Experimental Investigation of Pressure Drop for Gas / Shear Thinning Fluid Flows in a Horizontal Pipe

Munzarin Morshed[1], Serag Moustafa M. Alfareq[1], Aziz Rahman[2], Syed Imtiaz[1]

[1]Memorial University of Newfoundland, St. John's, NL, Canada
[2]Texas A&M University at Qatar (TAMUQ), Doha, Qatar

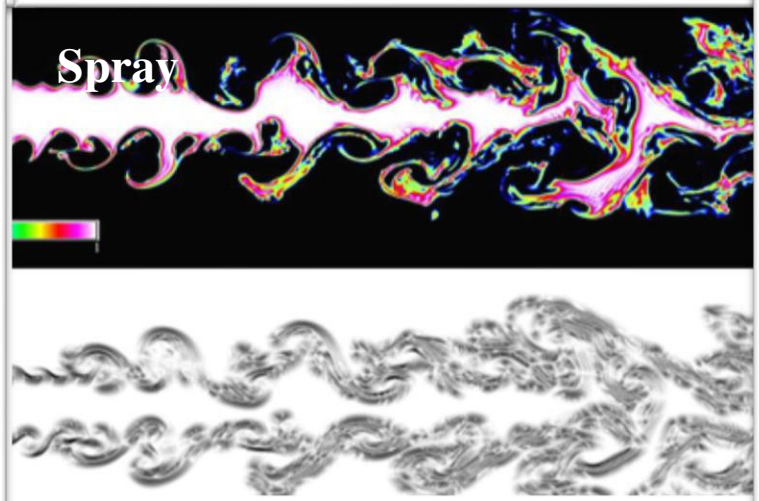
Introduction





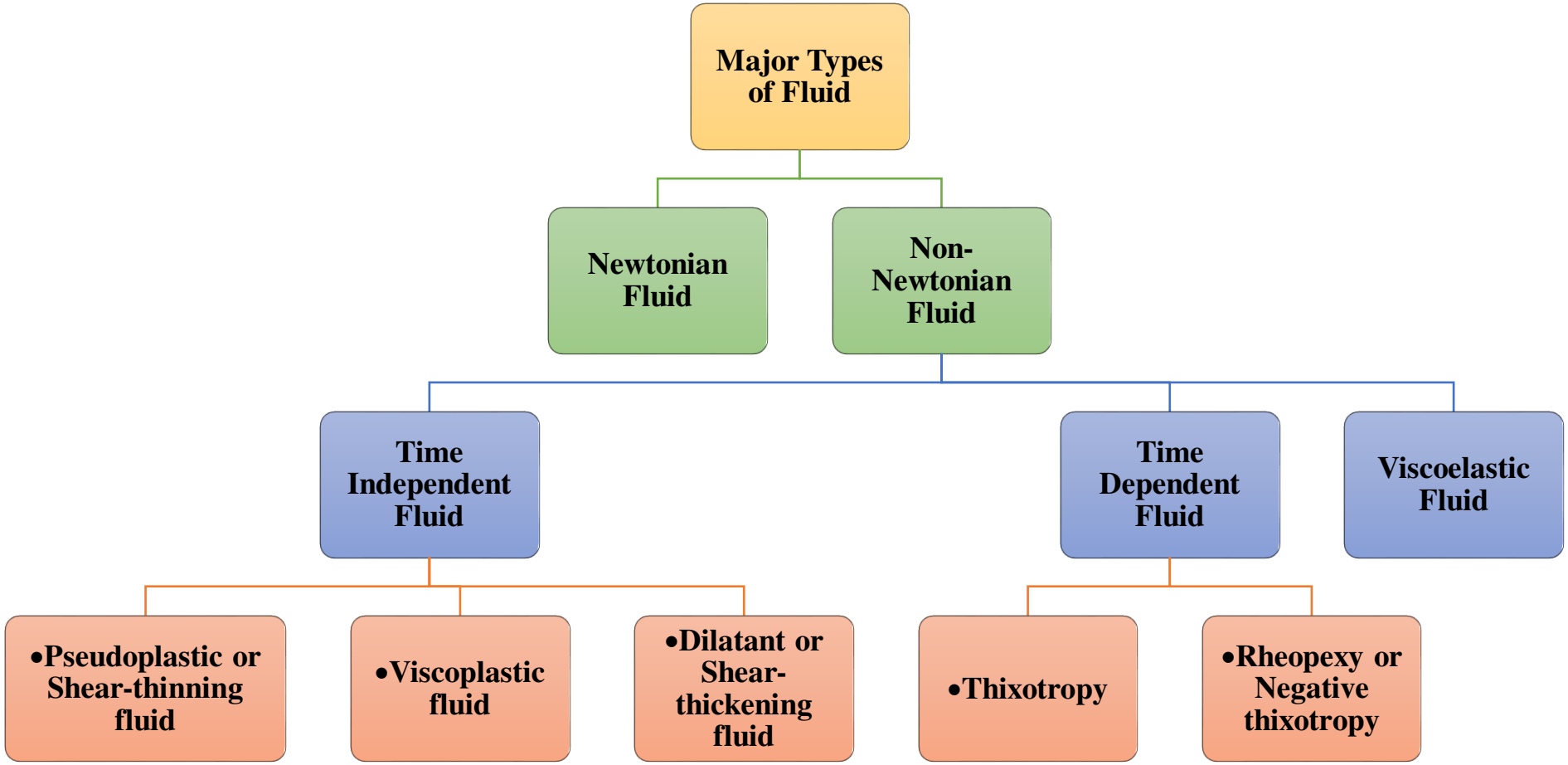




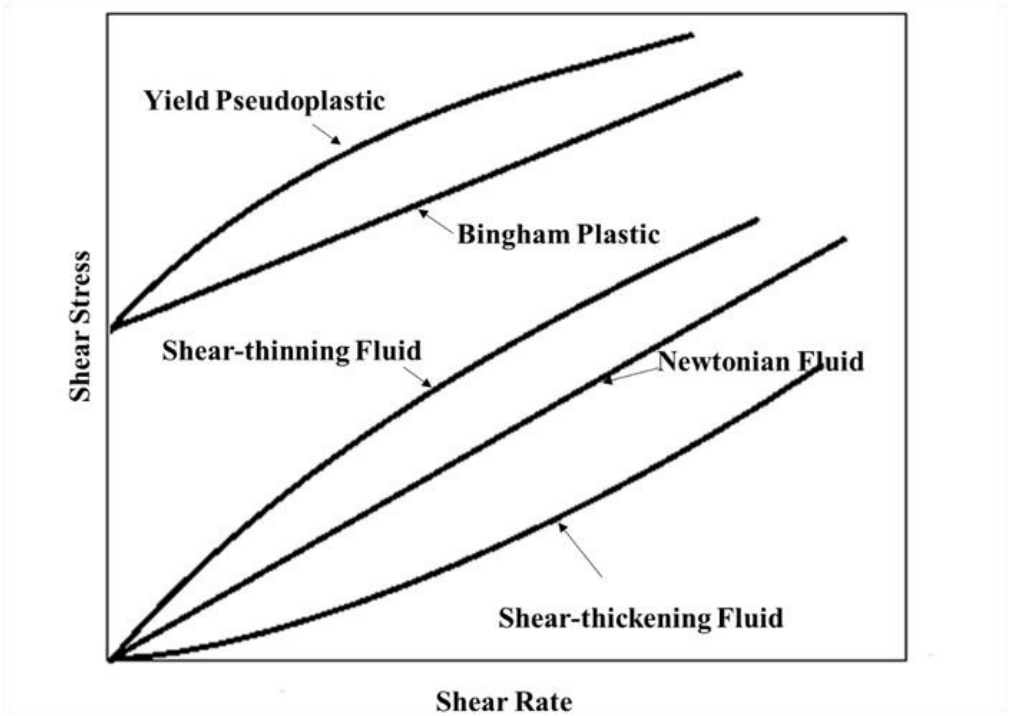




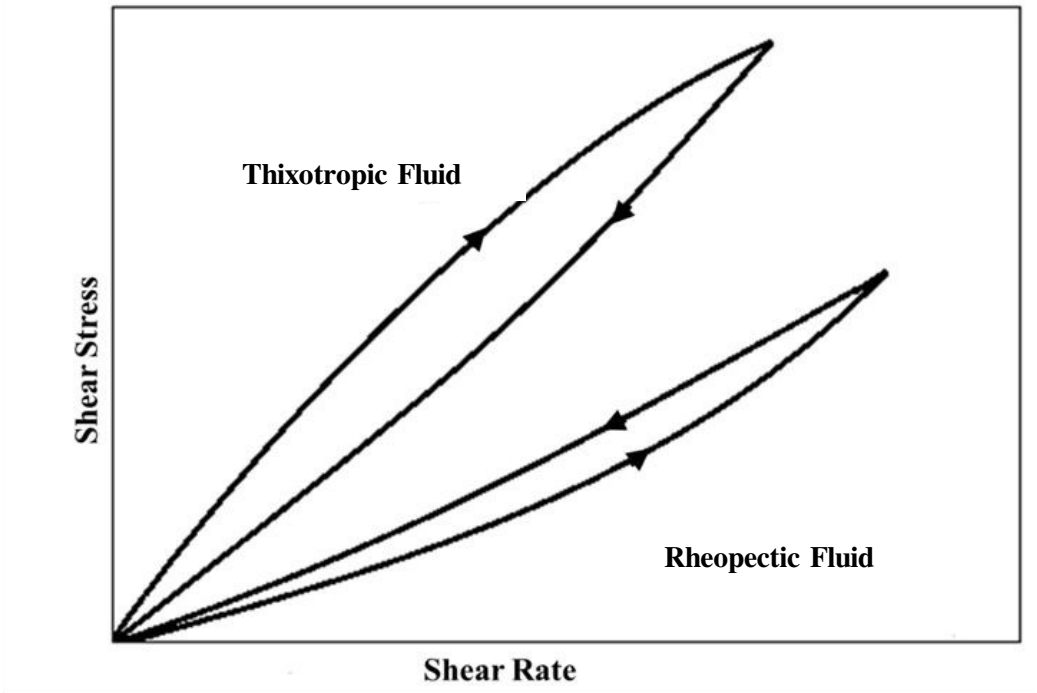
Different Types of Fluid



Types of Non-Newtonian Fluid



Time-independent fluid flow behaviour.



