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Simulation and Modification of Standard Pipette Tip for Atomizing Spray Effect

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Simulation and Modification
of Standard Pipette Tip
for Atomizing Spray Effect

Major Qualifying Project

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By

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Date:

Approved:

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Abstract

Currently no pipette tips exist which aim to create a full-cone, uniform spray. The spreading of liquid after ejection from a multipurpose pipette tip was analyzed. A computer model was developed to simulate the current-multipurpose pipette tip and analyze internal forces. Results showed that surface tension is the primary fluid property for the formation of a spray. The use of an internal interference mechanism or Venturi effect is proposed to break apart surface tension and create a spray effect.

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Acknowledgements

We would like to thank Professor Shivkumar for the guidance and insight he provided us with throughout the course of this project, Professor Savilonis for his initial consultation regarding fluid behavior, the members of Zhang Lab at UMASS Medical School for providing resources and workspace for this project, Adriana Hera for the software training, as well as the local companies we spoke with during the design phase. We would like to express appreciation to Alex Meyer, Dan Ritchie, Danica Rili, Brianna Ledwith and Bridget Stevens for their help in formatting, proofreading and providing suggestions in writing this report.

The project report for this project was prepared in the form of a journal paper that will be submitted to *Journal of Medical Devices*. After a brief explanation of the primary goals of the project, this paper is presented in its entirety.

Introduction

Pipettes can be found in countless medical and research facilities around the globe. They provide a convenient mechanism of delivering a desired volume of solution to a target location. When a pipette tip is attached, the volume displacement created by the pipette mechanism corresponds to a volume displacement in the tip which allows for the operator to draw up and dispense a solution of a known volume. Interchangeable and disposable tips have been developed for pipettes with a wide range of functions. These functions include internal vapor filters to prevent contamination, varying tip lengths to control exit behavior and various materials to control fluid-tip interactions. A number of generic tips have been developed for general use where there are no specialized applications. Such tips are typically a single continuous piece made from polypropylene. In order for a pipette tip to be considered standard, the head must be able to fit multiple pipettes from different manufacturers so there is little variance among commercial pipette tips. Polypropylene is the most commonly used material due to its hydrophobic properties; these properties help reduce fluid-to-tip adherence and maximize fluid recovery. The lack of these interactions allows for the transfer of viscous liquids.

With generic pipette tips, the fluid behavior upon exit typically depends on the operator. If the operator is to eject a fluid, such as water, by pressing down on the plunger with a higher degree of force, the fluid will exit the tip in a continuous stream. Little research has been conducted to develop an opposite effect, where internal shear stresses and turbulence are increased to break surface tension for the creation of an atomizing effect upon ejection.

The aim of this paper is to describe the analysis and simulation of a current generic pipette tip, and its fluid dynamics for the purpose of modification to create an atomizing effect. Uses include topical delivery of suspended cells or drugs using common pipettes and industry standards. Several mechanisms to break surface tensions of various fluids within the pipette tip are proposed. In addition there are propositions for modified stem and nozzle designs to create a full-cone, uniform spray pattern.

Objectives

The main objectives of this project were:

- To experimentally characterize fluid behavior in a generic pipette tip
- To create a computer model of the generic pipette tip for the characterization of internal forces
- To understand how pipette tip characteristics and internal forces affect fluid exit behavior
- To propose modifications to the generic pipette tip for the creation of a spray effect

The following paper was submitted to the *Journal of Medical Devices*.

The Journal of Medical Devices was chosen because it is an established, peer-reviewed journal with several submission types. The aim of the journal is to publish research and development of new medical devices and instrumentation. The device proposal in this project has potential use in drug delivery systems and no other pipette tips with such properties currently exist. The journal does not require a full-length research paper and has the opportunity to publish a ‘Design Innovation’ paper which focuses on novel devices including those with limited clinical or engineering device. Considering the expenses related with prototyping, this project fits the design innovation submission type.

Additional information and all measured data can be found in the appendices.

Simulation and Modification of Standard Pipette Tip for Atomizing Spray Effect

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Pipette tips are an essential component of everyday laboratory procedures. Existing pipette tips typically eject a continuous stream of liquid. A continuous stream is sufficient for most applications but there are procedures which would benefit from atomization of the liquid exiting the pipette tip. Procedures include topical drug delivery, cell culture and staining. Currently no standardized and disposable pipette tips exist which aim to create a full-cone, uniform spray. The spreading of liquid after ejection from a multipurpose pipette tip was analyzed based upon differences in fluid density, viscosity, surface tension and exit velocity. A computer model was created to simulate the current-multipurpose pipette tip. Using the model, internal forces were analyzed which provided fluid characteristics including: capillary effects, turbulence, shear forces and effects of intrinsic fluid properties on exit behavior. Experimental results showed surface tension as the predominating fluid property for the creation of a spray. Model analysis showed that Newtonian fluids exhibited laminar flow with a low degree of capillary effect. The model exhibited low shear forces, typical droplet formation and shape. This indicates that surface tension of the fluid is the most influential characteristic in the development of stream-like exit behaviors. Proposed changes to the existing pipette tip include the breaking apart of surface tension through the Venturi effect or use of an internal interference mechanism. The proposed internal interference mechanism is a thread of decreasing radius terminating at an opposing thread near the outlet to increase turbulence and break apart surface tension.

