Investigation of the Large Liquid Structure in Fuel Injection

by

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Abstract

A previously-developed method of obtaining a more optimal liquid fraction field ($\beta$) for numerical analysis of injected liquid jet breakup as compared to the original $\alpha$ field is overviewed. Using this field, an improved post-processing method is developed to determine the wavelength spectrum of the intact liquid core. This process is further developed to account for more uneven flows and both versions of the process are verified against an earlier method used in other research to determine wavelength behavior based on the $\alpha$ field only.

For the following cases, all of which were simulations performed in InterFoam, the above methods were not used because the types of results that were focused on were not related to the wavelength of the intact liquid core. To cover a wide range of case setups, a well-established regime map is used to set up cases in the Rayleigh, intermediate, and atomization regimes. Using an appropriate three-dimensional domain space for each case, the set of simulations is completed and the results processed and analyzed. From these results, the Rayleigh regime is determined to be of little interest to the scope of this project, namely the region preceding the primary atomization point in the jet.

A second case list is developed, based on the findings and lessons learned during the more general, earlier case map. These cases are designed to determine the effects of varying liquid injection velocity on the injected jet performance. The analysis of them reveals that the velocity changes produce important variances in behavior. Potential plans for additional cases lists are outlined, and additional potential future work is highlighted.
Acknowledgements

Without the guidance and instruction of my advisor, Professor Mario Trujillo, this work would not have been possible. I have learned very much from him in both the classroom as well as in meetings to discuss my research, and his attention to detail has kept me focused and on track throughout this experience. In addition, because this work has finalized my decision to pursue graduate education and research, I am thankful for his advice during the application process and my decision-making phase.

In addition to Prof. Trujillo, the graduate students in his group, specifically Soumil Gurjar, Arpit Agarwal, and Douglas Ryddner, have offered guidance, support, and remained patient during my learning-phase this year. Additionally, Joshua Leach of the Engine Research Center has been very helpful for technical assistance as well as questions regarding parallel computing on the clusters the group uses.

I would like to thank the Faustin-Prinz committee and the Department of Mechanical Engineering for supporting students in their pursuit of undergraduate research. In my case, the opportunity has driven me to pursue more experience in research, and I will always remember this project and the excellent lessons learned.
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1 Introduction

While much focus is put on alternative energy sources in recent research, the use of petroleum fuels is not predicted to decrease over the next 25 years [1]. While traditional gasoline use is predicted to decrease, diesel and other fuels will increase in usage. As a result, liquid fuel injection will continue to be a major focus of research in increasing fuel efficiency and performance. A major point of interest in fuel injection (and in other applications involving an injected liquid) is the breakup characteristics as the jet atomizes in the full atomization regime.

The Volume of Fluid (VoF) numerical methodology can be used to determine multiphase (liquid/gas) behavior, making it an effective method for analyzing injection breakup. In this project, a new method to analyze a key behavior of the injected jet (the wavelength spectrum of the liquid core prior to full atomization) is developed and verified based on an improved solver in interFoam, a liquid-gas problem solver that uses the OpenFOAM and C++ libraries [2]. Additionally, several sets of cases spanning multiple regimes of predicted breakup are developed and completed in interFoam. These cases provide insight into the factors that significantly alter the behavior of the injected jet during atomization.

2 Background

2.1 Injection and Breakup of the Intact Liquid Core

The study of the breakup and atomization of an injected liquid jet in a gaseous environment involves multiple breakup regions. While some initial droplet formation may occur beforehand, complete breakdown of the liquid structure does not occur until the point of primary atomization, shown in Figure 1. Beyond this region, the extent of which will oscillate within some range over time, there is no longer a continuous liquid structure extending upstream to the injection site, and farther downstream the remaining ligaments and droplets completely atomize. The scope of the project considers the region of the jet prior to this point of primary atomization.
Figure 1: The downstream region of an atomizing liquid jet, illustrating the point of primary atomization (circled in red), where the intact liquid core completes breakup and liquid downstream consists of broken ligaments and droplets.