Time-dependent fluid behaviour.

Non-Newtonian Fluid Power Law

- The power-law model or Ostwald de Waele model is most commonly used for a limited range for shear-thinning and shear-thickening fluid.

$$\mu_n = K\left(\dot{\gamma}_{yx}\right)^{n-1}$$

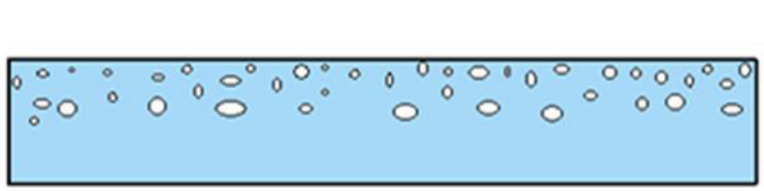
- *K* and *n* represent fluid consistency coefficient and flow behavior index respectively or power law index. When *n=1*, that means the fluid is Newtonian and when the n value decreases the degree of shear-thinning increase.

Non-Newtonian Fluid Power Law

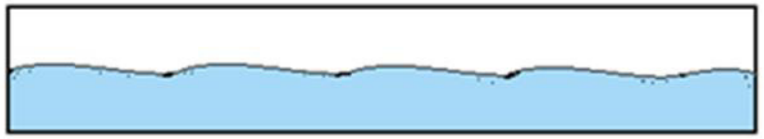
For,	$n<1$, the fluid represents shear-thinning characteristics
	$n=1$, the fluid represents Newtonian characteristics
	$n>1$, the fluid represents shear-thickening characteristics

Gas /Newtonian Horizontal Flow Regimes

- Multiphase flow is the fusion of two or more distinct phases (such as solid, water, and gas) flowing through a pipeline



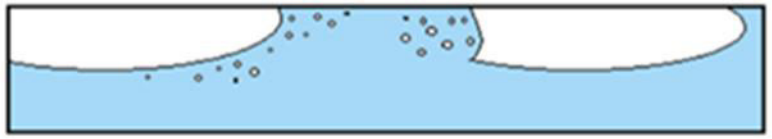
Bubble Flow



Stratified Flow



Plug Flow

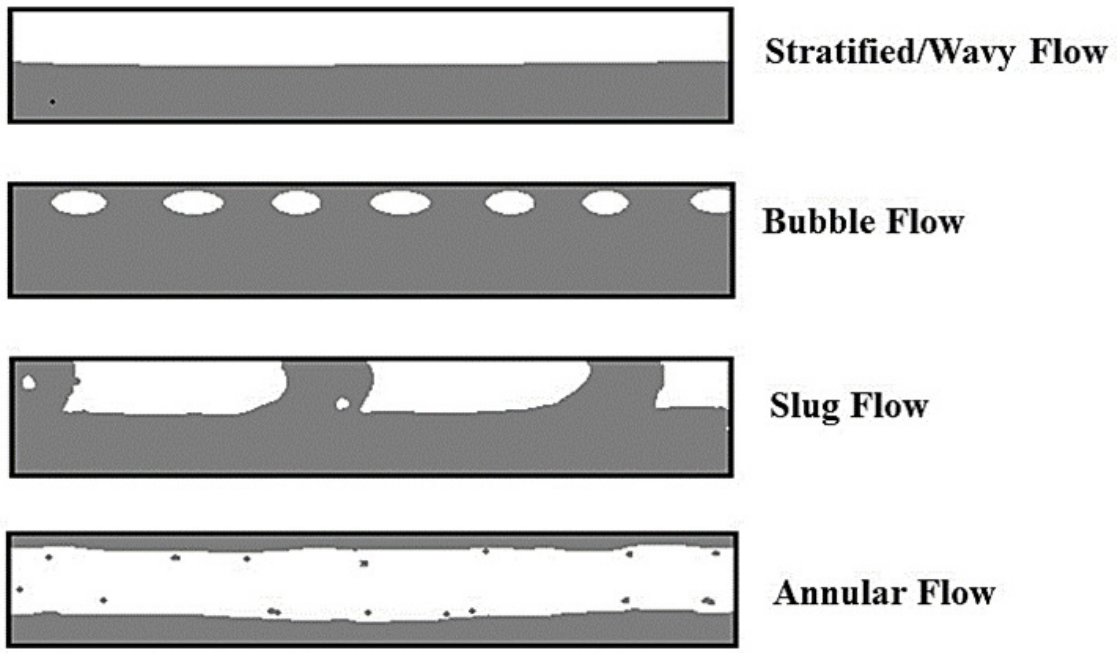


Slug Flow



Annular Flow

Gas/Non-Newtonian Flow Regimes

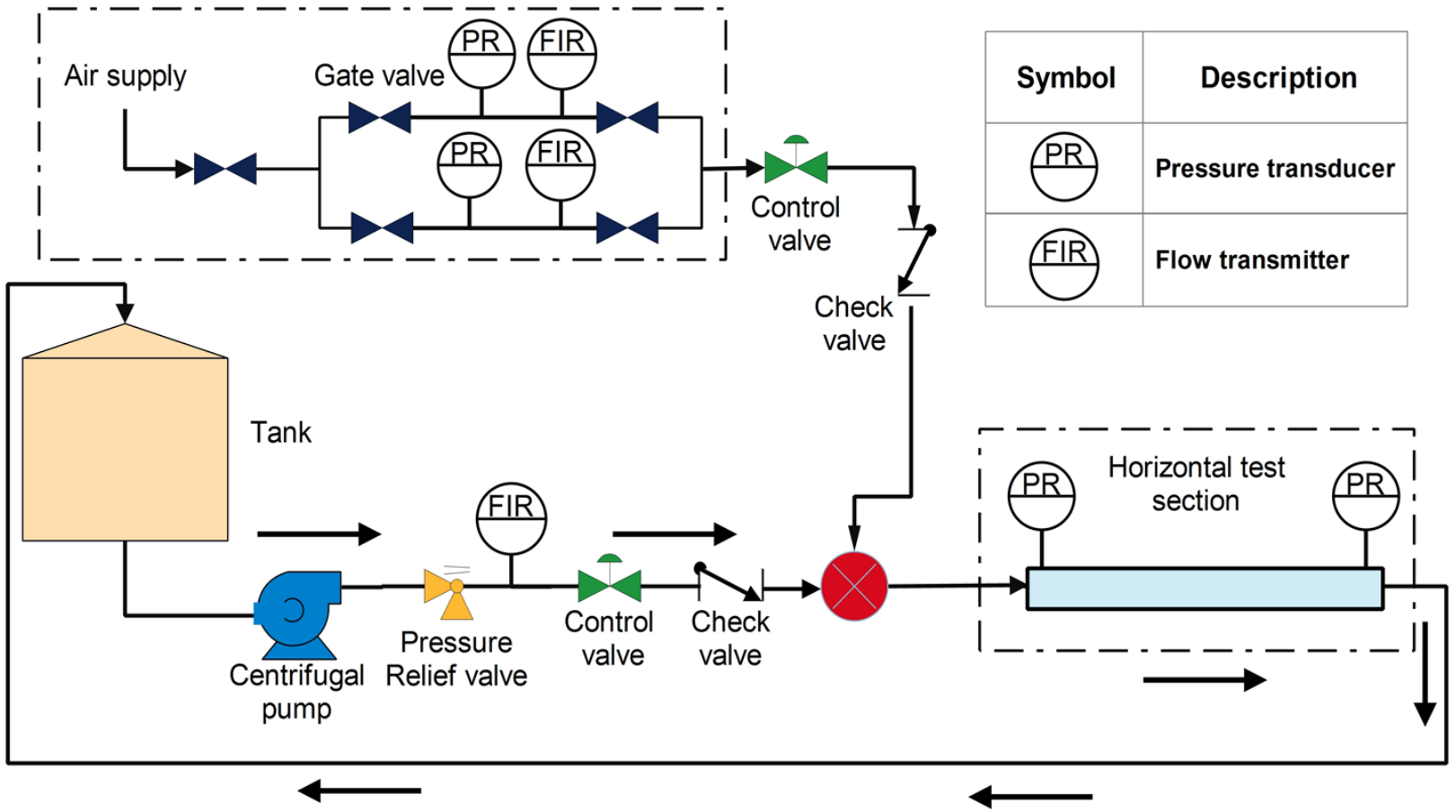


- Between Gas/Newtonian and gas/non-Newtonian fluid major difference seen in bubble flow and slug flow regime.
- Due to high viscosity the bubbles could not break easily and collide together to form bigger gas bubbles.

