Real time x-ray analysis of liquid-DT fill level in fill-tube capsules to control solid-layer thickness

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September 2018

1. Abstract

The current permeation capsule-filling technique limits the capsule materials to polymers. Future OMEGA experiments will use spherical capsules filled via a fill tube to allow variability in capsule materials. In the filling process, spherical fill-tube capsules are first cooled to cryogenic temperatures and filled with liquid deuterium-tritium (DT), which is then frozen to form a uniformly distributed layer of solid DT on their interior. During initial filling, the liquid level is observed via x-ray phase-contrast imaging normal to the direction of gravity, presenting a meniscus symmetric about the gravitational axis. A series of MATLAB programs were developed to control the liquid-DT fill level in fill tube capsules. The main program acquires near real time phase-contrast images and uses an algorithm to compute the solid thickness when uniformly frozen. The program achieves the desired fill level from user input using a proportional integral derivative (PID) controller. Once the program stabilizes the estimated final thickness within ±1 μm of the desired thickness for a specified time period, the program rapidly freezes an ice plug in the fill tube, blocking any liquid from leaving or entering the capsule. Since a small amount of liquid leaves the capsule when the ice plug forms due to its contraction, a bias is calculated, the capsule is heated back into the liquid phase of DT, and the process is repeated taking the bias into account. The program was successfully implemented to deterministically control capsule filling, and it was proven to be reproducible with a <30 min settling time to achieve the fill required to produce the desired thickness.

2. Introduction

Nuclear fusion offers the prospect of an environmentally friendly energy source with an almost infinite fuel source – deuterium (D) from seawater and tritium (T) bred in a reactor. To achieve fusion, elemental hydrogen isotopes deuterium and tritium must be heated to millions of degrees and compressed to hundreds of Gbar [1]. This causes the D-T hydrogen nuclei to overcome the electrostatic repulsion force between them and combine to form a helium nucleus, and release energy in the form of an energetic neutron.

The University of Rochester's Laboratory for Laser Energetics (LLE) has the mission of conducting fusion research. Inertial-confinement fusion is one method of fusion, implemented at LLE, in which a microscopic target is irradiated by high-power lasers. The energy from the laser is delivered uniformly onto the surface of the target, rapidly heating the shell, and causing ablation of the outer surface that drives implosion of the inner surface. The implosion of the shell compresses the DT to the high pressure required for fusion.

As the deuterium-tritium (DT) filled capsules are imploded by OMEGA's 60 laser beams, both the uniformity of the laser beams and the quality of the capsule are extremely important. A lack of uniformity causes hydrodynamic instabilities, which contribute to mixing of the shell and fuel in the target and spoiling the efficiency of the fusion reactions.

Efforts are being made to optimize the surface uniformity of the capsule. The current permeation-filling process may be leaving debris on the target shells and causing radiation damage to the polymeric capsules that releases condensable contamination (CH_4, CO, CO_2) on their interior. Another advantage of the fill-tube filling method is that it allows for the use of alternate ablators such as beryllium, silicon, and high-density carbon (HDC) [2] which are not permeable to DT. Both the possibility of permeation filling causing imperfections and the desire from scientists to experiment with alternative capsule materials necessitate the development of the fill-tube filling method.

