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Uncertainty Analysis for Multiphase Flow: A Case Study for Horizontal Air-Water Flow Experiments

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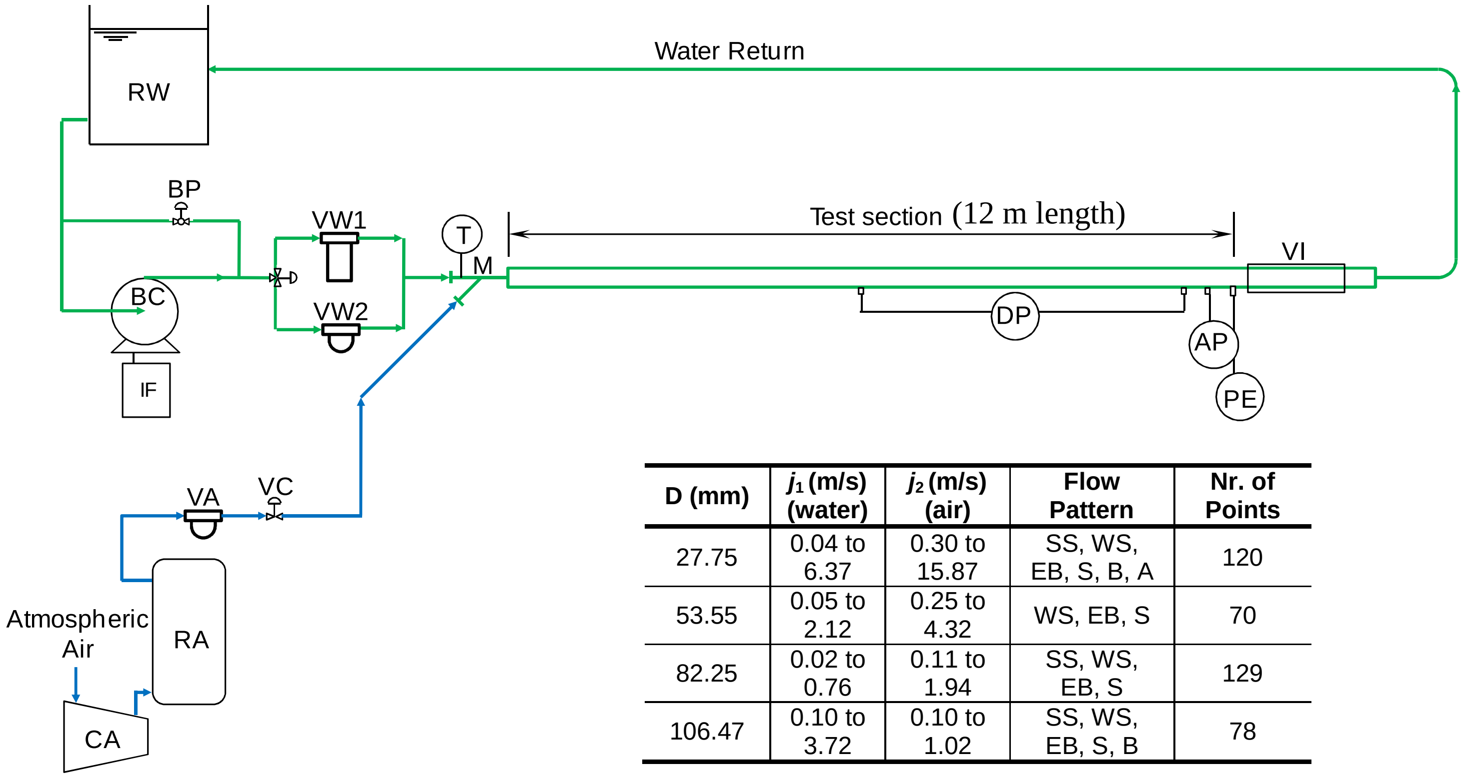
Introduction

- To improve the quality of experimental result
- To describe a simple methodology for calculating uncertainties in multiphase experiments
- To identify and to quantify sources of uncertainty for the velocity and pressure results

