INVESTIGATION OF WETTABILTY AND THE THRESHOLD FOR SPLATTER OR SPLASH
EXPERIMENT PROPOSAL

MATTHEW K. OWEN
THERMAL FLUIDS AND THERMAL PROCESSING LABORATORY
University of Cincinnati
Table of Contents

1. Revision Notes: .......................................................... Pg 2
2. Introduction: ...................................................................... Pg 2
3. Literature Review: .......................................................... Pg 2
4. Experiment: ....................................................................... Pg 4
   4.1. Experiment Purpose: .................................................... Pg 4
   4.2. Proposed Methods: ....................................................... Pg 4
   4.3. Experiment Set-Up: ...................................................... Pg 5
   4.4. Experiment Costs: ....................................................... Pg 5
5. Expected Results: .......................................................... Pg 5
6. Expected Discussion: ...................................................... Pg 5
7. Timeline: ........................................................................ Pg 5
8. Conclusions: ............................................................... Pg 6
9. References: ................................................................. Pg 6
10. Appendices: ..................................................................... Pg 7
    10.1. Bill of Materials (BOM) ............................................... Pg 7
    10.2. Experiment Gantt Chart ............................................. Pg 8
    10.3. Liquid Shield Dimensions ......................................... Pg 9
    10.4. Abstract submitted to IMECE .................................. Pg 10
    10.5. MSD Sheets for Chemicals ...................................... Pg 11
1. **Revision Notes:**
   2015-04-05 This is the initial copy to the experiment proposal. No alterations or revisions have yet taken place.

2. **Introduction:**
   Droplets impinging upon surfaces are perhaps some of the most ubiquitous events in daily life, yet a complete understanding of how to predict what happens after impingement has yet to be accomplished.

   Of these events after impingement, the threshold for splatter and/or splash is of interest because it can lead to secondary droplets which may aerosolize, which is the liquid being in droplets small enough to be carried by the surrounding air. It follows logically then they could be inhaled, and if the liquid is toxic, contains carcinogens, or contains pathogens for humans, this could lead to detrimental health issues. This could be especially true for long term exposure. Notable examples include cutting fluids in machining and manufacturing processes, pesticides, spray paint, or contaminated blood.

   Knowing this, there is a certain imperative to investigate that threshold so that the process can be controlled for the sake of preserving human health. One particular property which has yet to be explored for this purpose is wettability, or the interaction between the cohesive and adhesive forces between the surface and the liquid. This proposal sets out to justify an experiment to explore the effect of wettability on the threshold and behavior of splatter and/or splash, layout the experiment procedure and set-up, and explain what the expected results are.

3. **Literature Review:**
   Already there exists a rich body of research reported in the literature investigating different aspects of droplet impingement upon a dry surface and the resulting splatter or splash. Researchers have looked into different properties such as surface tension, viscosity, impact velocity, impact angle, depth of fluid on the substrate, surface geometry, surface roughness, surface composition (granular or solid), porosity, charge, surface elasticity, air pressure, and temperature. There has been research into single droplets and multiple droplets, as well as limited work in liquid jets impinging a surface. In terms of effects, research has also gone into understanding the different stages of droplet impacts such as droplet eccentricity before impact, spreading, recoil, jetting, corona, fingering, and fragmentation. It’s known that Weber and Ohnesorge numbers have a relationship with surface roughness and film thickness when predicting number of secondary droplets and deposition or splash thresholds. Of interest as well is the effect of wettability, but, despite this, there has been little work to expand knowledge of its influence or characterize its effects beyond droplet spreading.

   **1977, Stow and Stainer:** Unconcerned with drop dynamics at impact, more concerned about the products that occur afterwards. They experimented with drop radius and impact velocity, and in the course of their experiments observed that for smooth surfaces there was considerably less splashing than for the rough surfaces. This is not directly related to wettability, but is the first instance of attention being paid to the surface properties. They did come up with an equation for velocity, droplet radius, and number of droplets.

   \[ N_{\text{droplets}} = 3.25R^3V^2 - 63 \]

   **1981, Stow and Hadfield:** The purpose of their paper was to investigate the relationship between roughness and the splashing threshold. They used HE30 aluminum alloy as it was soft and easily able to be changed from rough to smooth. It was also corrosion resistant. There
was also a commercially polished stainless steel plate used as a control. The liquid used was distilled water. They then came up with results.