2.1. Cryogenic Fill-tube Test Facility (CFTF)

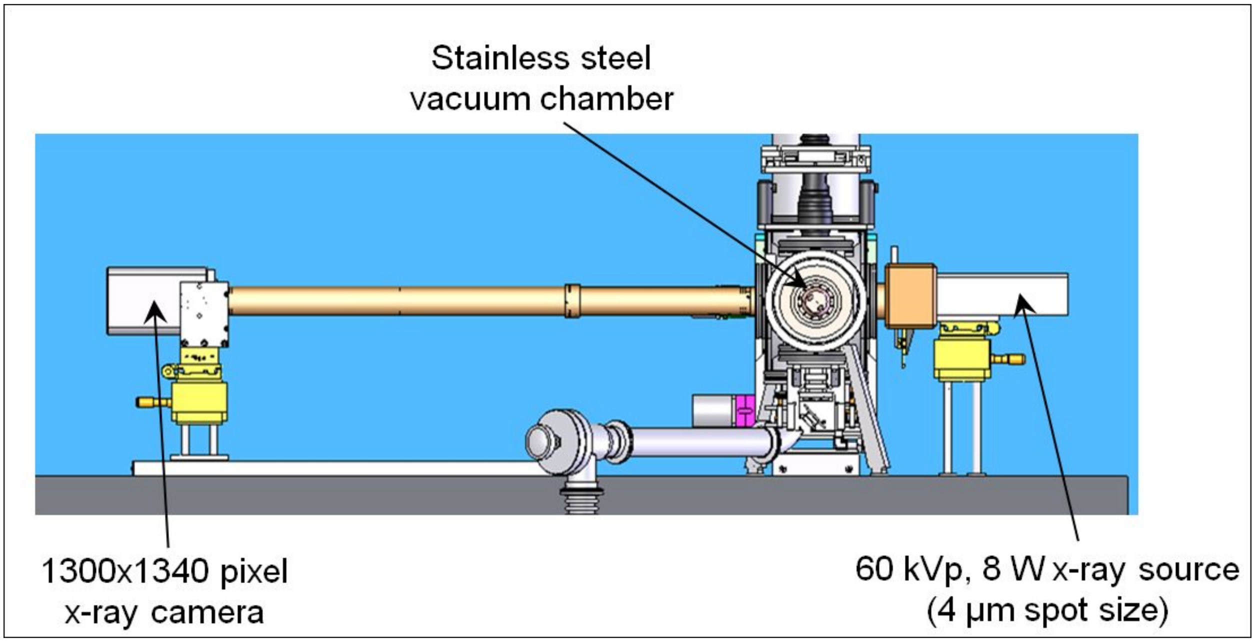

Figure 1. CAD representation of the x-ray phase-contrast system in the fill-tube experimental apparatus.

Figure 1 depicts the CFTF which researchers at LLE use to determine the parameters required to produce high-quality targets using the fill-tube method. The stainless-steel vacuum chamber contains the capsule. During the filling process, the capsule is illuminated by an x-ray source and imaged onto an x-ray camera to observe the filling process. This viewing is in near real time; multiple three-second long frames are acquired and averaged during image collection to reduce noise in the process.

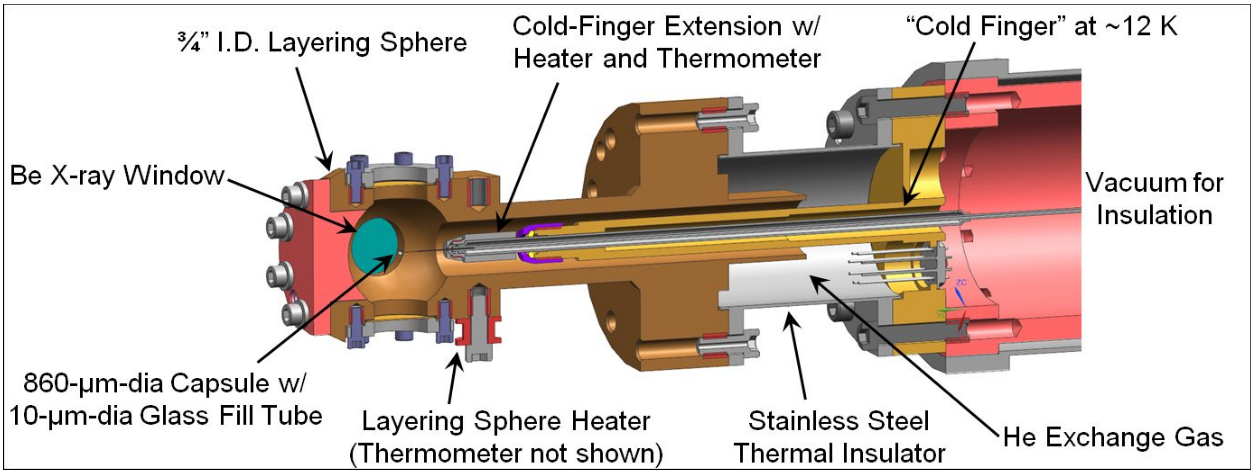

Figure 2. CAD cross section representation of the layering sphere that houses the fill-tube target.

Figure 2 depicts the layering sphere assembly inside of the stainless-steel vacuum chamber displayed in Figure 1. The orientation of this apparatus is horizontal, and situated such that the x-ray camera in Figure 1 views through the beryllium (Be) viewing window. The capsule, held within the ¾-inch-diameter layering sphere, is an 860-μm-diameter polymeric capsule with an 8-μm-thick wall. Holding the capsule in place is a 10-μm-diameter glass fill tube, which connects to a stainless-steel capillary tube exiting the right of the diagram to a gaseous-DT reservoir. To control the fill level in the capsule, the layering sphere's temperature is controlled using a heater and thermometer connected to it. The temperature of the layering sphere is initially controlled at ~19 K and the gaseous DT condenses into the liquid phase as it enters the capsule. An increase in layering-sphere temperature causes the pressure of the DT vapor above the liquid inside the capsule to increase, driving the liquid DT out of the capsule. The opposite effect occurs when the layering sphere is cooled; this process allows filling or emptying the capsule with very fine control using mK temperature changes.

Unfortunately, the relationship between the temperature of the layering sphere and the liquid level in the capsule is not necessarily deterministic. There is no reproducible temperature for any liquid level due to fluctuations in the ratio of deuterium and tritium in the reservoir and the initial pressure in the reservoir. As a result of this, programming an automated capsule filling process must include a temperature control loop with feedback from the x-ray camera.