Experimental Facilities and Procedures

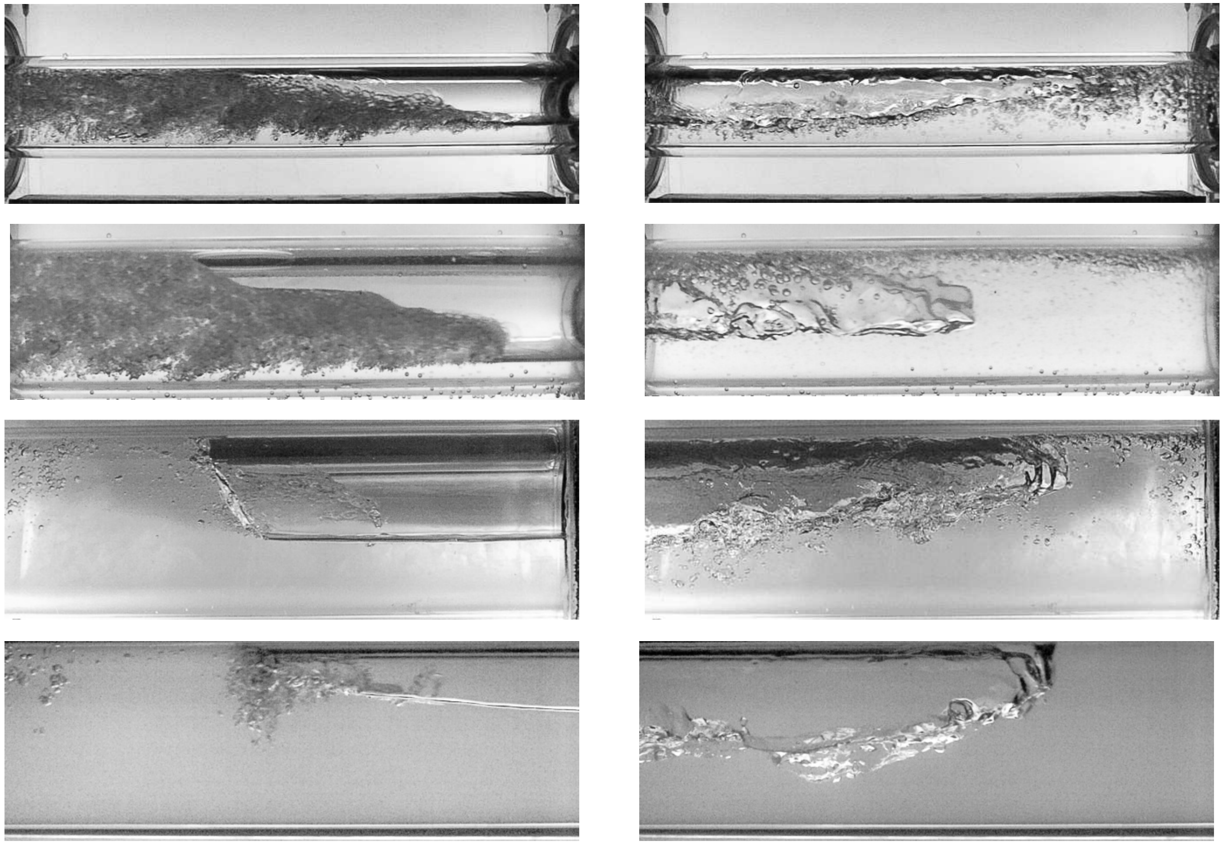


D (mm)	j_1 (m/s) (water)	j_2 (m/s) (air)	Flow Pattern	Nr. of Points
27.75	0.04 to 6.37	0.30 to 15.87	SS, WS, EB, S, B, A	120
53.55	0.05 to 2.12	0.25 to 4.32	WS, EB, S	70
82.25	0.02 to 0.76	0.11 to 1.94	SS, WS, EB, S	129
106.47	0.10 to 3.72	0.10 to 1.02	SS, WS, EB, S, B	78

Experimental Facilities and Procedures

- Understand the diameter influence mainly on two-phase pressure drop:

Slug flow: Front part Rear part



1 in — j_1=1,03 m/s e j_2=2,18 m/s

2 in — j_1=0,13 m/s e j_2=2,80 m/s

3 in — j_1=0,09 m/s e j_2=1,49 m/s

4 in — j_1=0,57 m/s e j_2=0,51 m/s

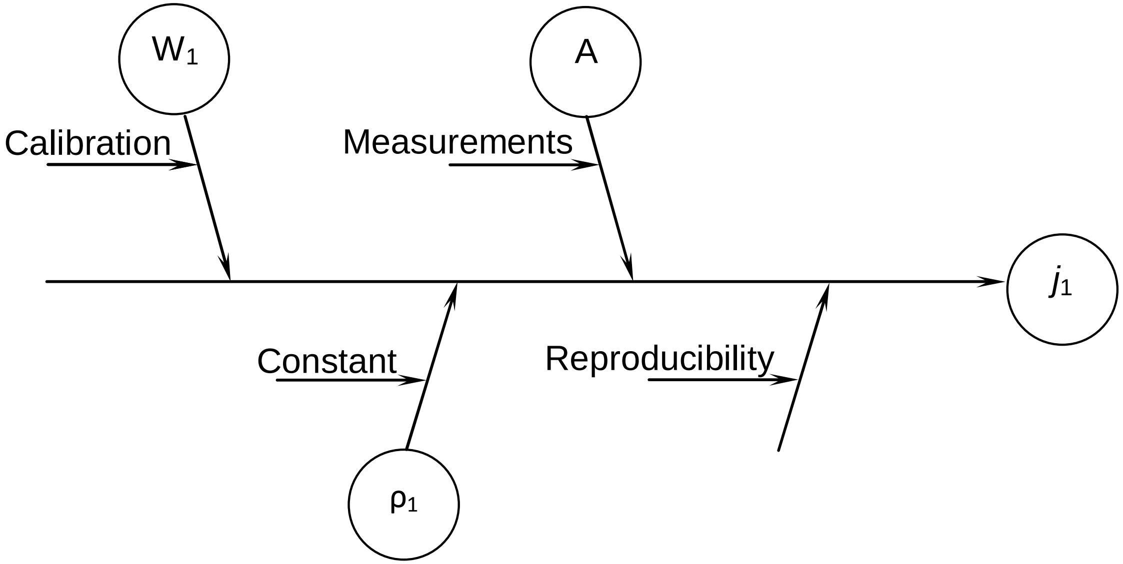
Uncertainties

11 steps:

1. Define physical quantity
2. Define a physical model
3. Define a mathematical model
4. Identify the sources of uncertainty
5. Organize the sources and look for cause and effect relations
6. Quantify the variability of each source
7. Reduce to standard uncertainty
8. Determining the combined standard uncertainty
9. Look for correlated input quantities
10. Define reliability
11. Determining expanded uncertainty