Objectives

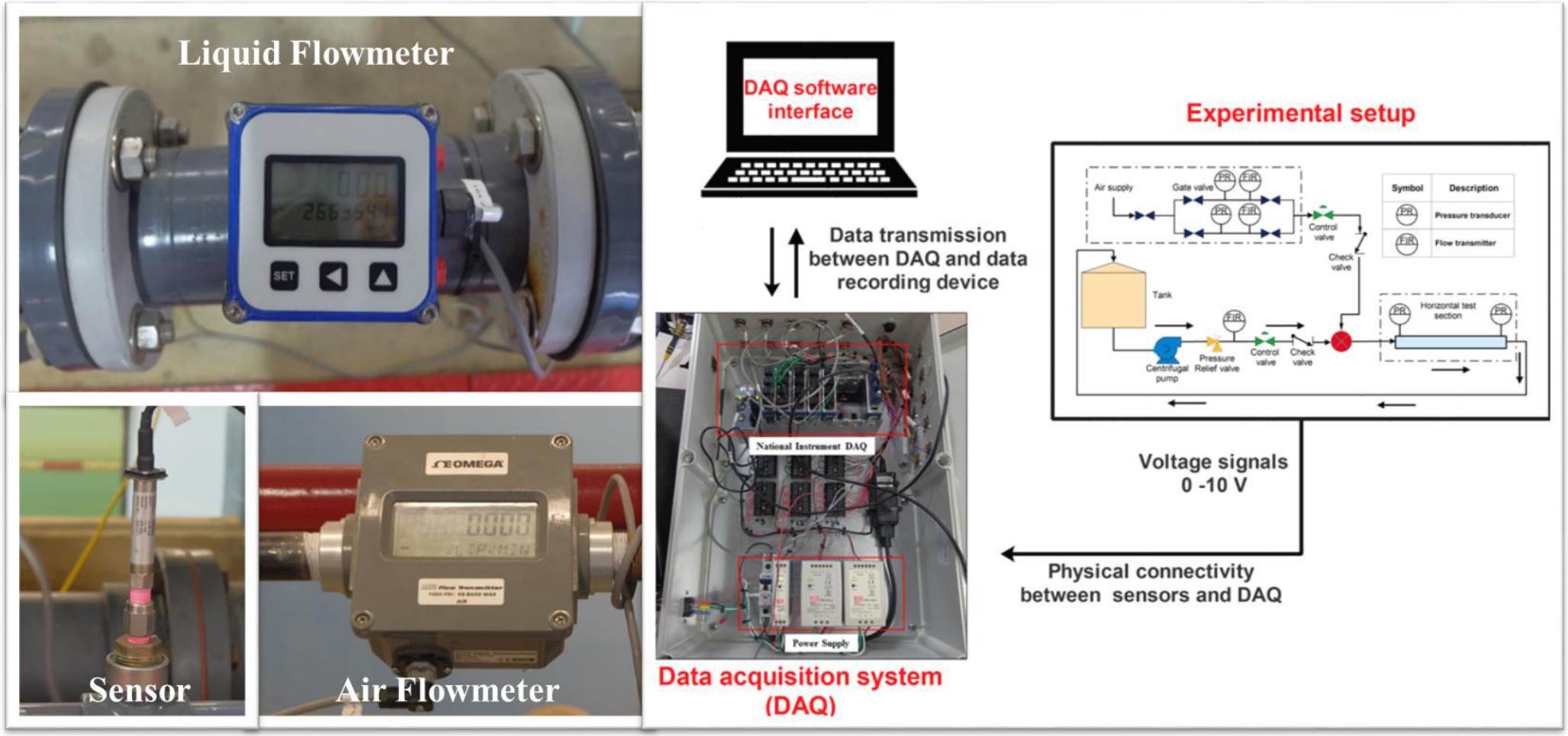
- Characterization of 2-phase Newtonian/gas and non-Newtonian /gas flow.
- Develop a flow regime map for the experimental setup and validate with the existing literature
- Analysis of slug frequency two-phase flow in a pilot scale setup.
- Characterization of pressure signals using frequency domain analysis (i.e. Wavelet).

Experimental Set-up



Schematic of Experimental Setup (Horizontal Test Section).

Experimental Setup *(cont.)*



Experimental Setup *(cont.)*



Experimental Setup

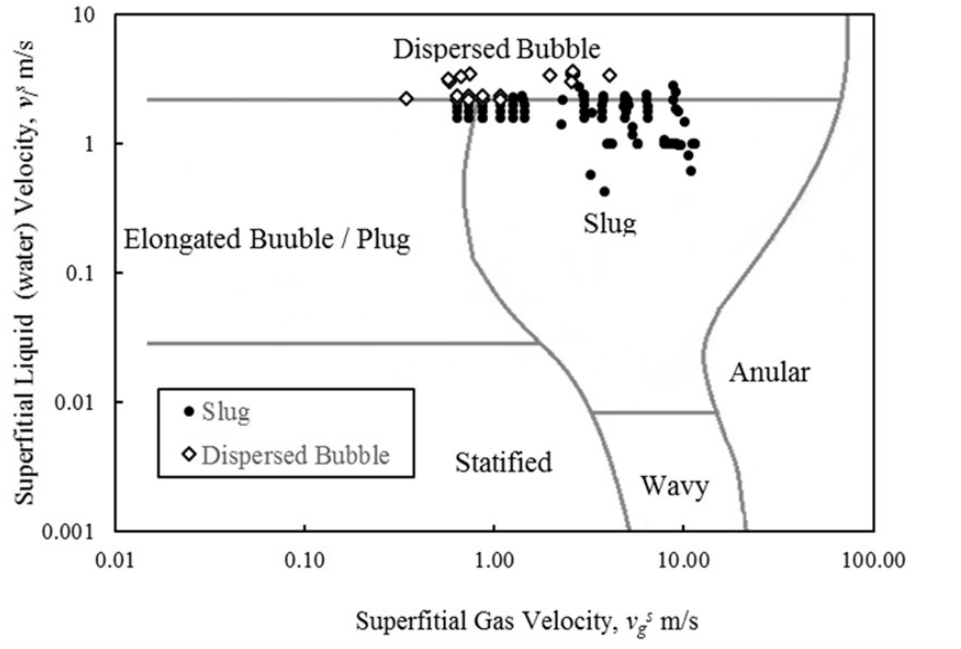
Experimental Setup *(cont.)*

- The experimental set-up has horizontal, vertical and inclined section and
- In this experiment only the horizontal test section is considered.
- The experimental setup is 60 meter long closed cycle system for water with 2.9 inch inner diameter PVC clear pipe and flexible pipe and open cycle system for air.
- There are two Omega PX603-100G5V pressure transducer with a range of 0 to 100 psi in the horizontal test section.

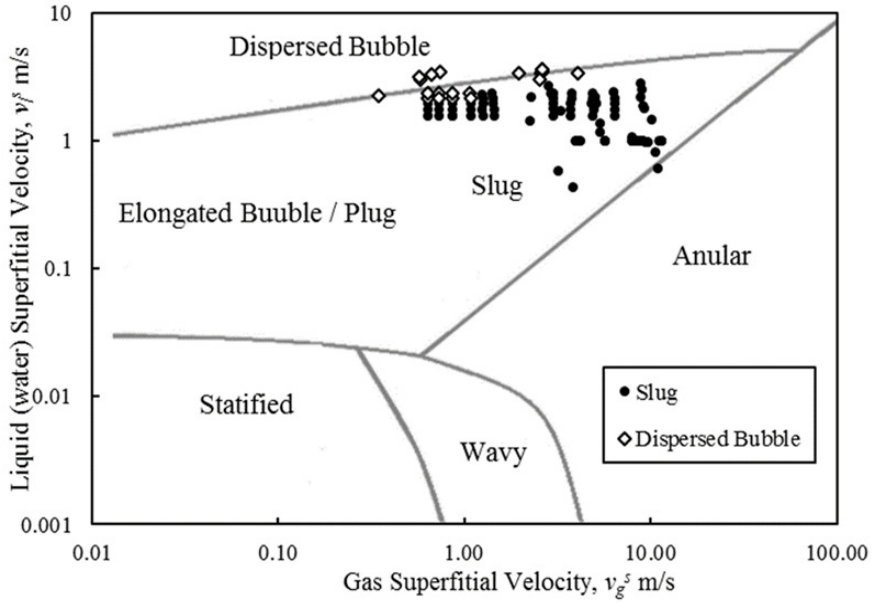
Experimental Conditions

Newtonian Fluid	Water
Non-Newtonian Fluid	0.1% Xanthan Gum solution
Liquid velocity range	1.5 m/s to 2.5 m/s
Air Velocity range	2.9 m/s to 6.4 m/s

Flow Maps *(Newtonian/gas Flow)*



Comparison of the Mandhane et al. (1974) (adapted) flow regime map with experimental data obtained for horizontal gas/Newtonian flow.

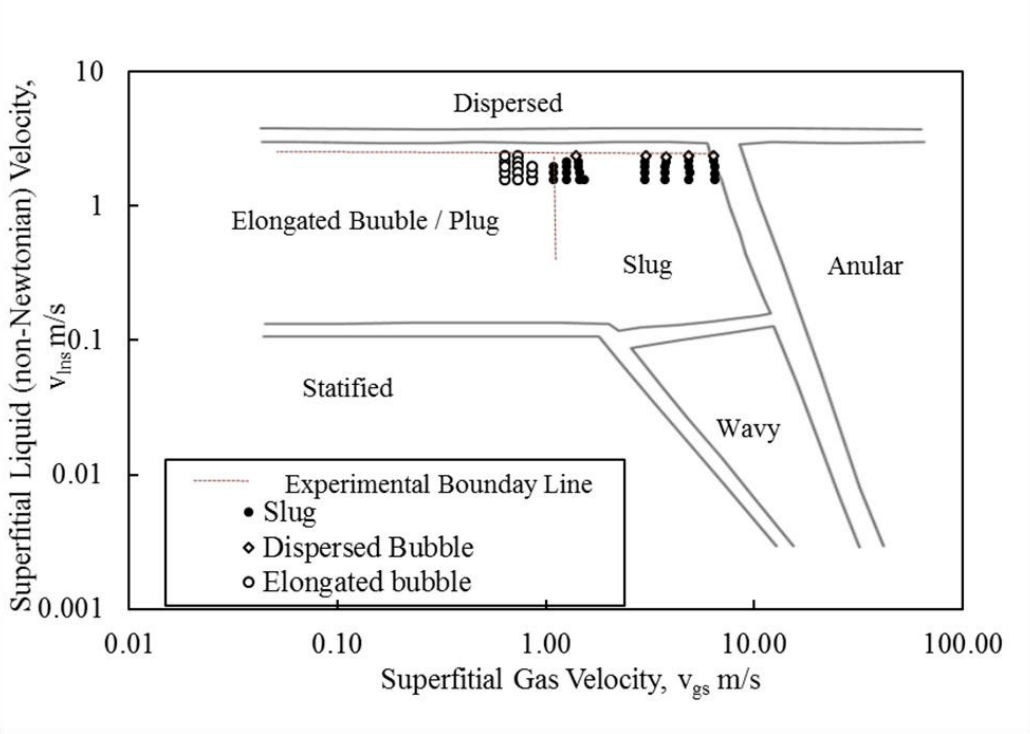


Comparison of the Taitel & Dukler (1976) (adapted) flow map with experimental data for horizontal gas/Newtonian flow.

Source:

1. Mandhane, J.M. et al., 1975. Critical Evaluation of Holdup Prediction Methods for Gas-Liquid Flow in Horizontal Pipes. Journal of Petroleum Technology, 27(08), pp.1–17.
2. Taitel, Y. & Dukler, A.E., 1976. A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow. AIChE Journal, 22(1), pp.47–55.