One other important feature of the apparatus is the cold finger extension. This is a subset of the cold finger (the element cooling the entire system), which surrounds the fill tube. It is used to control the state of the DT in the fill tube close to the capsule. This metal “bullet” has the ability to heat and cool rapidly, allowing an ice plug to form nearly instantaneously within the fill tube when heat is removed. This gives the ability to terminate any DT flow to or from the capsule once the desired liquid level has been achieved. Unfortunately, there is a slight amount of liquid DT that leaves the capsule when the ice plug forms due to contraction of the liquid during solidification; this must be accounted for. Once the desired thickness is obtained within one micrometer, and checked after the ice plug is formed, the capsule is slowly cooled so that a single DT seed crystal grows and converts the liquid to the solid phase.

This freezing process takes place over a period of up to fifteen hours both to slowly form a single crystal and to allow for beta layering. Beta layering occurs when radioactive tritium releases an energetic beta particle. The beta particle deposits its energy into the solid DT to produce volumetric heating. Thicker regions of the solid receive more energy than thinner regions. Sublimation of the DT occurs – thicker regions sublime and redeposit in the thinner regions; this results in a uniform layer of solid DT on the inside surface of the capsule. The thickness of the layer must be uniform within 1-µm-rms and must be within one micrometer from the desired thickness.

3. Automation Process

The main objective of this work was to automate the fill process of a fill-tube capsule to make it more efficient than the current “human control loop” running the process at LLE. This includes filling the capsule to a desired thickness, creating an ice plug, and compensating for any bias occurring during the ice-plug freezing process. A MATLAB program was developed for this purpose and is structured as shown in Figure 3.

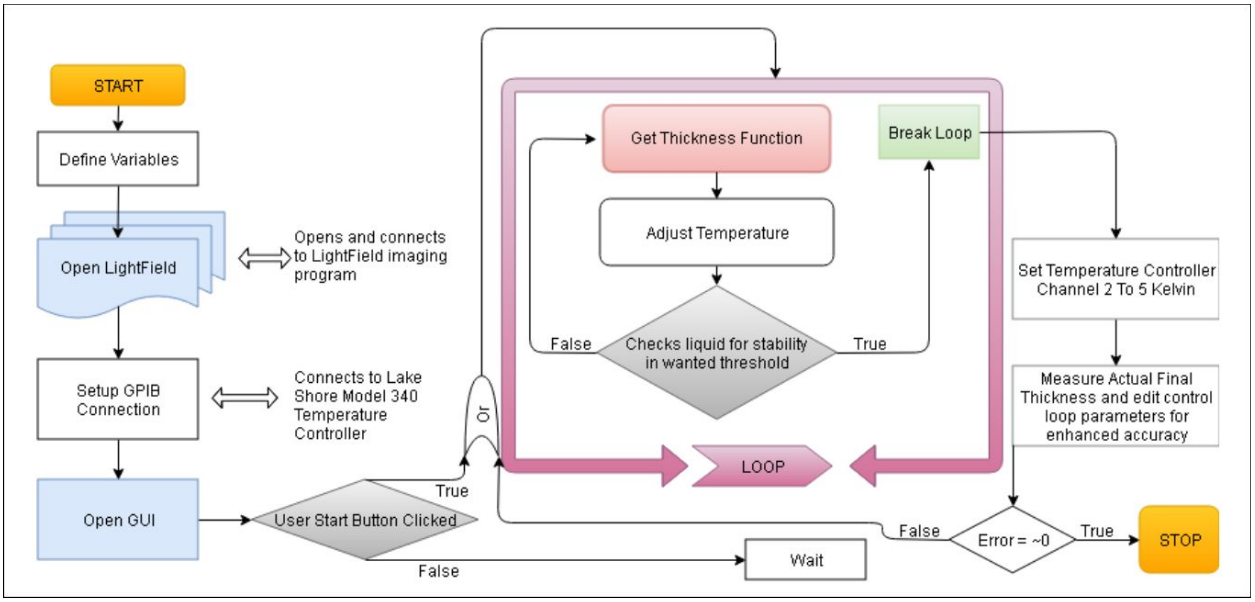

Figure 3. Flowchart diagram outlining high level logic flow of the program used to automate the fill process.

The program begins by setting multiple global variables. These variables such as current time and current estimated thickness are used throughout the program and in most functions, so globalizing them is practical. The program then connects to the necessary systems: First, the program opens an instance of LightField®, an imaging program designed to be used with the x-ray camera in the experimental setup, and connects it with the MATLAB program so it is running in parallel. Next, the program sets up a general purpose interface bus (GPIB) connection with the LakeShore® Model 340 temperature controller, allowing information to be sent to it and received from it. This connection allows the program to acquire and set the current temperature of the layering sphere and the cold-finger extension. Following these initial connections, the program opens a graphical user interface (GUI) so the user can input the desired thickness, image options, and various other important parameters. Once the user clicks a button labeled "Start" on the GUI, the program begins.

