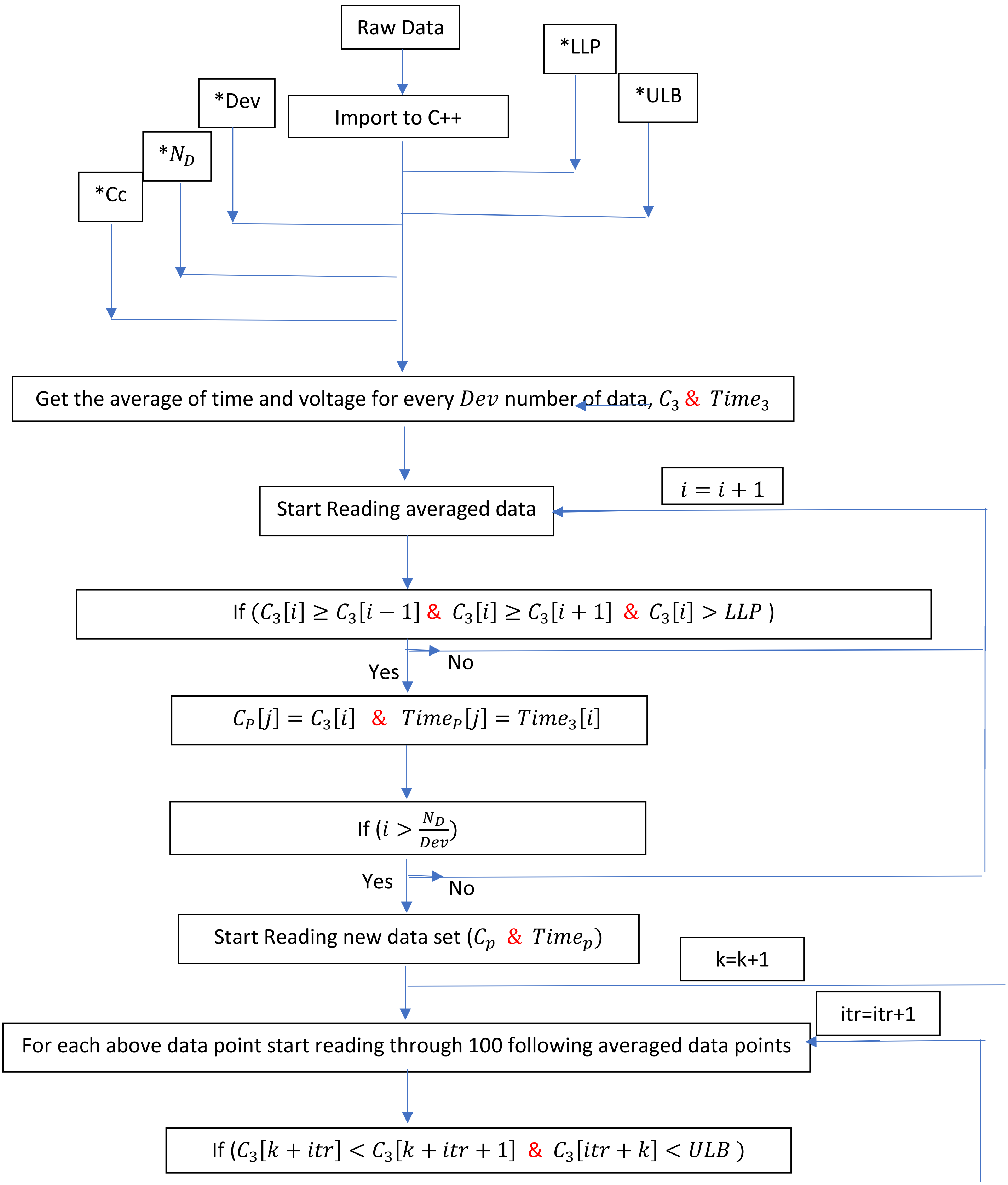
Capacitance Data Analysis

Preface

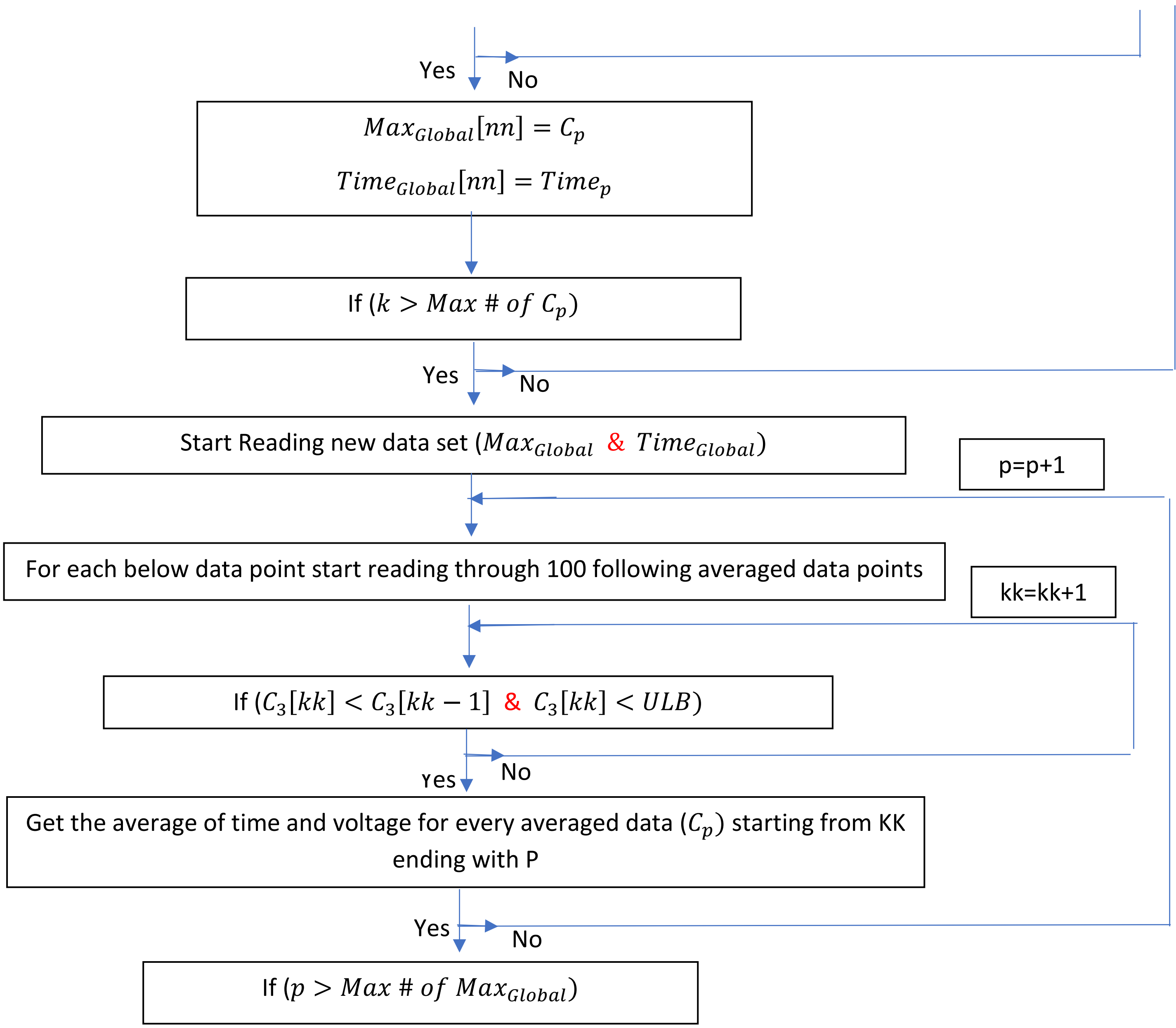
Three probes are installed in our facility that could measure and report voltage at their locations. Probe 1, is very close to the inlet, 2nd probe is in the middle and the last probe is near outlet where more developed flow is expected. Since the water and gas have different conductivities, the measured voltage is a function of liquid and gas percentage. To perfectly use the data generated by the probe to obtain required parameters, a simulator needed to be developed to analyze the data and return useful parameters. The analysis later is compared to other methods including image analysis, quick closing valve holdup measurements and videos.

The parameters expected to be obtained are slug liquid holdup, slug length, film liquid holdup, film length, transitional velocity, slug frequency and bubble distribution in slugs.

Flow Chart



Raw Data
Import to C++
*LLP
*ULB
*Dev
*N_D
*Cc
Get the average of time and voltage for every Dev number of data, C_3 & $Time_3$
Start Reading averaged data
$i = i + 1$
If ($C_3[i] \geq C_3[i-1]$ & $C_3[i] \geq C_3[i+1]$ & $C_3[i] > LLP$)
Yes
No
$C_P[j] = C_3[i]$ & $Time_P[j] = Time_3[i]$
If ($i > \frac{N_D}{Dev}$)
Yes
No
Start Reading new data set (C_p & $Time_p$)
k=k+1
itr=itr+1
For each above data point start reading through 100 following averaged data points
If ($C_3[k+itr] < C_3[k+itr+1]$ & $C_3[itr+k] < ULB$)



Dev: The number which the total data points are divided to

N_D: Total data points

Cc: Capacitance Censor number which is wanted to be evaluated.

LLP: Lower Limit Peak

ULB: Upper Limit Bottom

Slug and film hold up and length

This section will be explained by an example. In below plot, you can see that each peak (associated to one slug) is determined by blue circles. The orange squares are the averaged H_{lls} and the gray triangles are average film hold up.

For each slug, from the peak back to the previous minimum, normally a steep line is seen. It is believed that that line represents each slug. And comparatively, the right line (from the peak to the next bottom is film and the averaged hold up is for film section.