1 Introduction

Pipettes can be found in countless medical and research facilities around the globe. They provide a convenient mechanism of delivering a desired volume of solution to a target location. While many types of pipettes are available on the market, the piston-driven air-displacement variable-volume type is the most commonly used (1). This type of pipette uses a plunger to displace a specific volume of air within the pipette device (2). When a pipette tip is attached, the volume displacement created by the pipette mechanism corresponds to a volume displacement in the Tip which allows for the operator to draw up and dispense a solution of a known volume. Interchangeable and disposable tips have been developed for pipettes with a wide range of functions (3) (4) (5). These functions include internal vapor filters to prevent contamination, varying tip lengths to control exit behavior and various materials to control fluid-tip interactions.

A number of generic tips have been developed for general use where there are no specialized applications (6). Such tips are typically a single continuous piece made from polypropylene. They are composed of three sections, the stem, head and midsection. The head is the attachment point to the pipette and the stem is the tapering portion, which terminates at the exit nozzle. In developing pipette tips for special applications, the stem and exit nozzle are the most common targets of modification. In order for a pipette tip to be considered standard, the head must be able to fit multiple pipettes from different manufacturers so there is little variance among commercial pipette tips. Polypropylene is the most commonly used material due to its hydrophobic properties; these properties help reduce fluid-to-tip adherence and maximize fluid recovery (7). The lack of these interactions allows for the transfer of viscous liquids. When other pipette tip materials such as glass or polystyrene are used for the transfer of viscous liquids, the fluid can adhere to the material walls and remain in the pipette tip after the bulk of the fluid is ejected leading to sample loss. Ideally, complete and accurate ejection of fluid from the pipette tip will occur which requires a hydrophobic material similar to polypropylene.

With generic pipette tips, the fluid behavior upon exit typically depends on the operator. If the operator is to eject a fluid, such as water, by pressing down on the plunger with a high degree of force, the fluid will exit the tip in a continuous stream; if the operator presses the plunger with less force, the water will exit the tip drop-wise (8). This method has various benefits; for example, decreased internal shear forces which would otherwise damage cells or unstable compounds. Shear forces are of particular concern when mammalian cells, such as stem cells, are involved (9). Certain specialized tips have been researched and developed to minimize the amount of internal shear developed and in turn provide a low-turbulence exit to minimize mixing (10); these tips can be found in most laboratories today.

Little research has been conducted to develop an opposite effect, where internal shear stresses are increased to break surface tension and create an atomizing effect upon ejection. One drug delivery device has entered the US consumer market with the aim to atomize a drug for subcutaneous injections (11). The device, developed by Avant Drug Delivery Systems Inc., uses a unique pressurized system with a reusable tip design to atomize a drug and inject it under the skin through a hole which is created by the atomized drug itself. This is an intricate system which requires bulky external machinery and is designed solely for subcutaneous injection.

The aim of this paper is to describe the analysis and simulation of a current generic pipette tip, and its fluid dynamics for the purpose of modification to create an atomizing effect. Uses include topical delivery of suspended cells or drugs using common pipettes and industry standards. Several mechanisms to break surface tensions of various fluids within the pipette tip have been proposed. In addition there are propositions for modified stem and nozzle designs to create a full-cone, uniform spray pattern.

2 Materials and Methods

In order to gain a better understanding of the current design, a rack of 1ml pipette tips was purchased from USA Scientific (TipOne® 101-1000 µl blue, model 1111-2721) and the tip dimensions were measured using a generic caliper. A comparable 101-1000µl pipette was available (Eppendorf Series 2100 Research Pipettor). The flow behaviors of the following liquids through the pipette tip were analyzed: glycerol, LB Broth, ethanol and distilled-deionized water (ddH$_2$O). The glycerol, LB Broth powder and ethanol were purchased from Fisher Scientific. The LB Broth was prepared by dissolving 10g of the purchased LB powder into 40ml of ddH$_2$O then autoclaving using a negative displacement, 30 minute exposure and 15 minute drying cycle. Assessment of the pipette tip was also conducted by creating a 3 Dimensional Model of the tip using Solidworks CAD & subsequent study of various fluid flows through the constructed model using ANSYS FLUENT programming to establish quantitative results. Typical laboratory use of the tip provided baseline information for mathematical modeling to approximate data that was unable to be assessed in the lab environment. Model analysis of fluid behavior when variables such as pressure and velocity are applied or fluid properties change. Statistical analyses used were ANOVA, linear regression and t-test.

2.1 Pipette Pressure. The pressure the pipette was capable of developing was found by attaching a length of 3.175 mm diameter hose to the pipette tip which was attached to the pipette. The other end of the hose was attached to a pressure gauge (Ashcroft 25 Duralife Vacuum Pressure Gauge-30Inhg/30Psi). The pipette plunger was depressed to its first stop and the pressure was read. The plunger was then depressed through the second stop until there was no remaining travel, where the pressure was recorded again. This procedure was repeated 10 times and the values averaged.

2.2 Spread Test. In an effort to determine the existing spray patterns of the generic pipette tip, a pair of concentric circles with an outer diameter of 76.2mm and inner diameter of 38.1mm, were printed on paper. The outer ring was 76.2mm because that is about the typical diameter of a standard cell-culture dish. The paper was then tacked to a flat piece of Styrofoam and covered with Parafilm (Fisher Sci stock no. ACA PM996 CS/12). 1000µl of each fluid was drawn into the pipette tip using the pipette and ejected at maximum pressure from a height of 76.2mm over the concentric circles. The length and width of the resulting liquid mass was measured (the resultant value in mm^2 is known as spreading). Each spray was performed 6 times for each liquid. During the ethanol spread test, a layer of glycerol was poured over the Parafilm and the spread test was repeated for this liquid alone.