The program enters the main loop, where it spends most of its time running. The loop continually estimates the final thickness of the current liquid-filled capsule and adjusts the temperature to empty or fill the capsule. If it reads that the estimated final thickness is within one micrometer of the desired thickness for three iterations of the loop, shown by the "Checks liquid for stability in wanted threshold" diamond in the flowchart, it breaks the loop. The program then sets channel 2 of the temperature controller to 5 K. Channel 2 controls the cold finger extension, so lowering this temperature creates a freeze plug in the fill tube, restricting all liquid flow. Due to the small amount of liquid that escapes from the capsule as the ice plug contracts, the program estimates the final thickness once more after the freeze plug is formed, and calculates a bias representing the amount of liquid that escaped while the fill tube was freezing. The program then accounts for this by adding the bias to the desired thickness value, remelts the freeze plug, and attempts to acquire the desired thickness repeatedly until it is achieved.

3.1. Image Acquisition - The Get Thickness Function

The get thickness function is portrayed as a red rectangle in Figure 3, and is situated as the first element within the loop. This function contains various elements shown in Figure 4.

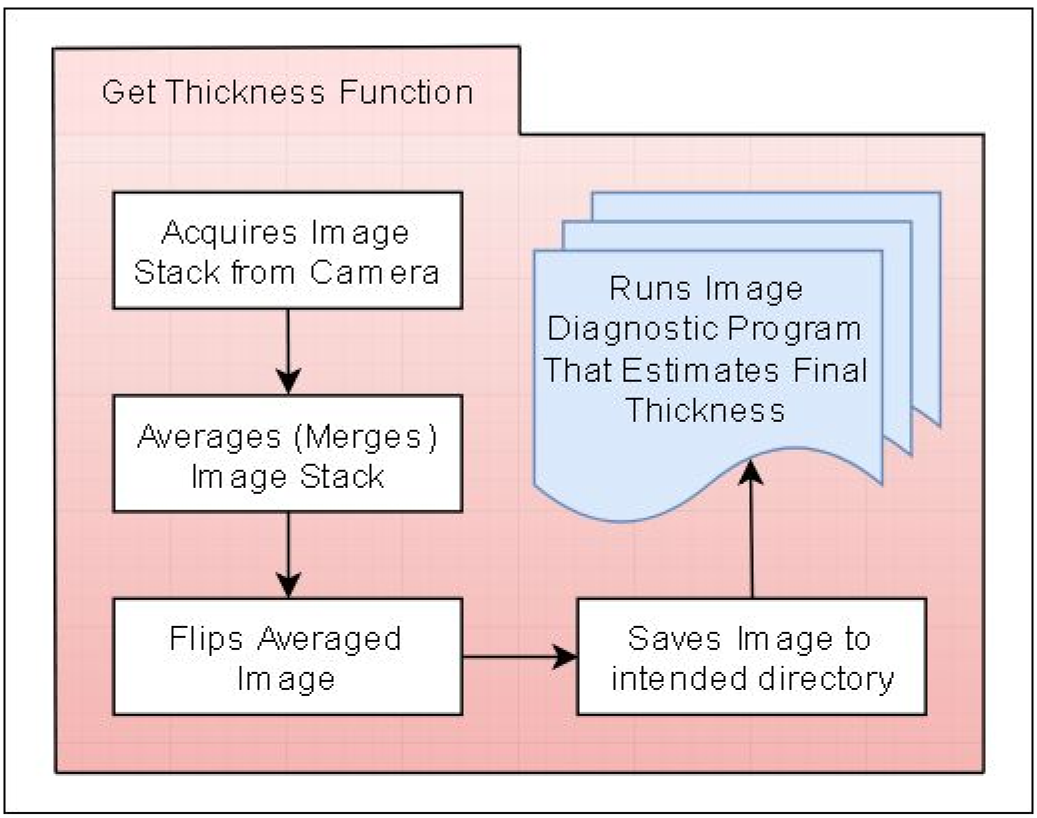

Figure 4. Get Thickness function flow diagram.

To begin the function, the program acquires an image stack, a tagged image format file (TIFF) which stores multiple images within one file. The program's connection with LightField® makes this simple, taking only one line of code. These images are deconstructed into separate value arrays, with only one layer of the third dimension due to them being black and white (not colored). Then, each pixel (X, Y) is averaged with pixels in other images (X_n, Y_n). This produces an "averaged" image, with well-defined gradients. Since the x-ray camera is mounted upside down with respect to gravity, the image is then flipped. This edited image is saved for future reference, and is run through a diagnostic program. The diagnostic program uses Gaussian fit models and gradient image-evaluation techniques to identify the lines in the left image of Figure 5 representing the capsule shell and liquid-vapor DT boundary. The program then assumes rotational symmetry around the gravitational axis and uses both geometric techniques and the density difference between liquid and solid to estimate the solid thickness if the liquid DT in the capsule was completely frozen into a uniform layer. This is indicated by *t* in the right image of Figure 5.