The basis for the parameter selection in this report comes from the regimes of breakup established by Reitz and Bracco for round liquid jets [3], shown in Figure 2. To briefly summarize, the Rayleigh breakup regime, which is predicted for combined low Reynold’s and Ohnesorge numbers, is where surface tension is expected to dominate resulting in structures that are very firmly held together and do not follow the same breakup behavior. At higher values, an intermediate region is predicted, followed by the more typical atomization regime. In this setting, the Reynold’s number is defined as

$$Re_{l,h} = \frac{\rho_i U_{inj} h}{\mu_l},$$

and the Ohnesorge number is defined as

$$Oh_{l,h} = \frac{\sqrt{We_{l,h}}}{Re_{l,h}},$$

with

$$We_{l,h} = \frac{\rho_i U_{inj}^2 h}{\sigma}.$$
The values chosen for the test cases in this research were selected to span this region and observe as wide a range of jets as possible.

![Figure 2: The regimes of breakup for a liquid jet established by Reitz and Bracco [3].](image)

### 2.2 Volume of Fluid Numerical Methodology

The Volume of Fluid (VoF) numerical methodology involves a Navier-Stokes equation solver and implicit interface capturing (in this application between the gas/liquid phases) to determine physical behavior. It is well established as a methodology for studying flows such as the jets under consideration.

For the scope of this project, the essential VoF numerics are outlined. In a two or three dimensional domain that consists of liquid and gas regions, \( I \) is defined as zero (0) for regions defined as gas, and one (1) for points consisting of liquid. If the domain is divided into a finite number of cells (as in a computer simulation), and \( I \) is integrated over the volume, \( \alpha \) can be defined as the result of the integration for each cell; this is the liquid fraction. If a cell consists entirely of gas, this value will be zero, and if it consists entirely of liquid, this value will be equal to one. For individual cells that contain regions of both gas and liquid, \( \alpha \) is a value between 0 and 1. For example, a cell that is exactly one half gas and one half liquid will have \( \alpha = 0.5 \).
A major benefit of this method of solving is that it defines liquid interface cells where $0 < \alpha < 1$, allowing higher order calculations to be focused in these regions and saving computational cost in regions consisting entirely of gas or liquid sufficiently far from the interface.

Considering conservation of mass and beginning with the governing equation,

$$\frac{d\rho}{dt} + \nabla \cdot (\mathbf{U} \rho) = 0 .$$

It is shown in [2] this equation can be rewritten in terms of the liquid fraction, with $\alpha$ replacing $\rho$. This is achieved by defining density in terms of the densities of the liquid and gas regions and the liquid fraction field. Integrating over the domain results in,

$$\frac{d\alpha}{dt} + \nabla \cdot (\mathbf{U} \alpha) = 0 .$$

This result is an equation that can be used by the solver to maintain mass conservation during simulations.

### 2.3 InterFoam Introduction

This research utilizes InterFoam, a liquid-gas problem solver that utilizes the OpenFOAM and C++ libraries. Utilizing the basic definition of the $\alpha$ field described in the previous section, InterFoam simulates two and three dimensional cases by employing finite volume discretization and solving the Navier-Stokes equations [2].

By providing a variety of mesh generation methods, interFoam provides the opportunity to define meshes that restrict finer definition to regions of higher computational importance, saving computational time in other regions, in addition to the time saved by limiting higher order calculations to the interfaces, as mentioned in the preceding section. In the current work, this is significant because it allows the region well beyond the point of primary atomization, which is not of primary concern, to be defined using a coarser mesh.

Additionally, InterFoam provides relatively simple methods of parallel processing, pausing cases, restructuring execution parameters in a partially completed case, and other features that allow efficient and effective use for complex, three-dimensional cases such as the
ones completed in this project. Finally, visualization and the corresponding analysis is performed in EnSight post-processing software.

2.4 Previous Work in Liquid Core Analysis Using Liquid Fraction

Analysis of the intact liquid core based solely on the $\alpha$ field faces several issues. The two main categories of these issues are (1) the unresolved regions where liquid fractions between 0 and 1 lead to a lack of clarity in certain regions and (2) the resolved structures that are not part of the intact liquid core.

Unresolved structures or extensive (multiple-cells-thick) regions of intermediate liquid fractions require criteria to determine how each cell will be categorized, either as a liquid or a gas. In the analysis of the liquid structure, a common feature to compare is the wavelength spectrum [4]. This is the range of wavelengths observed in the oscillations of the intact liquid core, seen in Figure 3.

**Figure 3:** $\alpha$ field cross-section for a typical injection case, showing the oscillations prior to the region of primary atomization.