For each slug, the time associated with film and slug are known and if transitional velocity is known, the length can be determined. So V_{tb} should be firstly measured. The next section, the methodology used to get the V_{TB} is explained.

General procedure

The simulator consists of two main bodies including two separate functions. The first one is responsible of producing averaged data and a file with locally high and low points. The user will be asked to enter the number that they want to divide the total numbers to and get the average. The program is set to give the averaged data by six to a hundred. Later in the same function, the averaged data will be schemed through and all peaks and bottoms will be chosen. However, intuitively, some of them will be associated with slugs that are aimed and desired to be picked. In the following graph, there are two points which show the rise of holdup from a minimum point as an indication of slug arrival. The maximum voltage which is recorded by capacitance censor is believed at the very end of slug where bubble concentration is least. The following picture shows a typical behavior of slugs passing by with their captured voltage signals by capacitance censor.

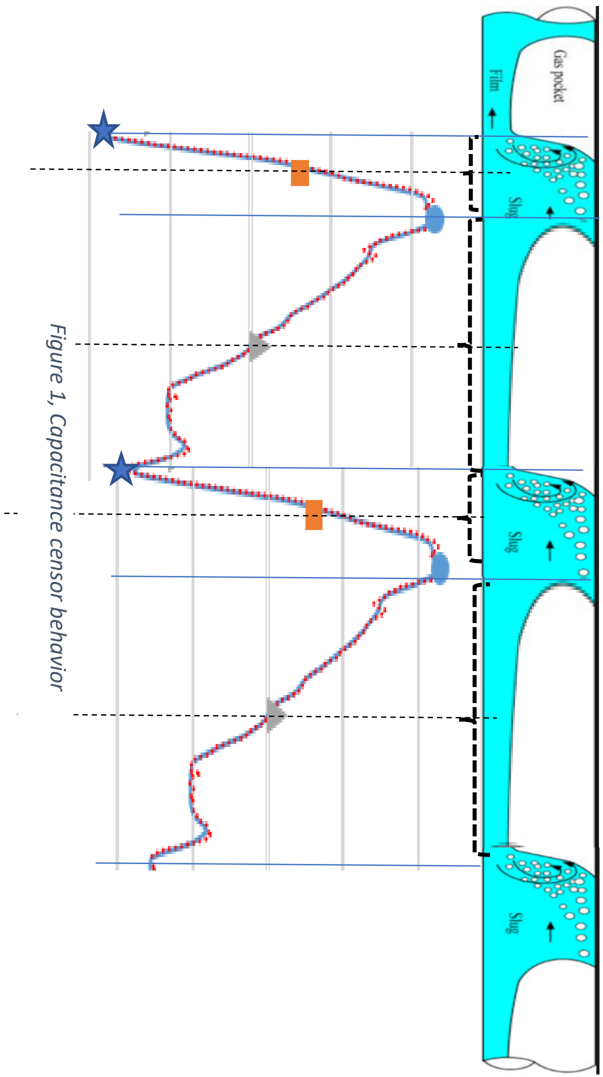


Figure 1, Capacitance censor behavior

The dark blue stars are representing the picked bottom points, the light blue circles are peaks, the orange squares are the timely averaged voltages of slugs and finally the gray triangles are the averaged voltages of films.

The above speculations were examined by experimental tests (liquid holdup measurements from image analysis, quick closing valve liquid holdup determination, pictures and videos of slugs) and it is found out that some assumptions above are not totally valid. The main reason of invalidity of data is due to interfering of capacitance censor probes with the flow. To be more elaborate, when the slug passes by, the ideal case will be immediate removal of fluid from the probe. By observing several tests, it is found out that the probe will not be dried out immediately and a splash of water will form on the probe while the slug has already passed. This makes it obvious that we cannot use the averaged voltages of film section to get film liquid hold up. Fortunately, the mentioned splash will end at some point where it is the minimum voltage point exactly before the next slug reaches. This means the best bet will be the minimum points already determined by the previous function to be closest to film liquid holdup.

In addition, by looking closely to the flow, it is found out that a slug is preceded by a wave of flow which does not have bubbles in and should not be considered as a typical slug. This behavior is common in lower gas rates. One example is shown in the following section.

