flow_rate_8_2nd_third_degree(1:2000,1000);
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_9=T_high_surface_temp_with_fin_
0_36_flow_rate_9_2nd_third_degree(1:2000,1000);
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_10=T_high_surface_temp_with_fin_
0_36_flow_rate_10_2nd_third_degree(1:2000,1000);

```

```

Temp_dist_average_after_fin_low_surf_temp_0_36_flow_2nd_1=mean(T_low_surface_temp_wit
h_fin_0_36_flow_rate_1_2nd_third_degree(1:2000,1000:1500),2);

```



```

Temp_dist_average_before_fin_low_surf_temp_0_36_flow_2nd_8=mean(T_low_surface_temp_wi
th_fin_0_36_flow_rate_8_2nd_third_degree(1:2000,2100:2600),2);
Temp_dist_average_before_fin_low_surf_temp_0_36_flow_2nd_9=mean(T_low_surface_temp_wi
th_fin_0_36_flow_rate_9_2nd_third_degree(1:2000,2100:2600),2);
Temp_dist_average_before_fin_low_surf_temp_0_36_flow_2nd_10=mean(T_low_surface_temp_w
ith_fin_0_36_flow_rate_10_2nd_third_degree(1:2000,2100:2600),2);

```

```

Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_1=mean(T_high_surface_temp_
with_fin_0_36_flow_rate_1_2nd_third_degree(1:2000,2100:2600),2);
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_2=mean(T_high_surface_temp_
with_fin_0_36_flow_rate_2_2nd_third_degree(1:2000,2100:2600),2);
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_3=mean(T_high_surface_temp_
with_fin_0_36_flow_rate_3_2nd_third_degree(1:2000,2100:2600),2);
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_4=mean(T_high_surface_temp_
with_fin_0_36_flow_rate_4_2nd_third_degree(1:2000,2100:2600),2);
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_5=mean(T_high_surface_temp_
with_fin_0_36_flow_rate_5_2nd_third_degree(1:2000,2100:2600),2);
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_6=mean(T_high_surface_temp_
with_fin_0_36_flow_rate_6_2nd_third_degree(1:2000,2100:2600),2);
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_7=mean(T_high_surface_temp_
with_fin_0_36_flow_rate_7_2nd_third_degree(1:2000,2100:2600),2);
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_8=mean(T_high_surface_temp_
with_fin_0_36_flow_rate_8_2nd_third_degree(1:2000,2100:2600),2);
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_9=mean(T_high_surface_temp_
with_fin_0_36_flow_rate_9_2nd_third_degree(1:2000,2100:2600),2);
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_10=mean(T_high_surface_temp
_with_fin_0_36_flow_rate_10_2nd_third_degree(1:2000,2100:2600),2);

```

```

Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd=[Temp_dist_line_before_fin_low_
surf_temp_0_36_flow_2nd_1 Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_2
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_3
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_4
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_5
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_6
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_7
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_8
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_9
Temp_dist_line_before_fin_low_surf_temp_0_36_flow_2nd_10];
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd=[Temp_dist_line_after_fin_low_su
rf_temp_0_36_flow_2nd_1 Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_2
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_3
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_4
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_5
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_6
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_7
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_8
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_9
Temp_dist_line_after_fin_low_surf_temp_0_36_flow_2nd_10];
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd=[Temp_dist_line_before_fin_hig
h_surf_temp_0_36_flow_2nd_1 Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_2
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_3
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_4
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_5

```