These oscillations can be determined, among other methods, by placing probes in the region where waves are most pronounced. Compiling the results from the probes, it is possible to use MATLAB or other systems to determine the span of time between points where liquid is present, which combined with velocity data can determine the length of core that passed, providing the wavelength. However, resolving $\alpha$ values between 0 and 1, as noted earlier, presents a challenge to this process. In earlier research, a standard, such as taking all $\alpha > 0.5$ to be liquid, has been established. This approach would benefit from a more absolute definition of liquid vs gas cells.
More significantly, the introduction of additional broken-off structures and bubbles in the field around the liquid core introduce a high potential for “noise” in the results. For instance, if a probe is taking readings at a point and every point where liquid passes through is considered to be a new peak, signaling a complete wavelength has passed, problems will arise if additional droplets trigger this method by passing through the probe. Some approaches to addressing this include only taking points where a certain number of consecutive time-steps register a liquid, which is essentially having a limit for the minimum size of the structure passing through, and probe placement intended to be in locations where these excess structures are not as common. Successful research has been conducted using these approaches, though the benefits of a method to more rigorously define liquid vs. gas cells for post-simulation liquid core analysis remain obvious.

2.5 $\beta$ and Filtered $\beta$ Solvers

To address the limitations of relying on the $\alpha$ field to process results of cases, a new $\beta$ field is introduced in recent research [5]. The main goal is to clear away broken structures and droplets to leave a single liquid core in the domain. In addition, introducing secondary filtering of this $\beta$ field provides a fully resolved structure that leaves no cells with ambiguous contents; every cell is either liquid ($\beta_{\text{filtered}} = 1$) or gas ($\beta_{\text{filtered}} = 0$).

To summarize the method used in the $\beta$ solver previously written in interFoam [5], several pre-defined values are established. A diffusivity, which is set to a high magnitude (~1e8), is used in combination with a gradient and temporal derivative balance that results in clearing cells that are not directly connected via a liquid path to the injection site. This is done by originating the inlet as $\beta = 1$ with the entire domain set to $\beta = 0$. By setting the diffusivity of the liquid sufficiently high enough, the following balance

$$ \frac{d\beta}{dt} = \nabla D_{\text{liq}} \beta,$$

which is initiated and solved over one time step every time that a $\beta$ filtered field is to be generated, can capture the entire liquid core. Additionally, a liquid threshold is established for use after the non-liquid core structures have been removed. This value will determine, for the cells that still have $\beta$ between 0 and 1, the threshold where cells will either be labeled as liquid or
gas. In this overview, some details of the results are not covered at length, such as the challenges of preventing “smearing” where $\beta$ incorrectly appears to signify liquid at points along the core where $\alpha$ is near zero.

With a $\beta$ field established that offers clear benefits for analysis over the original $\alpha$ field, the focus is to develop and optimize methods to determine wavelength spectrums for injected liquid structures using this new field.

3 Filtered $\beta$ Analysis Method Improvement

In this section, the development and verification of a method to determine wavelength characteristics of an injected liquid jet using the filtered $\beta$ field is explained. This work is completed in MATLAB 2015a.

3.1 Criteria for Wavelength Recognition

Compared to the methods used to determine liquid and gas cells based on the $\alpha$ field, the filtered $\beta$ field, as described in the preceding section, already determines which cells have a liquid fraction somewhere between gas and liquid (i.e. interfacial cells) and assigns either state based on an established liquid threshold. As a result, all cells are already resolved to one state or the other, and so the script that was written during this project was structured to not require a threshold of its own, making that part of the processing marginally leaner.

Additionally, because droplets and broken-off structures have been removed from the domain (in the $\beta$ field specifically) there is no need to account for the possibility of non-liquid core structures interfering with the probe measurements. Therefore, every period where liquid comes into contact with the probe is registered as the next peak in the oscillating core, and the wavelength is determined from that basis as opposed to verifying that the liquid is in fact part of the liquid core during each iteration. This makes the code leaner.