2.3 Exit Velocity Test. A dismantled gas chromatography (GC) system (Philips PU 4500) was used to eject each fluid at a specified linear flow velocity to test the effect on spreading by exit velocity. The inner tubing had a length of 50mm and inner diameter of 0.32mm. After the nitrogen was expelled and collected, the system was primed with each fluid and set to eject at liquid-specific velocity intervals. The GC software would present an error (Error Message: Outside of Operating Range) when set to eject water at velocities below 70 mm/s so water was ejected at 10 mm/s intervals from 70-130 mm/s. A similar error was seen for DMSO below 47.5 mm/s so DMSO was ejected at 12.5 mm/s intervals from 47.5-122.5 mm/s. Ethanol was ejected at 20 mm/s intervals from 20-140 mm/s to reduce the number of tests and lower the risk of damaging the inner tubing as the device's instruction manual cautioned against prolonged contact of the inner mechanisms with alcohols. Glycerol was ejected at 20 mm/s intervals from 10-130 mm/s. The tubing was removed from the flow-through container and suspended at a height of 76.2 mm over a similar paper-Parafilm setup as mentioned in 2.2. Each test was performed six times and the ethanol experiment (as in 2.2) was performed over a layer of glycerol.

2.4 Computational Model Analysis. A computer animated design was created by measuring the dimensions of a TipOne® 101-1000 µl blue, model 1111-2721 with a caliper. An internal mesh was established inside the CAD pipette tip which emulated liquid phase behavior. The mesh was subjected to pressure and velocity inputs which returned vectors and gradients corresponding to fluid flow and stresses in the fluid mesh. CFD provisions allow for further understanding of the fluid behavior, with considerations for the following characteristics represented by equations 1-7.

Eq:1 $$We = \frac{\rho v^2 l}{\sigma}$$ Eq:2 $$\mathrm{Re} = \frac{\rho V L}{\mu}$$

Weber & Reynolds numbers were assessed to compare the inertial forces of the fluid versus surface tension and viscosity, respectively. Weber values refer to droplet shape during formation, with Reynolds assessing the turbulence of the fluid.

Eq:3 $$\mathrm{Eo} = \frac{\Delta\rho\, g\, L^2}{\sigma}$$ Eq:4 $$Mo = \frac{g\mu_c^4\,\Delta\rho}{\rho_c^2\sigma^3}$$

Eötvös number refers to the effect of surface tension on the body force of the system. Morton number correlates to the effect of density change between interfacing fluids versus the surface tension.

Eq:5 $$Oh = \frac{\mu}{\sqrt{\rho\sigma L}}$$ Eq:6 $$La = \frac{\sigma\rho L}{\mu^2}$$

These values are inversely proportional ($La=Oh^{-2}$) and measure viscosity versus surface & inertial forces and which has a greater influence on the dispersion of liquids in gases. These equations dictate droplet dispersion in gases, specifically when surface tension & inertial forces outweigh viscous effects.

Eq:7 $$\mathrm{Ca} = \frac{\mu V}{\gamma}$$

The capillary number indicated the effect of viscous forces versus surface tension when the interface is between two immiscible liquids or between liquid and gas phases.

This study focuses on establishing typical droplet formation and fluid dispersion tendencies from the TipOne® 101-1000 µl blue, model 1111-272. In order to quantify these behaviors, the dimensionless parameters listed above must be assessed to provide information on current designs so that approaches may be taken to create a spraying affect through the manipulation of these values in novel approaches.

3 Experimental Results and Discussion

An important aspect of developing a new pipette tip design involves understanding the current pipette tip and the resultant fluid behavior. The following sections aim to describe the characteristics of the pipette, current pipette tip, fluid behavior in the current tip and suggestions for creating the desired spray effect.

3.1 Pipette Pressure. It was found that the pipette pressure came to a maximum pressure of 66.19±0.76 kPa at the first stop and 68.95±1.03 kPa through the second stop. More tests would need to be conducted to characterize the pressures of other model pipettes which may contain different internal components and in turn put out different pressures. This is important because the proposed design is expected to be standardized and interchangeable among most pipette models so additional maximum pressure data is needed before finalizing design dimensions.

3.2 Spread Test. When maximum pressure was applied to the pipette and 1000µl of liquid was ejected: water, DMSO, ethanol and glycerol exhibited spreading of 0.941±0.001 cm^2, 1.39±0.049 cm^2, 15.4±0.159 cm^2 and 0.86±0.017 cm^2 respectively. Several plots were constructed based upon fluid properties, to better characterize the spread behavior. Figure 1a shows the effect of viscosity on spread. The coefficient of determination (R^2) was found to be 0.091 suggesting that there is little to no correlation of viscosity to degree of spreading. Figure 1b shows the effect of surface tension on spreading. The data suggests a reasonable correlation between surface tension and spreading (R^2=0.724). It can be seen that as the surface tension increases, the degree of spreading drops significantly. Figure 1c shows the effect of density on spreading; the graph suggests a reasonable correlation between density and surface tension (R^2=0.710). Additional tests would need to be performed to confirm this correlation as the liquids used here: water, DMSO, ethanol and glycerol have proportional densities and surface tensions. Water has a density of 1.003 g/cm^3 and surface tension of 7.197 dyn/mm, DMSO has a density of 1.10 g/cm^3 and surface tension of 4.319 dyn/mm, ethanol has a density of 0.789 g/cm^3 and surface tension of 2.227 dyn/mm, and glycerol has a density of 1.261 g/cm^3 and surface tension of 6.4 dyn/mm. The data shows that for these liquids there is some correlation between increased density and surface tension (R^2=0.4475). The implication is that the dependent spread behavior will be similar for both independent variables. This requires more tests to show either stronger or lack of correlation.