```
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_6
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_7
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_8
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_9
Temp_dist_line_before_fin_high_surf_temp_0_36_flow_2nd_10];
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd=[Temp_dist_line_after_fin_high_
surf_temp_0_36_flow_2nd_1 Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_2
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_3
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_4
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_5
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_6
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_7
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_8
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_9
Temp_dist_line_after_fin_high_surf_temp_0_36_flow_2nd_10];
Temp_dist_average_before_fin_low_surf_temp_0_36_flow_2nd=[Temp_dist_average_before_fi
n_low_surf_temp_0_36_flow_2nd_1
Temp_dist_average_before_fin_low_surf_temp_0_36_flow_2nd_2
Temp_dist_average_before_fin_low_surf_temp_0_36_flow_2nd_3
Temp_dist_average_before_fin_low_surf_temp_0_36_flow_2nd_4
Temp_dist_average_before_fin_low_surf_temp_0_36_flow_2nd_5
Temp_dist_average_before_fin_low_surf_temp_0_36_flow_2nd_6
Temp_dist_average_before_fin_low_surf_temp_0_36_flow_2nd_7
Temp_dist_average_before_fin_low_surf_temp_0_36_flow_2nd_8
Temp_dist_average_before_fin_low_surf_temp_0_36_flow_2nd_9
Temp_dist_average_before_fin_low_surf_temp_0_36_flow_2nd_10];
Temp_dist_average_after_fin_low_surf_temp_0_36_flow_2nd=[Temp_dist_average_after_fin_
low_surf_temp_0_36_flow_2nd_1
Temp_dist_average_after_fin_low_surf_temp_0_36_flow_2nd_2
Temp_dist_average_after_fin_low_surf_temp_0_36_flow_2nd_3
Temp_dist_average_after_fin_low_surf_temp_0_36_flow_2nd_4
Temp_dist_average_after_fin_low_surf_temp_0_36_flow_2nd_5
Temp_dist_average_after_fin_low_surf_temp_0_36_flow_2nd_6
Temp_dist_average_after_fin_low_surf_temp_0_36_flow_2nd_7
Temp_dist_average_after_fin_low_surf_temp_0_36_flow_2nd_8
Temp_dist_average_after_fin_low_surf_temp_0_36_flow_2nd_9
Temp_dist_average_after_fin_low_surf_temp_0_36_flow_2nd_10];
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd=[Temp_dist_average_before_f
in_high_surf_temp_0_36_flow_2nd_1
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_2
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_3
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_4
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_5
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_6
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_7
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_8
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_9
Temp_dist_average_before_fin_high_surf_temp_0_36_flow_2nd_10];
Temp_dist_average_after_fin_high_surf_temp_0_36_flow_2nd=[Temp_dist_average_after_fin_
_high_surf_temp_0_36_flow_2nd_1
Temp_dist_average_after_fin_high_surf_temp_0_36_flow_2nd_2
Temp_dist_average_after_fin_high_surf_temp_0_36_flow_2nd_3
Temp_dist_average_after_fin_high_surf_temp_0_36_flow_2nd_4
Temp_dist_average_after_fin_high_surf_temp_0_36_flow_2nd_5
Temp_dist average after fin high surf temp 0 36 flow 2nd 6
```

```

Temp_dist_average_after_fin_high_surf_temp_0_36_flow_2nd_7
Temp_dist_average_after_fin_high_surf_temp_0_36_flow_2nd_8
Temp_dist_average_after_fin_high_surf_temp_0_36_flow_2nd_9
Temp_dist_average_after_fin_high_surf_temp_0_36_flow_2nd_10];

grayscale_25_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut(:,2500);
grayscale_27_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut(:,2500);
grayscale_29_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut(:,2500);
grayscale_31_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut(:,2500);
grayscale_33_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut(:,2500);
grayscale_35_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut(:,2500);
grayscale_37_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut(:,2500);
grayscale_39_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut(:,2500);
grayscale_36_flow_low_heating=grayImage_low_surface_temp_with_fin_0_36_flow_rate_cut_
1(:,2500);
grayscale_36_flow_high_heating=grayImage_high_surface_temp_with_fin_0_36_flow_rate_cu
t_1(:,2500);

grayscale_results_2nd_2500=[grayscale_25_2nd grayscale_27_2nd grayscale_29_2nd
grayscale_31_2nd grayscale_33_2nd grayscale_35_2nd grayscale_37_2nd grayscale_39_2nd
grayscale_36_flow_low_heating grayscale_36_flow_high_heating];

Temperature_calibration_curve=[grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut(1
000,2500)
    grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut(1000,2500)
    grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut(1000,2500)
    grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut(1000,2500)
    grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut(1000,2500)
    grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut(1000,2500)
    grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut(1000,2500)
    grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut(1000,2500)];

grayscale_25_2500_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut(:,2
500);
grayscale_27_2500_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut(:,2
500);
grayscale_29_2500_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut(:,2
500);
grayscale_31_2500_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut(:,2
500);
grayscale_33_2500_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut(:,2
500);
grayscale_35_2500_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut(:,2
500);
grayscale_37_2500_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut(:,2
500);
grayscale_39_2500_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut(:,2
500);
grayscale_26_flow_low_heating_2500_column=grayImage_low_surface_temp_with_fin_0_36_fl
ow_rate_cut_1(:,2500);

```

