Using the Landau-Levich Law to Seal Seams in Waterproof Clothing

by

Cole Houston

Submitted to the

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in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

In high performance waterproof clothing, seam tape and welds fail before other parts of the garment. This paper examines a method of sealing seams in which the needle waterproofs the holes it creates by sealing them with a film of a thickness governed by the Landau-Levich law. The equation governing Landau-Levich behavior is combined with equations describing hole geometry to develop a phase space describing the fluidic and geometric properties necessary to seal a hole.

A manual proof of concept test is performed which demonstrates that the basic method works. The needle speed of a standard sewing machine is then measured as is the size of the hole made by a standard sewing machine needle. These values are then used to calculate the viscosity of a fluid that will satisfy the conditions described by the phase space. An adhesive with the calculated viscosity is made and is used on a test bed to seal holes made by a needle. Each individual hole is sealed and further tests show that the seals are waterproof.

Both the proof of concept and test bed experiments confirm the theory and it is concluded that needle speed, film length, and viscosity are the variables that can be controlled to tune hole sealing.

Thesis Supervisor: Anette Hosoi

Title: Professor of Mechanical Engineering

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1.0 Introduction

Seams are the greatest weakness of waterproof garments since they can fail in two ways. Water can leak through the row of holes created in the fabric by the needle and the small air gap between the two pieces of fabric. These problems are currently resolved by sealing each seam with tape that bonds to the waterproof membrane or a weld that joins the two pieces. However, both the tape and weld often delaminate long before the fabric ceases to be waterproof. In addition, since the adhesive needs to bond to the membrane through the fabric layer, it is currently impossible to use a fabric that has a high loft backing. [1]

This paper examines a method of waterproofing seams in which the needle seals the holes it creates. The process starts when the needle is dipped in an adhesive bath after it pierces the fabric. As the needle is pulled out of the bath, it is coated with a layer of adhesive of a thickness dictated by the Landau-Levich law. The adhesive seals the hole as it is wiped off of the needle by the fabric. This method could increase the range of fabrics used in making waterproof clothing, increase the lifetime of garments, and be a key innovation in the outdoor garment industry.

2.0 Theoretical Background

2.1 Landau-Levich Law

The Landau-Levich law describes the process of dip coating where a plate or cylinder is withdrawn from a viscous fluid bath.[2]–[4] The thickness of the fluid layer entrained is a result of a balance between viscous and surface tension forces. The thickness varies with the capillary number and length according to:

$$h_\infty = 0.945 l_c Ca^{2/3} \tag{1}$$

where h_∞ is the film thickness, $l_c = \sqrt{\sigma/\rho g}$ is the capillary length, and $Ca = \mu U/\sigma$ is the capillary number.

2.2 Geometrical Constraints for Hole Sealing

In order to fully seal the hole, the volume of adhesive pulled up by the needle must be greater than or equal to the volume of the hole. The volume of a hole made in the fabric by a needle is given by:

$$Volume = d\pi r_H^2 \tag{2}$$

where d is the thickness of the fabric and r_H is the radius of the hole. The amount of fluid wiped off of the needle by the fabric is:

$$Volume = l\pi(h_\infty^2 - r_n^2 - r_H^2) \tag{3}$$

where l is the length of the fluid film on the needle, r_n is the radius of the needle, and r_H is the radius of the hole. By combining Equations 2 and 3, the necessary film thickness for a given needle and fabric geometry is:

$$h_\infty = \sqrt{r_n^2 + \frac{l+d}{l} r_H^2} \tag{4}$$

When Equation 4 is combined with the Landau-Levich equation (Equation 1), we get the relationship:

$$k_{fluid} \geq \frac{1}{0.945} k_{geom} \tag{5}$$

with dimensionless numbers $k_{fluid} = \frac{l_c}{r_n} Ca^{2/3}$ and $k_{geom} = \sqrt{1 + \frac{l+d}{l}\left(\frac{r_H^2}{r_n^2}\right)}$.

In addition, the outer radius of the film must be greater than the radius of the hole. If this is not the case, then no fluid will be wiped off of the needle by the fabric. This condition is given by the following equation

$$k_{fluid} > \frac{1}{0.945} k_{hole} \tag{6}$$

with dimensionless numbers $k_{fluid} = \frac{l_c}{r_n} Ca^{2/3}$ and $k_{hole} = \frac{r_H}{r_n} - 1$.