Flow Map *(Non-Newtonian/gas Flow)*

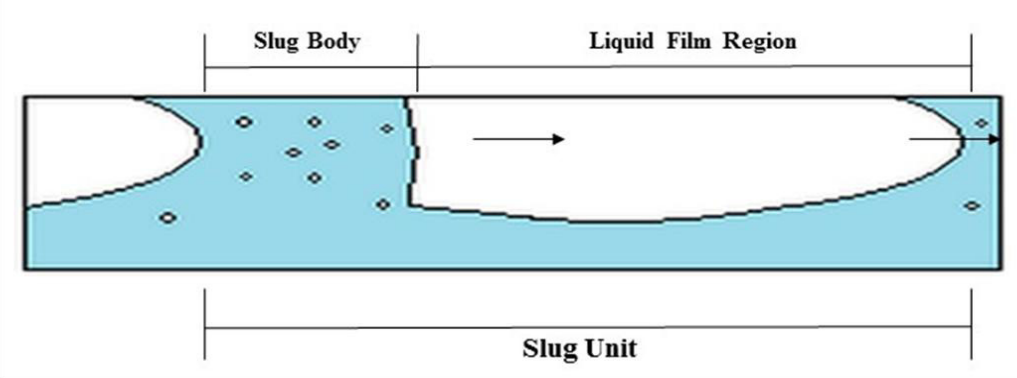


Chhabra & Richardson (1984) (adapted) flow regime map for gas/non-Newtonian horizontal flow.

Source: Chhabra, R.P. & Richardson, J.F., 1984. Prediction of flow pattern for the co-current flow of gas and non-Newtonian liquid in horizontal pipes. The Canadian Journal of Chemical Engineering, 62(4), pp.449–454.

Slug Unit

- In two phase flow when the liquid slugs are separated by bullet shaped gas pockets it is slug flow and slug frequency is the number of slug passing a specific point with time.



Different part of a Slug unit; [adapted from Dukler & Hubbard (1975)]

Source: Dukler, A.E. & Hubbard, M.G., 1975. A model for gas-liquid slug flow in horizontal and near horizontal tubes. Industrial & Engineering Chemistry Fundamentals, 14(4), pp.337–347.

Slug Frequency *(Air/Newtonian Fluid Flow)*

- Slug flow can create an unwanted situation like pipeline mutability or damage the equipment due to its hammering which is also called slug frequency.
- The most used slug flow model was described by Hubbard & Dukler (1966), Gregory & Scott (1969), Greskovich & Shrier (1972) who reorganized Gregory & Scott (1969), Heywood & Richardson (1979), Zabaras (1999) are the most known researcher who used different slug flow model and analyzed air/Newtonian slug frequency described slug frequency equations.
- Rosehart et al. (1975), Otten & Fayed (1977), Picchi et al. (2015) analyzed air/non-Newtonian slug frequency described slug frequency equations.

Slug Frequency *(Air/non-Newtonian Fluid Flow)*

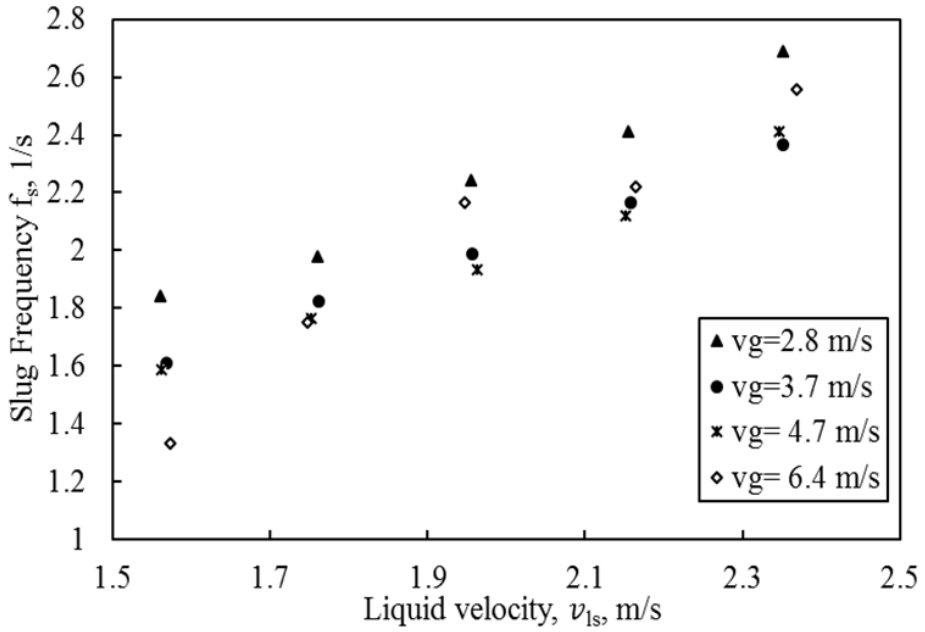
- Gregory & Scott (1969) suggested a velocity dependent empirical equation where slug frequency was correlated with a form of Froude number.

$$N_{f_s} = \frac{v_l}{gd}\left[\frac{(v_m^0)^2}{v_m} + v_m\right]$$

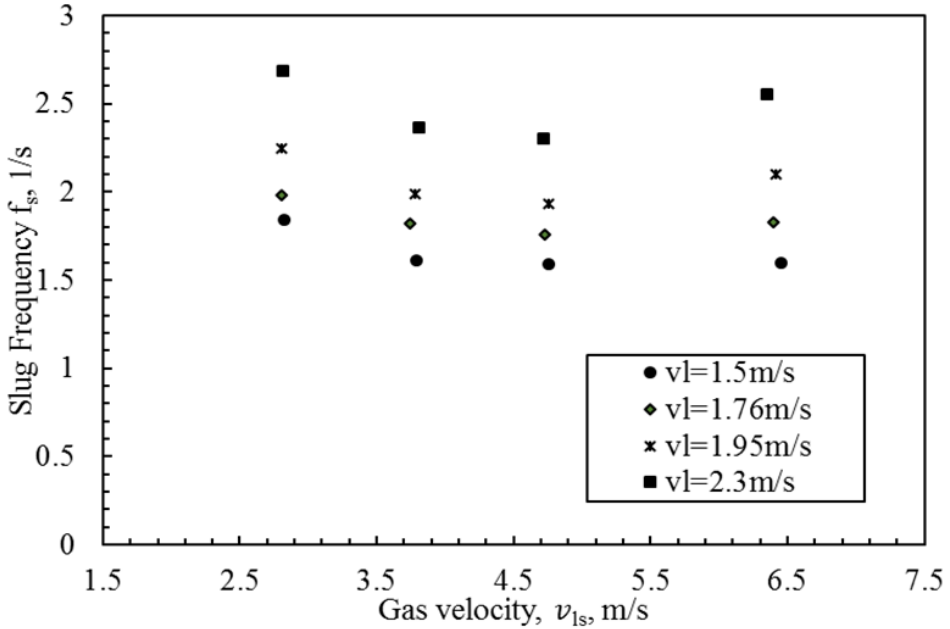
- v_m^0 was taken 6 m/s and from slug frequency vs. slug Froude number graphs Gregory & Scott (1969) achieved the equation.

$$f_s = 0.0157\left(N_{f_r}\right)^{1.20}_{slug}\ \mathrm{sec}^{-1}\ .$$

Slug Frequency *(Air/Newtonian Fluid Flow)*



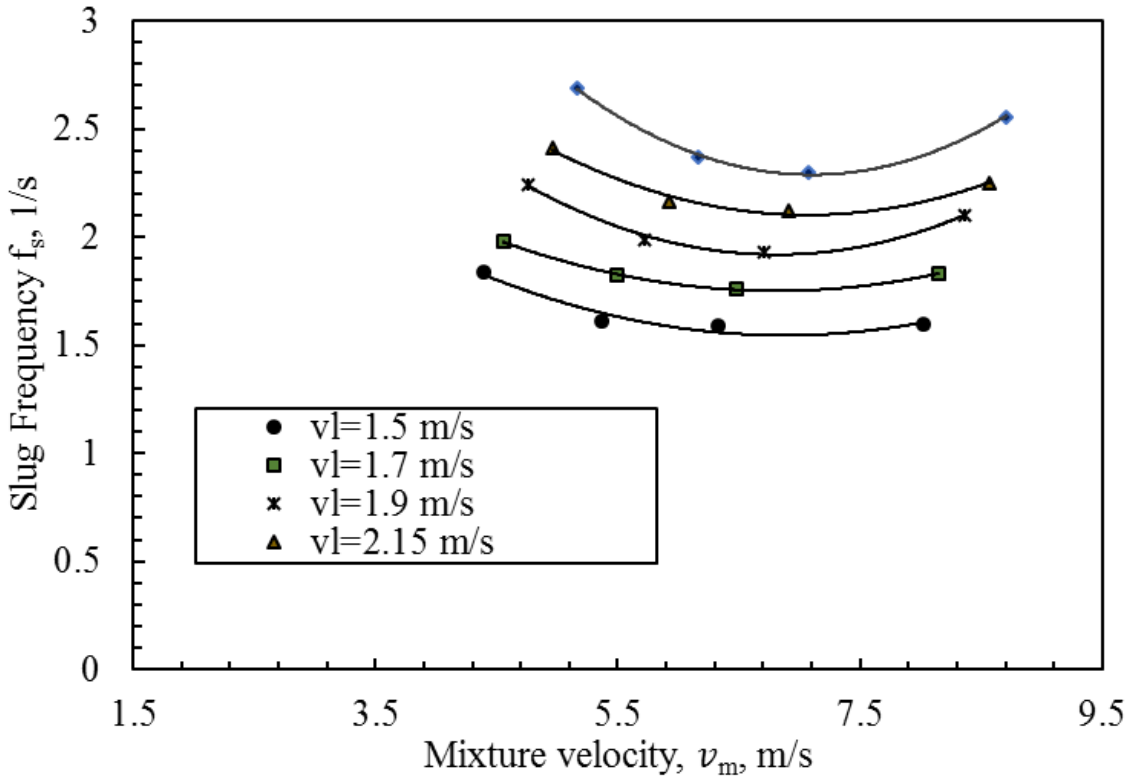
Effect of liquid superficial velocity on slug frequency for air/water flow.



Effect of gas superficial velocity with slug frequency for air/water two-phase flow.