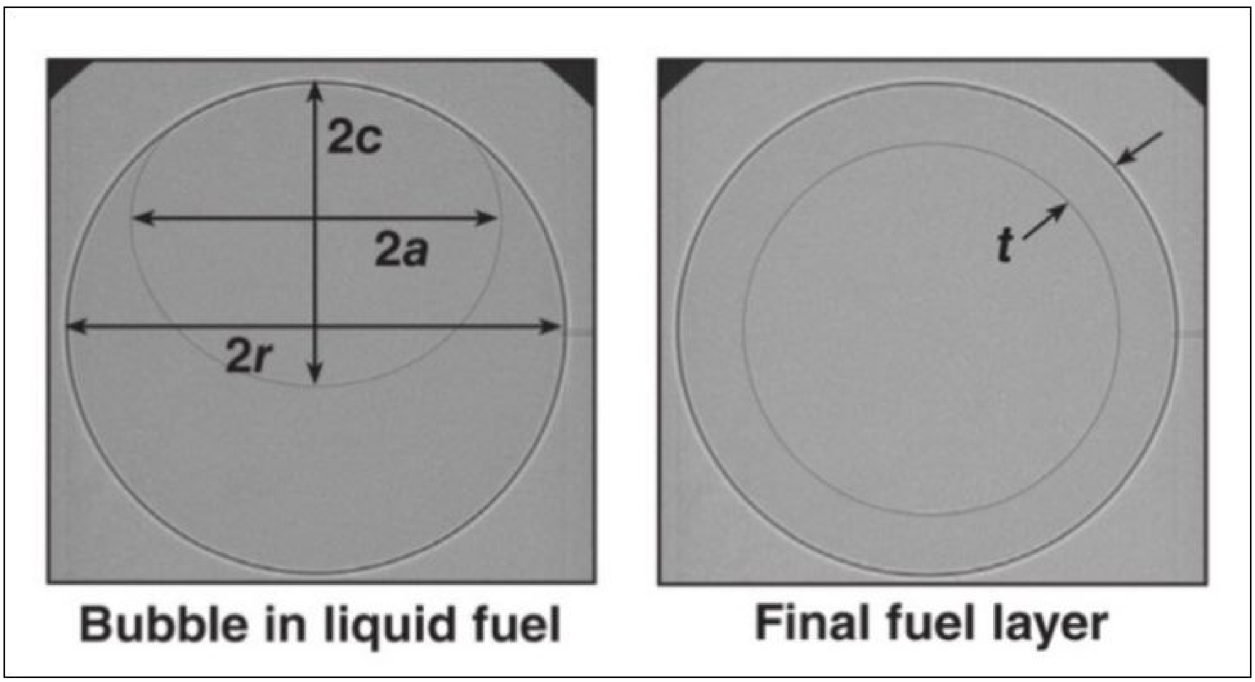

Figure 5. DT-filled fill tube capsules.
The left image is a liquid-DT-filled capsule. The liquid meniscus forms an elliptical bubble; the capsule's perimeter is the outer circle. The right image is the solid-DT-filled capsule; the solid DT forms a symmetric layer within the capsule. Both images show the fill tube on the right.

3.2 Temperature Adjustment - PID Control Loop

Following the image recognition and thickness estimation stage, the program adjusts the temperature of the layering sphere, indirectly controlling the thickness of liquid DT in the capsule. A proportional integral derivative (PID) controller was implemented to best achieve the desired thickness.