3.3 Exit Velocity Test. The effect of exit velocity on spreading for each liquid was tested using a temporarily dismantled gas chromatography system. The GC system was used to develop a consistent spray in the same setup as in the spread test (section 2.2). Figure 1d shows the spreading behavior as a function of exit velocity. A linear regression was performed and the following slopes were found for water, DMSO, ethanol and glycerol respectively: 0.0012 mm·s, 0.056 mm·s, 0.0375 mm·s and 0.0036 mm·s suggesting that there is little increase in spreading as a function of exit velocity. An analysis of variance (ANOVA) showed a p-value of 0.99 suggesting that there is no significant difference in spread among the different exit velocities. Error bars are standard deviations in figure 1d and R^2 for water, DMSO, ethanol and glycerol were 0.691, 0.983, 0.875 and 0.629 respectively. Water and DMSO provided consistent results with little variation between test repeats but ethanol and glycerol spreading showed increased standard error with subsequent tests. This error is likely a limitation of the equipment used as glycerol is very dense, viscous and has a high surface tension with Newtonian fluid behavior (12). Ethanol experienced unexpected behavior upon contact with the spread measurement surface. In certain cases where the exit of the tubing was not perpendicular to the surface, the ethanol would 'ricochet' off the surface, forming a triangular spread pattern extending beyond any measurable surface. Additional fixation hardware was needed to immobilize the exit tubing in a 'perpendicular-as-possible' orientation to achieve circular spreading behavior. The fixation procedure proved to be challenging, inconsistent and likely resulted in the increasing standard error with increased exit velocity where the extra precision could not be achieved.

The effect of viscosity, surface tension and density on spreading at various velocities was examined to further characterize spreading behavior. Figures 1a, 1b and 1c depict the effect of viscosity, surface tension and density respectively on spreading. There is near-perfect overlap among data points suggesting there is little effect on spreading by increasing exit velocity regardless of the liquid's viscosity, surface tension or density. This is consistent with the findings of the ANOVA earlier in this section.

3.4 Suggestions for Spray Development. It was found that the pipette maximum pressure is 68.95±1.03 kPa which places an important limitation on a revised pipette tip design; ideally the design will be capable of generating spray at a lesser pressure. This pressure limitation is particularly important because successful pipetting is largely operator dependent. Therefore spray development must occur in a wide range of pressures such that any operator can perform the task with ease.

The spread tests showed that fluid spread when pipetted from 76.2 mm above a surface primarily depends on surface tension and density although more experiments need to be conducted to confirm the effects of density. Further evidence can be seen in the exit velocity tests. It was shown that exit velocity does not have a significant effect on spreading between velocities of 10-120 mm/s. It was shown that ethanol has the weakest surface tension of the four given fluids and spread the furthest. Water and glycerol had the strongest surface tensions and spread the least which suggests that a revised pipette tip design would have to be capable of breaking the surface tension of a given fluid sufficiently to create any sort of spreading effect. The mechanism used to break apart the surface tension would have to be within the confines of the pressure limitations set forth by the pipette.

One method of creating a spray effect could be through the use if the Venturi effect. This would help overcome the pressure limitation that is put forth by the pipette. The Venturi effect has been successfully used in industrial-type spray nozzles (13) (14). The pipette tip in such a case would likely be an attachment that fits over the existing pipette tip with slits cut for the introduction of air for the Venturi effect, this proposed model is shown in 3a.

Another method of spray creation found in literature is the use of an internal interference mechanism (IIM). An IIM is a mechanism which creates a high-speed laminar flow then presents an obstacle to create a high degree of turbulence. An example of this can be seen in several 90-degree, full-cone spray nozzles. One such example contains an internal vane structure for the creation of swirling and turbulent fluid motion (15) (19). Another example uses a deflector to create a full cone spray pattern. In this example, a fluid with laminar flow impacts a series of vanes at the nozzle exit which are angled with increasing perpendicularity away from the center of the exit (16). A simple but less uniform example uses a series of externally facing vanes about a pin of increasing radius to spin and spray a fluid (17). One final method uses a pair of perpendicular vanes in an 'S' shape which causes turbulence when the fluid contacts the vanes then spin as the fluid escapes the nozzle end (18). Further modeling will be needed for the selection of an optimal nozzle for this application.