```

grayscale_26_flow_high_heating_2500_column=grayImage_high_surface_temp_with_fin_0_36_
flow_rate_cut_1(:,2500);

```

```

grayscale_results_2nd_2500_column=[grayscale_25_2500_column_2nd
grayscale_27_2500_column_2nd grayscale_29_2500_column_2nd
grayscale_31_2500_column_2nd grayscale_33_2500_column_2nd
grayscale_35_2500_column_2nd grayscale_37_2500_column_2nd
grayscale_39_2500_column_2nd grayscale_26_flow_low_heating_2500_column
grayscale_26_flow_high_heating_2500_column];

```

```

grayscale_25_1000_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut(:,1
000);
grayscale_27_1000_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut(:,1
000);
grayscale_29_1000_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut(:,1
000);
grayscale_31_1000_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut(:,1
000);
grayscale_33_1000_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut(:,1
000);
grayscale_35_1000_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut(:,1
000);
grayscale_37_1000_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut(:,1
000);
grayscale_39_1000_column_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut(:,1
000);
grayscale_26_flow_low_heating_1000_column=grayImage_low_surface_temp_with_fin_0_36_fl
ow_rate_cut_1(:,1000);
grayscale_26_flow_high_heating_1000_column=grayImage_high_surface_temp_with_fin_0_36_
flow_rate_cut_1(:,1000);

```

```

grayscale_results_2nd_1000_column=[grayscale_25_1000_column_2nd
grayscale_27_1000_column_2nd grayscale_29_1000_column_2nd
grayscale_31_1000_column_2nd grayscale_33_1000_column_2nd
grayscale_35_1000_column_2nd grayscale_37_1000_column_2nd
grayscale_39_1000_column_2nd grayscale_26_flow_low_heating_1000_column
grayscale_26_flow_high_heating_1000_column];

```

```

grayscale_25_20_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut(20,:);
grayscale_27_20_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut(20,:);
grayscale_29_20_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut(20,:);
grayscale_31_20_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut(20,:);
grayscale_33_20_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut(20,:);
grayscale_35_20_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut(20,:);
grayscale_37_20_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut(20,:);
grayscale_39_20_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut(20,:);
grayscale_26_flow_low_heating_20_raw=grayImage_low_surface_temp_with_fin_0_36_flow_ra
te_cut_1(20,:);
grayscale_26_flow_high_heating_20_raw=grayImage_high_surface_temp_with_fin_0_36_flow_
rate_cut_1(20,:);

```

```

grayscale_results_2nd_20_raw=[grayscale_25_20_raw_2nd; grayscale_27_20_raw_2nd;
grayscale_29_20_raw_2nd; grayscale_31_20_raw_2nd; grayscale_33_20_raw_2nd;
grayscale_35_20_raw_2nd; grayscale_37_20_raw_2nd; grayscale_39_20_raw_2nd;
grayscale_26_flow_low_heating_20_raw; grayscale_26_flow_high_heating_20_raw];

grayscale_25_50_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut(50,:);
grayscale_27_50_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut(50,:);
grayscale_29_50_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut(50,:);
grayscale_31_50_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut(50,:);
grayscale_33_50_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut(50,:);
grayscale_35_50_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut(50,:);
grayscale_37_50_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut(50,:);
grayscale_39_50_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut(50,:);
grayscale_26_flow_low_heating_50_raw=grayImage_low_surface_temp_with_fin_0_36_flow_r
ate_cut_1(50,:);
grayscale_26_flow_high_heating_50_raw=grayImage_high_surface_temp_with_fin_0_36_flow
_rate_cut_1(50,:);

grayscale_results_2nd_50_raw=[grayscale_25_50_raw_2nd; grayscale_27_50_raw_2nd;
grayscale_29_50_raw_2nd; grayscale_31_50_raw_2nd; grayscale_33_50_raw_2nd;
grayscale_35_50_raw_2nd; grayscale_37_50_raw_2nd; grayscale_39_50_raw_2nd;
grayscale_26_flow_low_heating_50_raw; grayscale_26_flow_high_heating_50_raw];