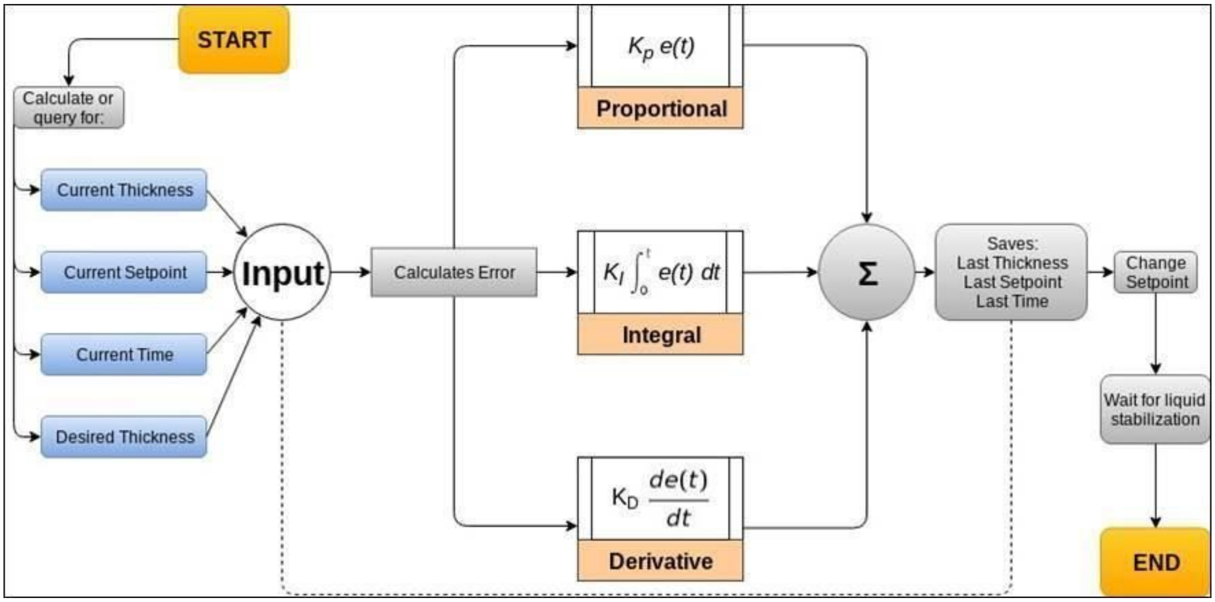

Figure 6. Temperature Adjustment flow diagram.
A PID loop is integrated into the temperature adjustment block of the general program flow diagram.

To determine the temperature change of the layering sphere required to meet the desired thickness, three terms of an error function were implemented, as indicated in Fig. 6. The error function *e(t)* is a function of time based on the difference between the desired thickness and the current estimated solid thickness. The first term of the temperature change is the proportional term. This element calculates a proportion of the error between the desired thickness and the current estimated solid thickness, and sets its input to the temperature change to this. Unfortunately, this term alone will cause the calculated thickness to either oscillate around or to approach but never reach the desired thickness; the integral and derivative terms fix this. The derivative term estimates the next thickness after the same temperature change as the previous temperature change, and uses this to either increase (if the next estimated thickness is still below the desired thickness) or decrease (if the next estimated thickness is above the desired thickness) the temperature change. Finally, the integral term sums up the area under the error vs time graph. This term makes it so that the desired thickness is rapidly achieved rather than being approached asymptotically over a long period of time. After these three are calculated, they are summed to give a logical temperature change. The program logs the new temperature, setpoint, and time, changes the setpoint, and waits for the liquid to stabilize for one minute before continuing the loop. The wait time, indicated as the stabilization time in Figure 7, was initially set to sixty seconds, and is an approximation to the time it takes for the liquid level to settle after the setpoint of the layering sphere is changed. This is necessary so each setpoint change has its own observable independent effect on the layer thickness.

4. Results

Initially, arbitrary values were used as constant coefficients of the proportional, integral, and derivative terms; as a result, the desired thickness was never achieved. The thickness versus time graph displayed oscillatory tendencies around the desired thickness. After appropriately tuning the PID controller, the subsequent test runs with various initial fill levels proved successful. Examples of successful runs are shown in Figures 7-9.

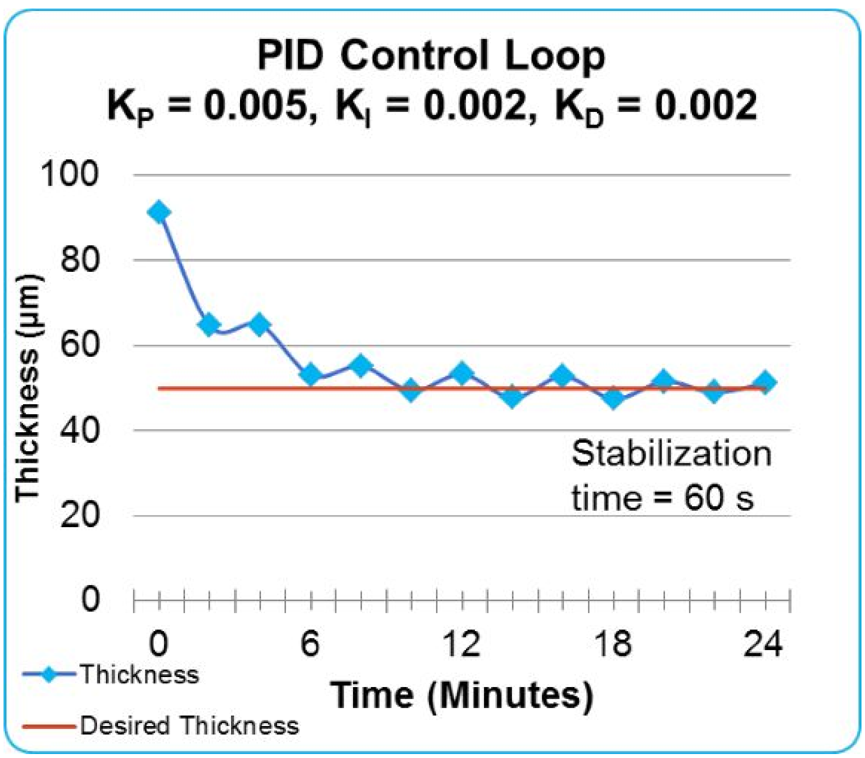

Figure 7. Estimated solid thickness vs time graph with an untuned PID controller.