3.2 Analysis Script

The following description covers the first successful $\beta$ field analysis script as well as the improved script. Both methods are verified in subsequent sections.
3.2.1 Initial Version of Analysis Script

The method used to analyze the probe data initially involves processing and splitting up the $\beta$, time, and velocity data at the point or points under consideration. With the data processed into callable tables, the code runs through all time steps. Once the cell in question is marked as liquid, this change in $\beta$ is marked as the first (or next) beginning of a wavelength. After recording the velocity at that point, the time until the next rise in $\beta$ is measured. This allows $\beta$ to drop back to a value of zero as the current peak moves past the probe in time, and then triggers once the next peak has hit the probe. Using the initial velocity for the current wavelength and the time between peaks, the length of the oscillation is determined. This is stored, and the loop begins again, beginning the process of documenting the next wavelength. Once the script has run through the entire range, it plots the wavelength results in a histogram for analysis and comparison of results.

3.2.2 Further Improvements to Analysis Script

One of the key disadvantages of the first $\beta$ script is the use of the velocity at the first peak for the entire wavelength calculation. For steady flows, this is not expected to change significantly, but under some conditions, it is possible for the velocity of the core to be non-uniform assuming that the shape of the core is not constant and can change to an extent. In this case, it is preferable to obtain an average velocity covering all of the time-steps during which the current liquid peak is in contact with the probe. This results in a better approximation for determining the wavelength that includes a more comprehensive estimation based on more data.

In addition, the histogram script was improved to provide more consistent bins between cases (for comparison between them) and the ability to read from hundreds of probes in one run, providing the option to plot any number of histograms from the larger pool of data. Because of the fact that the optimal location for a probe, which exists near the peak of the wave at a given distance downstream and far enough upstream from the primary atomization point, is not typically known when initializing a case (unless the case has been simulated before), a net of probes is generally spread out over the predicted region of usefulness.

From this higher number of probes, it is beneficial to run and compare many histograms from the data to quickly and efficiently determine which probes were in locations that were
optimal for recording passing wavelengths. These optimal locations are then also verified by post-process visualization in EnSight.

3.3 Verification

Verification of the script is initially carried out with a benchmark against a previous code that uses the \( \alpha \) field only, and this is followed by a comparison between the original and improved \( \beta \) field analysis scripts.

3.3.1 Verification of \( \beta \) Method with Original \( \alpha \) Analysis Method

For initial verification, a two dimensional case was used to verify that the script worked and that it could produce the desired histograms. For a more useful analysis, verification between the \( \beta \) method and the original \( \alpha \) method was conducted using identical probe points for each method. A cross-section of the domain mesh with essential dimensions is shown in Figure 4. The properties of the injected liquid were adapted from [6] to simulate a relevant fuel used in prior research. A view of the three-dimensional flow is shown in Figure 5.

![Cross-sectional cutaway of the three-dimensional mesh used in verification of the \( \beta \) solver solution methods. Note that DDx* signifies the level of refinement from the coarsest mesh at the far end of the domain. This mesh is designed to provide the finest resolution over the entire path of the intact liquid core.](image)

**Figure 4:** Cross-sectional cutaway of the three-dimensional mesh used in verification of the \( \beta \) solver solution methods. Note that DDx* signifies the level of refinement from the coarsest mesh at the far end of the domain. This mesh is designed to provide the finest resolution over the entire path of the intact liquid core.
Figure 5: Appearance of the injection case used for the verification of the β methods.

A radial mesh layout was considered as opposed to the square mesh used in this research to address the overall cylindrical geometry of the injected jet, but the success of previous work using similar mesh refinement levels and injection conditions while using square mesh setups, combined with the ease of modifying square grids during long simulations, made the approach more appealing. The inlet profile, while not perfectly round due to the square geometry, was divided across its diameter by 16 divisions, allowing fine enough refinement to make the results valid according to previous validations.

The 90 µm inlet diameter was chosen based on previous research in injected liquid sheets. The domain size and scaling, similarly, was generated for this project based on the dimension ratios of successful domains used in previous research simulations.

With the domain and inlet condition established, probe placement was determined throughout the predicted region where it would be most feasibly to detect actual wavelengths. As noted earlier, after collection, these locations were visually confirmed to be regions where the oscillations were notable.

The script used for the α method comparison was only slightly modified from its original version used in previous research for the sake of generating histograms with the same bins as the β method script. Therefore, no modifications were made to the logic for the α method script. Using the probe data from the case outlined previously, histograms for several dozen probes
were generated and compared. Examples of the histograms are found in Figures 6 and 7, representing several dozen histogram comparisons.