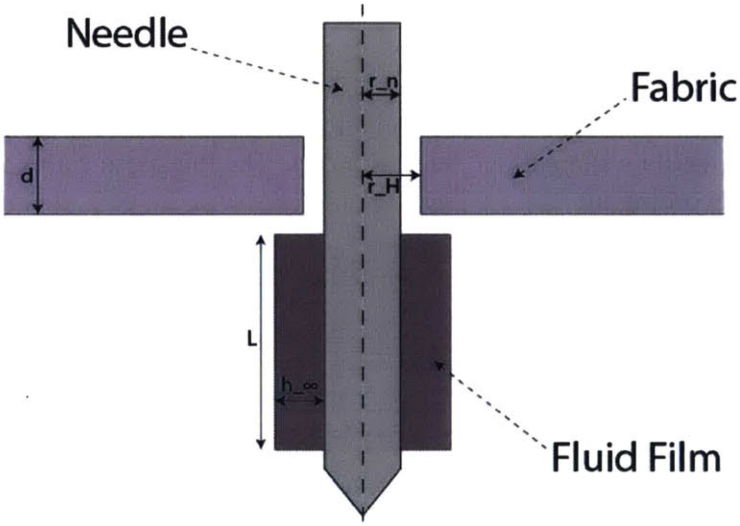

Figure 2-1) Diagram of the needle, film, and fabric.

2.3 Phase Space Calculations

In order to seal a hole, Equations 5 and 6 must both be satisfied. When they are, k_{fluid} is in the white region of Figure 2-2 for both k_{hole}, and k_{geom}. For any given geometry, the white region represents the space for which a hole will be sealed, while the blue region represents the space for which the hole will not be sealed. Movement of k_{fluid} up the axis corresponds to greater amounts of fluid being entrained on the needle and results in a larger adhesive bead. Since most of the geometric variables are fixed, the variables that can be changed in order to tune hole sealing are the fluid viscosity, the length of the film on the needle, the needle speed, and the needle diameter.

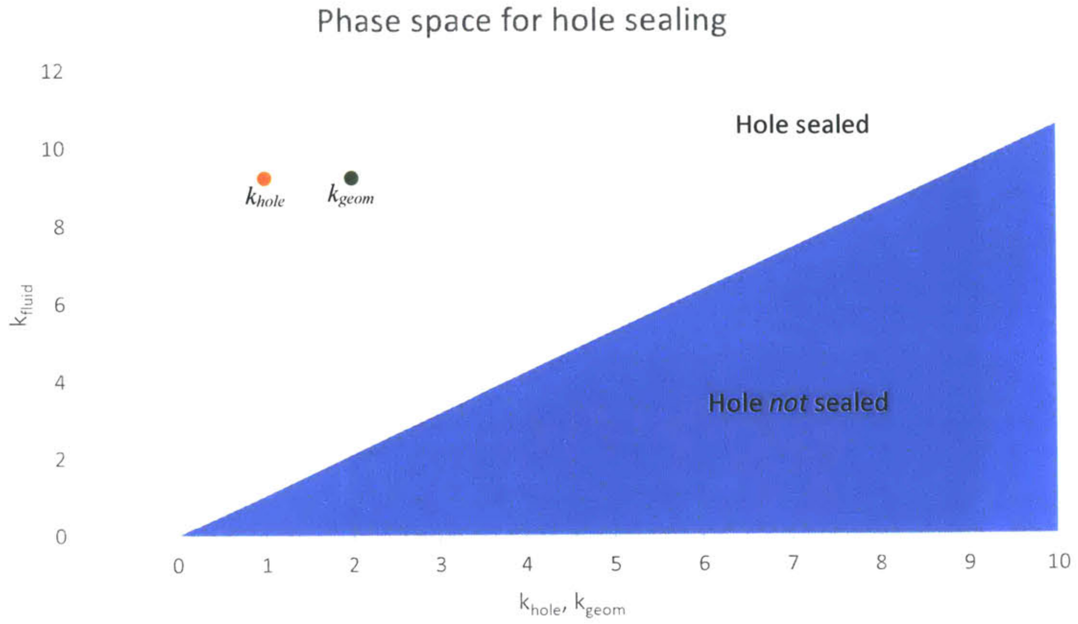

Figure 2-2) This graph shows the phase space for an adhesive that will successfully seal the hole by satisfying both fluidic and geometric properties. Points where k_{fluid} is in the white region for both k_{hole} and k_{geom} will seal the hole. The points labeled k_{hole} and k_{geom} correspond to the k_{fluid} of the test bed experiments.