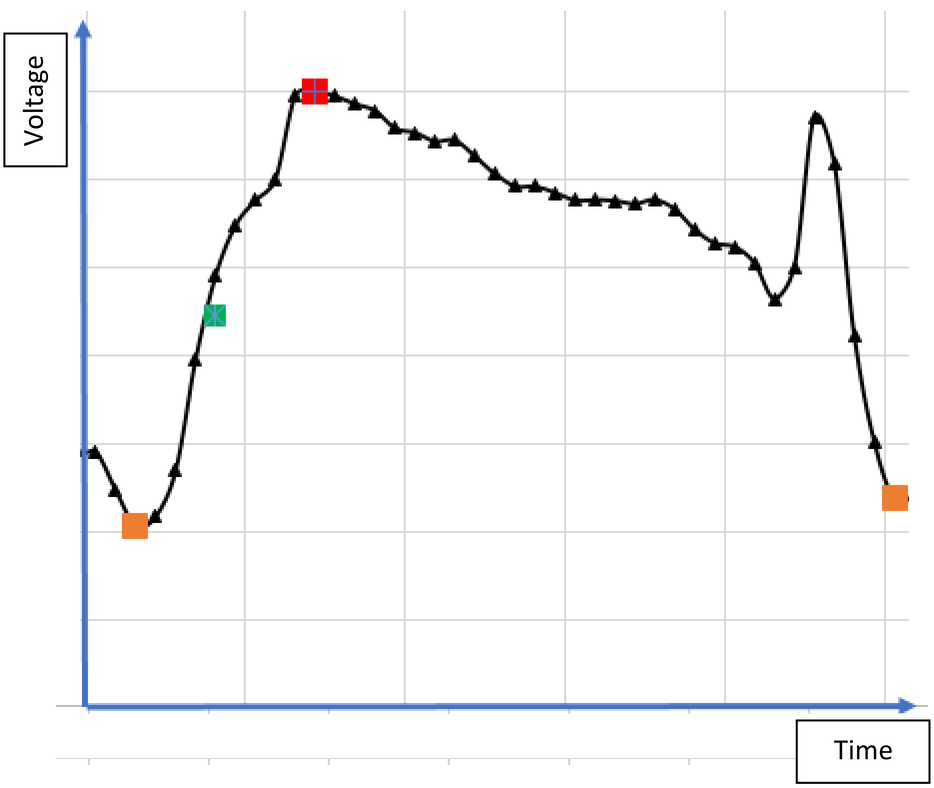


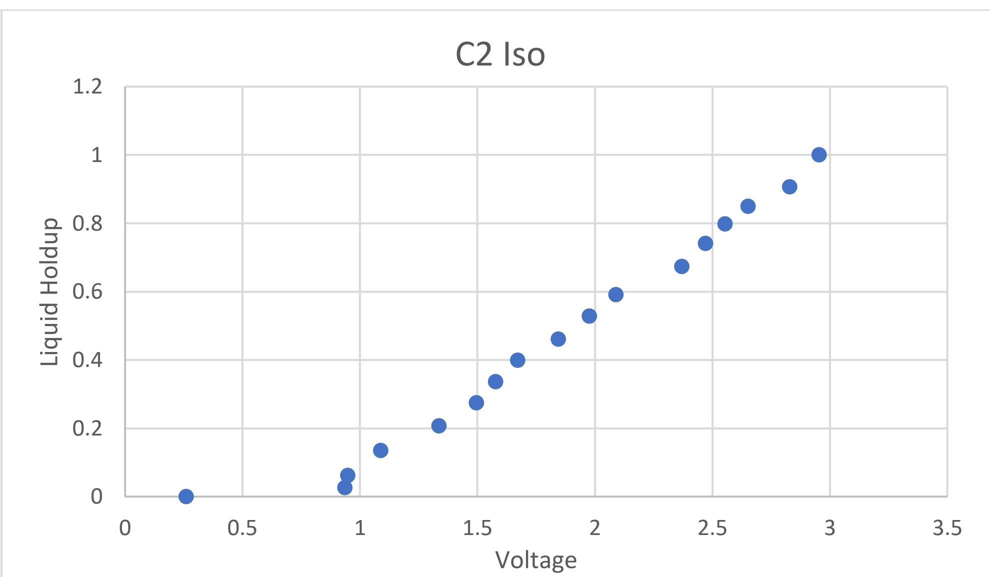
Figure 2, Slug with a spike at the end

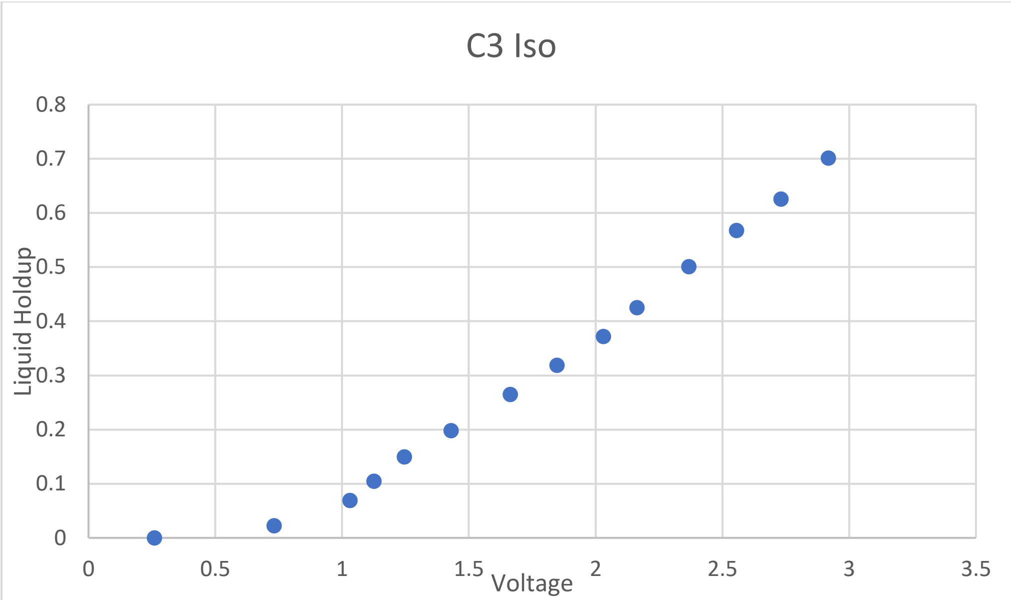
Slug and Film Length

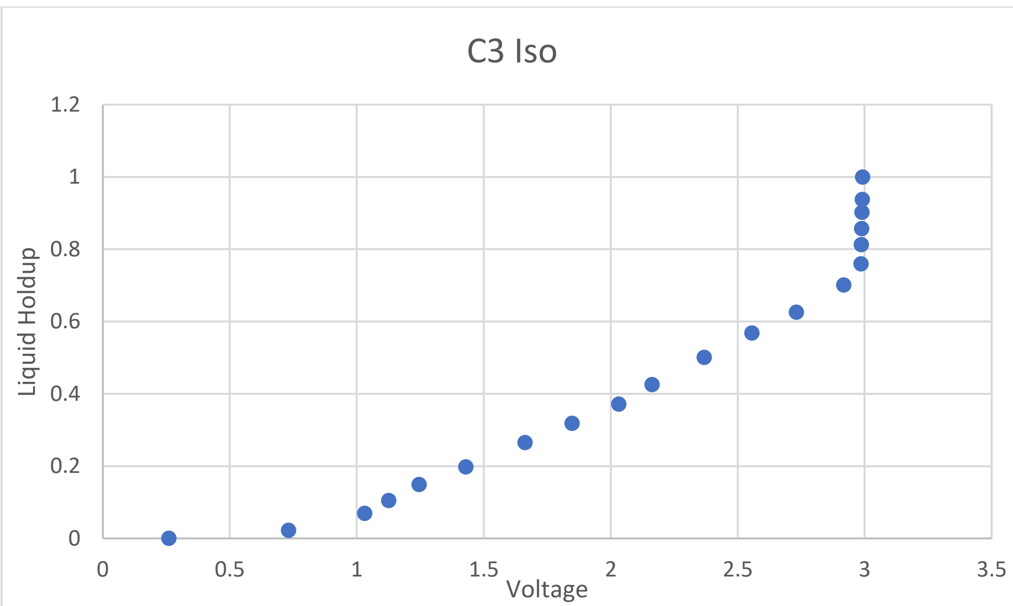
For each slug, from the peak back to the previous minimum, normally a steep line is seen. It is believed that that line represents each slug. And comparatively, the right line (from the peak to the next bottom is film and the averaged hold up is for film section. For each slug, the time associated with film and slug are known and if transitional velocity is known, the length can be determined. So V_{tb} should be firstly measured. Later, the methodology used to get the V_{TB} is explained.

Calibration

At first it was expected to see a linear relationship between holdup and measured voltage by capacitance censors meaning that the lowest and highest possible voltages should correspond to zero and one in terms of holdup respectively. However, this behavior was not observed in probe 3 when it was exposed to known liquid volume (holdup) when It was above 0.8. In other words, probe 3 shows low sensitivity when the holdup is more than 0.8. The following graph shows the voltage versus known liquid holdup for all probes.







At the end of this report, some analysis is included with the step-by-step calibration. In addition, linear relationship between voltage and holdup was assumed which the end points were used for calibration (0 and 1) in case where capacitance censor behaves differently dynamically. The analysis shows fairly consistent systematic results

Experimental procedure of voltage vs. holdup calibration

Total volume of the test section was first measured and then known volumes of liquid was taken out step by step while capacitance censor data was recorded. By knowing the holdup, the corresponding voltage was measured and the above charts were resulted.

Some difficulties appeared in the process of calibration and one of them was, not having symmetrical bubble when the liquid was drained out at high holdup values. The problem was mitigated by separating the test section into two and do the same exact process for each section. The first section consists of probe 1 & 2 and the other one is where probe 3 is located. This made it possible to have more symmetrical and lengthened bubble while liquid holdup was being measured.

Choosing Peak and Bottom Points

As mentioned, the simulator requires to have two limits in order to choose the peak and bottom points. For example, such signals (figure 3) have been produced and we want to captured those that are slugs and ignore those small spikes which are not slugs. When you set your high limit as high as it is required, it will only choose those peaks that are more than that value and ignores those that are just spikes (proto-slugs). This makes it dependent on user's judgment to make sure that the limits are set correctly and slugs are only picked up.

The simulator picks those maximums that are above a certain limit which is called "Lower Limit Peak" and then move backward through the data till a minimum that is less than a certain value is met. The second limitation is called "Upper Limit Bottom". Now at the point, those peaks that had already the mentioned characterizations (explained above) will be considered as slugs for frequency determination. It is noteworthy to say that the reported frequency is highly dependent on the two limitations. Further experiments should be done to determine these two limits. In another word, LLP is the minimum voltage of a slug and UPB is the maximum voltage of film.

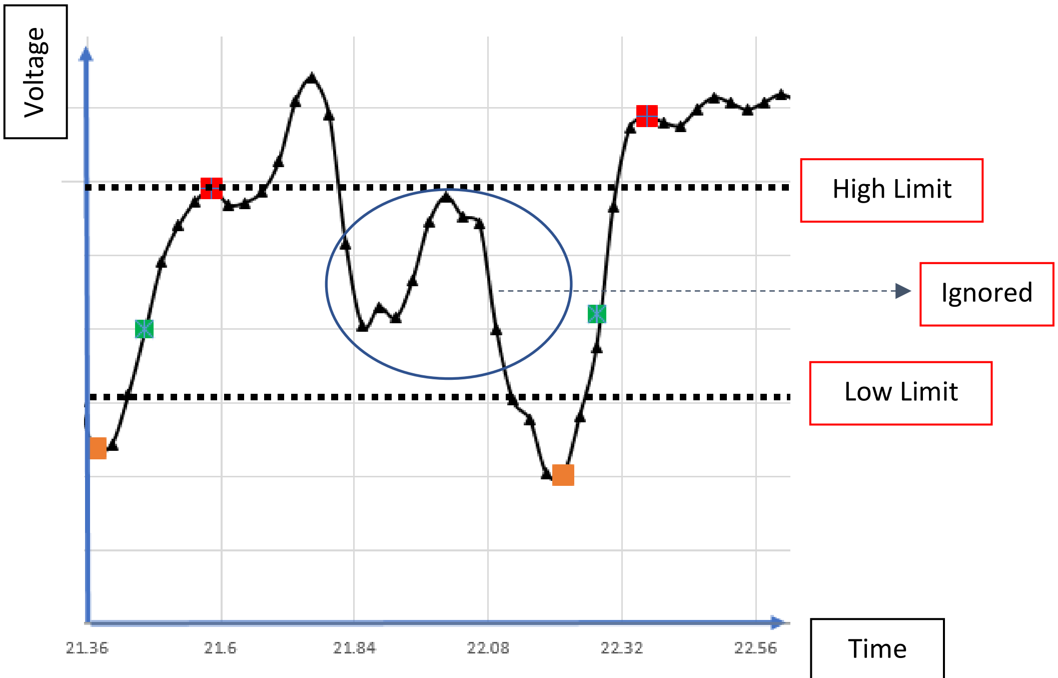


Figure 3, Correct high and low limit picking

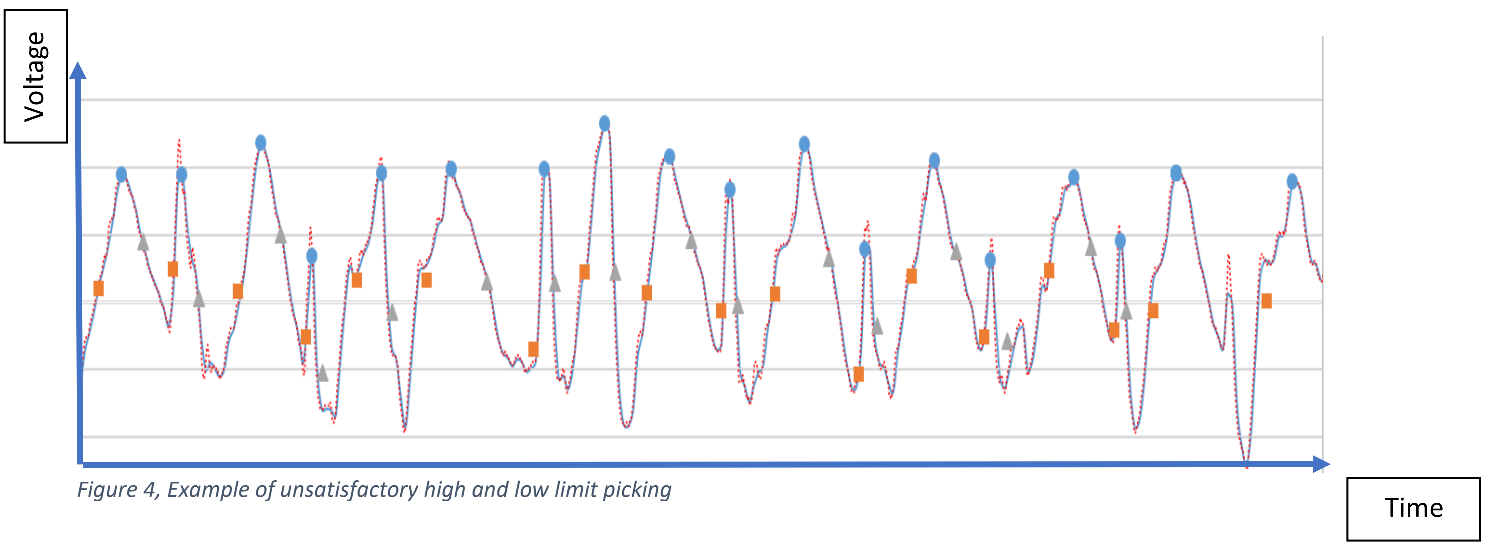


Figure 4, Example of unsatisfactory high and low limit picking

In every test, the high and low limits were changed till nearly all slugs are picked. In order to do so, signals for two minutes should be plotted and then then visually can be judged if every slug are picked. If the results were satisfactory, those values will be set for high and low limits. And then further parameter calculations will be proceeded. The explained procedure should be followed to give an accurate answer for frequency. In separate file, the simulator will produce the total number of slugs which are detected for the given time range.

synchronized tests

Later synchronized tests were used and images of each slug and the video of the flow were compared to the capacitance sensor data. We found out when a bump is seen, it is not necessarily a slug and could be a lengthened wave that will not bridges the pipe. However, sometimes these irregularities are mistaken with actual slugs and more in depth result analysis of such synchronized tests will be improved the simulator.