Their first conclusion was roughness made a difference and derived a simple equation for the surface they were working with

\[ S_T = RV_T^{1.69} \]

Where for their surface \( S_T \) was equal to 7.4 and should be noted that it is not dimensionless and applies only to water and \( T \) denotes the critical velocity for splashing.

When they took \( N \) to be zero for equation there was an incorrect interdependence, and suggested the following form

\[ N = kR^3V^2 - f(R) \]

Where \( k \) is a constant, and \( f(R) \) is found through the simultaneous solution of the paper’s equations 1, 2b, and 3 under the conditions that \( N = 0 \) and \( V = V_T \). This led to

\[ N = 3.25R^3V^2 - 17.8R^{1.82} \]

They found after further manipulation that they could change the equation and manipulate it to take the form

\[ (Re_T)(We_T)^2 = \xi \]

Where \( \xi \) is a function, they believe, of surface roughness only.

They also found that the roughness did not make a difference in the time dependence of the spread factor.

1993, Rein: This was an article review of the state of research of droplets impacting surfaces. At this time, under the author’s survey of parameters governing the impact of a droplet, the parameters of the solid surface were just plane vs curved, smooth vs rough, and unyielding vs yielding. There was no clear mention of wettability and the splashing threshold. The author commented on the 1981 Stow and Hadfield equation, mentioning but not referencing from where it comes from, that it could be related as

\[ RV^2 \sim We_T < S_T \]

1995, Mundo, Sommerfeld, Tropea: This paper investigated surface roughness and its effects. They concluded that there was correlation between the Re and Oh number

\[ K = Oh \cdot Re^{1.25} \]

if the normal velocity component of the impinging droplets is used in the dimensionless numbers. They also presented a theoretical approach to the Oh number, which rearranged can provide the contact angle, however it is unclear from their explanation which contact angle or when the contact angle is. It is

\[ \Theta = \arccos \left( 1 - \frac{12 + (Oh)^2((Re)^2 - 4.5 \cdot \beta_{max}^4 \cdot Re))}{3\beta_{max}^2} \right) \]

where \( \beta_{max} = \frac{d_{max}}{d} \) where \( d \) is the droplet diameter and max refers to the maximum expansion diameter.

There has been further work done with wettability by Rioboo and Wu, however acquiring the dissertations has been problematic and receiving them through the University of Cincinnati Library is pending.
With this experiment, I plan to investigate \((Re_T)(We_T)^2 = \xi\) and determine if there is any possibility of modifying it to account for wettability instead of roughness. Barring that, characterize the splashing threshold with respect to wettability.

4. **Experiment:**

4.1. **Experiment Purpose:**

The purpose of this experiment is to illuminate upon the effect of wettability on the threshold of splatter and splash.

4.2. **Proposed Methods:**

The proposed method is to have droplets drip upon a substrate and take photographs of the impingement. The substrates are chosen for their different wettabilities, for simplicity. Those wettabilities will vary from hydrophobic to hydrophilic. Also, the substrates will be mechanically or chemically polished to be smooth to mitigate surface geometry.

The liquids shall be initially distilled water, but later viscosity and surface tension will be altered by adding other chemicals.
The process shall be to test each substrate with the chosen liquid at different drop velocities. Once all substrates have been tested, the next liquid shall be tested against the substrates at different velocities. This process shall be repeated until sufficient data has been collected.

4.3. Experiment Set-Up:

Figure 1 shows the experimental set-up.