3.0 Experimental Work

3.1 Initial Tests

3.1.1 Measuring the Diameter of the Holes Made by Needles

To calculate the fluid properties necessary to seal a hole, the diameter of the holes made by the needle need to be measured. To do this, needles with a diameter of 750 microns, 900 microns, and 1000 microns [5] are used to pierce a piece of cloth by hand. This is done both for waxed cotton cloth and Polartec's NeoShell fabric. [6]

Images of the holes are captured with a microscope using a halogen light at 10x magnification. An image of a 1 mm scale is used for size calibration.

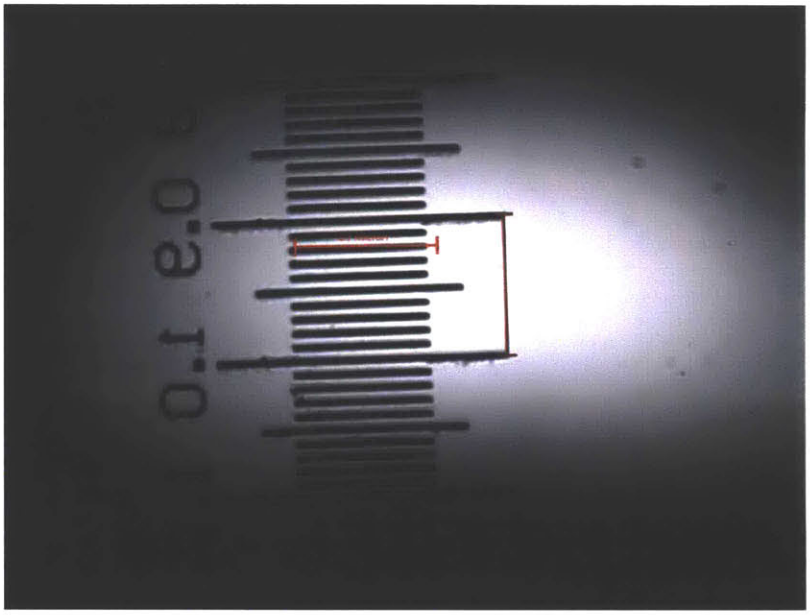

Figure 3-1) Scale with 0.1 millimeter measurement line segment.