grayscale_25_100_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut(100,:);
grayscale_27_100_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut(100,:);
grayscale_29_100_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut(100,:);
grayscale_31_100_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut(100,:);
grayscale_33_100_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut(100,:);
grayscale_35_100_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut(100,:);
grayscale_37_100_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut(100,:);
grayscale_39_100_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut(100,:);
grayscale_26_flow_low_heating_100_raw=grayImage_low_surface_temp_with_fin_0_36_flow_r
ate_cut_1(100,:);
grayscale_26_flow_high_heating_100_raw=grayImage_high_surface_temp_with_fin_0_36_flow
_rate_cut_1(100,:);

grayscale_results_2nd_100_raw=[grayscale_25_100_raw_2nd; grayscale_27_100_raw_2nd;
grayscale_29_100_raw_2nd; grayscale_31_100_raw_2nd; grayscale_33_100_raw_2nd;
grayscale_35_100_raw_2nd; grayscale_37_100_raw_2nd; grayscale_39_100_raw_2nd;
grayscale_26_flow_low_heating_100_raw; grayscale_26_flow_high_heating_100_raw];

grayscale_25_200_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut(200,:);
grayscale_27_200_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut(200,:);
grayscale_29_200_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut(200,:);
grayscale_31_200_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut(200,:);
grayscale_33_200_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut(200,:);
grayscale_35_200_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut(200,:);
grayscale_37_200_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut(200,:);
grayscale_39_200_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut(200,:);
grayscale_26_flow_low_heating_200_raw=grayImage_low_surface_temp_with_fin_0_36_flow_r
ate_cut_1(200,:);
grayscale_26_flow_high_heating_200_raw=grayImage_high_surface_temp_with_fin_0_36_flow
_rate_cut_1(200,:);

```

```

grayscale_results_2nd_200_raw=[grayscale_25_200_raw_2nd; grayscale_27_200_raw_2nd;;
grayscale_29_200_raw_2nd; grayscale_31_200_raw_2nd; grayscale_33_200_raw_2nd;
grayscale_35_200_raw_2nd; grayscale_37_200_raw_2nd; grayscale_39_200_raw_2nd;
grayscale_26_flow_low_heating_200_raw; grayscale_26_flow_high_heating_200_raw];

grayscale_25_500_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_25_cut(500,:);
grayscale_27_500_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_27_cut(500,:);
grayscale_29_500_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_29_cut(500,:);
grayscale_31_500_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_31_cut(500,:);
grayscale_33_500_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_33_cut(500,:);
grayscale_35_500_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_35_cut(500,:);
grayscale_37_500_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_37_cut(500,:);
grayscale_39_500_raw_2nd=grayImage_average_with_fin_0_46_flow_rate_2nd_39_cut(500,:);
grayscale_26_flow_low_heating_500_raw=grayImage_low_surface_temp_with_fin_0_36_flow_r
ate_cut_1(500,:);
grayscale_26_flow_high_heating_500_raw=grayImage_high_surface_temp_with_fin_0_36_flow
_rate_cut_1(500,:);

grayscale_results_2nd_500_raw=[grayscale_25_500_raw_2nd; grayscale_27_500_raw_2nd;;
grayscale_29_500_raw_2nd; grayscale_31_500_raw_2nd; grayscale_33_500_raw_2nd;
grayscale_35_500_raw_2nd; grayscale_37_500_raw_2nd; grayscale_39_500_raw_2nd;
grayscale_26_flow_low_heating_500_raw; grayscale_26_flow_high_heating_500_raw];

figure;
contour( T_low_surface_temp_with_fin_0_36_flow_rate_1_2nd_third_degree,500);
title('low surface temperature heating - 0.36 kg/s - 1')
xlabel('pixels');
ylabel('pixels');
caxis([25 32]);
colorbar;

figure;
contour( T_low_surface_temp_with_fin_0_36_flow_rate_2_2nd_third_degree,500);
title('low surface temperature heating - 0.36 kg/s - 2')
xlabel('pixels');
ylabel('pixels');
caxis([25 32]);
colorbar;

figure;
contour( T_low_surface_temp_with_fin_0_36_flow_rate_3_2nd_third_degree,500);
title('low surface temperature heating - 0.36 kg/s - 3')
xlabel('pixels');
ylabel('pixels');
caxis([25 32]);
colorbar;

figure;
contour( T_low_surface_temp_with_fin_0_36_flow_rate_4_2nd_third_degree,500);

```