**Figure 6:** $\alpha$ and $\beta$ method results for a probe point presented in histograms. Note that the overall number of wavelengths counted is slightly higher for the $\alpha$ method, as is expected.

**Figure 7:** $\alpha$ and $\beta$ method results for a second probe point presented in histograms. Note that the overall number of wavelengths counted is slightly higher for the $\alpha$ method, as is expected.

The results were largely comparable, and were found to consistently have the same number of total wavelength occurrences within 10% difference of each other. The outlying values were where the most noticeable differences that occurred. Additionally, the $\alpha$ method results, on average, had more occurrences of shorter wavelengths and several more total occurrences observed. This was to be expected based on the “noise” inherent in the $\alpha$ method described above. Due to other structures and droplets triggering the wavelength counter prematurely, the $\alpha$
method is understood to be error-prone in that regard. Therefore, the results are largely comparable, and the β method is successfully verified against the α method.

3.3.2 Verification of Improved β Method

With the improvements made to the β method script, as well as the improved histogram plotter, which was added to both the original and improved β scripts, comparison tests using the same probed data from the previous verifications were run. These results showed strong agreement between the methods, which was expected because of the case parameters, which produced an oscillating liquid core with relatively calm characteristics. The benefit of the improved β solver would mainly exist in cases where the liquid core behaves more sporadically. In this case, the desired result was to ensure that the improved method produced comparable results to the original under steady conditions. This was confirmed, and example histograms from this verification are found in Figures 8 and 9.

![Histograms](image)

**Figure 8:** β and improved β method results for a probe point presented in histograms. Note that the total number of wavelengths counted is the same for both methods, as is expected.
Figure 9: β and improved β method results for a second probe point presented in histograms. Note that the total number of wavelengths counted is the same for both methods, as is expected.

In summary, the results for comparing the α and β methods, as well as the improved β method, compare with each other well, verifying the new methods developed in this work. While there was at most a 10% difference in the result between the α and β trials, the previous research in this field is primarily focused on the order of magnitude of the wavelength spectrum. The difference observed is smaller than the scope being considered, and the improved process is preferred because it eliminates the error associated with droplet obstructions as well as the need for a liquid threshold at the post-processing level.

4 Injection Simulation Cases

The second focus of this work involved developing and running simulations over the breakup regimes overviewed in the preceding background description. Because the breakup behavior under consideration was not limited to cases where significant liquid core oscillations are noted, it was not useful to this part of the project to utilize the β method developed earlier in the project.

4.1 First Case Set

For the first set of cases, the main focus was to span as much of the overall regime map as possible, resulting in some cases that were unusual in their conditions. Additionally, the injection velocity profile was altered to determine the effects of alternate profiles on the breakup behavior downstream.
4.1.1 Domain Setup

The domain that was developed in the verification of the $\beta$ analysis methods and was shown in Figure 4 was used for this first case set as well. For some cases, the refinement of the finer mesh regions was expanded downstream if the liquid core was found to extend beyond the domain, but these changes were limited and not of importance to the overall simulation results.

4.1.2 Case Conditions

Based on the types of injection profiles outlined in the background, case conditions were chosen to span the Rayleigh, intermediate, and full atomization regimes. A map of these cases is shown in Figure 10. The parameters that were altered to achieve conditions in the various regions of the regimes under consideration are compiled in Table 1.

![Figure 10: Map of the first set of cases.](image)
Table 1: Liquid and gas phase properties, injection velocities, and key dimensionless numbers for the first set of cases. The values in grey are constant across all cases, and the highlighted values were varied to achieve the desired conditions.

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4.2 Results of First Case Set

Given the wide range of case parameters tested, the injection profiles and behaviors of the injections varied heavily. For the cases in the Rayleigh regime (1, 4, and 7), surface tension dominated the injected liquid, resulting in a non-atomizing stream passing through the domain space. Figure 11 provides a cross-section of Case 1, showing the single liquid structure progressing through the domain.

Figure 11: Cross-section of a Rayleigh regime case showcasing the surface tension-dominated, non-atomizing flow.

Cases 2 and 3, in the intermediate and atomization regimes respectively, had Ohnesorge numbers about one order of magnitude higher than most injection cases in previous literature. Case 2 in the intermediate regime exhibited significant ligaments beyond the point of primary atomization. Case 3, as with the other atomization regime cases (and as expected) displayed more and smaller droplets beyond the liquid core.
**Figure 12:** Case 2 profiles showing the significant ligaments formed beyond the breakup of the intact liquid core.