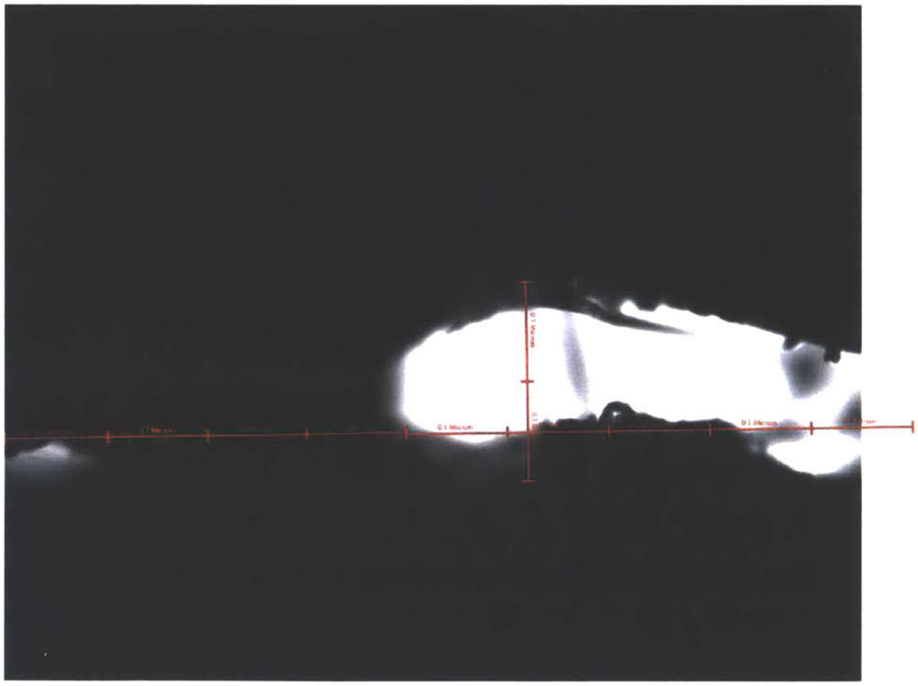

Figure 3-2) 1000 micron hole in waxed cotton with measurement line. The hole is about 900 microns long and about 200 microns wide.

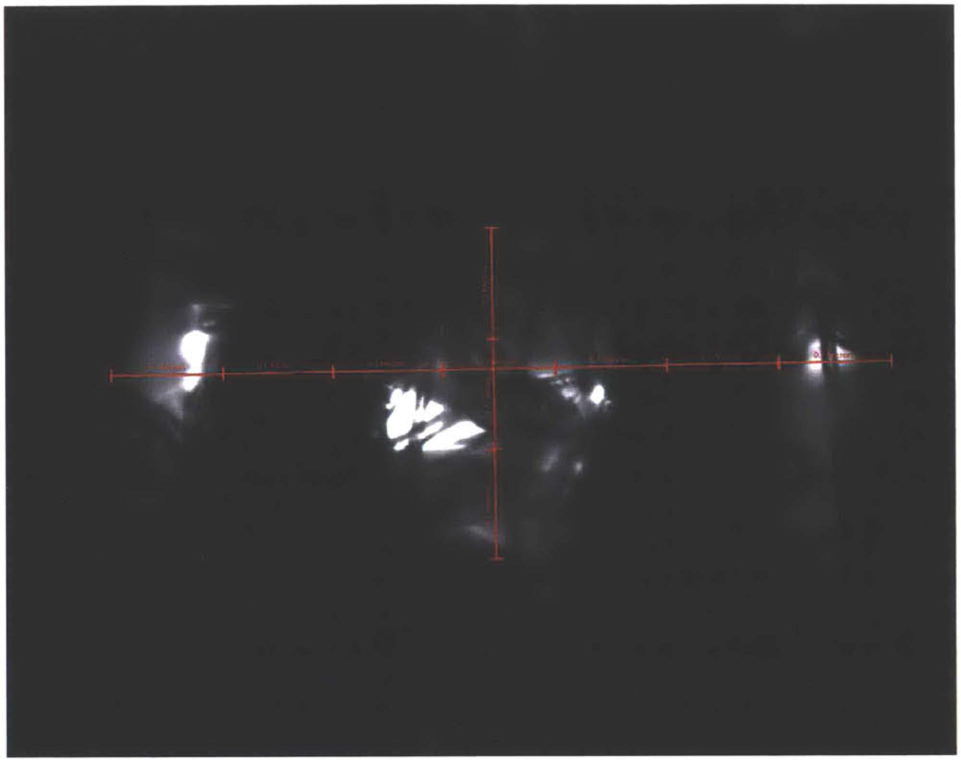

Figure 3-3) 1000 micron hole in Polartec NeoShell with measurement line. The hole is about 700 microns long and 200 microns wide.

For both fabrics, the hole is not round. Instead, it is elongated in direction of the fabric's weave. However, the long dimension is not bigger than the diameter of the needle and the shorter direction is much smaller than the diameter of the needle. In the case of the NeoShell sample, the long direction appears to be shorter than the needle diameter. This is probably due to the threads recovering their initial position after having been pushed aside.

3.1.2 Initial Proof of Concept Test

First, the waxed cotton fabric is tested for waterproofness. A fabric square is attached by a rubber band to the mouth of a bottle filled with 21.5 cm of water. The bottle is turned upside down and no water leaks through the fabric.

To test that a needle can pull up enough fluid to seal a hole, a hot glue gun is clamped to the table with the tip of the gun pointing up. After the gun heats up and the tip is filled with glue, a 900 micron needle is poked through the fabric by hand, dipped into the glue, and then drawn back through the fabric. After the glue dries, the fabric is affixed with a rubber band to the opening of the bottle filled with 21.5 cm of water so that the sealed hole is in the center of the opening. When the bottle is inverted, no water leaks through the hole, demonstrating that the method is viable.