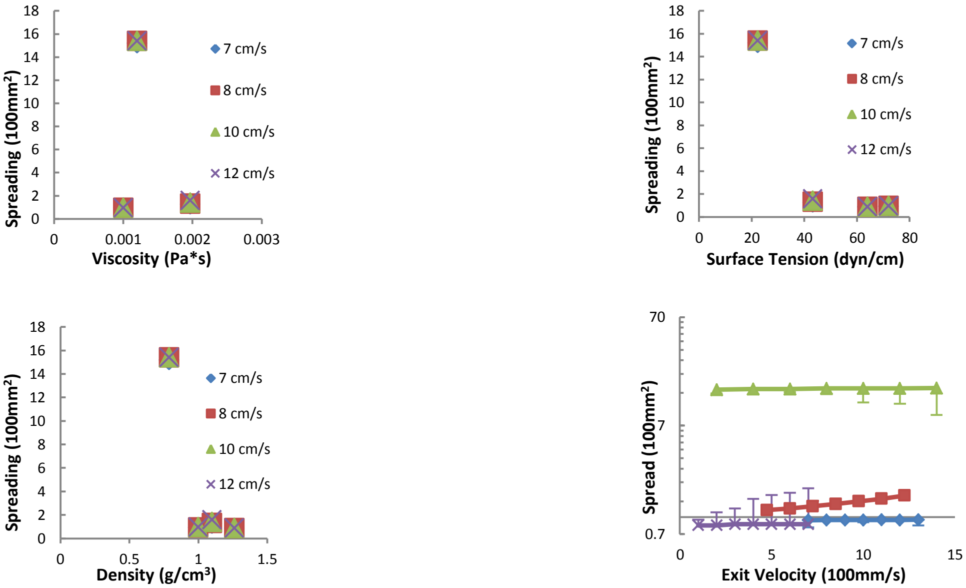

Figure 1: *Clockwise from top left*: a) The effect of viscosity on spreading. b) The effect of surface tension on spreading. c) The effect of density on spreading. d) The effect of exit velocity; error bars are standard deviation (triangle-ethanol, square-DMSO, diamond-water, x-glycerol).

4 Modeling Results and Discussion

In order to accurately simulate fluid behavior in a new pipette tip design, a model needs to be created that accurately represents the experimental data found for an existing generic pipette tip. The following sections aim to describe outcomes of modeling the current pipette tip, the testing of the model and proposed changes to create the desired spray effect.

4.1 Model Analysis. Desired parameters were characterized using exit velocities and applied pressure found in testing. The densities (being previously mentioned), viscosity values (in Pa-s) used while assessing the flow mechanics of water, DMSO, ethanol and glycerol were $8.9e^{-4}$, $1.966e^{-3}$, $1.07e^{-3}$ and 1.2, respectively. Figures 2a-d represent plots computational results for fluid characteristics with varying velocity to view the trend and behavior of each liquid.

Figure 2a refers to the Weber number at the exit and transfer into droplets, with a typical droplet forming a diameter = 1mm initially. The slopes displayed in the legend compare the values of the fluids' $\rho D/\sigma$. This ratio for density:surface tension provides understanding of droplet formation at varying speeds, notably the spherical-assessment of the droplets as the velocity increases. Low weber numbers indicate more spherical drops forming upon expulsion, specifically all these fluids pertaining to We>1(20). These values for Weber show that there is a corresponding "finesse ratio" quantified by the proportion of length to width of the droplet, characterized by the equation:

Eq:8 $$h = (1 - \frac{9}{32} * We + \frac{63}{640} * We^2)(20)$$

As Weber numbers increase the radius of the droplet becomes more distorted with ratios in length:height becoming 2-3% out of equilibrium per .01m/s for the various fluids.

Figure 2b shows the Reynolds number of each fluid as it passes through the outlet face of Diameter, D = 1mm at the corresponding velocity. The slope of each fluid in the plot is equivalent to D/ν, diameter in ratio to the kinematic viscosity of the fluid. Viscous forces are most notably significant in glycerol. All fluids maintained laminar flow through the model, ranging from .01-145 depending on velocity and viscosity. Water sustained the highest measured Reynolds values and highest average of 78.3-145.4 & 111.86, respectively followed by ethanol and DMSO, with glycerol being the least turbulent (Re_{avg}=.0736) of the measured fluids.

Figure 2c plots the capillary number of each fluid with change in velocity. The slope of each fluid pertains to the ratio of its viscosity to surface tension, μ/σ. Noting this, it is understandable that viscosity plays a significantly higher role for glycerol than the other studied fluids, whereas surface tension is the precursor to evaluating the capillary tendencies in water, ethanol and DMSO at low velocities.

Figure 2d shows the wall shear for each fluid over the velocity interval. The linear trend attached to the legend compares the viscosities of the observed fluids. Understandably glycerol computations resulted in higher shear forces than other fluids at the pipette outlet, with comparable velocities between fluids having magnitude differences of 10^2-10^3 Pa in shear forces. Glycerol results were omitted from this figure to focus on fluid of comparable intrinsic properties. The shear forces for water, DMSO and ethanol were calculated to be .99±.03Pa, 1.86±.05Pa and .96±.04Pa, respectively at .1m/s. DMSO approximated twice the shear forces of water and ethanol across similar velocity intervals.

Other dimensionless values of the fluids were calculated with respect to droplet diameter in order to determine various relationships between fluid properties at D=.001m. Ohnesorge values were measured as .00333, .00902, .0081 and 4.2241 with Eotvos numbers were calculated to be .1361, .2496, .347 and .1931 for water, DMSO, ethanol and glycerol, respectively. As the droplet diameter was augmented, Eotvos values increased exponentially, while Ohnesorge values decreased exponentially. Morton numbers were $1.681e^{-11}$, $1.653e^{-9}$, $1.4978e^{-9}$ and 61.54 for water, DMSO, ethanol and glycerol, respectively.

These dimensionless parameters are significant in the characterization of fluid behavior for model analysis and manipulation(22). Results evidence fluid mechanics which may be able to be manipulated to create more unstable behavior in pipette tips. Low pressure and shear forces in the current model indicate that the fluids with lower viscosities (water, DMSO, ethanol) could travel at higher velocities and still maintain internal forces that would not be damaging to particulates which may be present in the solution, i.e. LB broth solutions with cells. This increase in velocity would provide more turbulence and droplet formations which move towards ellipsoidal. By increasing this distortion of droplet dimensions, it creates a greater likehood for droplet separation as the diameter grows. Quantitative results from both experimental data and model analysis indicate significant effects of surface tension on fluid dispersion and droplet formations.