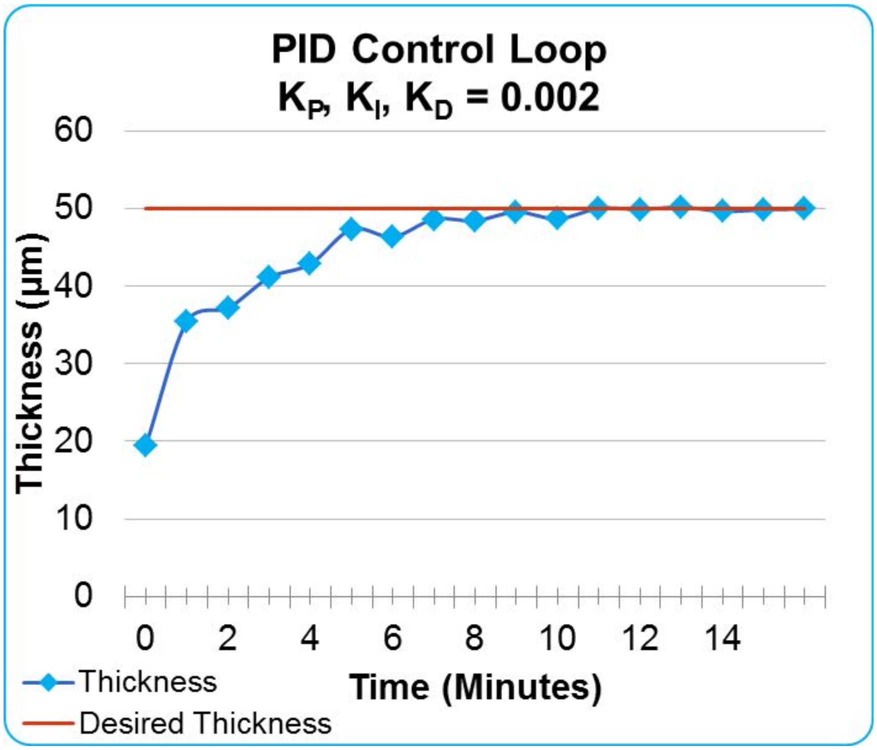

Figure 8. Estimated solid thickness vs time graph after tuning
Successful underfilled approach.

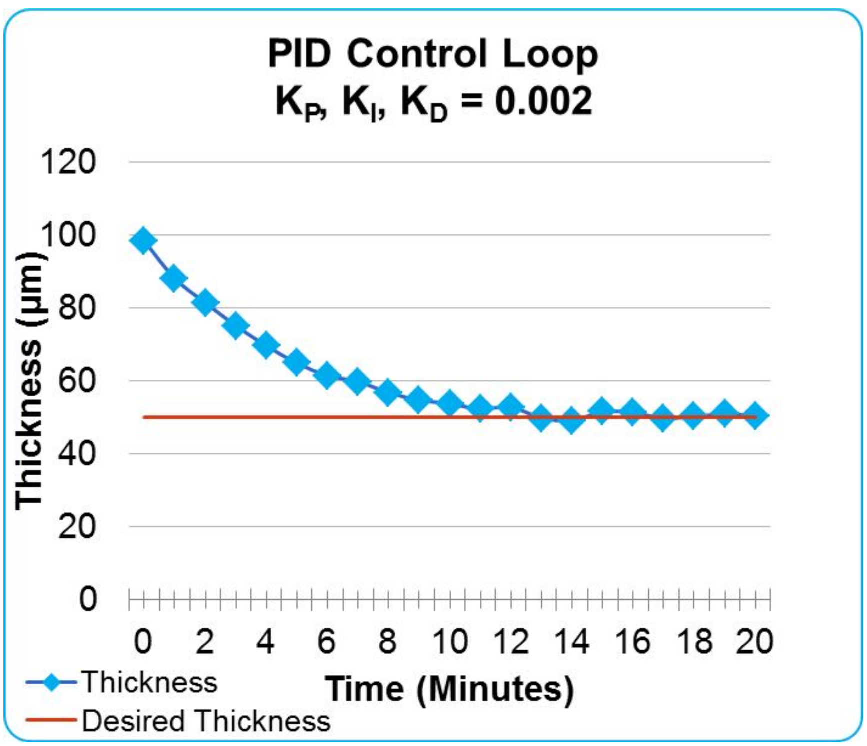

Figure 9. Estimated solid thickness vs time graph after tuning
Successful overfilled approach

Decreasing the stabilization time from sixty seconds to thirty seconds resulted in a decreased time to achieve the desired thickness as shown in Figure 10.