To verify that the no leak condition is not a property of the fabric, a hole is poked in a piece of fabric using a 900 micron needle. The fabric is then attached to the mouth of the bottle filled with 21.5 cm of water with the hole in the center of the opening. When the bottle is inverted, a leak results, showing that the hot glue is preventing leakage.

3.2 Test Bed Experiments

3.2.1 Measuring the Maximum Speed of a Sewing Machine

To determine the viscosity of the fluid needed to seal a hole, it is necessary to measure the maximum speed of a needle on a standard sewing machine. A Casio Exilim EX-FC100 is used to shoot a 420 FPS video of a Singer Stylist 7258 running at maximum speed. The video is analyzed using Logger Pro.

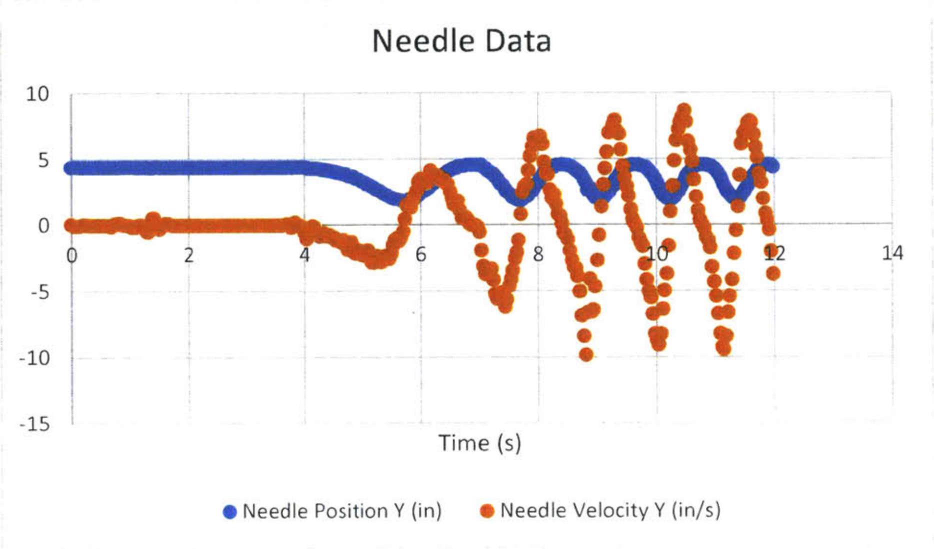

Figure 3-4) Needle position and velocity as measured in Logger Pro 3.

The absolute values of the highest speeds (ignoring outliers) are averaged to find a maximum needle speed of 7.17 in/s or 0.196 m/s.

3.2.2 Building a Test Bed

To more rigorously test the method, a test bed modeled after the camshaft mechanism that drives the needle of a sewing machine is built. It is designed to run at the measured speed of the Singer Stylist 7258.

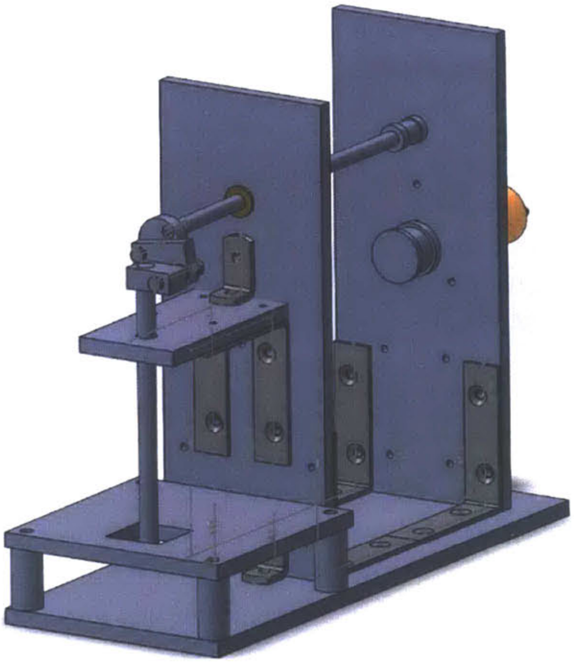

Figure 3-5) Solidworks model of initial test bed assembly.