Transitional Velocity Determination

The characteristic of a slug (shape, wideness) will change considerably from capacitance sensors and it cannot be traced by numerical simulation to be matched knowing the fact that it has passed all three censors at different times. In other words, the noises are too severe that disable numerical approaches to detect a specific peak (slug) from three capacitance censors.

So, a manual systematic approach will be introduced that if it is followed, it will give an averaged velocity.

Steps:

1- Get the averaged data to reduce the noises as much as possible. The two graphs below shows how averaging raw data can make the data smoother.

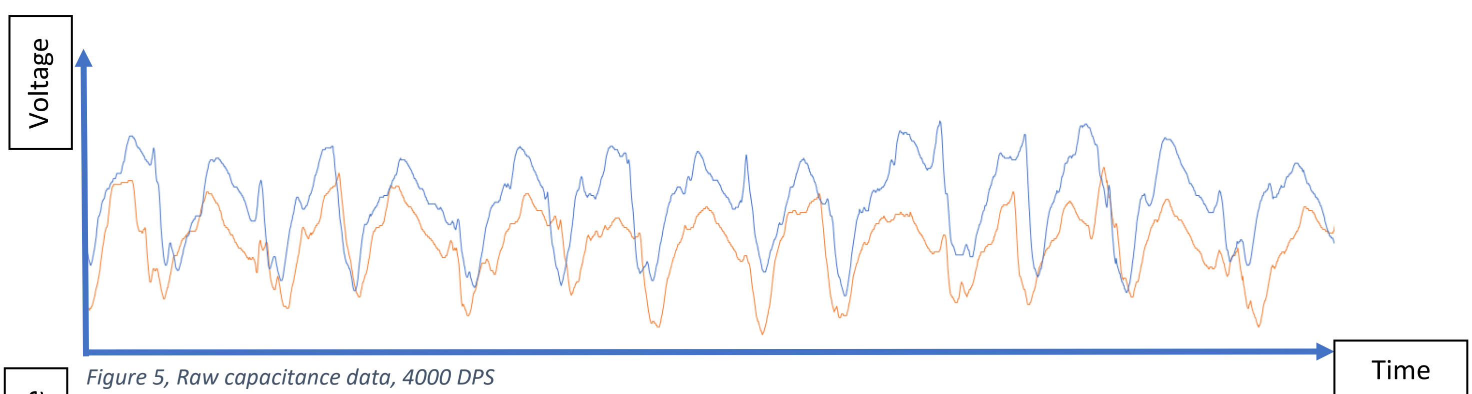
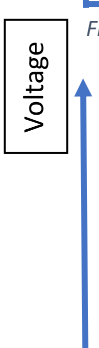


Figure 5, Raw capacitance data, 4000 DPS



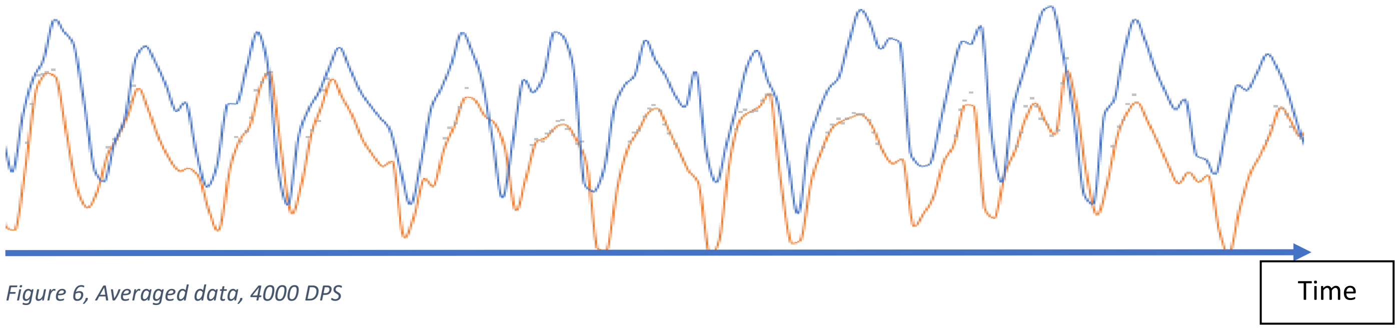


Figure 6, Averaged data, 4000 DPS

2- In the second step, <u>each</u> distinctive bump will be manually matched with its associated peak of the other probe and report the time difference. Make a table with at least 20 matched peaks with their time differences. Also since we know the length between probes, we can immediately calculate the velocity for each peak and then average them.

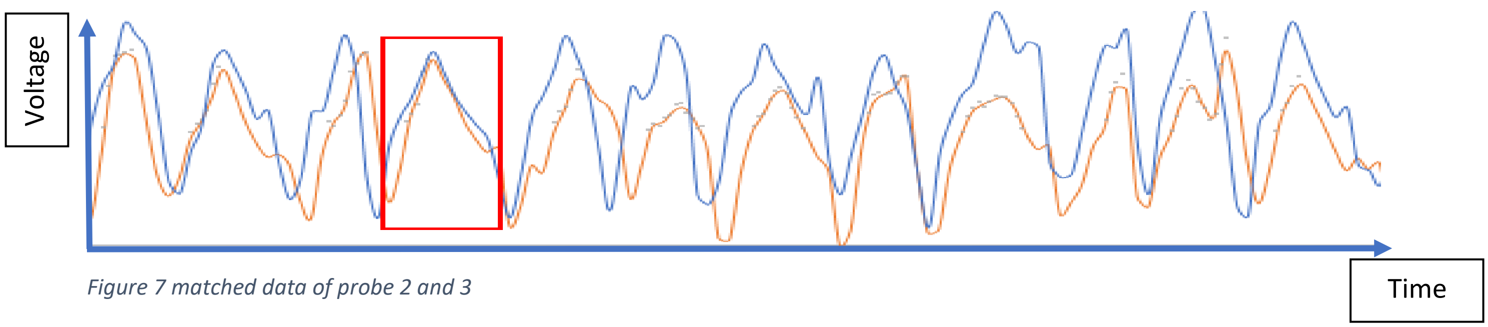


Figure 7 matched data of probe 2 and 3

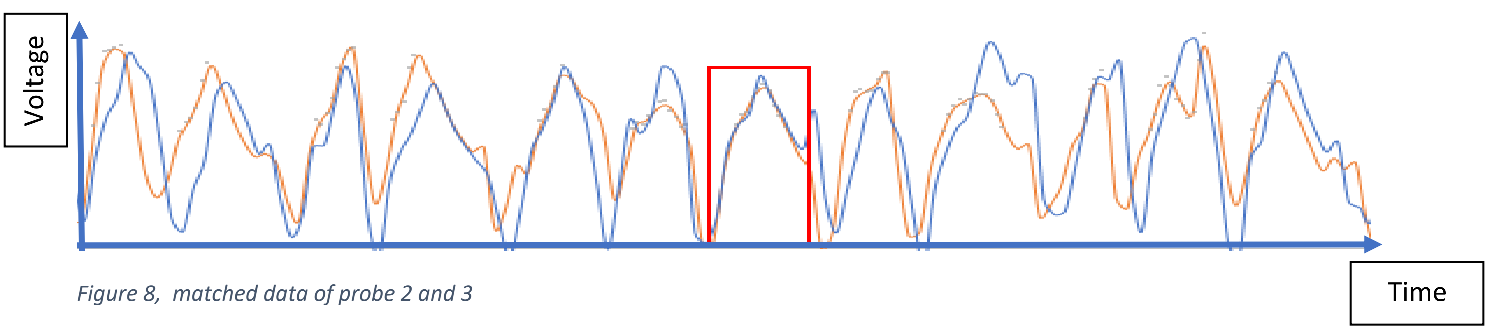
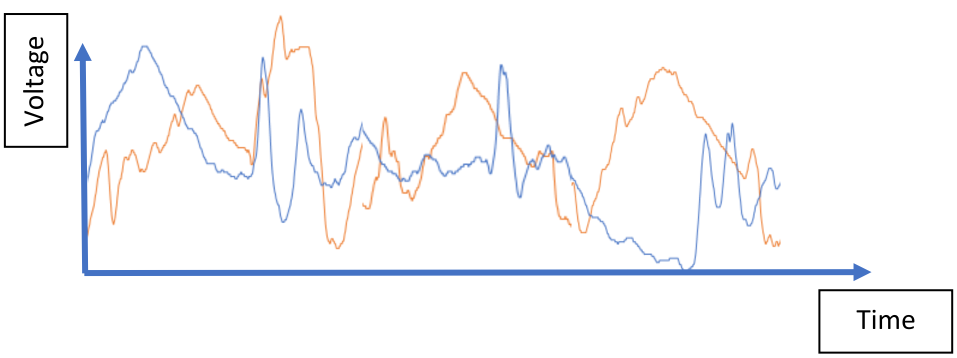


Figure 8, matched data of probe 2 and 3

Time Difference	Velocity
0.2	3.2
0.2	3.2
0.2	2.9
0.2	3.2
0.3	3.5
0.2	3.2
0.3	3.5
0.2	2.6
0.2	3.2
0.3	3.5
0.2	2.9
0.3	3.5
0.2	2.9
0.2	3.2
0.2	2.4
0.2	3.2
Average	3.1

The next plot will show some irregularities even though the above perfect match between data are seen for the dame file.