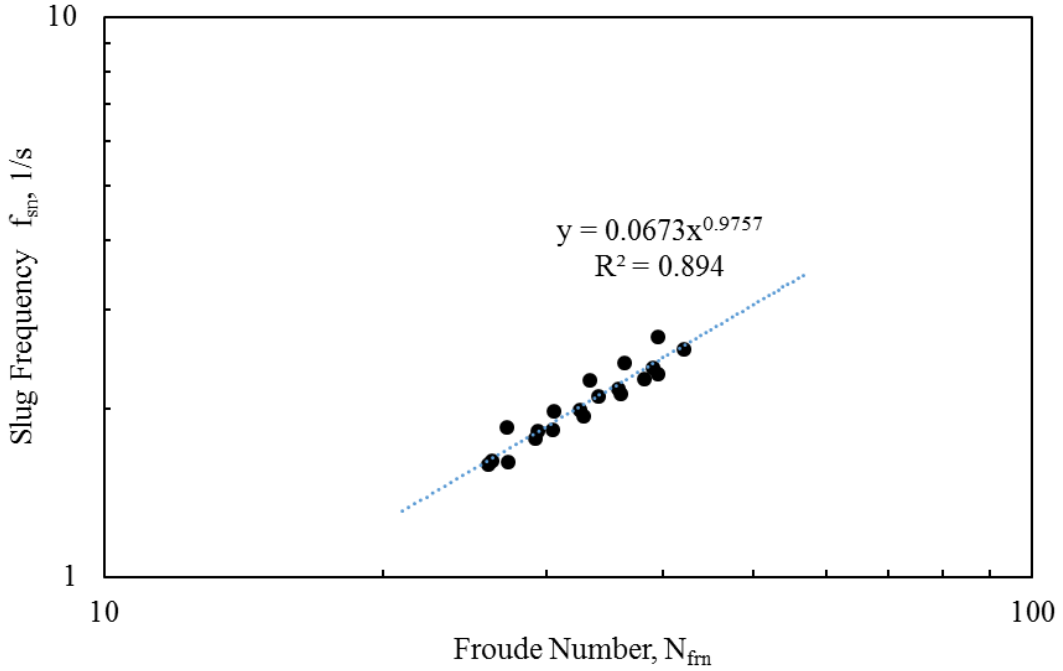
Slug Frequency *(Air/Newtonian Fluid Flow)*

- Depends on superficial gas velocity.
- At constant liquid flow rate slug frequency decreased with increasing gas velocity and created an inverted curve
- This phenomenon occurred due to the transition from Slug to Dispersed bubble flow.
- At higher gas flow rates, the turbulence in the flow starts increasing and the unit slug starts to break down and the number of slugs increases.

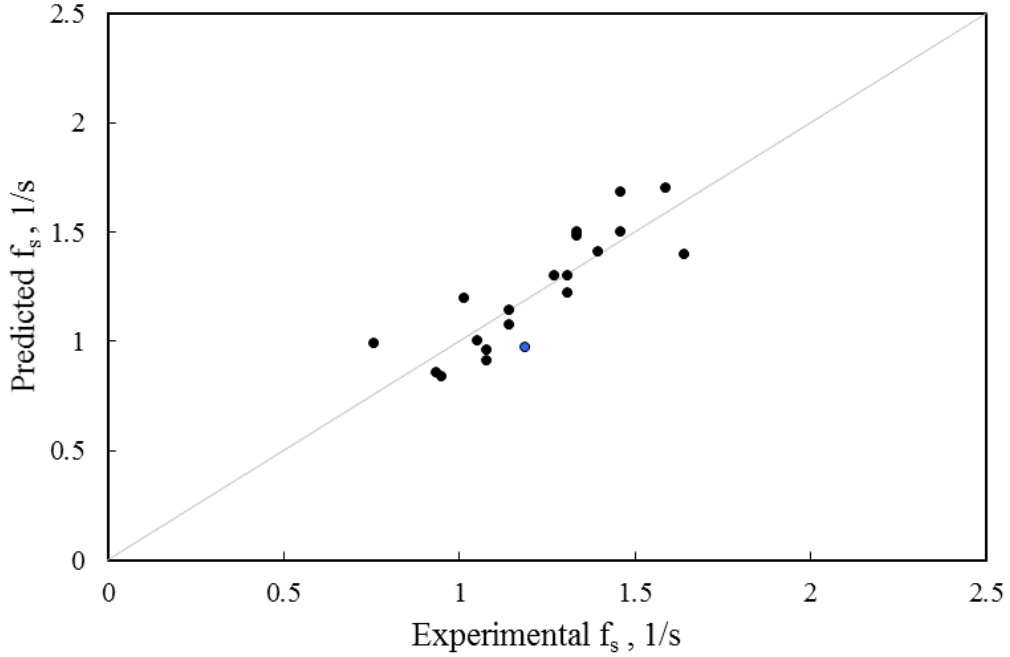


Slug frequency vs mixture velocity for air/water flow.

Slug Frequency *(Air/Newtonian Fluid Flow)*

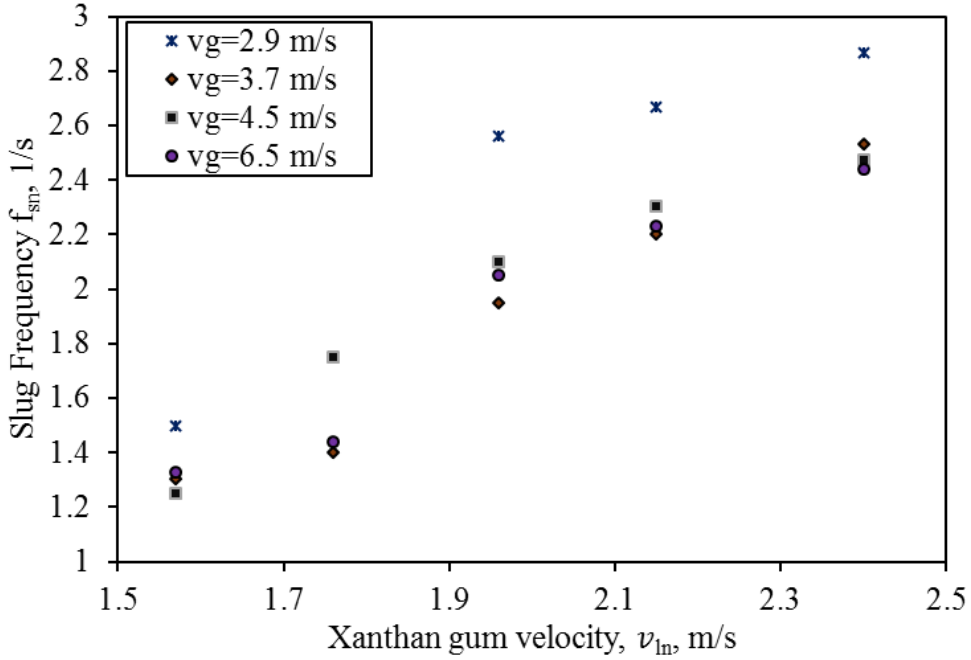


Slug frequency vs. Froude number for air/water flow where R^2=0.89

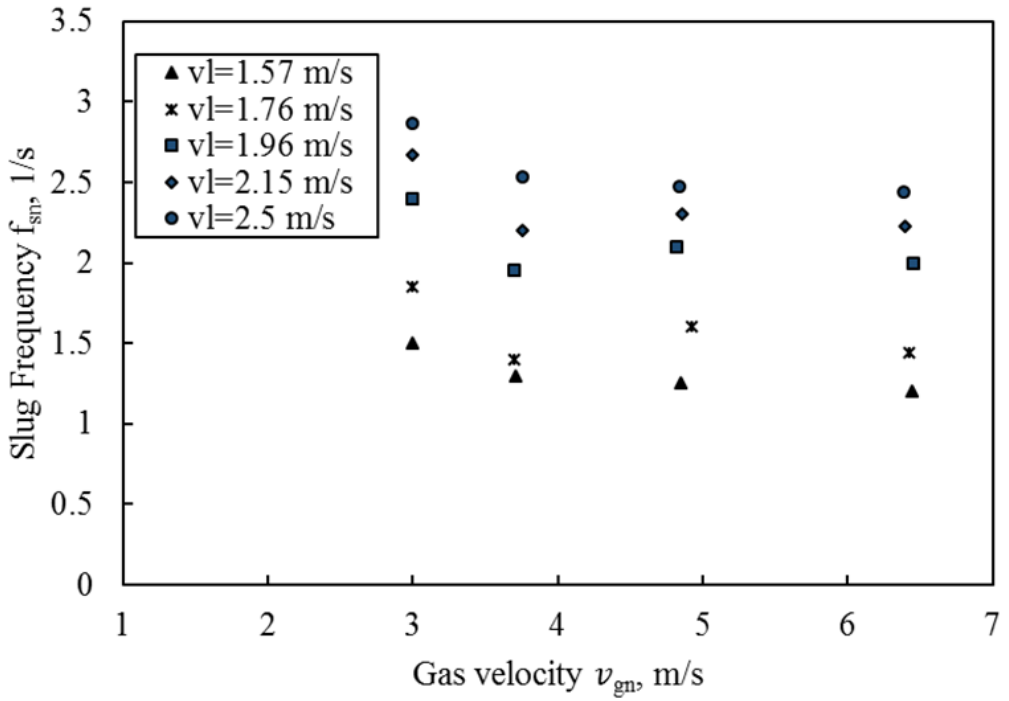


Experimental slug frequency for air-water system compared to the predictions by Gregory & Scott (1969) correlation with standard deviations.