4.2 Proposed models for further investigation. In order to create unstable fluid flow and stream disintegration, there is an apparent need for additional mechanisms which can operate inside of or around the model tip(23). This focuses upon altering droplet diameters in a couple different fashions. Internal mechanisms which have created shear flows as in the device mentioned in section 3.4, with a vane structure to increase turbulence(15). A device may also be attached to the outside of the pipette tip in order to influence droplet diameter and increase turbulence due to stream break up via venture fluid flow. These models, figure 3a,b show conceivable design parameters. The former model contains 2 helical vanes which are mirrored to abruptly change the direction of flow inside the pipette model. The latter model uses air influx surrounding the outlet of the TipOne® 101-1000 µl blue, model 1111-272 in order to create contrasting phases of fluid before leaving the apparatus.

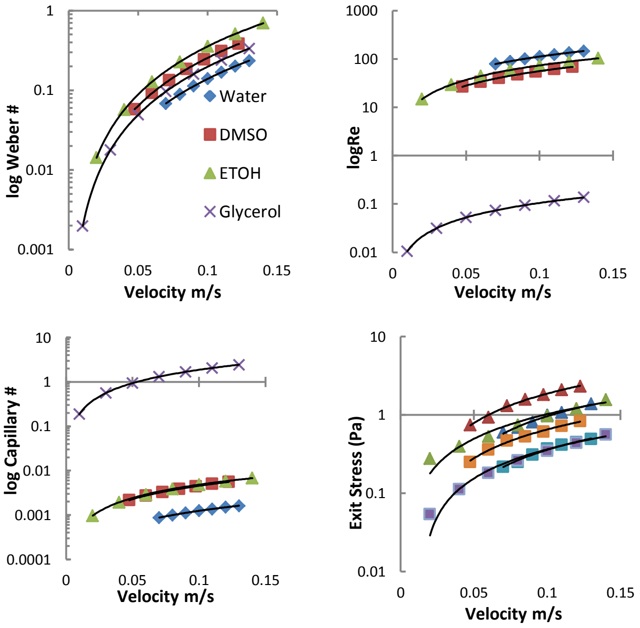

Figure 2: *Clockwise from top left*: a) Mean Weber # with respect to velocity for given fluids b) Mean Reynolds # with respect to velocity for the given fluids [markers same as 2a]. c) Capillary number for fluids as velocity increases [markers same as 2a]. d)

Exit Shear & Pressure of fluids with respect to velocity [red triangle-DMSO shear, green triangle-ethanol shear, blue triangle-water shear, orange square-DMSO pressure, purple square-ethanol pressure, blue square-water pressure].

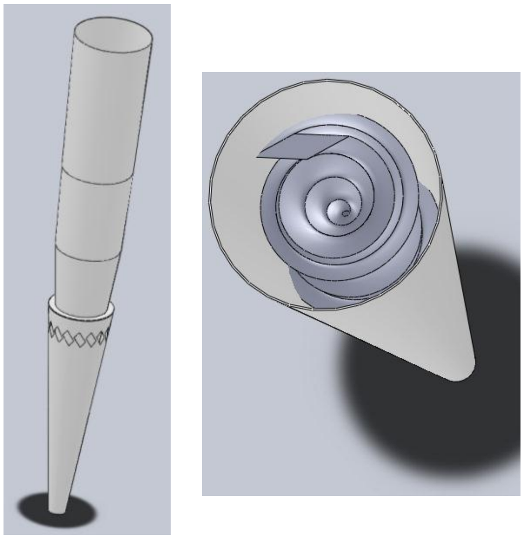

Figure 3: *Left-to-Right:* a) 16-slot Venturi assembly. b) Spiraled Vane Structure.

5 Conclusions

Through the experimental tests and modeling, several methods of developing a standardized, interchangeable and disposable pipette tip have been discovered. It was experimentally found and confirmed by the computer simulation that surface tension is the primary variable in the development of spray behavior. In order to break apart the surface tension of a fluid within the pipette tip device, multiple possibilities exist. One option is to create a venturi effect through the 'tip-on-a-tip' method which would allow an influx of air which would increase the turbulence within the tip as can be seen in figure 3a. Another is to create resistance within the pipette tip to increase shear forces and turbulence such as a series of spiraled vanes as proposed in figure 3b. Some preliminary model testing of the Venturi and vane pipette tips has been performed but these designs need to first be prototyped. Once prototyping has been done, more information can be gathered to determine if there is sufficient internal shear and turbulence to create the spray effect or if a combination of these designs needs to be evaluated.