BUT, the approximation is fairly acceptable and it is valid.

Manual to analyze data

1- Convert data from voltage to holdups using step-by-step calibration.
2- First get averaged data for probe 2 and 3 by running the simulator.

3- Plot the averaged data for 2 minutes.
4- Compare the data for two probes and match them to calculate slug velocity (V_{TB}). The right procedure of V_{TB} calculation is previously explained.
5- Then take a look at the plotted data in probe 3 and try to come up with the first guess of two limits.
6- Now run the simulator again, and input the correct value for transitional velocity with the two limits.
7- Copy the analysis file ("check.txt") and plot the data on the same graph of step 2.
8- Scheme through the analysis and the picked peaks and bottoms. If all the expected slugs are chosen at the right location convert.
9- Get the histogram of each parameter and get a normal distribution fit to it. The arithmetic mean of the fitted normal distribution will be the representative value. Please note that for nearly all parameters, normal distribution will work the best.

Results and discussions

Firstly, the analyzed data using step-by-step calibration is shown. Later the analysis of end-points calibration is done.

Step-by-Step calibration

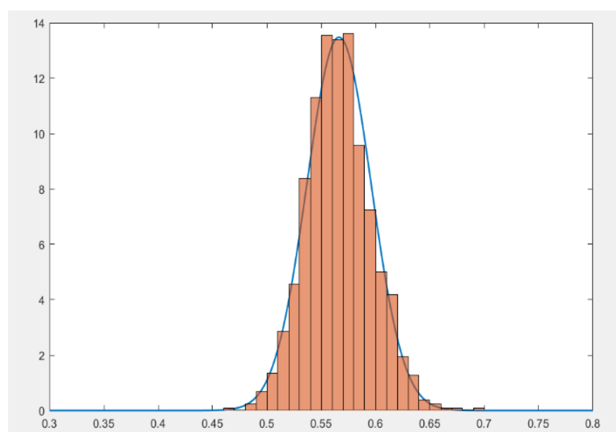
Test #1

Liquid Rate: 0.85 m/s

Gas Rate: 1.4623 m/s

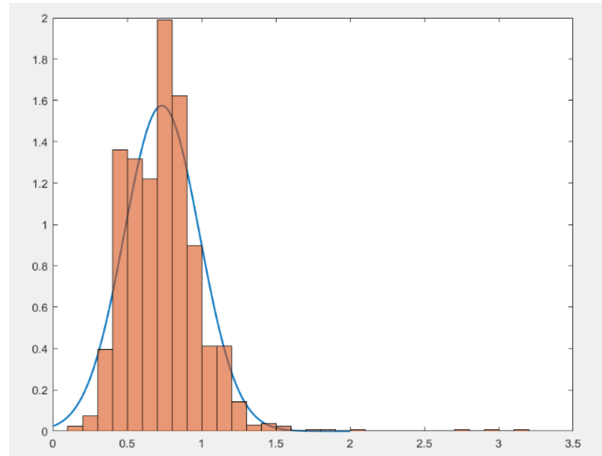
Slug liquid holdup:

```
Normal distribution
     mu = 0.566398    [0.56481, 0.567986]
  sigma = 0.029596    [0.0285152, 0.0307625]
```



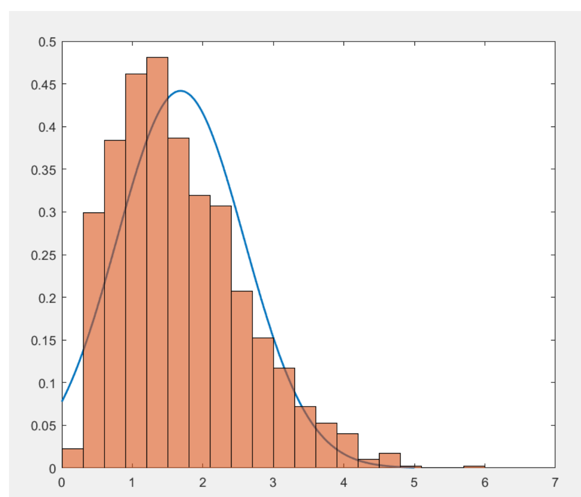
Slug Length:

```
Normal distribution
      mu = 0.733148    [0.719558, 0.746737]
   sigma = 0.253301    [0.244051, 0.263285]
```



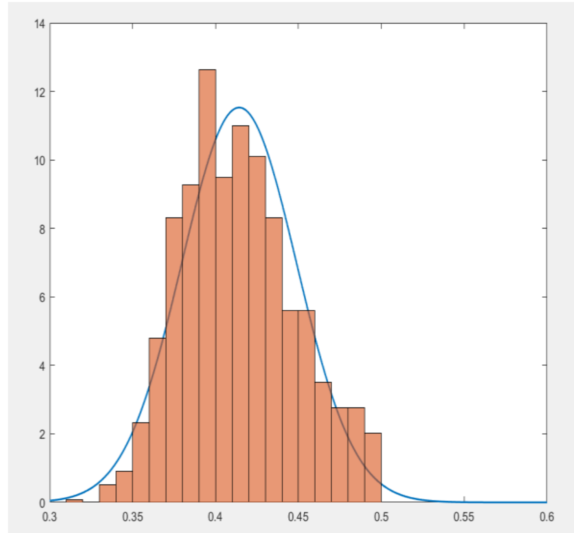
Film Length:

```
Normal distribution
      mu =  1.68339    [1.63494, 1.73184]
   sigma = 0.903048    [0.870071, 0.938643]
```



Film liquid hold up:

```
Normal distribution
     mu =   0.414211    [0.412355, 0.416068]
  sigma = 0.0346036    [0.0333399, 0.0359675]
```



Upper Limit: 0.65

Lower Limit: 0.5

Theoretical value for HLLS: 0.79815

Frequency: 76.87

VTB: 3.081 m/s

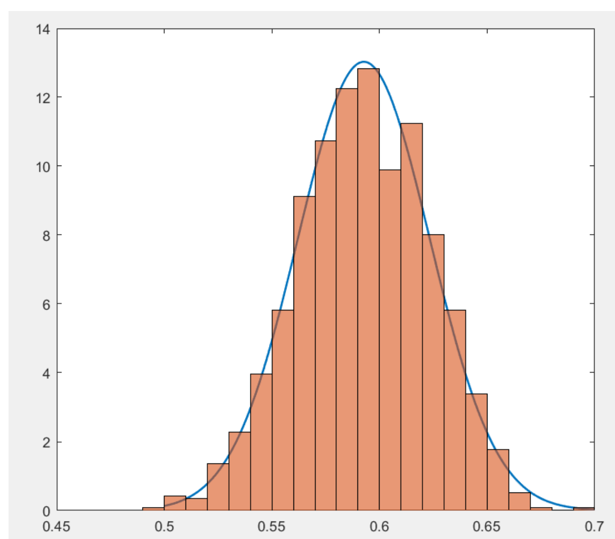
Test #2

Liquid Rate: 0.85 m/s

Gas Rate: 1.806 m/s

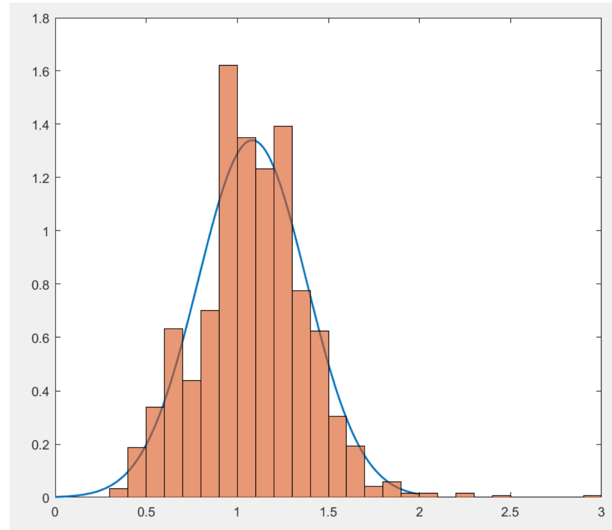
Slug liquid holdup:

```
Normal distribution
     mu =   0.592688    [0.590942, 0.594434]
  sigma = 0.0306166    [0.0294312, 0.0319023]
```



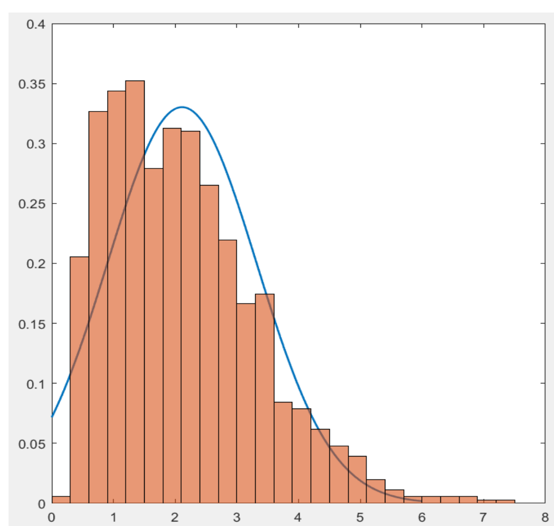
Slug Length:

```
Normal distribution
      mu =   1.08219    [1.06522, 1.09916]
   sigma = 0.297675    [0.28615, 0.310175]
```