Slug Frequency *(Air/non-Newtonian Fluid Flow)*



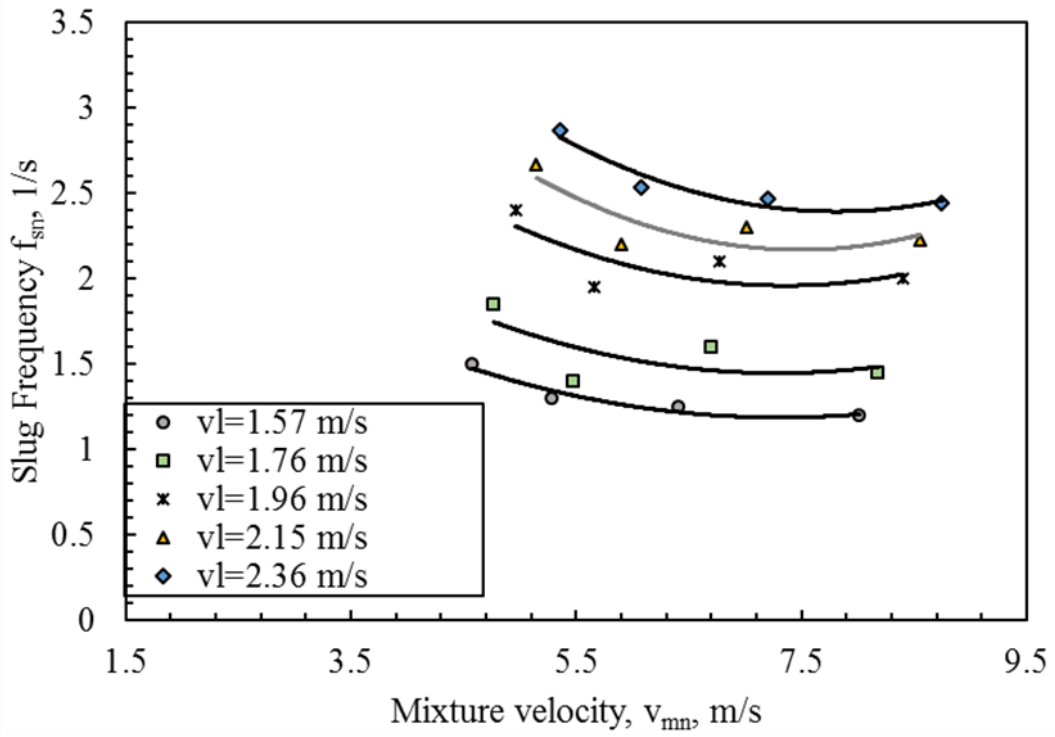
Effect of liquid superficial velocity on slug frequency for air/non-Newtonian flow.



Effect of gas superficial velocity with slug frequency for air/ non-Newtonian two-phase flow.

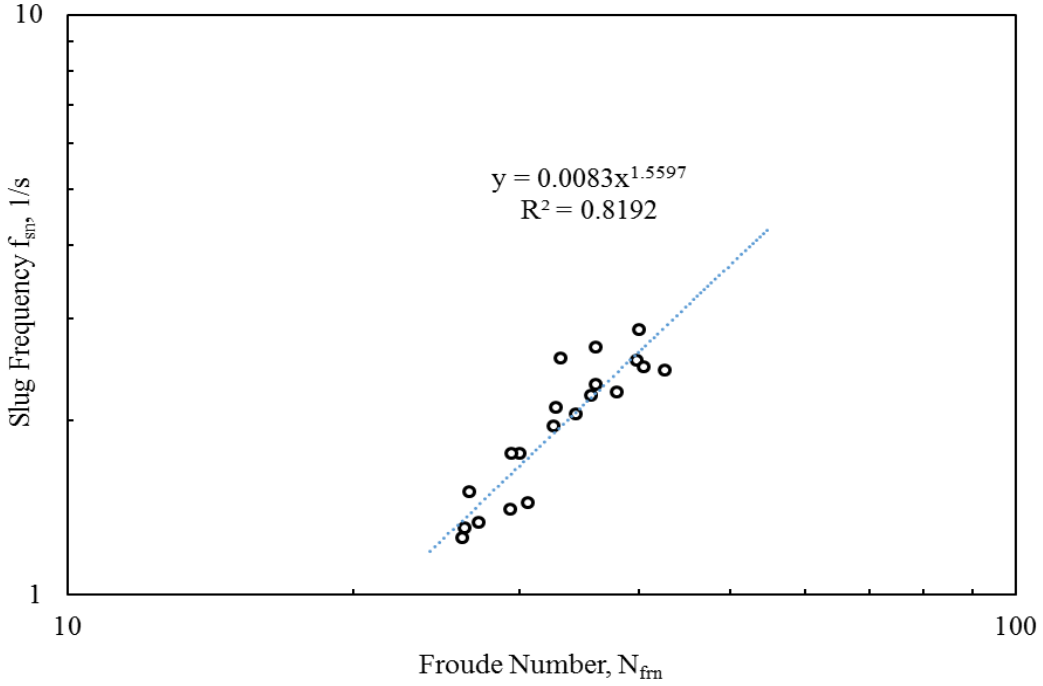
Slug Frequency *(Air/non-Newtonian Fluid Flow)*

- Depends on superficial gas velocity.
- At constant liquid flow rate slug frequency decreased with increasing gas velocity
- The gas/Newtonian minimum mixture velocity slug frequency occurred a lot earlier than the gas/non-Newtonian two-phase flow which is an effect of viscosity.
- Otten & Fayed (1977) also got the similar patterns for his air/non-Newtonian flow.
- Water viscosity at 20 °C is 1 cP and the experimental viscosity of 0.1% Xanthan gum is 2.4 cP, which is little more viscous than the water.

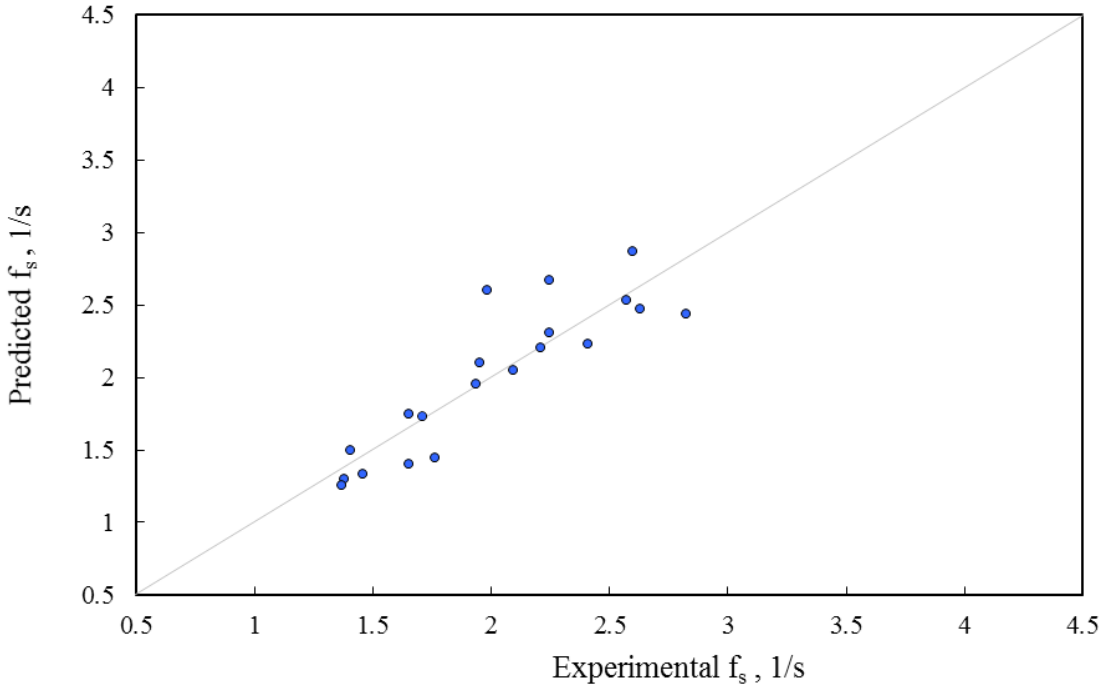


Slug frequency vs mixture velocity for air/non-Newtonian flow.

Slug Frequency *(Air/non-Newtonian Fluid Flow)*



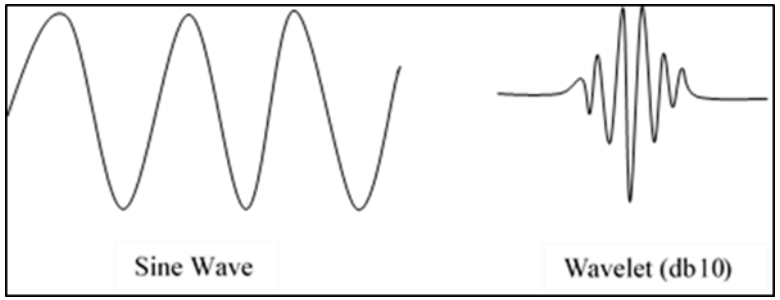
Slug frequency vs. Froude number for Air/Xanthan gum solution.



Experimental slug frequency for air/non-Newtonian system compared to the predictions by Gregory & Scott (1969) correlation with standard deviations.

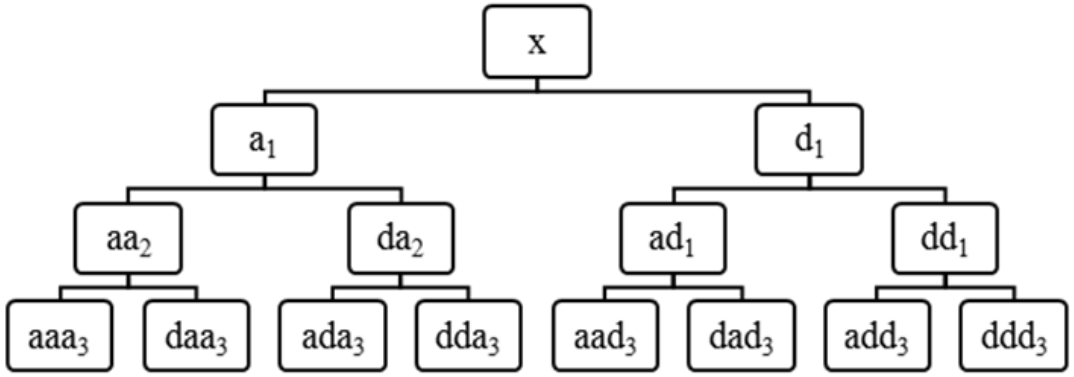
Signal Analysis

- To identify the flow patterns, high-speed photography, gamma ray tomography, particle image velocimetry (PIV), neutron radiography, pressure fluctuation, etc. are the most common methods.
- Park & Kim, (2003), Blaney (2008) , De Fang et al. (2012), Sun et al. (2013) are the most popular name who used wavelet transformation to analyze multiphase flow signals.
- Wavelet transformation is better than Fourier Transformation. Wavelets are asymmetrical and uneven waveforms of adequately limited duration which have a zero average value. Example: Wavelet transformation of sine wave.