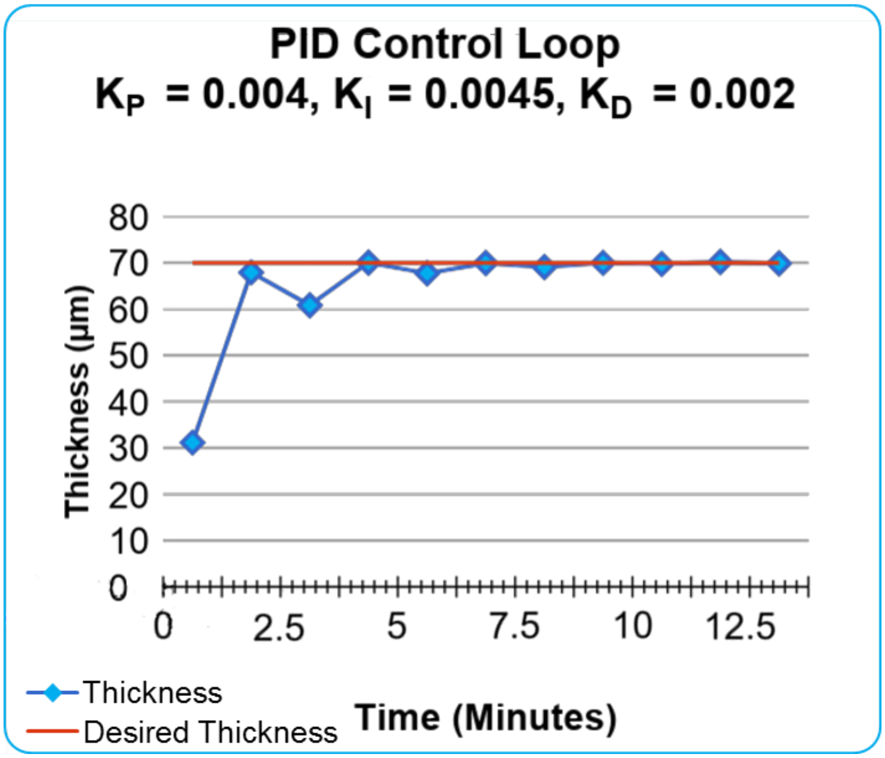

Figure 10. Estimated solid thickness vs time graph after tuning
Successful run after decreasing liquid stabilization time.

The program has the ability to successfully fill a capsule to a desired state from any initial liquid level, above or below the desired thickness. On average, the program can achieve a desired thickness within one micrometer in one to three attempts after determining the bias required to compensate for contraction in the fill tube as the ice plug forms. Each attempt takes from ten to twenty minutes, making this method of fill-tube capsule filling much more deterministic than the previous manual-estimation method.

5. Conclusion

A series of programs were written to automate the fill process for fill-tube capsules. An x-ray camera was used to observe the capsule during the fill process, and a temperature controller was used to control the liquid-DT fill level within the capsule.

A graphical user interface was implemented to allow a user to easily use the system, and an underlying computational model was used to accurately obtain the desired solid-DT final thickness. The computational model incorporated a PID controller to adjust the temperature of the layering sphere, which adjusted the liquid fill level accordingly.

The program was able to produce a liquid meniscus that would result in the desired solid-layer thickness from an overfilled or underfilled state. By tuning the PID controller, this goal was able to be achieved within only thirty minutes - comprising three freeze plug attempts of ten minutes each. It is anticipated that with additional investigation of the coefficients of each PID term, the system can be further optimized to converge in a still shorter time.

6. Acknowledgements

I would like to thank those who assisted me in the completion of my project. First, I thank Dr. Stephen Craxton for providing high school students like myself with the opportunity to work in a research-based environment by managing this program. His ability to gather a group of diverse and amiable students made my time at LLE immensely enjoyable. Secondly, I would like to thank my fellow work interns in the Annex Conference Room. These students that I worked with in close proximity helped create a work environment promoting hard work and support in our various tasks, crafting my experience in a beneficial manner. Third, I would like to thank my advisor Dr. Dana Edgell for assisting me in my code development. Finally, I would like to give a special thanks to my advisor Mr. Mark Wittman for spending a considerable amount of time working to help me understand and overcome difficulties. His efforts to bring me up to speed in the Cryogenic Fill-tube Test Facility took countless hours and much patience, and for his efforts I am grateful.

7. References

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