The experiment will be illuminated by an ARRI Arrilux 125 and a simple white surface will reflect and diffuse the light. The liquid of choice is forced through a dropper at a constant flow rate by a Chemyx Nexus 3000 syringe pump. The droplets will detach from dropper and accelerate towards the substrate below. The resulting impingement will be recorded by a NAC Hi-Dcam II with a Nikon AF Micro Nikkor with 105 mm lens at 1:2.8D taking photos at 8000 frames per second. The images will be transferred to a computer for processing and analysis.

A liquid shield schematic is found in Appendix 10.3. It shall have a lower wall which faces the camera to avoid taking photography through a medium other than air.

4.4. Experiment Costs Initial Projections:

The Bill of Materials (BOM) is presented in full in Appendix 10.1. The proposed experiment will test Teflon PTFE, Type 1 PVC, Optically Clear Cast Acrylic, Pyrex, 430 Stainless Steel, 110 Soft Copper, and paraffin wax for an initial price estimate of $70.01 before tax and shipping. Alternate materials can be non-porous high-alumina ceramic, lead, or any number of other plastics.

The camera, stand, pump, lights, white background, and dropper are available for use in the TFTPL, and will not need to be purchased.

The liquid shield and will need to be constructed from purchased materials. This will include the purchase of optically clear acrylic. This shall cost $32.96 before tax. The set-up shall be glued together with LocTite Super Glue Gel for an estimated price of $5.00, and the substrate shall be adhered to by the stand with Plastina non-hardening modelling clay which is available in the lab but may be purchased for $3.59 before tax.

The last purchases shall the liquids. Distilled water and other chemicals are expected to cost up to $30 if otherwise unavailable in TFTPL.

Total projected cost is around $147 before taxes and shipping. Ways to bring down the cost shall be investigated, but this is a first look estimate.

5. Expected Results:

The expected results are a set photos which will be of different stages of splatter or splash and show different structures depending on the wettability of the substrate and liquid properties.

6. Expected Discussion:

The expected discussion will detail the analysis at attempting to modify the Stow and Hadfield equation to account for wettability or other characterization of the results.

7. Timeline:

The proposed timeline is located in Appendix 10.2 in detail. However, a brief overview is presented here. There are seven phases. The first phase is limited to experimental set-up which will conclude at the end April. Phases 2 through 5 are the experiment itself which will last through the first half of September. Phase 6 is analyzing the data, which while occurring informally throughout the course of the experiment, should be formally concluded by the end of September. The whole of October 2015 should be devoted to Phase 7, which is the write
up of the final experiment report, presentation, and poster. This is open to revision as this is the first experiment by the author.

8. **Conclusions:**
   
   An experiment to investigate the role of wettability in splatter and splash is required because this particular property has yet to be investigated. This could have benefits in the future when designing industrial or medical environments or tools because by understanding what conditions lead to splatter and splash shall lead to the ability to control it and prevent potential harm to human health.

   This experiment, if conducted properly, shall accomplish this by the end of October, 2015.