```

title('low surface temperature heating - 0.36 kg/s - 4')
xlabel('pixels');
ylabel('pixels');
caxis([25 32]);
colorbar;

figure;
contour( T_low_surface_temp_with_fin_0_36_flow_rate_5_2nd_third_degree,500);
title('low surface temperature heating - 0.36 kg/s - 5')
xlabel('pixels');
ylabel('pixels');
caxis([25 32]);
colorbar;

figure;
contour( T_low_surface_temp_with_fin_0_36_flow_rate_6_2nd_third_degree,500);
title('low surface temperature heating - 0.36 kg/s - 6')
xlabel('pixels');
ylabel('pixels');
caxis([25 32]);
colorbar;

figure;
contour( T_low_surface_temp_with_fin_0_36_flow_rate_7_2nd_third_degree,500);
title('low surface temperature heating - 0.36 kg/s - 7')
xlabel('pixels');
ylabel('pixels');
caxis([25 32]);
colorbar;

figure;
contour( T_low_surface_temp_with_fin_0_36_flow_rate_8_2nd_third_degree,500);
title('low surface temperature heating - 0.36 kg/s - 8')
xlabel('pixels');
ylabel('pixels');
caxis([25 32]);
colorbar;

figure;
contour( T_low_surface_temp_with_fin_0_36_flow_rate_9_2nd_third_degree,500);
title('low surface temperature heating - 0.36 kg/s - 9')
xlabel('pixels');
ylabel('pixels');
caxis([25 32]);
colorbar;

figure;
contour( T_low_surface_temp_with_fin_0_36_flow_rate_10_2nd_third_degree,500);
title('low surface temperature heating - 0.36 kg/s - 10')
xlabel('pixels');
ylabel('pixels');
caxis([25 32]);
colorbar;

```

```
figure;
contour( T_high_surface_temp_with_fin_0_36_flow_rate_1_2nd_third_degree,500);
title('high surface temperature heating - 0.36 kg/s - 1')
xlabel('pixels');
ylabel('pixels');
caxis([27 37]);
colorbar;
```

```
figure;
contour( T_high_surface_temp_with_fin_0_36_flow_rate_2_2nd_third_degree,500);
title('high surface temperature heating - 0.36 kg/s - 2')
xlabel('pixels');
ylabel('pixels');
caxis([27 37]);
colorbar;
```

```
figure;
contour( T_high_surface_temp_with_fin_0_36_flow_rate_3_2nd_third_degree,500);
title('high surface temperature heating - 0.36 kg/s - 3')
xlabel('pixels');
ylabel('pixels');
caxis([27 37]);
colorbar;
```

```
figure;
contour( T_high_surface_temp_with_fin_0_36_flow_rate_4_2nd_third_degree,500);
title('high surface temperature heating - 0.36 kg/s - 4')
xlabel('pixels');
ylabel('pixels');
caxis([27 37]);
colorbar;
```

```
figure;
contour( T_high_surface_temp_with_fin_0_36_flow_rate_5_2nd_third_degree,500);
title('high surface temperature heating - 0.36 kg/s - 5')
xlabel('pixels');
ylabel('pixels');
caxis([27 37]);
colorbar;
```

```
figure;
contour( T_high_surface_temp_with_fin_0_36_flow_rate_6_2nd_third_degree,500);
title('high surface temperature heating - 0.36 kg/s - 6')
xlabel('pixels');
ylabel('pixels');
caxis([27 37]);
colorbar;
```

```
figure;
contour( T_high_surface_temp_with_fin_0_36_flow_rate_7_2nd_third_degree,500);
```

```

title('high surface temperature heating - 0.36 kg/s - 7')
xlabel('pixels');
ylabel('pixels');
caxis([27 37]);
colorbar;

figure;
contour( T_high_surface_temp_with_fin_0_36_flow_rate_8_2nd_third_degree,500);
title('high surface temperature heating - 0.36 kg/s - 8')
xlabel('pixels');
ylabel('pixels');
caxis([27 37]);
colorbar;

figure;
contour( T_high_surface_temp_with_fin_0_36_flow_rate_9_2nd_third_degree,500);
title('high surface temperature heating - 0.36 kg/s - 9')
xlabel('pixels');
ylabel('pixels');
caxis([27 37]);
colorbar;

figure;
contour( T_high_surface_temp_with_fin_0_36_flow_rate_10_2nd_third_degree,500);
title('high surface temperature heating - 0.36 kg/s - 10')
xlabel('pixels');
ylabel('pixels');
caxis([27 37]);
colorbar;

```