**Figure 13:** Case 3 profiles showing more complete atomization at the end of the intact liquid core.
Cases 5 and 6 were in the range tested in previous literature, and had profiles most closely representing previous work involving cylindrical liquid injection breakup. Cases 8 and 9, with lower Ohnesorge numbers, were similar to the other cases in their regimes.

**Figure 14:** Profiles from Case 5. This case (along with Case 6 shown in Figure 15) uses parameters closest to previous work in interFoam involving liquid injection.

**Figure 15:** Profiles from Case 6, showing denser atomization into smaller droplets.
Figure 16: Profiles from Case 8, showing less dramatic breakup and significantly larger ligaments beyond the liquid core.

Figure 17: Injection profiles for Case 9.
4.2.1 Effects of Velocity Profile

In addition to the parameters discussed previously, the profile of the velocity at the inlet was changed using the groovyBC functionality in interFoam. The three profiles tested were the standard flat-hat and two power-law profiles based on the following equations:

\[ U = U_0 \left( 1 + \sqrt{\frac{y_{\text{position}} + x_{\text{position}}^2}{\text{radius}_{\text{inlet}}} \right)^{\frac{1}{b}} \]

\[ U = U_0 \left( 1 + \sqrt{\frac{y_{\text{position}} + x_{\text{position}}^2}{\text{radius}_{\text{inlet}}} \right)^{\frac{1}{c}} \]

Cases 2, 3, 5, 6, and 8 were carried out for these three profiles (other cases were only done using the flat-hat profile used previously). The \( \frac{1}{4} \) power law profile, most notably, was observed to cause a longer intact liquid core, ranging from 5-15% longer overall when comparing identical case parameters. Besides this, no change in the physical behavior of the injections, the degree of atomization beyond the liquid core, or any other noticeable effects were observed, and for the pending second set of cases, it was determined that the flat-hat inlet profile was the only profile requiring testing.

4.2.2 Summary of Changes Needed for Second Case Set

The results of the first set of cases revealed a need to reduce the number of parameters varied. The decision to vary multiple parameters was made due to the goal of spanning the breakup regimes as widely as possible. However, determining the notable cause of differences between the cases was not possible given the variety of changes made, leading to uncertainty as to the underlying causes of the differing behaviors. Therefore, a more specific region of the breakup regime map was chosen. The region closer to real-world fuel injection parameters was selected, and the single parameter of injection velocity was chosen to be varied. Preliminary investigation into varying viscosity in an alternate set of cases revealed dramatic physical differences, but the parameters were outside the range of actual fuels.

4.3 Second Case Set

Four cases were setup similarly to the first set of nine, as outlined in the following sections.
4.3.1 Domain Setup

The same domain described previously was reused in the new set of cases. Some limited degree of additional refinement was made for the first case (mentioned in the following description) to allow sufficient capturing of the liquid core for that case.

4.3.2 Case Conditions

The parameters used for the cases were based on the parameters used for testing the β solver, and are included in Table 2. The inlet velocities tested were 10, 20, 50, and 100 m/s. The regime map with the updated case list is shown in Figure 18.

**Table 2:** Liquid and gas phase properties, injection velocities, and key dimensionless numbers for the second set of cases.

<table>
<thead>
<tr>
<th>Case (#)</th>
<th>Diam. (µm)</th>
<th>ρ_{gas} (kg/m³)</th>
<th>ρ_{liq} (kg/m³)</th>
<th>μ_{gas} (Pa·s)</th>
<th>μ_{liq} (Pa·s)</th>
<th>σ (N/m)</th>
<th>U (m/s)</th>
<th>Re_{liq} (-)</th>
<th>We_{liq} (-)</th>
<th>Oh_{liq} (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>50</td>
<td>666.7</td>
<td>4.06E-05</td>
<td>2.00E-02</td>
<td>2.50E-04</td>
<td>1.00E+01</td>
<td>8.00E+02</td>
<td>1.00E+02</td>
<td>1.25E-02</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>50</td>
<td>666.7</td>
<td>4.06E-05</td>
<td>2.00E-02</td>
<td>2.50E-04</td>
<td>2.00E+01</td>
<td>1.60E+03</td>
<td>4.00E+02</td>
<td>1.25E-02</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>50</td>
<td>666.7</td>
<td>4.06E-05</td>
<td>2.00E-02</td>
<td>2.50E-04</td>
<td>5.00E+01</td>
<td>4.00E+03</td>
<td>2.50E+03</td>
<td>1.25E-02</td>
</tr>
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<td>50</td>
<td>666.7</td>
<td>4.06E-05</td>
<td>2.00E-02</td>
<td>2.50E-04</td>
<td>1.00E+02</td>
<td>8.00E+03</td>
<td>1.00E+04</td>
<td>1.25E-02</td>
</tr>
</tbody>
</table>