Uncertainties

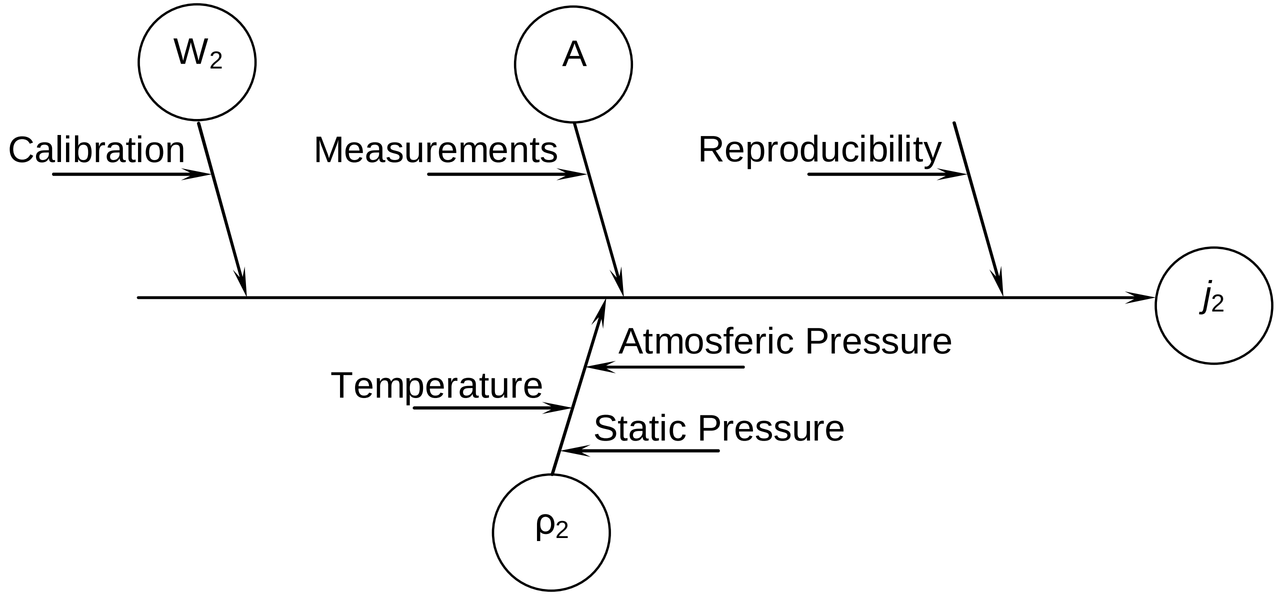
- Water superficial velocity



$$j_1 = \frac{W_1}{\rho_1 A}$$

Uncertainties

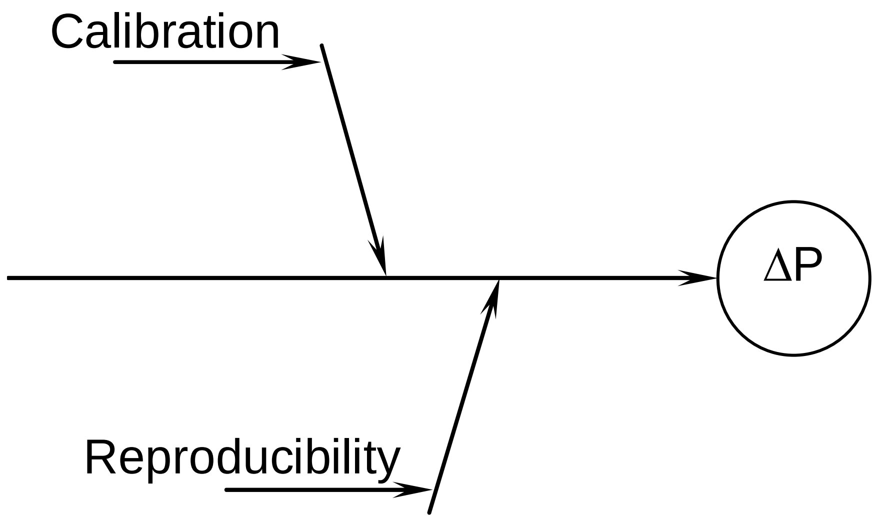
- Air superficial velocity



$$j_2 = \frac{W_2}{\rho_2 A} = \frac{W_2}{\frac{(P_{atm} + P_{est})}{RT} A} = \frac{W_2 RT}{(P_{atm} + P_{est})A}$$

Uncertainties

- Pressure drop (single phase and two-phase)



Uncertainties

- Quantifying and reduce

Uncertainties of meter and sensor calibrations: (type B)	• $u(X) = \frac{U(X)}{k}$
Uncertainties of measurements: (type A)	• $u(X) = \frac{\sigma(X)}{\sqrt{n}}$ • $u(\overline{X}) = \frac{s(\overline{X})}{\sqrt{n}}$
Uncertainties of method, instrument resolution or values fluctuation: (type B)	• $u(a) = \frac{a}{\sqrt{3}}$ (for rectangular distribution) • $u(a) = \frac{a}{\sqrt{6}}$ (for triangular distribution)

Where:

X = physical quantity
k = coverage factor
σ = standard deviation
s = biased estimator of standard deviation

n = number of samples
a = assigned value, instrument resolution or greater difference

Uncertainties

- Combined standard uncertainty

Area: $$u_C(A) = \sqrt{\left[\frac{\partial A}{\partial D}.u(D)\right]^2}$$

Air density: $$u_C(\rho_2) = \sqrt{\left[\frac{\partial \rho_2}{\partial P_{atm}}.u(P_{atm})\right]^2 + \left[\frac{\partial \rho_2}{\partial P_{est}}.u(P_{est}\right]^2 + \left[\frac{\partial \rho_2}{\partial T}.u(T)\right]^2}$$