Signal Analysis

- Two types of wavelet analysis which are Discrete wavelet transform and Continuous wavelet transform.
- The Discrete Wavelet Packet Decomposition is a wavelet transform where the wavelets are separately sampled. In this analysis, the original signal is divided into two parts, approximations and details. Wavelet packet analysis decomposition tree is given below,

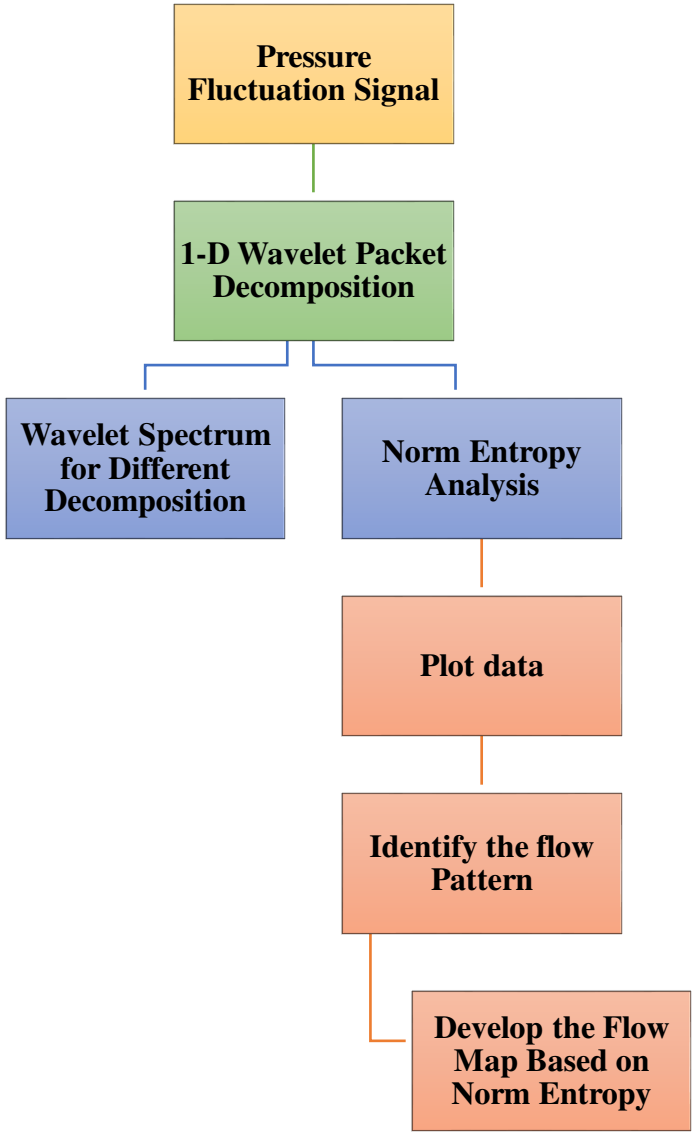


Wavelet Analysis

- Wavelet entropy represents the nonuniformity of states, which is an ideal parameter measure the ordering of unsteady signals (Uyar et al. 2008). The total energy entropy of the original signal should be summation of the coefficient energy entropy (Sun et al. 2013)
- This entropy formula is used in MATLAB to calculate norm entropy. The concentration in l^P norm where, $1 \leq P < 2$. Now $E(s) = |s_i|^P$ so $E(s) = \sum_i |s|^P = \left|\left|s\right|\right|_P^P$, where P is the power of norm entropy (Misiti et al. 1996).
- The wavelet entropy can find small or abnormal frequencies. Therefore, it can find different characteristics of multiphase flow.

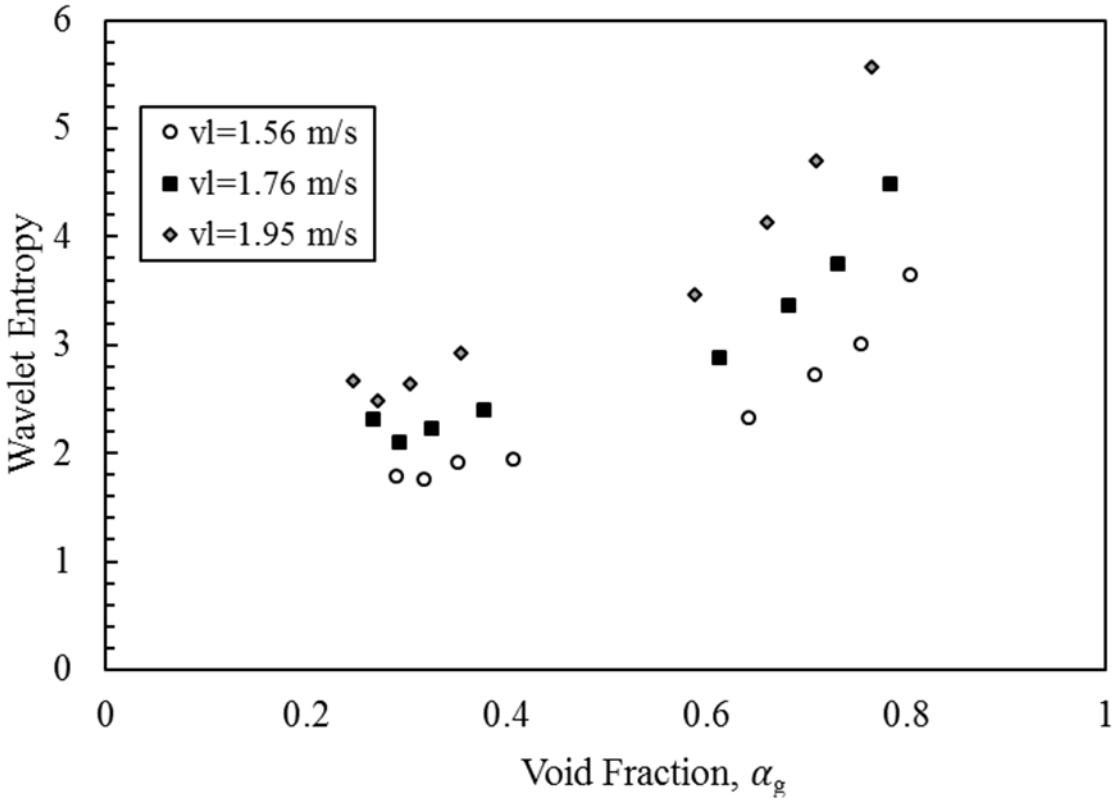
Wavelet Analysis

- This study aims to characterize two-phase flow pattern using norm entropy based on wavelet packet decomposition of the pressure signal.
- The steps of wavelet decomposition for different flow pattern identification are,



Wavelet Entropy Analysis

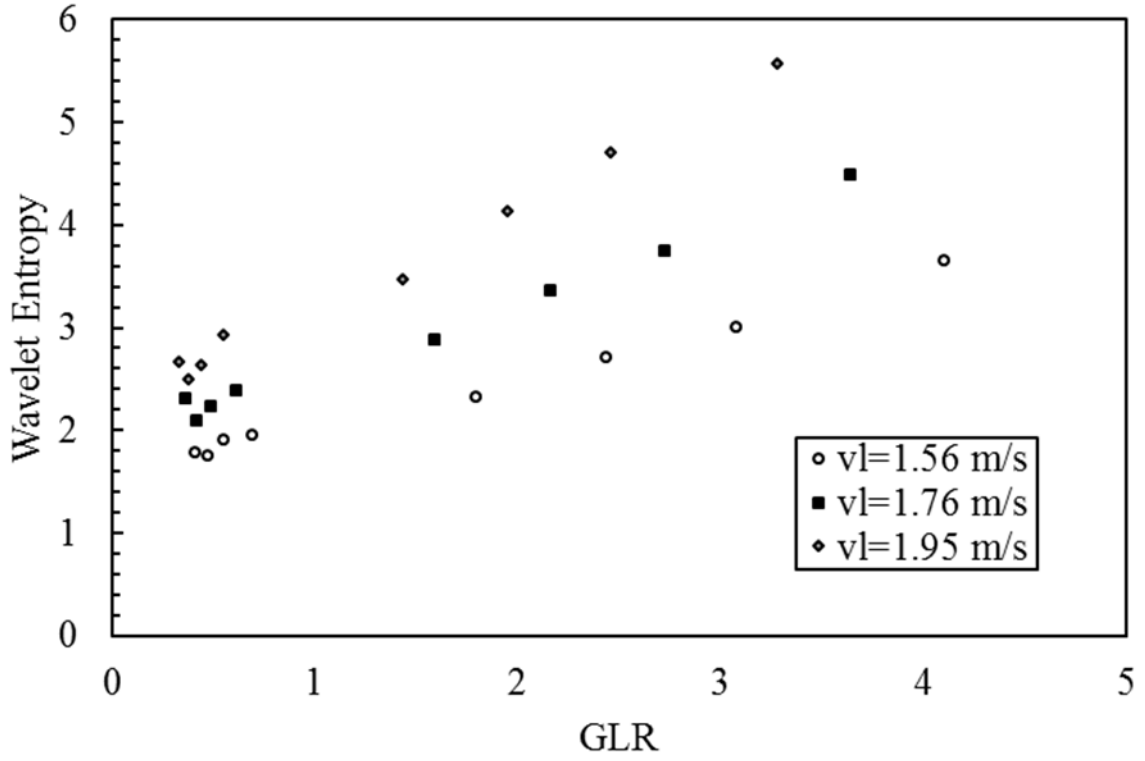
- Wavelet entropy increased with the increase of the pressure signal fluctuation.
- The entropy values of the pressure fluctuation data have been compared with void fraction ($\alpha_g = \frac{v_g^s}{v_g^s + v_l^s}$).
- The fluctuation of the pressure and entropy increases with the increase of void fraction ratio for gas/water flow



Change of wavelet entropy with gas void fraction for gas/Newtonian fluid.