9. **References:**
   


10. Appendices:

10.1. Bill of Materials (BOM)

<table>
<thead>
<tr>
<th>Material</th>
<th>Reason</th>
<th>Source</th>
<th>P/N</th>
<th>Size</th>
<th>#</th>
<th>Cost</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teflon PTFE</td>
<td>Hydrophobic</td>
<td>McMaster Carr</td>
<td>8545K13</td>
<td>0.0625&quot;x6&quot;x6&quot;</td>
<td>1</td>
<td>15.24</td>
<td>15.24</td>
</tr>
<tr>
<td>Type 1 PVC</td>
<td>Hydrophobic</td>
<td>McMaster Carr</td>
<td>8747K105</td>
<td>0.375&quot;x6&quot;x6&quot;</td>
<td>1</td>
<td>4.36</td>
<td>4.36</td>
</tr>
<tr>
<td>Optically Clear Cast Acrylic</td>
<td>Mid Range</td>
<td>McMaster Carr</td>
<td>8560K178</td>
<td>0.0625&quot;x6&quot;x12&quot;</td>
<td>1</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Stainless Steel-430</td>
<td>Mid Range</td>
<td>McMaster Carr</td>
<td>1294T26</td>
<td>0.060&quot;x6&quot;x6&quot;</td>
<td>1</td>
<td>15.84</td>
<td>15.84</td>
</tr>
<tr>
<td>Soft Copper-10</td>
<td>Mid Range</td>
<td>McMaster Carr</td>
<td>8963K504</td>
<td>0.043&quot;x6&quot;x6&quot;</td>
<td>1</td>
<td>12.57</td>
<td>12.57</td>
</tr>
<tr>
<td>Paraffin Wax</td>
<td>Hydrophobic</td>
<td>McMaster Carr</td>
<td>1085K194</td>
<td>1lb</td>
<td>1</td>
<td>5.82</td>
<td>5.82</td>
</tr>
<tr>
<td>Distilled Water</td>
<td>Initial test Liquid</td>
<td>Kroger</td>
<td></td>
<td>1 gallon</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Other chemicals</td>
<td>To change properties</td>
<td>?</td>
<td></td>
<td></td>
<td>2</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>General-Purpose Plastics Selector Pack</td>
<td>Different Plastics</td>
<td>McMaster Carr</td>
<td>533K17</td>
<td>1/2&quot;x2&quot;x2&quot;</td>
<td>4</td>
<td>56.44</td>
<td>56.44</td>
</tr>
<tr>
<td>Nonporous High-Alumina Ceramic</td>
<td>Different Metal</td>
<td>McMaster Carr</td>
<td>031K272</td>
<td>1/16&quot;x6&quot;x6&quot;</td>
<td>1</td>
<td>4.15</td>
<td>4.15</td>
</tr>
<tr>
<td>Lead</td>
<td>Hydrophobic</td>
<td>McMaster Carr</td>
<td>986K304</td>
<td>0.060&quot;x6&quot;x6&quot;</td>
<td>1</td>
<td>3.59</td>
<td>3.59</td>
</tr>
<tr>
<td>Mid Range</td>
<td>Hydrophobic</td>
<td>McMaster Carr</td>
<td>1294T26</td>
<td>0.060&quot;x6&quot;x6&quot;</td>
<td>1</td>
<td>3.59</td>
<td>3.59</td>
</tr>
<tr>
<td>Mid Range</td>
<td>Hydrophobic</td>
<td>McMaster Carr</td>
<td>8476K16</td>
<td>0.060&quot;x6&quot;x6&quot;</td>
<td>1</td>
<td>3.59</td>
<td>3.59</td>
</tr>
<tr>
<td>Mid Range</td>
<td>Hydrophobic</td>
<td>McMaster Carr</td>
<td>8740K185</td>
<td>0.060&quot;x6&quot;x6&quot;</td>
<td>1</td>
<td>3.59</td>
<td>3.59</td>
</tr>
<tr>
<td>McMaster Carr</td>
<td>?</td>
<td>McMaster Carr</td>
<td>8560K171</td>
<td>1/16&quot;x1'x1'</td>
<td>4</td>
<td>5.82</td>
<td>23.28</td>
</tr>
<tr>
<td>McMaster Carr</td>
<td>?</td>
<td>McMaster Carr</td>
<td>8560K178</td>
<td>1/16&quot;x6&quot;x12&quot;</td>
<td>5</td>
<td>2.6</td>
<td>13</td>
</tr>
<tr>
<td>Plastalina Non-Hardening Modeling Clay</td>
<td>Adhere Substrate to stand</td>
<td>jerrysartarama.com</td>
<td>V11695</td>
<td>1lb</td>
<td>1</td>
<td>3.59</td>
<td>3.59</td>
</tr>
<tr>
<td>Loctite Super Glue Ultra Gel Control</td>
<td>Glue shield walls together</td>
<td>Ace Hardware</td>
<td>not available</td>
<td>not available</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Shield Walls</td>
<td>Prevent mess</td>
<td>McMaster Carr</td>
<td>8560K171</td>
<td>1/16&quot;x1'x1'</td>
<td>4</td>
<td>10.75</td>
<td>42.98</td>
</tr>
<tr>
<td>Low Shield Wall/Substrate Stand</td>
<td>Prevent mess</td>
<td>McMaster Carr</td>
<td>8560K178</td>
<td>1/16&quot;x6&quot;x12&quot;</td>
<td>5</td>
<td>1.10</td>
<td>5.55</td>
</tr>
<tr>
<td>Placing a Non-Hardening Modeling Clay</td>
<td>Prevent mess</td>
<td>McMaster Carr</td>
<td>8560K171</td>
<td>1/16&quot;x1'x1'</td>
<td>4</td>
<td>10.75</td>
<td>42.98</td>
</tr>
<tr>
<td>Adhere Substrate to stand</td>
<td>Prevent mess</td>
<td>McMaster Carr</td>
<td>8560K178</td>
<td>1/16&quot;x6&quot;x12&quot;</td>
<td>5</td>
<td>1.10</td>
<td>5.55</td>
</tr>
</tbody>
</table>