Uncertainties

- Combined standard uncertainty

Air superficial velocity:

$$u_C(j_2) = \sqrt{\left[\frac{\partial j_2}{\partial W_2}.u(W_2)\right]^2 + \left[\frac{\partial j_2}{\partial A}.u_c(A)\right]^2 + \left[\frac{\partial j_2}{\partial \rho_2}.u_C(\rho_2)\right]^2 + u(Rj_2)^2}$$

Water superficial velocity:

$$u_C(j_1) = \sqrt{\left[\frac{\partial j_1}{\partial W_1}.u(W_1)\right]^2 + \left[\frac{\partial j_1}{\partial A}.u_c(A)\right]^2 + \left[\frac{\partial j_1}{\partial \rho_1}.u(\rho_1)\right]^2 + u(Rj_1)^2}$$

Pressure drop:

$$u_C(\Delta P) = \sqrt{u(\Delta P)^2 + u(R\Delta P)^2}$$

Uncertainties

- Reliability and degrees of freedom

Expanded uncertainty:

$$U = k.u_c$$

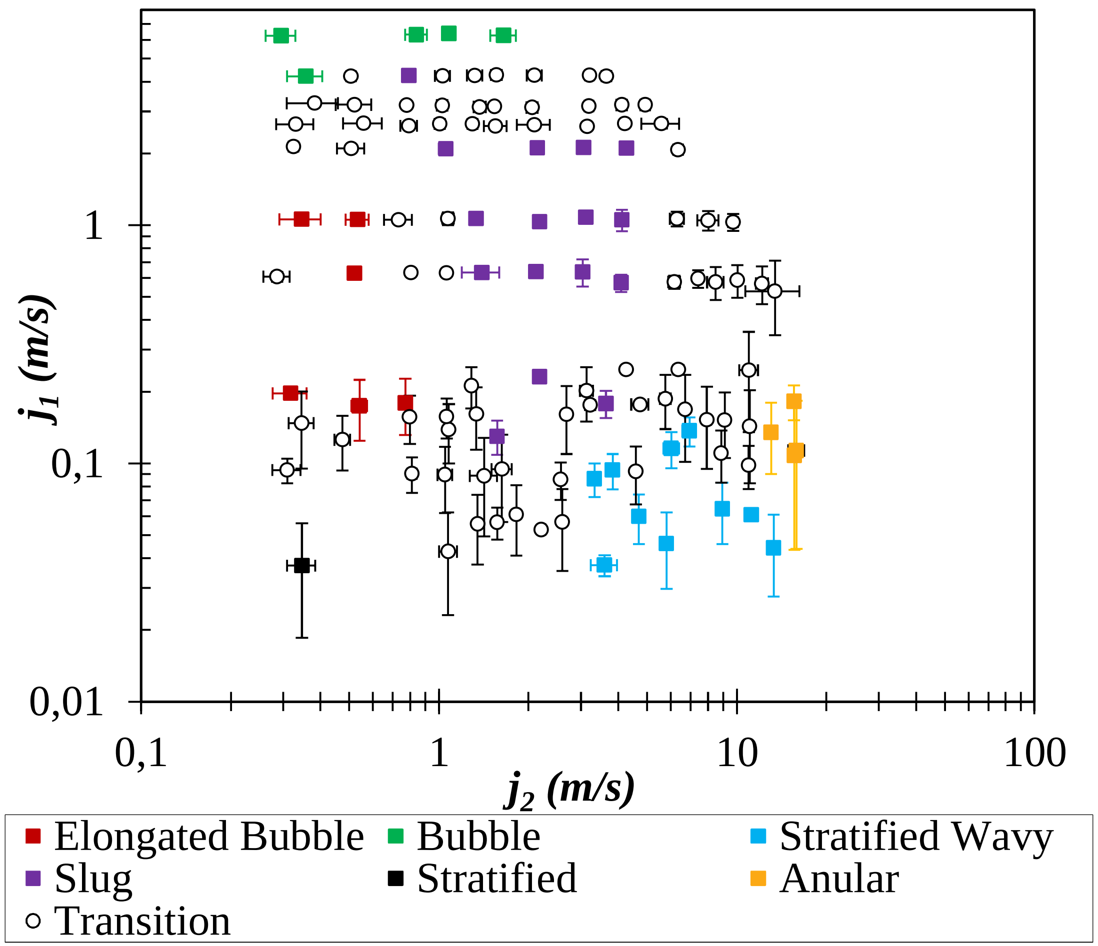
Coverage factor:

ν_{ef}	1	2	3	4	5	6	7	8	10	12	14	16
k_{t95}	13,97	4,53	3,31	2,87	2,65	2,52	2,43	2,37	2,28	2,23	2,20	2,17
N_{ef}	18	20	25	30	35	40	45	50	60	80	100	∞
k_{t95}	2,15	2,13	2,11	2,09	2,07	2,06	2,06	2,05	2,04	2,03	2,025	2,00

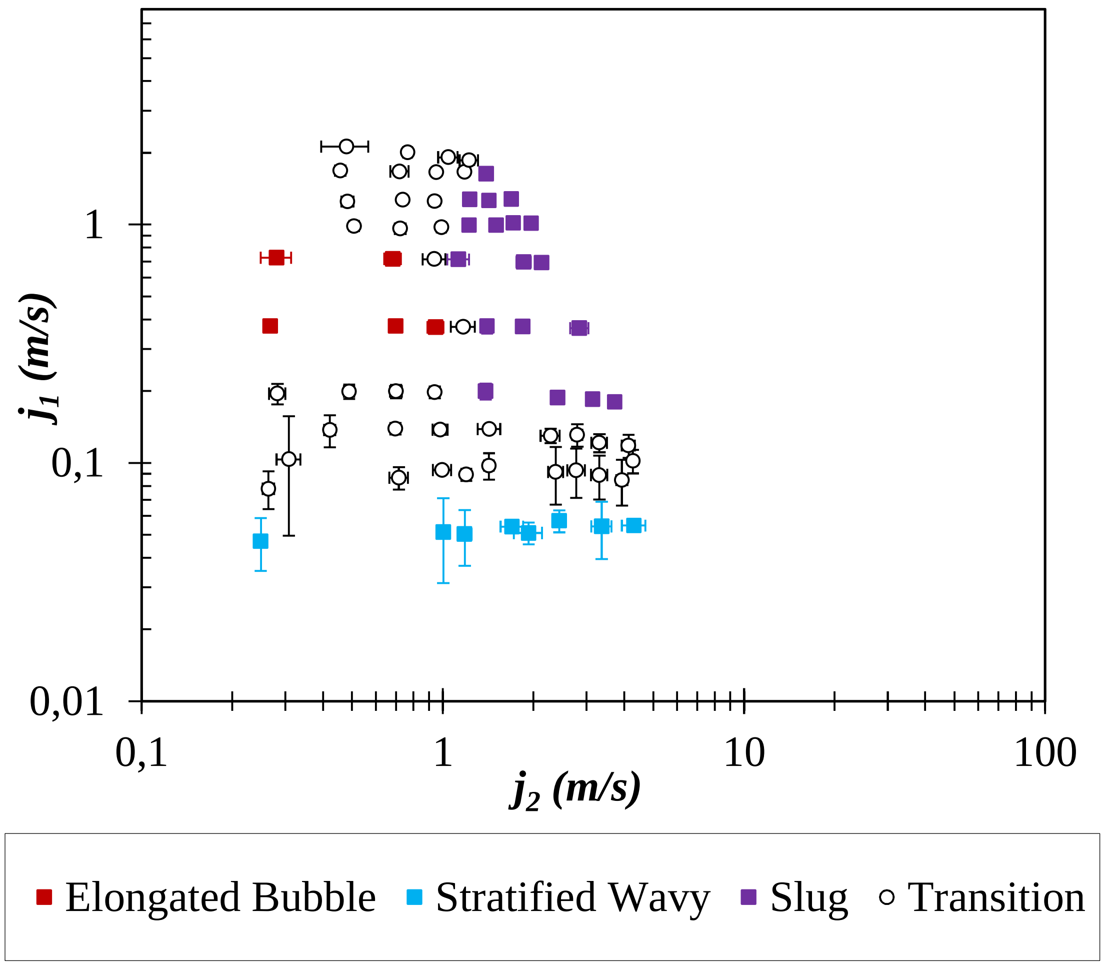
Degrees of freedom:

$$\nu_{ef} = \frac{u_c^4(y)}{\sum_{i=1}^{N} \frac{u_i^4(y)}{\nu_i}}$$

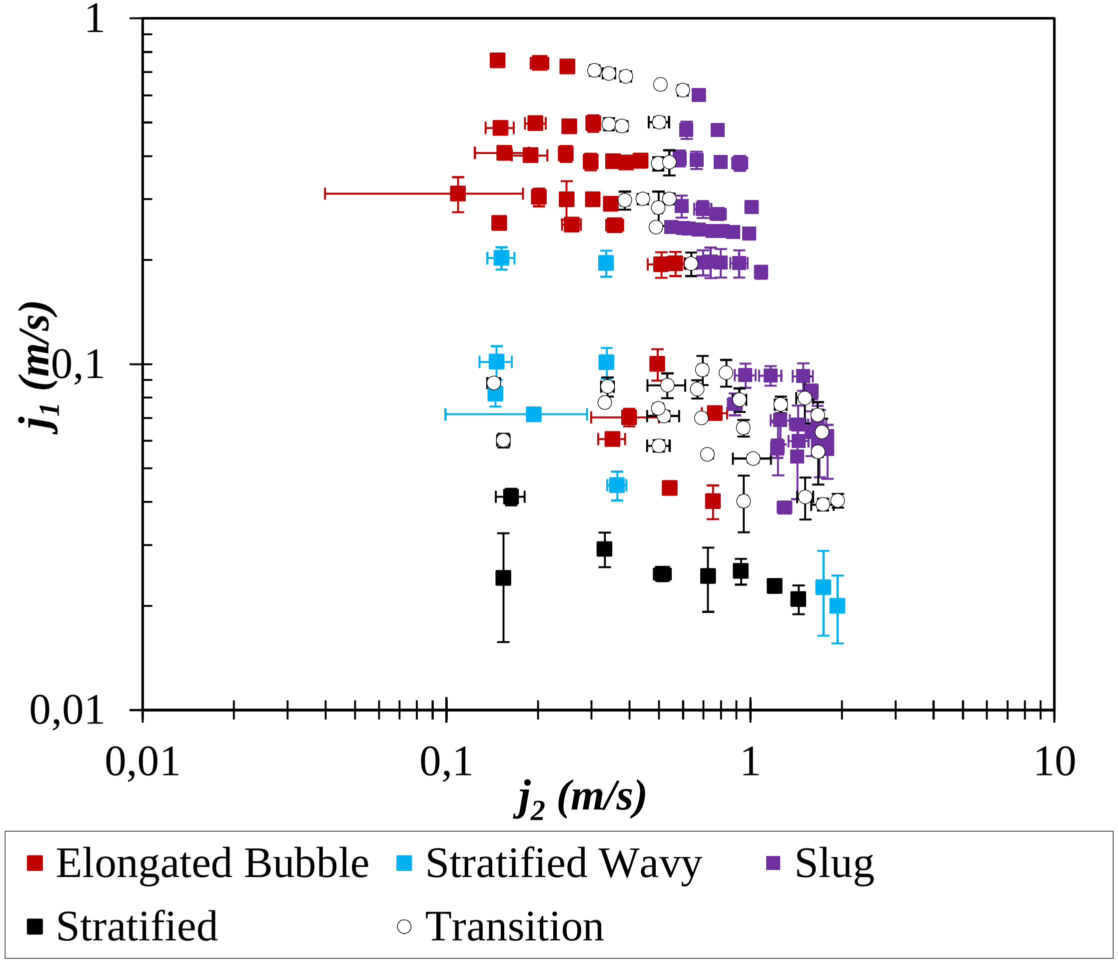
Results – Flow Patern Maps – 1 in



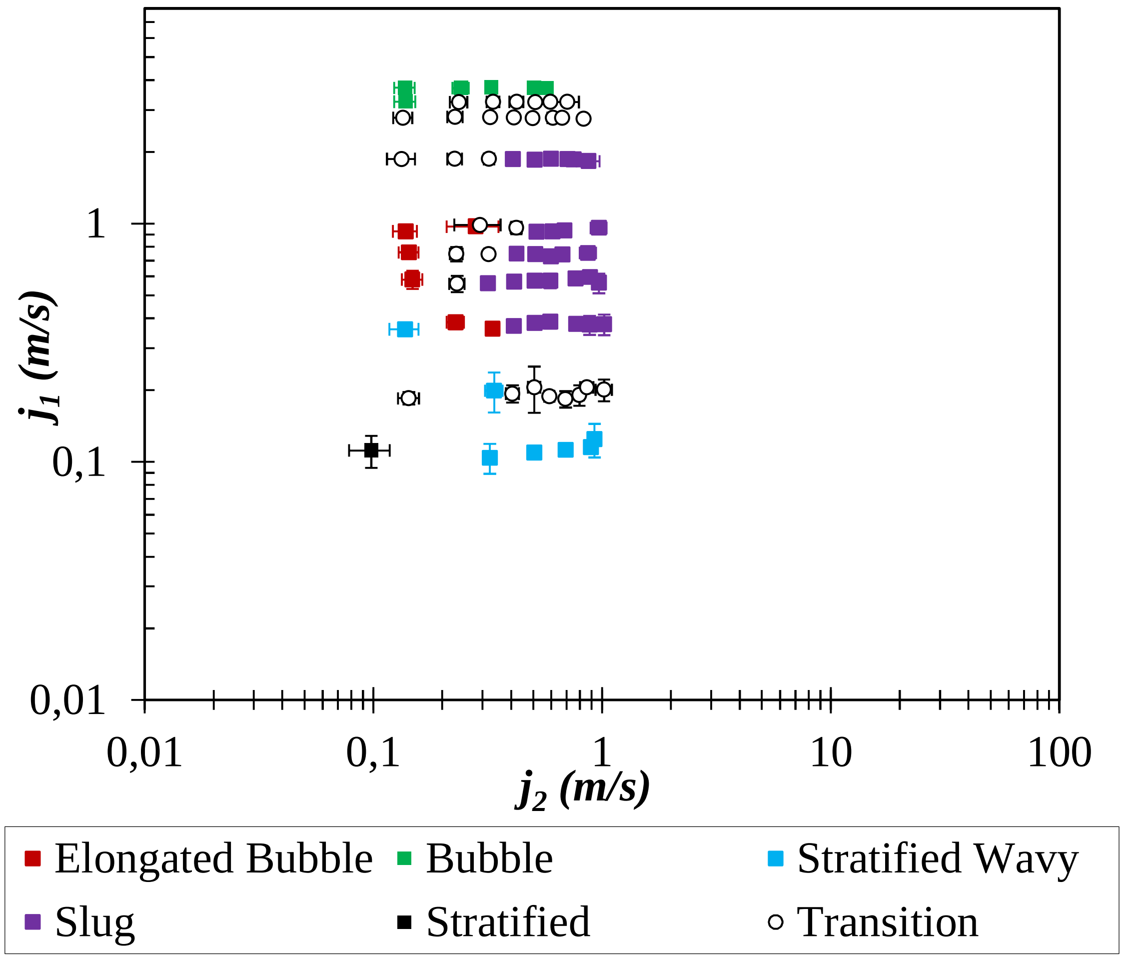
Results – Flow Patern Maps – 2 in