The test bed is powered by a 7.4 V LiPo battery and uses an Arduino Nano and a Vex Motor Controller 29 to control the speed of a Vigor B0-P5 motor. This allows the experimenter to test the system at different needle speeds. However, the motor does not have sufficient torque to pierce the fabric and so an alternate test bed is constructed.

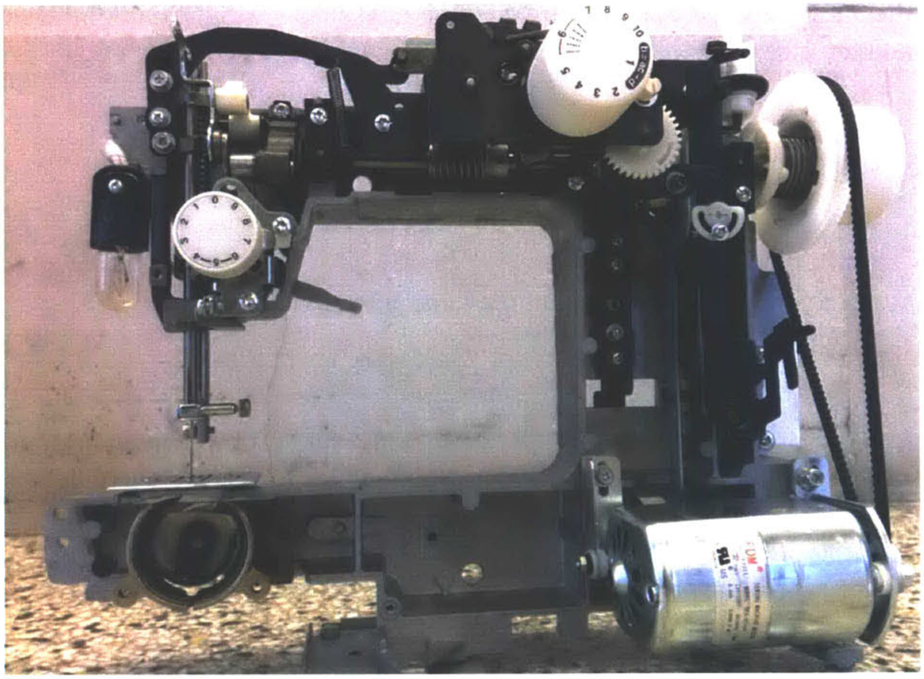

Figure 3-6) The modified Brother LS2125i used as a test bed. Shown without the adhesive bath.

A Brother LS2125i sewing machine is purchased and the enclosure and feed dog mechanism are removed, leaving the needle drive mechanism intact. The experimenter controls the needle speed via the standard foot pedal. While this does not allow the experimenter to run the machine at specific velocities, they can still run tests at approximately 0.196 m/s.

3.2.3 Calculating the Necessary Adhesive Viscosity

The target viscosity of the adhesive is found by solving Equations 5 and 6. All fluid parameters except for viscosity are assumed to be roughly equal to that of water, the needle diameter is 900 microns and, based upon the measurements taken with the microscope, the hole diameter is estimated to be 904 microns. The needle velocity is the measured value of 0.196 m/s, the length of the needle dipped in the fluid is estimated to be 1 cm, and the fabric thickness is estimated to be 1 mm. Consequently, the target viscosity must be greater than or equal to 0.71 Pas or about one thousand times the viscosity of water.

3.2.4 Calculating Dynamic Viscosity from Fluid Flowing Down a Slope

To determine if the theory is correct, the viscosities of several mixtures of Elmer's glue and water are measured to find one that has a viscosity of greater than or equal to 0.71 Pas. Since many measurements must be made in a short amount of time and they only have to be accurate to an order of magnitude, viscosity is measured using a method described by Herbert Huppert [7] in his paper on fluid flows on inclined planes.