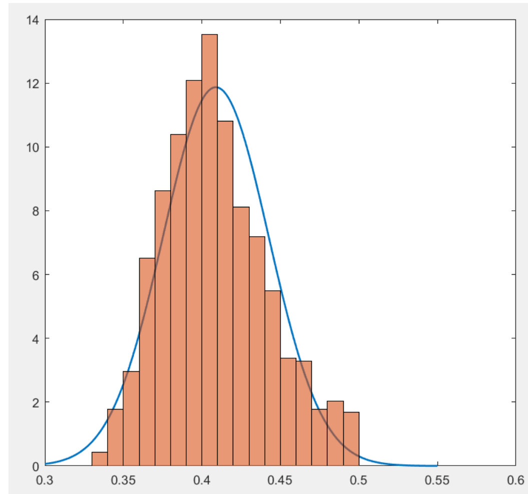
Film Length:

```
Normal distribution
      mu = 2.11069    [2.04178, 2.1796]
   sigma =   1.2081    [1.16131, 1.25885]
```



Film liquid holdup:

```
Normal distribution
     mu =   0.408862    [0.406946, 0.410778]
  sigma = 0.0336092    [0.032308, 0.0350206]
```



Upper Limit: 0.7

Lower Limit: 0.5

Theoretical value for HLLS: 0.773

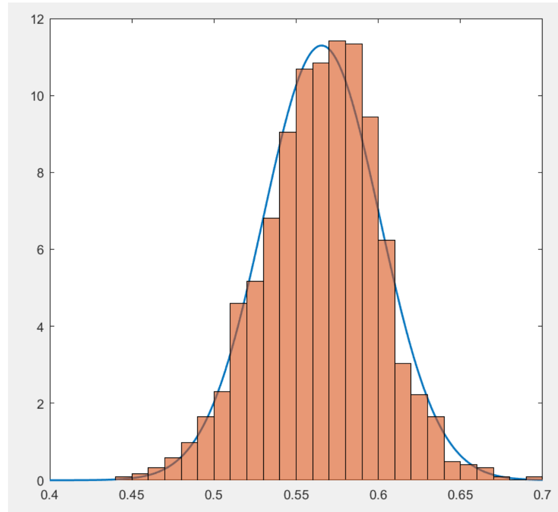
Frequency: 68.07

VTB: 3.604 m/s

Test #3

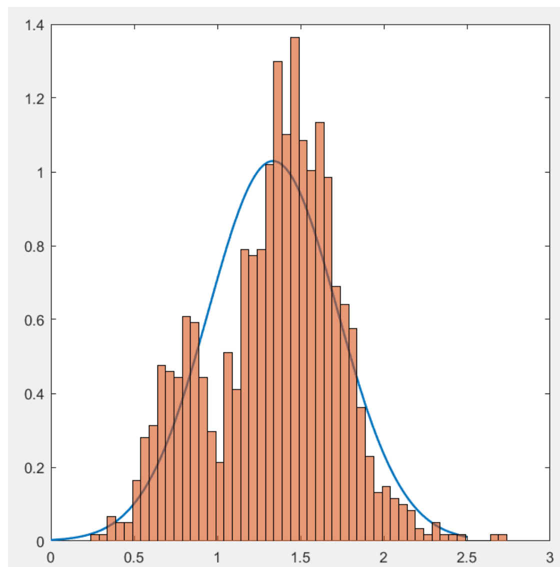
Liquid Rate: 0.85 m/s

Gas Rate: 2.227 m/s



Slug liquid holdup:

```
Normal distribution
     mu =   0.565438    [0.563452, 0.567424]
  sigma = 0.0353159    [0.0339665, 0.0367778]
```

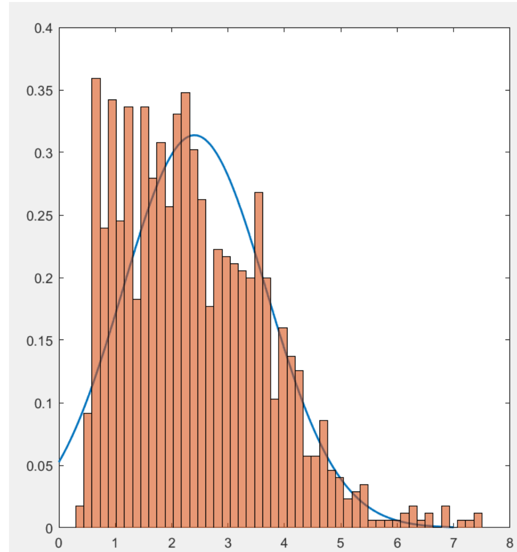


Slug Length:

```
Normal distribution
     mu =   1.33476    [1.31296, 1.35656]
  sigma = 0.387608    [0.372798, 0.403653]
```

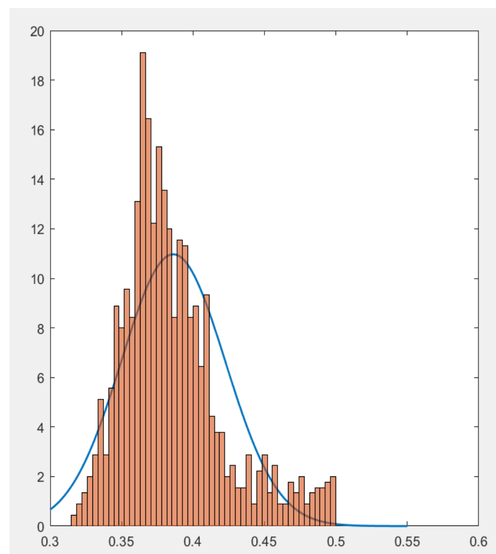
Film length:

```
Normal distribution
     mu = 2.40426    [2.33275, 2.47576]
  sigma = 1.27144    [1.22286, 1.32407]
```



Film liquid holdup:

```
Normal distribution
     mu =   0.386155    [0.384109, 0.388201]
  sigma = 0.0363732    [0.0349834, 0.0378788]
```



Upper Limit: 0.65

Lower Limit: 0.5

Theoretical value for slug liquid holdup: 0.742692

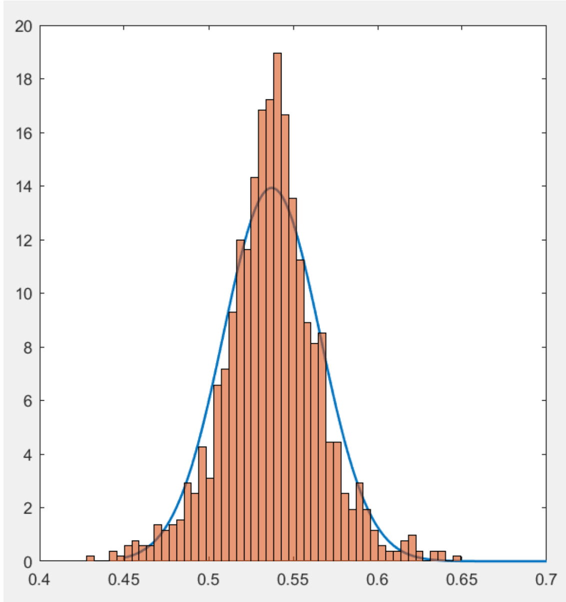
Frequency: 69.974

VTB: 4.34 m/s

Test #4

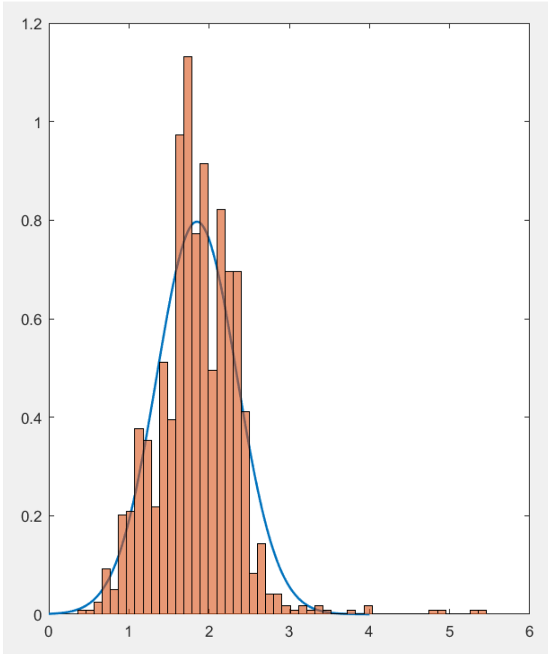
Liquid Rate: 0.85 m/s

Gas Rate: 2.83 m/s



Slug liquid holdup:

```
Normal distribution
      mu =  0.537343    [0.535699, 0.538987]
   sigma = 0.0286445    [0.0275286, 0.0298553]
```