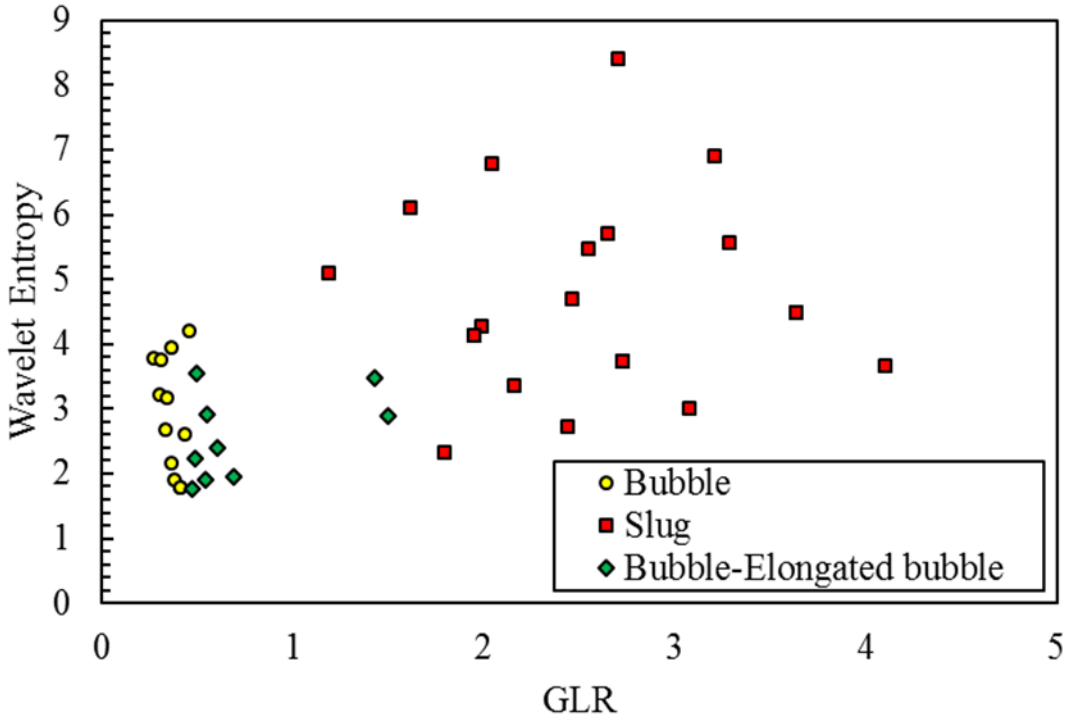
Wavelet Entropy Analysis

- Wavelet entropy increased with the increase of the pressure signal fluctuation.
- The entropy values of the pressure fluctuation data have been compared with gas to liquid volume flowrate ratio (GLR).
- The norm entropy change at the low GRL is not consistent as bubble flow and motion are random and complicated in bubble flow or bubble-slug transition flow region (Fan et al. 2013).



Change of wavelet entropy with gas void fraction for gas/Newtonian fluid.

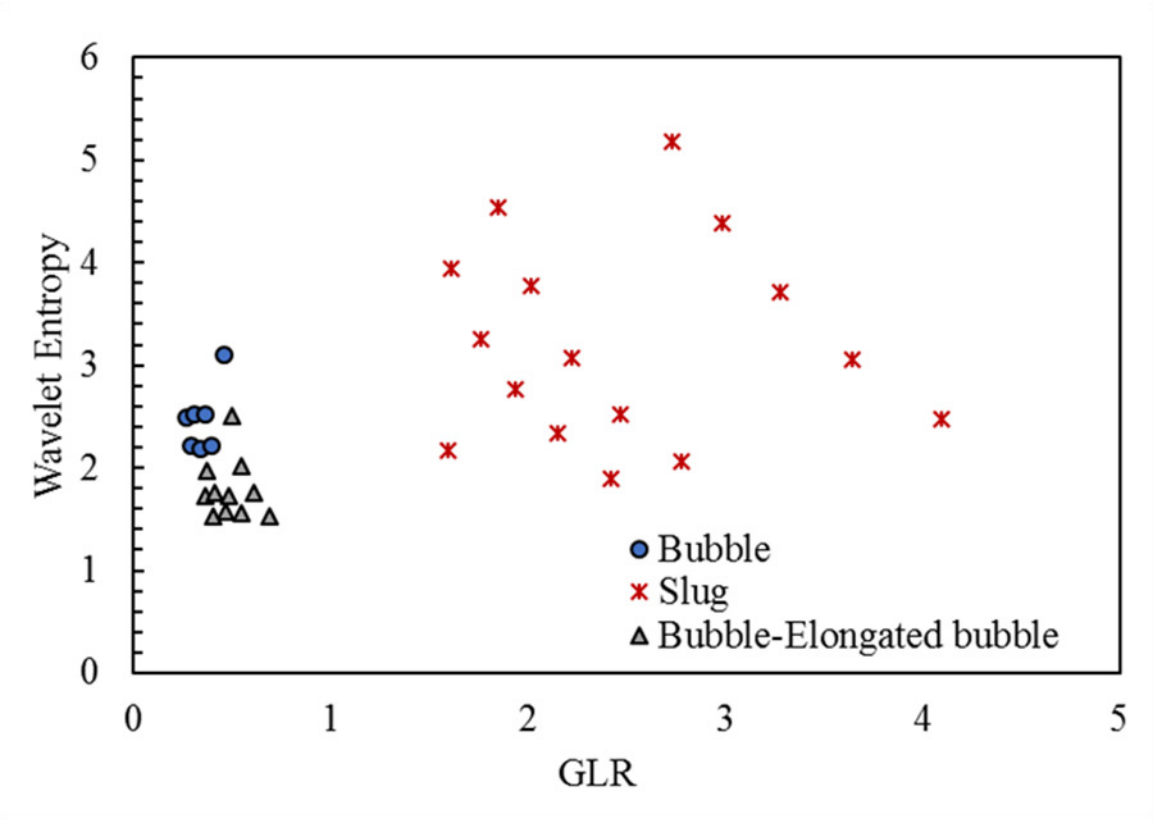
Wavelet Entropy Map *(Air/Newtonian Fluid Flow)*



Wavelet entropy flow map for gas/Newtonian flow.

- The wavelet norm entropy of bubble, bubble-elongated bubble and slug flow regime at different GLR combination for the experiment setup used in this study.
- The wavelet norm entropy value may vary with higher resolution sensors.
- Fan et al. (2013) and Sun et al. (2013) both got similar wavelet entropy changing pattern but their sensors.

Wavelet Entropy Map *(Air/non-Newtonian Fluid Flow)*



Wavelet entropy flow map for gas/non-Newtonian flow.

- The wavelet norm entropy of bubble, bubble-elongated bubble and slug flow regime at different GLR combination for the experiment setup used in this study.
- It is observed from the flow map that at similar GLR ratio air/non-Newtonian shows more elongated bubble than air/Newtonian flow.

Conclusion

- The horizontal flow regime maps using experimental data has been developed and validated with the existing literature.
- Slug frequency has been examined and compared with air/Newtonian and air/non-Newtonian fluid in the flow loop. The viscosity effect creates the major difference between gas/water and gas/0.1% Xanthan gum fluid flow.
- Pressure signal decomposition has been done for bubble and slug flow using wavelet packet transformation.
- 1-D wavelet packet decomposition can be potential methods to analyze multiphase flow experimental signals and find different characteristics and recognizing different flow patterns.

Future Work

- Developing two-phase vertical and inclined flow map for air/Newtonian and air/non-Newtonian flow.
- Installing screw type progressive cavity pump to understand the higher viscosity non-Newtonian flow characteristics with higher flow range.
- The experiments should be done in different diameter pipe to see the ramification of pipe diameter on the flow characteristics.
- One of the major future work should be using high resolution and high-frequency pressure sensors to detect the changes of flow structures and analyze it with 1-D wavelet packet decomposition.

References:

Blaney, S., 2008. Gamma radiation methods for clamp-on multiphase flow metering.

Chhabra, R.P. & Richardson, J.F., 1999. Non-Newtonian Flow: Fundamentals and Engineering Applications, Butterworth-Heinemann.

Fan, C., Ding, Y. & Ren, X., 2013. Wavelet entropy applied in gas-liquid two-phase flow. In Control Conference (CCC), 2013 32nd Chinese. pp. 8623–8627.

Hubbard, M.G. & Dukler, A.E., 1966. The characterization of flow regimes for horizontal two-phase flow. Proceedings of the 1996 Heat Transfer and Fluid, pp.100–121.

Gregory, G.A. & Scott, D.S., 1969. Correlation of liquid slug velocity and frequency in horizontal cocurrent gas-liquid slug flow. AIChE Journal, 15(6), pp.933–935.

Greskovich, E.J. & Shrier, A.L., 1972. Slug frequency in horizontal gas-liquid slug flow. Industrial & Engineering Chemistry Process Design and Development, 11(2), pp.317–318.

Misiti, M. et al., 1996. Wavelet toolbox. The MathWorks Inc., Natick, MA, 15, p.21.

Otten, L. & Fayed, A.S., 1977. Slug Velocity And Slug Frequency Measurements In Concurrent Air-Non-Newtonian Slug Flow. Transactions Of The Institution Of Chemical Engineers, 55(1), pp.64–67.

Park, S.H. & Kim, S.D., 2003. Characterization of pressure signals in a bubble column by wavelet packet transform. Korean Journal of Chemical Engineering, 20(1), pp.128–132.

Picchi, D. et al., 2015. Gas/shear-thinning liquid flows through pipes: Modeling and experiments. International Journal of Multiphase Flow, 73, pp.217–226.

Rosehart, R.G., Rhodes, E. & Scott, D.S., 1975. Studies of gas liquid (non-Newtonian) slug flow: void fraction meter, void fraction and slug characteristics. The Chemical Engineering Journal, 10(1), pp.57–64.

Sun, Z., Shao, S. & Gong, H., 2013. Gas--liquid Flow Pattern Recognition Based on Wavelet Packet Energy Entropy of Vortex-induced Pressure Fluctuation. Measurement science review, 13(2), pp.83–88.

Uyar, M., Yildirim, S. & Gencoglu, M.T., 2008. An effective wavelet-based feature extraction method for classification of power quality disturbance signals. Electric Power Systems Research, 78(10), pp.1747–1755.

Zabaras, G.J., Shell, E. & Co, P.T., 2000. Prediction of Slug Frequency for Gas / Liquid Flows. , (September), pp.252–258.

Flow Regime Video

• Camera Version	16001 (Phantom v2511)
• Resolution	1024x304
• Sample Rate	5000 Frame per Minute



Special Thank

to

Matt Curtis

Craig Mitchel

Trevor Clark

End



Thank You for Your Time and Attention

Question