**Figure 18:** The breakup regime map with the 2nd set of cases 1-4.
5 Results

The end results of the second phase of this project were the completed simulations for the second set of cases.

5.1 Second Case Set Results

With the injection velocity changes covering an order of magnitude (10-100 m/s), very noticeable differences occurred between the four cases. The 10 m/s injection velocity resulted in a smooth, globular core, with breakoff occurring around 120 inlet diameters into the domain and consisting of large spherical ligaments with similar diameters to the liquid core itself. The 20 m/s injection velocity had a similar breakup length in the domain, but exhibited small droplet development along the length of the liquid core, and some oscillation preceding the development of elongated ligaments past the tip of the liquid core.

Case 3 (50 m/s injection) had the features of Case 2 more prominently, a shorter breakup length around 100 diameters into the domain, and additional droplet formation alongside the ligaments beyond the core. Case 4 displayed the most dramatic atomization, similar to actual fuel injection, with more development of smaller ligaments and a higher density of droplets past atomization, which was observed around 67 diameters into the domain. Isometric views of the four cases are provided in Figures 19 and 20.

Figure 19: Cases 1 and 2 from the second set of simulations, focused on the point of breakup near 120 diameters into the domain space.
Figure 20: Cases 3 and 4 from the second set of simulations, focused on the point of breakup near 100 and 67 diameters into the domain space, respectively.

6 Future Work

Because this project consisted of two parts, the improvement of the wavelength determination method and the cases run across the regime map, the proposals for future work are likewise divided into two sections.

6.1 Wavelength Range Determination

With the script functioning and verified for using the $\beta$ field to determine the wavelength spectrum, it is ready to be used in cases where this information is yet to be established. Previous research [5][7] has extensively looked at this feature for injected liquid sheets. There is less data established for round injection jets, which are the focus of this project. As a result, cases similar to the ones executed during the other portion of this project could also be analyzed using this improved wavelength spectrum analysis. This could provide valuable insight into the results found in this VoF simulation compared to older documented results in the literature.

6.2 Case Set Results

For the case plans outlined for this project, the results revealed that the velocity changes made to alter the Reynolds’s Number while maintaining other values as constant had the most interesting effect on the jet breakup. Expanding upon this would be the next logical step. As mentioned previously, extreme velocities on either end of the spectrum make case management more difficult, but successfully running cases beyond the 10 to 100 m/s range tested in this work
would provide additional insight into the behavior of the jet and the type of relationship between velocity and breakup. Depending on these results, altering other values would provide insight into any other parameters that may be as significant as velocity in terms of altering jet behavior.

Finally, in addition to designing additional cases, a more analytical approach could be taken to analyze the results and compare them to theory. This would potentially bridge the gap between the results presented in this work and the projected results based on analytical work.

7 Conclusion

This work included the development and optimization of a wavelength spectrum-analyzing MATLAB script to utilize a newer β solver that is more efficient and accurate than the previous α field-based script. This new method was improved and verified, and found to work well for a sample three-dimensional case.

Additionally, a list of injection parameters was developed to cover multiple breakup regimes with the intent of observing and comparing the results. Because these results were examined differently than analyses focusing on wavelength of the intact liquid core, the MATLAB script developed earlier was not used. After the first set of cases was run, observations were made, specifically in regards to limiting the overall range of cases tested and planning to not cover the Rayleigh breakup regime in future case sets because of the lack of usefulness of those results.

As a result, a second, more refined case list was generated and completed. These results showed a strong correlation between significant changes in jet behavior and changes in velocity. Because this was found to be most significant, future work in relation to the finding was proposed. Finally, analytical work to compare with the numerical results was also suggested as an important future step.
References