Results – Flow Patern Maps – 3 in



Results – Flow Patern Maps – 4 in

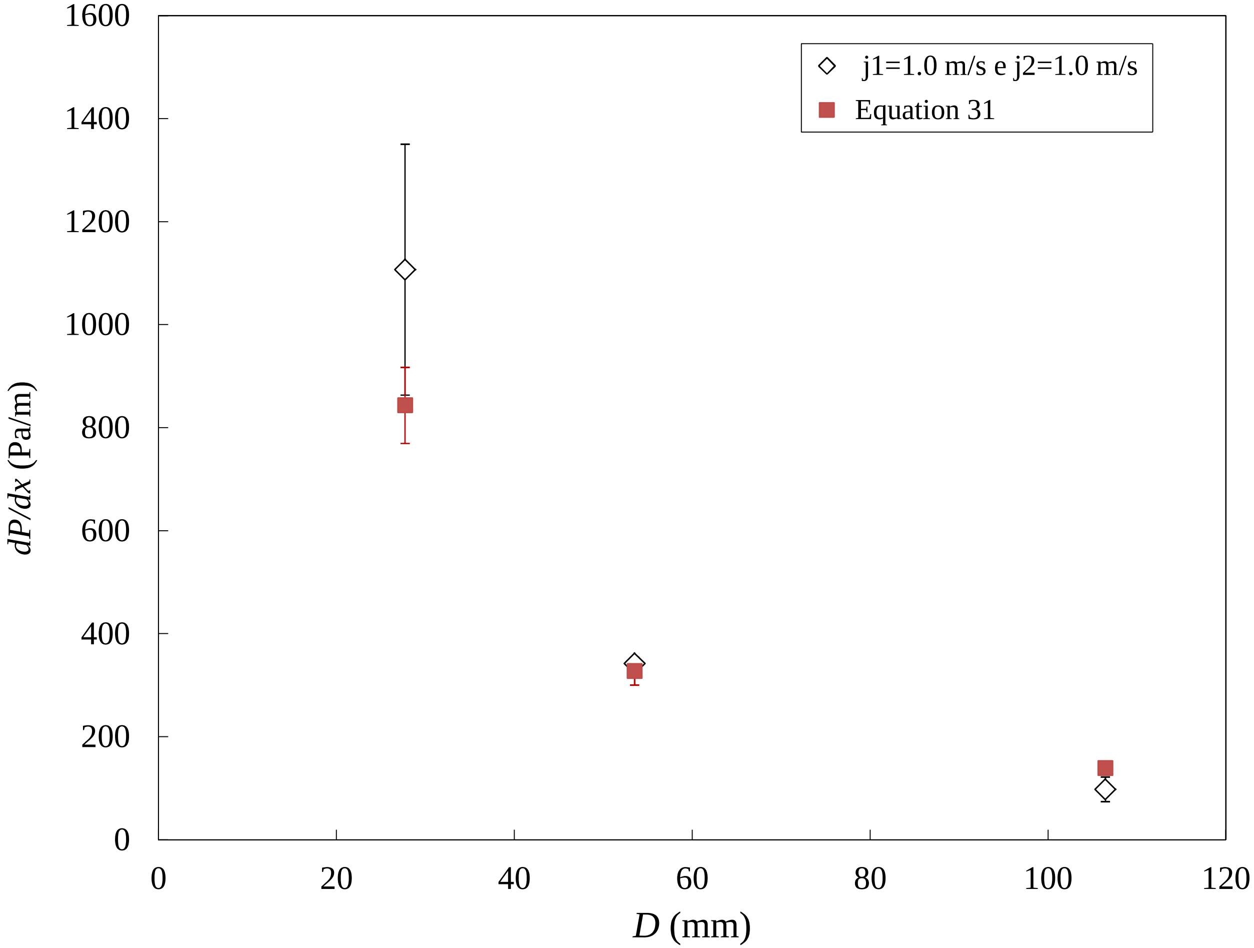


Results – Two-Phase Pressure Drop

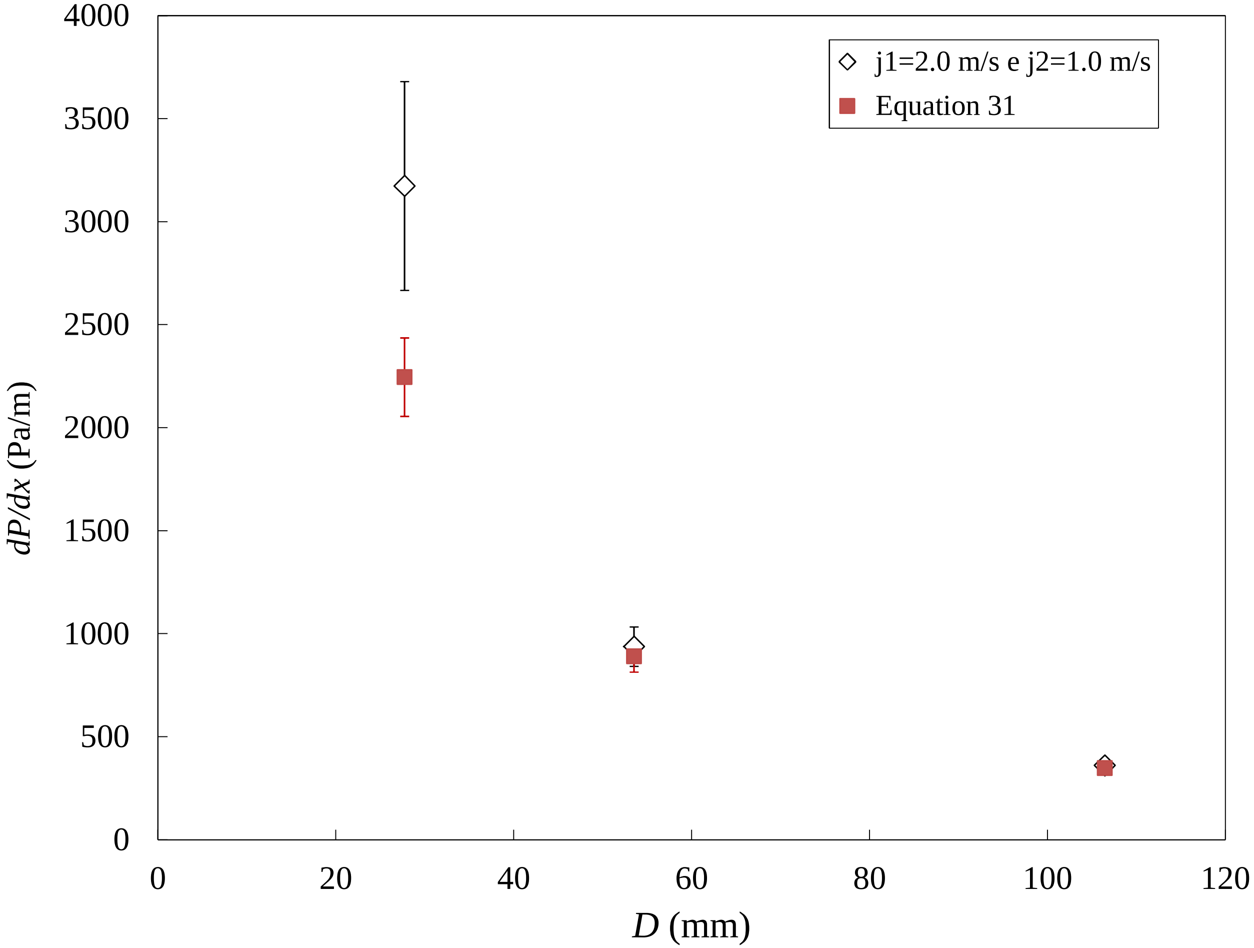
- Proposition for pressure drop variation with diameter