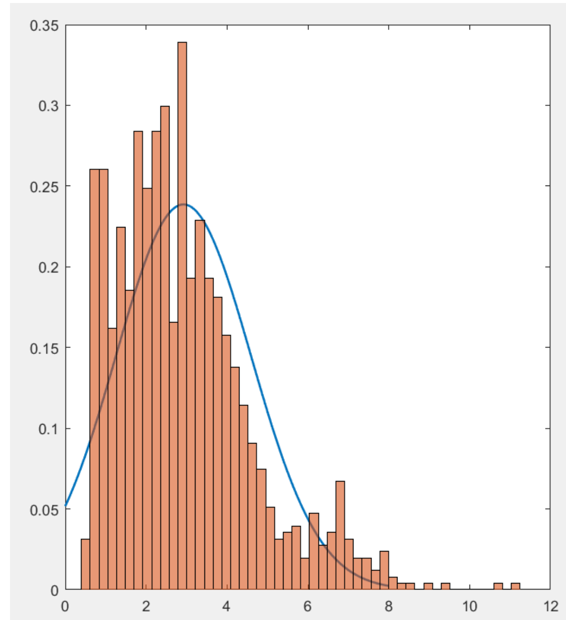


Slug liquid holdup:

```
Normal distribution
      mu =  1.84717    [1.81844, 1.8759]
   sigma = 0.500655    [0.481151, 0.521818]
```

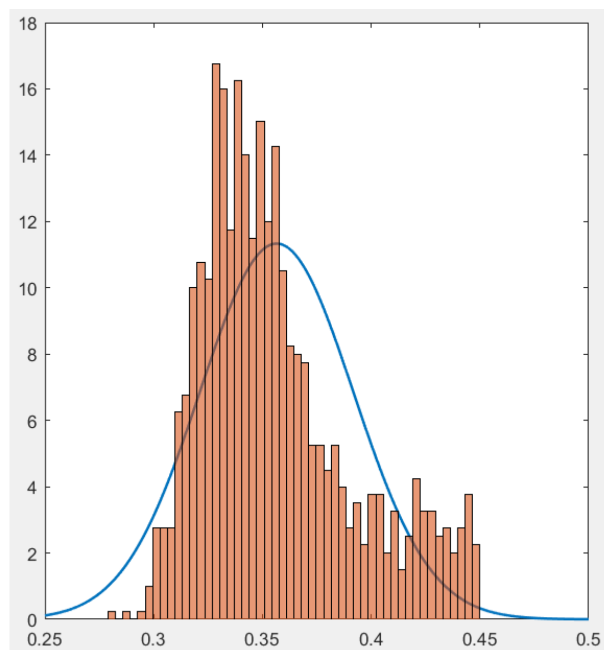
Film length:

```
Normal distribution
      mu = 2.92336    [2.82741, 3.01931]
   sigma =    1.672   [1.60687, 1.74268]
```



Film liquid holdup:

```
Normal distribution
      mu =   0.356505    [0.354485, 0.358525]
   sigma = 0.0352012    [0.0338299, 0.0366892]
```



Upper Limit: 0.65

Lower Limit: 0.45

Theoretical value for slug liquid holdup: 0.70

Frequency: 67.272

VTB: 5.32 m/s

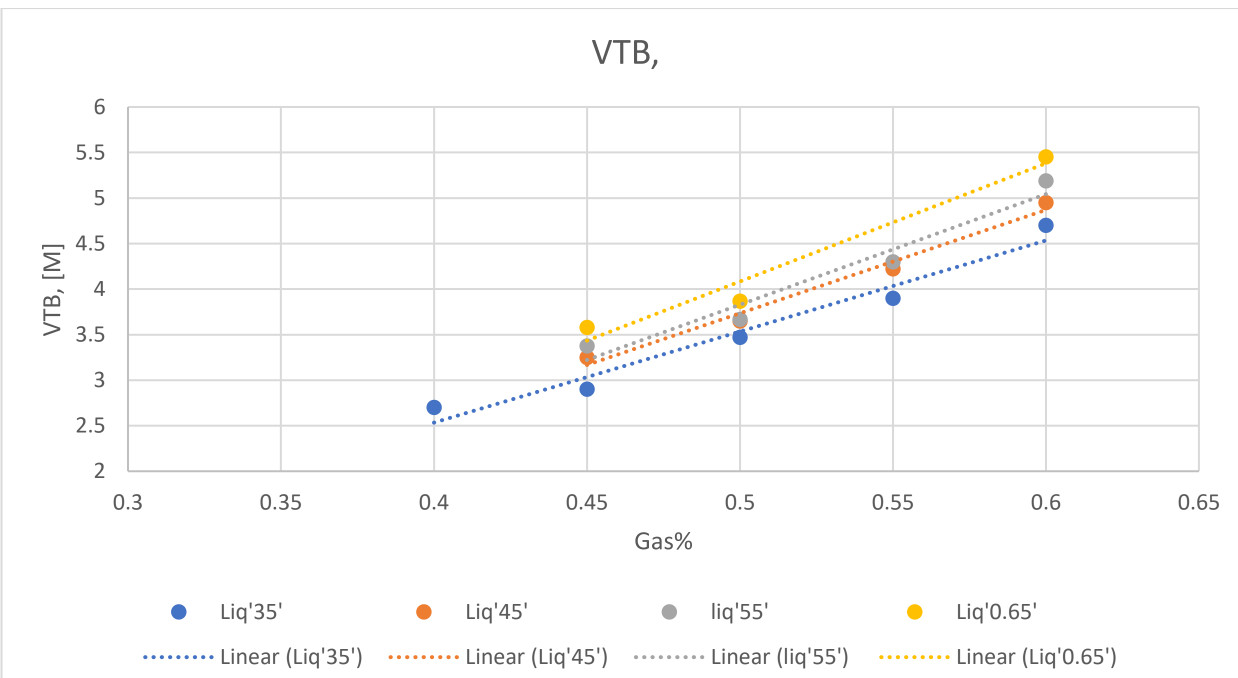
The following section is the summary of results for the case of $V_{sl} = 0.85\,\frac{m}{s}$

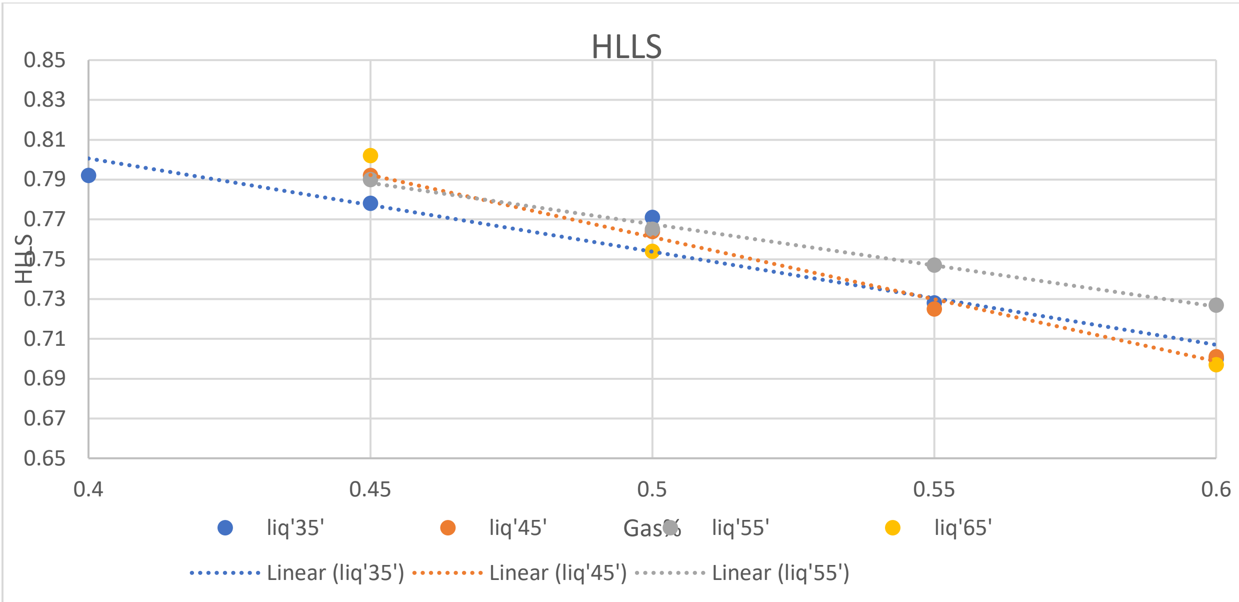
Gas Rate	HLLS	HLLS Theory	Ls	VTB	HLTB	Freq
1.4623	0.566	0.79815	0.733	3.08	0.414	76.87369
1.8065	0.593	0.772709	1.082	3.6	0.4088	68
2.2275	0.595438	0.742692	1.33476	4.33	0.386	69.97403
2.83	0.5373	0.701752	1.847	5.32	0.3565	67.27166