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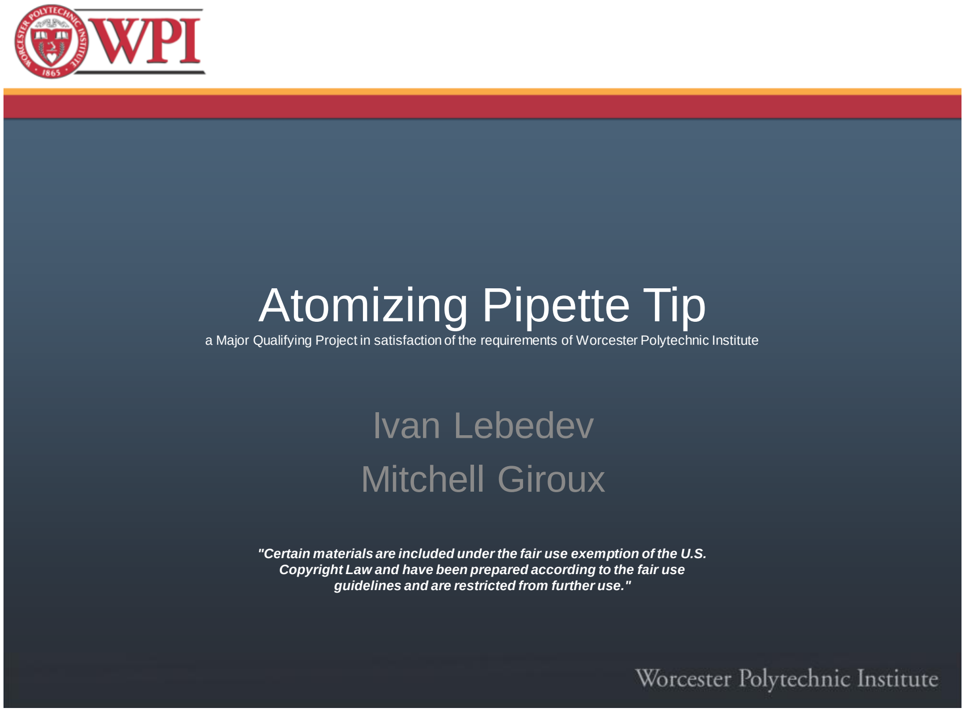
Appendices

Appendix A

Throughout the course of this project, several presentations were made to a number of companies including NyPro, TTE Inc, K&C Plastics and Micron Integrated Technologies. The purpose of these meetings was to discuss prototyping, distribution and design for manufacture. Further details cannot be described as each company signed a mutual non-disclosure agreement with this project group. The following are the PowerPoint slides from the presentation shown to each company:



Atomizing Pipette Tip

a Major Qualifying Project in satisfaction of the requirements of Worcester Polytechnic Institute

Ivan Lebedev

Mitchell Giroux

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Worcester Polytechnic Institute

Idea Origination

- Topical Drug Application
- Material Waste
  - Laboratory Staining
  - Bacterial Culture

Image courtesy of MadSci Network

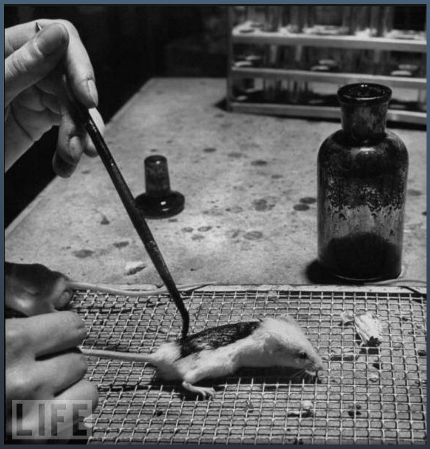


Image courtesy of Life Magazine

Spray Tips

- ‘Spray Pipette Tip’
  - Standardized
  - Uniform Spray
  - Disposable/Recyclable
  - No Cell Damage
- Pipette Tip – Spray Tip
  - “Tip For A Tip”
  - Fit Existing Tips
  - Above Functions

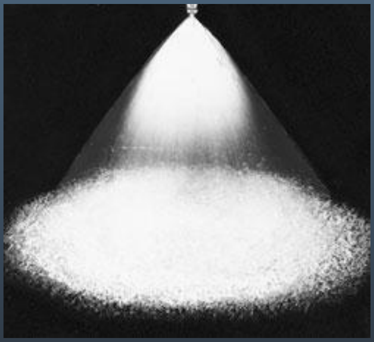
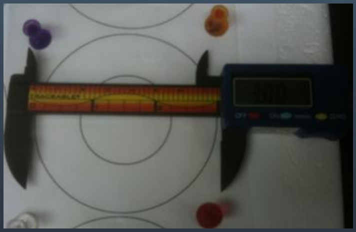


Image courtesy of Sealpump Engineering Limited

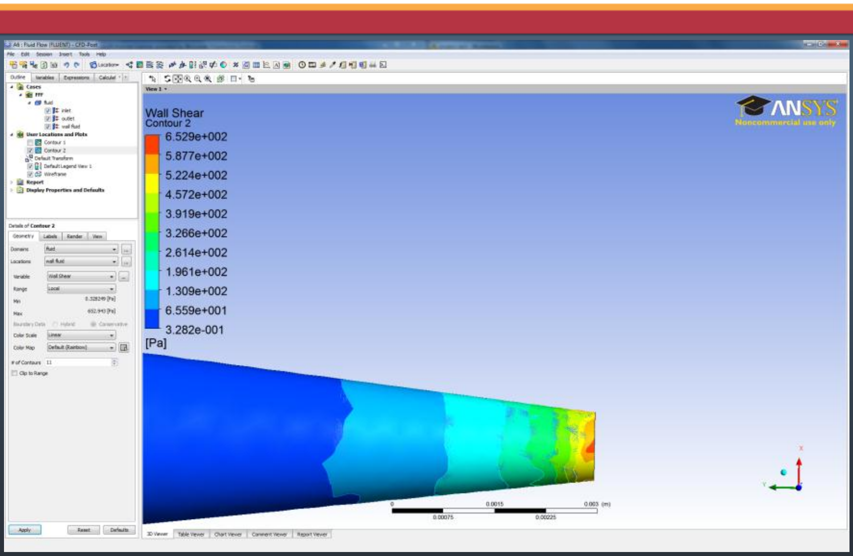
Completed Work

- Fluid Flow Simulation
  - SolidWorks, Fluent
- Existing Tip Tests
  - Spread Tests
    - $\mathrm{H_2}$0, Ethanol, LB Broth, Glycerol
  - Live Culture
  - Pipette Pressure
  - Exit Velocity
- Comparison
  - Model-Experimental



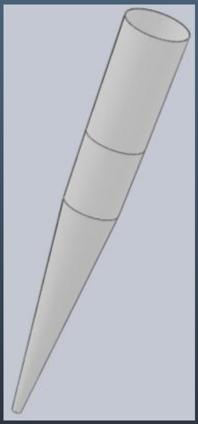
Equipment courtesy of Zhang Lab - UMMS

Fluid Flow Simulation



Current Work

- Nozzle Design Research
  - Existing Spray Nozzles
  - Capillary Effects
- Manipulation of Model
  - Dimensions
  - Break Surface Tension
- Increased Test Accuracy
  - Repeat Completed Tests
  - Different Pipettes


Left: Model of Existing Tip


Right: A Proposed Tip Design

Future Work

- Prototyping
  - Appx. 50 Tips
- Preliminary Tests
  - Spray Test
  - Viability
- Revisions
- Field Testing
  - 100-500 Tips
  - Samples to Labs

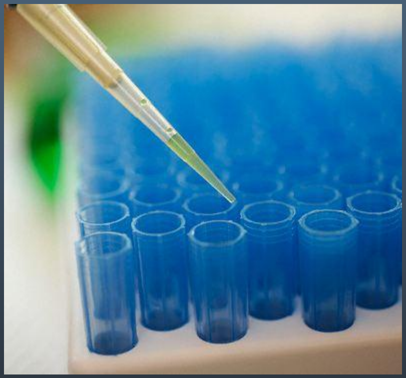


Image courtesy of corbisIMAGES

Desired Outcomes

- Effective Atomizing Pipette Tip
- Patented
- Laboratory Approved
- Ready to Manufacture
- Ready to Distribute

Image courtesy of Mark Lorch

Worcester Polytechnic Institute

Appendix B

The following tables contain the raw data found experimentally. Table 1 is from the spread test, Table 2 contains the effect of exit velocity on spreading and Table 3 contains the pipette pressure tests.

Table 1: Spread Test Raw Data

Water	Exit Velocity (cm/s)	Speading Velocity (cm/s)	Spreading (cm^2)	stdev
1000ul	7	0.01	0.938	0.13
	8	0.01	0.94	0.01
	9	0.02	0.94	0.02
	10	0.02	0.941	0.04
	11	0.02	0.942	0.01
	12	0.03	0.941	0.01
	13	0.035	0.948	0.11
DMSO	Exit Velocity (cm/s)	Speading Velocity (cm/s)	Spreading (cm^2)	stdev
1000ul	4.75	0.075	1.16	0.04
	6	0.075	1.2	0.05
	7.25	0.1	1.26	0.16
	8.5	0.1	1.32	0.17
	9.75	0.125	1.4	0.02
	11	0.125	1.48	0.01
	12.25	0.13	1.58	0.01
EtOH	Exit Velocity (cm/s)	Speading Velocity (cm/s)	Spreading (cm^2)	stdev
1000ul	2	5.5	15	1.2
	4	5.5	15.2	1.43
	6	5.5	15.2	0.95
	8	6	15.4	1.8
	10	6	15.4	3.97
	12	7	15.4	4.26
	14	8	15.5	6.72
Glycerol	Exit Velocity (cm/s)	Speading Velocity (cm/s)	Spreading (cm^2)	stdev

1000ul	1	0.016	0.84	0.11
	2	0.016	0.84	0.27
	3	0.016	0.86	0.34
	4	0.017	0.86	0.62
	5	0.017	0.86	0.74
	6	0.017	0.86	0.82
	7	0.017	0.86	0.99

Table 2: Effect of Exit Velocity on Spread

	Viscosity (Pa*s)	Surface Tension (dyn/cm)	Density (g/cm^3)
Water	0.001	71.97	1
DMSO	0.001966	43.19	1.1004
EtOH	0.0012	22.27	0.789
Glycerol	1.2	64	1.261
Water	Exit Velocity (cm/s)	Speading Velocity (cm/s)	Spreading (cm^2)
1000ul	7	0.01	0.938
	8	0.01	0.94
	9	0.02	0.94
	10	0.02	0.941
	11	0.02	0.942
	12	0.03	0.941
	13	0.035	0.948
DMSO	Exit Velocity (cm/s)	Speading Velocity (cm/s)	Spreading (cm^2)
1000ul	4.75	0.075	1.16
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	7.25	0.1	1.26
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	12.25	0.13	1.58
EtOH	Exit Velocity (cm/s)	Speading Velocity (cm/s)	Spreading (cm^2)
1000ul	2	5.5	15
	4	5.5	15.2

	6	5.5	15.2
	8	6	15.4
	10	6	15.4
	12	7	15.4
	14	8	15.5
Glycerol	Exit Velocity (cm/s)	Speading Velocity (cm/s)	Spreading (cm^2)
1000ul	1	0.016	0.84
	3	0.016	0.84
	5	0.016	0.86
	7	0.017	0.86
	9	0.017	0.86
	11	0.017	0.86
	13	0.017	0.86

Table 3: Pipette Pressure Test

Trial	Pressure at Stop 1 (kPa)	Pressure at Stop 2 (kPa)
1	64.17	69.38
2	67.6	68.74
3	67.42	68.57
4	66.26	68.95
5	66.19	67.14
6	66.94	68.93
7	68.22	68.52
8	65.97	67.55
9	65.18	69.23
10	66.24	68.91