$$-\left(\frac{dP}{dx}\right) = \frac{2}{d} f \rho J^2 = \left(0.092 \mu_m^{0.2} \rho_m^{0.8} J^{1.8}\right) d^{-1.2}$$

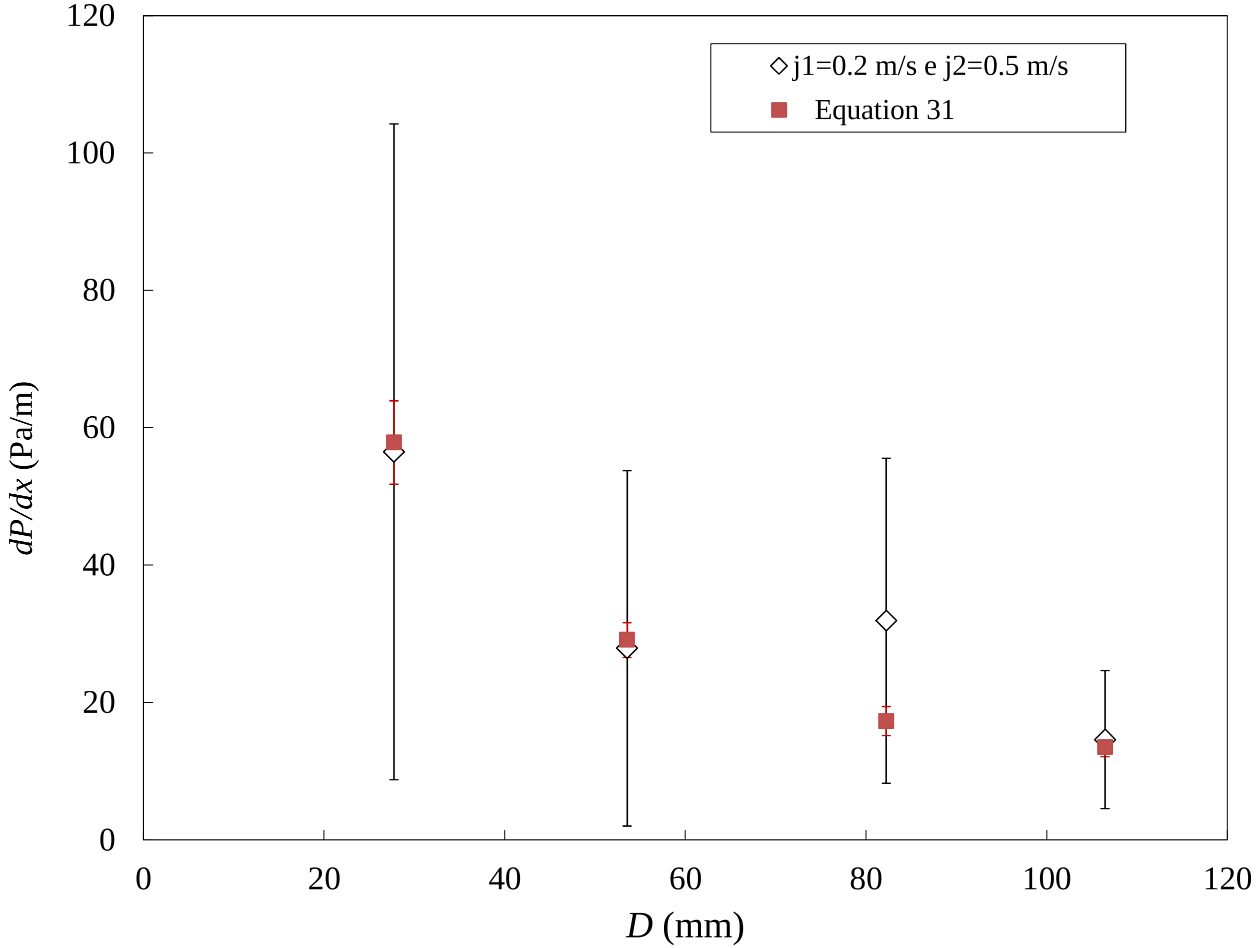
Results – Two-Phase Pressure Drop



Results – Two-Phase Pressure Drop



Results – Two-Phase Pressure Drop



Conclusion

1. Uncertainty for the flow pattern maps can help understand transition regions
2. Better knowledge about the pressure drop results
3. Uncertainty validate the homogeneous model as a good approach
4. Reproducibility of the results improves the quantification of the final uncertainties

Acknowledgments

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CEPETRO CENTRO DE ESTUDOS DE PETRÓLEO

ALFA Artificial Lift & Flow Assurance

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