As shown by Huppert, the thickness of a fluid is related to the kinematic viscosity by:

$$h = (\frac{v}{g}\sin\alpha)^{1/2}x^{1/2}t^{-1/2} \qquad 7)$$

where *h* is the fluid thickness, v is kinematic viscosity, *g* is gravity, α is the angle of the slope in degrees, *x* is the length of the slope, and *t* is the time it takes to reach the end of the slope. However, dynamic viscosity is related to kinematic viscosity by density such that:

$$\mu = \rho v \qquad 8)$$

and for a fixed volume *V*, thickness and length are related by a width *w* such that:

$$h = \frac{V}{wx} \qquad 9)$$

By substituting equations 8 and 9 into equation 7 and rearranging, one gets:

$$\mu = \frac{V^2 g\rho t}{wx^3 \sin\alpha} \qquad 10)$$

To measure the viscosity, an acrylic channel 1.75 in wide and 10.75 in long is built at a 30 degree angle to the horizontal. Ten milliliters of a mixture of Elmer's glue and water are upended on the top of the channel and the time it takes the fluid front to reach the end of the channel is measured. Three measurements are taken and the average value is used in Equation 10 to calculate viscosity. Density is estimated to be the density of water. A mixture of 6 parts Elmer's glue to 1 part water by weight has a viscosity of 0.75 Pas, reasonably close to the calculated viscosity.

Figure 3-7) The acrylic channel used to measure the viscosity of the mixtures of Elmer's glue and water.

3.2.5 Tests on Test Bed

The Elmer's glue and water mixture is placed in a small cup taped to the underside of the fabric support plate on the test bed. The sewing machine is turned on and a strip of fabric is fed through. As verified visually, the adhesive seals every hole made by the needle. However, since Elmer's glue is water soluble, the waterproofness is unable to be tested.

Figure 3-8) One of the tests done with the Elmer's glue mixture. Where the holes are close together, the adhesive forms a line instead of individual beads.

To test waterproofness, a metal bottle cap full of hot glue is taped in the same place as the cup and a strip of fabric is fed through the machine. Each hole is sealed and does not leak when placed beneath 21.5 cm of water.

4.0 Results and Discussion

The method proposed in this paper is sufficient to seal holes made in waterproof fabric by a standard sewing machine. The tests performed manually demonstrate that a thin film entrained on a needle by dip coating can seal a hole in fabric. The modified sewing machine test bed demonstrates that a film can seal many individual holes at a high speed and that these seals also hold under 21.5 cm of water. While this is far below industry standards, it is better than an unsealed hole. [8] As per visual inspection, every hole made by the needle during these tests is filled with sealant, showing that the method works consistently.

The test bed experiments also show that the theory is sound. Based upon the geometry of the hole and the Landau-Levich law, a phase space is constructed that guides selection of the adhesive. The Elmer's glue and water mixture that is created has a viscosity roughly the same as that predicted by the theory. As per visual inspection, it seals every hole. While it is not waterproof due to the solubility of Elmer's glue, it shows that the phase space accurately predicts a fluid that will seal a hole, given a specific geometry and needle speed.

Measurements of geometry show that needle size is not a significant variable. In the equations for both k_{hole}, and k_{geom} (Equations 5 and 6), the radius of the hole is always divided by the radius of the needle. For close measurements, such as the ones taken in this paper, the ratio is close to one and the equation is dominated by needle speed, fluid viscosity, and the length of the film on the needle. Since needle speed will vary even when sewing one seam, fluid viscosity and film length are the recommended variables to use to tune hole sealing.

There are several areas of future study to be investigated. The first area is a rigorous exploration of the phase space. The three variables of needle speed, viscosity, and the length of the film drawn up by the needle should be rigorously tested to see how they affect hole sealing. Setups that give values of k_{fluid} in both regions of the phase space should be tested to confirm that the theory is correct. Various values of k_{fluid} should be tested to determine if there is an envelope around the boundary of the space that limits the practicality of hole sealing. In the far future, it would be useful to create a computer program that would visualize this data and provide a tool for manufacturers to enter their geometry and tune their setup.

The more difficult area of study will be incorporating both a feed dog and an adhesive bath into the system. This will be a challenge since both components currently occupy the same space in the test bed – the feed dog was removed to make space for the bath. This difficulty could be overcome by changing the basic motion of the feed dog to leave space for the adhesive or by creating a custom needle that secretes fluid instead of relying on a bath. Since a true seam cannot be sewed without a feed dog, the method cannot be fully tested until this issue is resolved.

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