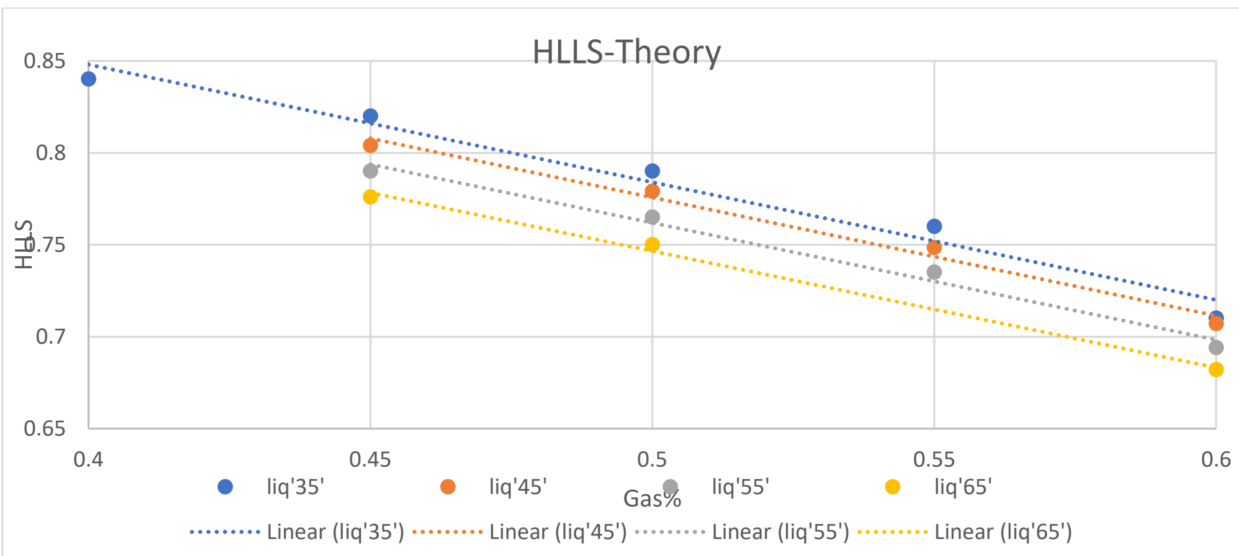
End-Points Calibration

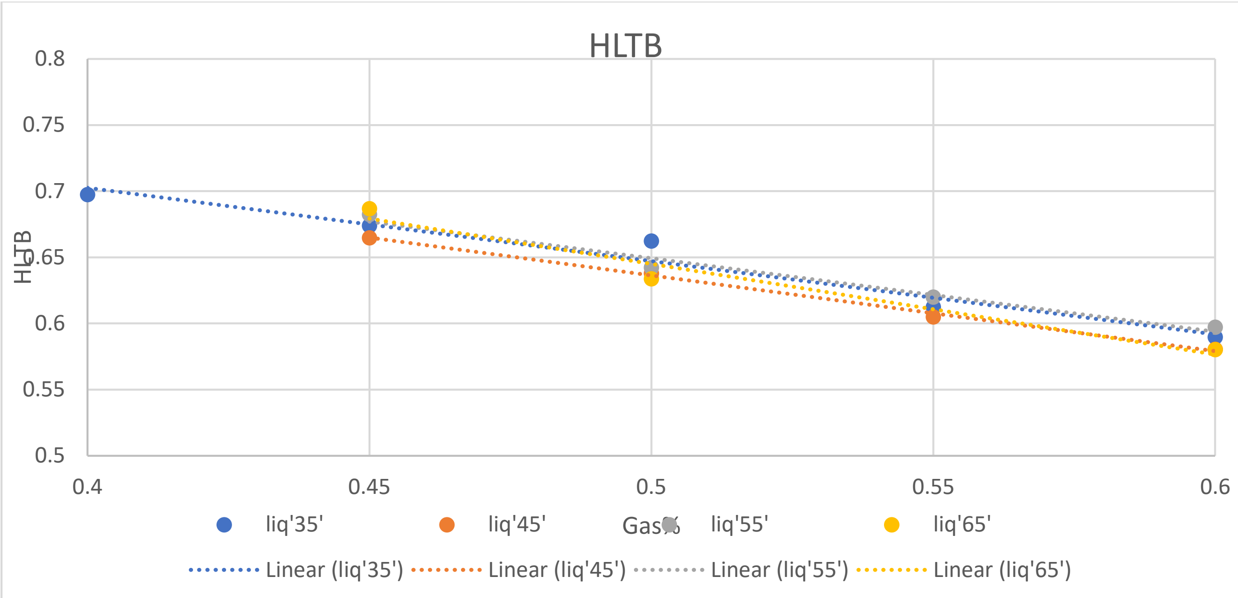
Please note that gas and liquid rates are expressed as the percentages and need to be converted to actual velocities. However, the main point was to see the behavior of measured and analyzed parameters and see if they behave systematically or no.

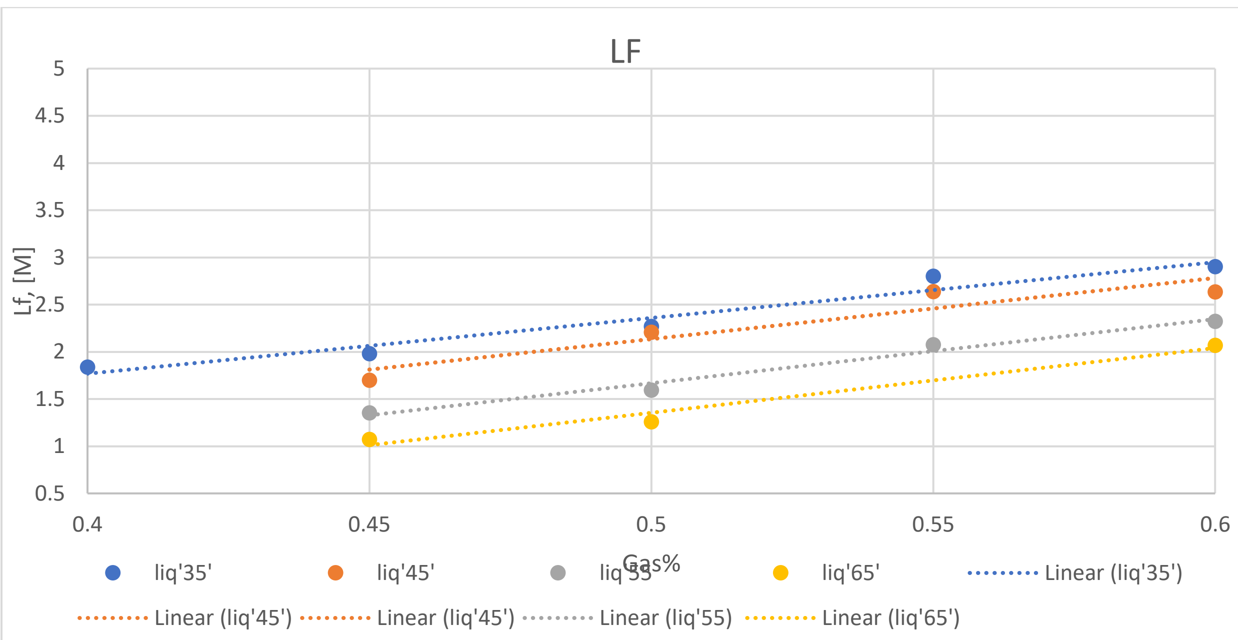
The important steps are comparing the analyzed data to other experimentally measured values as well as existing model predictions. The part has been started and it is being proceeded.

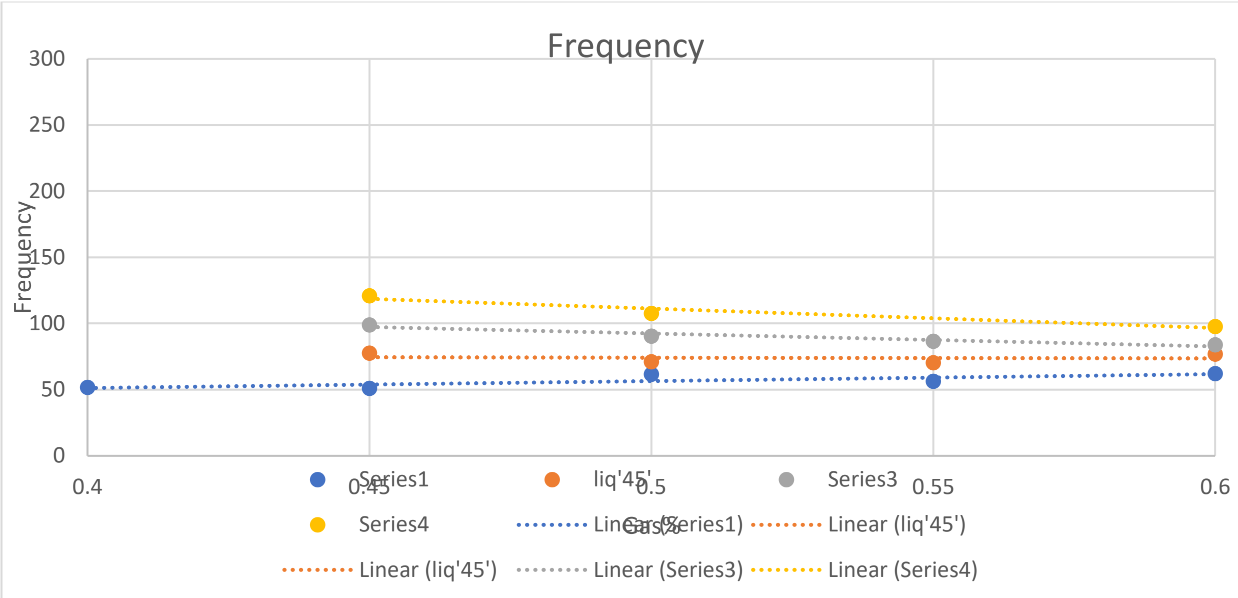



HLLS
HLLS
Gas%
liq'35'
liq'45'
liq'55'
liq'65'
Linear (liq'35')
Linear (liq'45')
Linear (liq'55')


HLLS-Theory
HLLS
Gas%
liq'35'
liq'45'
liq'55'
liq'65'
Linear (liq'35')
Linear (liq'45')
Linear (liq'55')
Linear (liq'65')


HLTB
0.8
0.75
0.7
0.65
0.6
0.55
0.5
HLTB
0.4
0.45
0.5
0.55
0.6
Gas%
liq'35'
liq'45'
liq'55'
liq'65'
Linear (liq'35')
Linear (liq'45')
Linear (liq'55')
Linear (liq'65')


LF
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
Lf, [M]
0.4
0.45
0.5
0.55
0.6
Gas%
liq'35'
liq'45'
liq'65'
Linear (liq'35')
Linear (liq'45')
Linear (liq'45')
Linear (liq'55)
Linear (liq'65')


Frequency
300
250
200
150
100
50
0
Frequency
0.4
0.45
0.5
0.55
0.6
Gas%
Series1
liq'45'
Series3
Series4
Linear (Series1)
Linear (liq'45')
Linear (liq'45')
Linear (Series3)
Linear (Series4)