Table 1: Bill of Materials
10.2. Experiment Gantt Chart
   Note: Far too large to insert into printed document. Please see the attached M.S. Excel sheet.
10.3. Liquid Shield Dimensions

![Liquid Shield Dimensions Diagram]

Figure 2: Liquid Shield Basic Dimensions
10.4. Abstract submitted to IMECE

Title:
Investigation of Wettability and the Threshold for Splatter or Splash for the Control of Fluids Hazardous to Human Health

First Author:
Matthew K. Owen, Master’s Student in TFTPL, University of Cincinnati

Co-Author 1: 
Prof. Dr. Milind Jog, TFTPL Co-Director, University of Cincinnati

Co-Author 2:
Prof. Dr. Jay Kim, Director of U.C. OSHE Program, University of Cincinnati

Abstract:
Aerosolization is the process in which a liquid or solid is reduced to small enough particles such that they can become carried by the air. Notable examples which should not be inhaled are cutting fluids in machining and manufacturing processes, as well as other chemicals or substances such as pesticides, spray paint, or contaminated blood. If inhaled, these can pose negative short term or long term health issues. One source of aerosols is the secondary droplets created from droplet splattering or splashing after impacting a dry or wetted surface. To minimize and better control this fully in future situations, an understanding of what factors and properties that enables or contributes to splatter or splash is important.

Already there exists a rich body of research reported in the literature investigating different aspects of droplet impingement upon a dry surface and the resulting splatter or splash. Researchers have looked into different properties such as surface tension, viscosity, impact velocity, impact angle, depth of fluid on the substrate, surface geometry, surface roughness, surface composition (granular or solid), porosity, charge, surface elasticity, air pressure, and temperature. There has been research into single droplets and multiple droplets, as well as limited work in liquid jets impinging a surface. In terms of effects, research has also gone into understanding the different stages of droplet impacts such as droplet eccentricity before impact, spreading, recoil, jetting, corona, fingering, and fragmentation. It’s known that Weber and Ohnesorge numbers have a relationship with surface roughness and film thickness when predicting number of secondary droplets and deposition or splash thresholds. Of interest as well is the effect of wettability, but, despite this, there has been little work to expand knowledge of its influence or characterize its effects beyond droplet spreading.

This investigation is intended to determine the relationship between wettability and threshold for splattering or splashing. This is done by collecting impact data from different water/ethanol mixtures impinging upon seven substrates ranging from hydrophilic (glass) to hydrophobic (Teflon). The liquid is slowly forced through a syringe creating reproducible droplets which impact the substrate. The impact is observed through high speed photography and the images are then analyzed and compared to property values. Different structures and stages such as fingering, fragmentation, and secondary droplets are the main focus. By varying the Reynolds, Weber, and Ohnesorge numbers by changing the impact velocity, viscosity, and surface tension, the relationship of wettability and splashing threshold to other properties are also investigated. Maps of splashing versus deposition along with corresponding equations are presented.
10.5. MSD Sheets for Chemicals

Loctite Super Glue: