An improved phenomenological model of annular two-phase flow with high-accuracy dryout prediction capability

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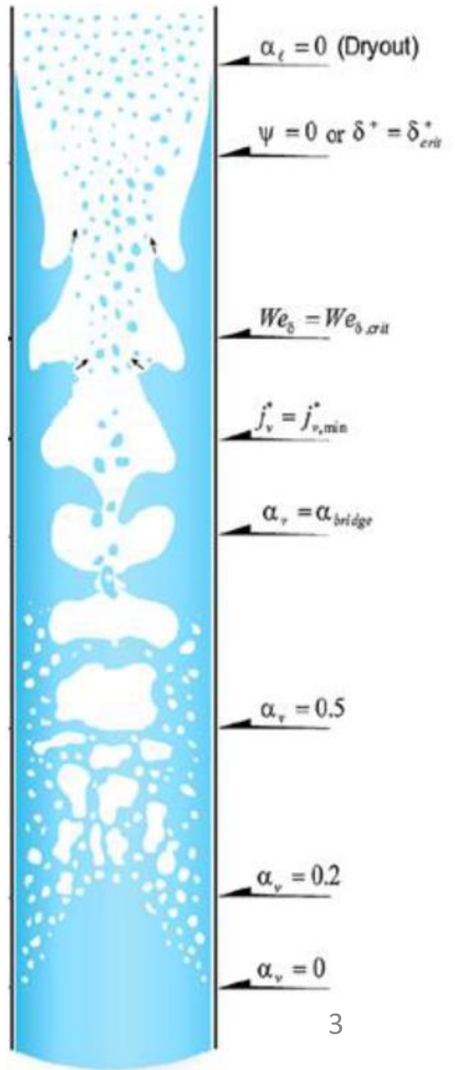
Agenda

1. Problem definition
2. Applied Approach
3. Experimental database
4. Calculation results
5. Solution
6. Current/Further work

Problem definition

BWR power limitations

1. Heat flux delivered to water
2. Dryout occurrence
    - Zero film flow
    - Non-zero film flow
3. Film flow on the rods
    - Entrainment-deposition
    - Initial Boundary Condition



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Applied Approach

- Based on the physical phenomena occurring in the annular flow Whalley et al. (1974) proposed a mathematical model which allows calculation of the axial variation of mass flux of the liquid film along the heated tube
- Various (around 30 so far) correlations for m_D and m_E have been proposed.
- In this work two correlations were used and compared.
  - Hewitt-Govan (1990)
  - Okawa et al. (2003)

$$\frac{dG_f}{dz} = \frac{4}{D_h}(m_D - m_E - m_g)$$

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Entrainment-deposition correlation

	Hewitt-Govan	Okawa et al. 2003
Entrainment	$m_{E,HG} = G_g \cdot 5.75 \cdot 10^{-5} \left[(G_f - G_{lfc})^2 \frac{D_h \rho_l}{\sigma \rho_g^2} \right]^{0.316}$	$m_{E,Okawa} = \frac{k_E f_i}{\sigma} \frac{G_f G_g D_h}{4} \cdot \sqrt{\frac{f_w \rho_l}{f_i \rho_g}} \left(\frac{\rho_l}{\rho_g} \right)^{0.111}$
Deposition	$m_{D,HG} = C \cdot 0.083 \cdot \max\left(0.3, \frac{C}{\rho_g}\right)^{-0.65} \sqrt{\frac{\sigma}{\rho_g D_h}}$	$m_{D,Okawa} = C \cdot 0.0632 \left(\frac{C}{\rho_g} \right)^{-0.5} \cdot \left(\frac{\sigma}{\rho_g D_h} \right)^{0.5}$

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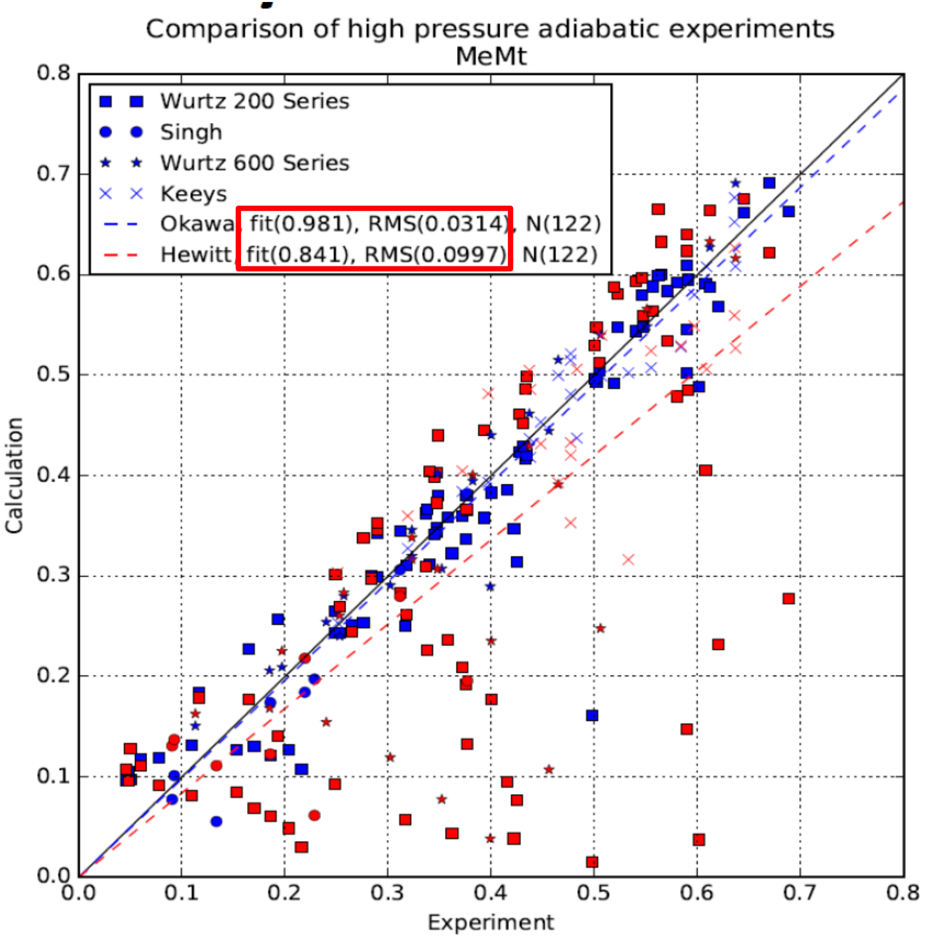
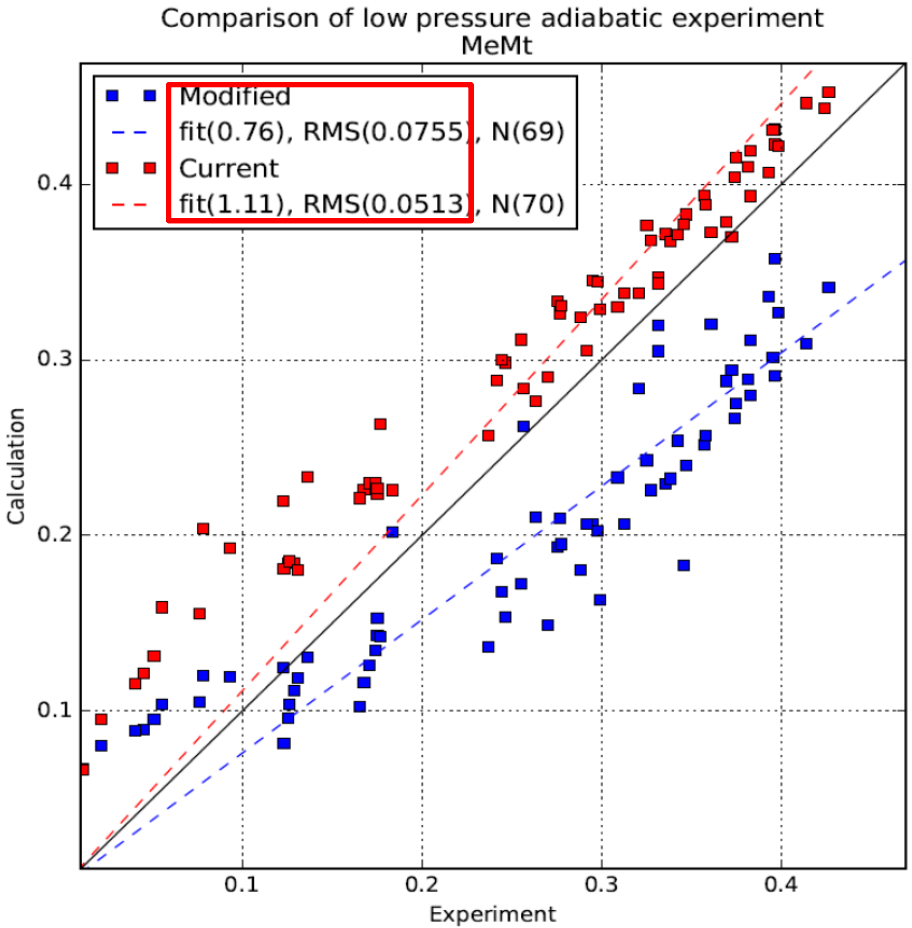
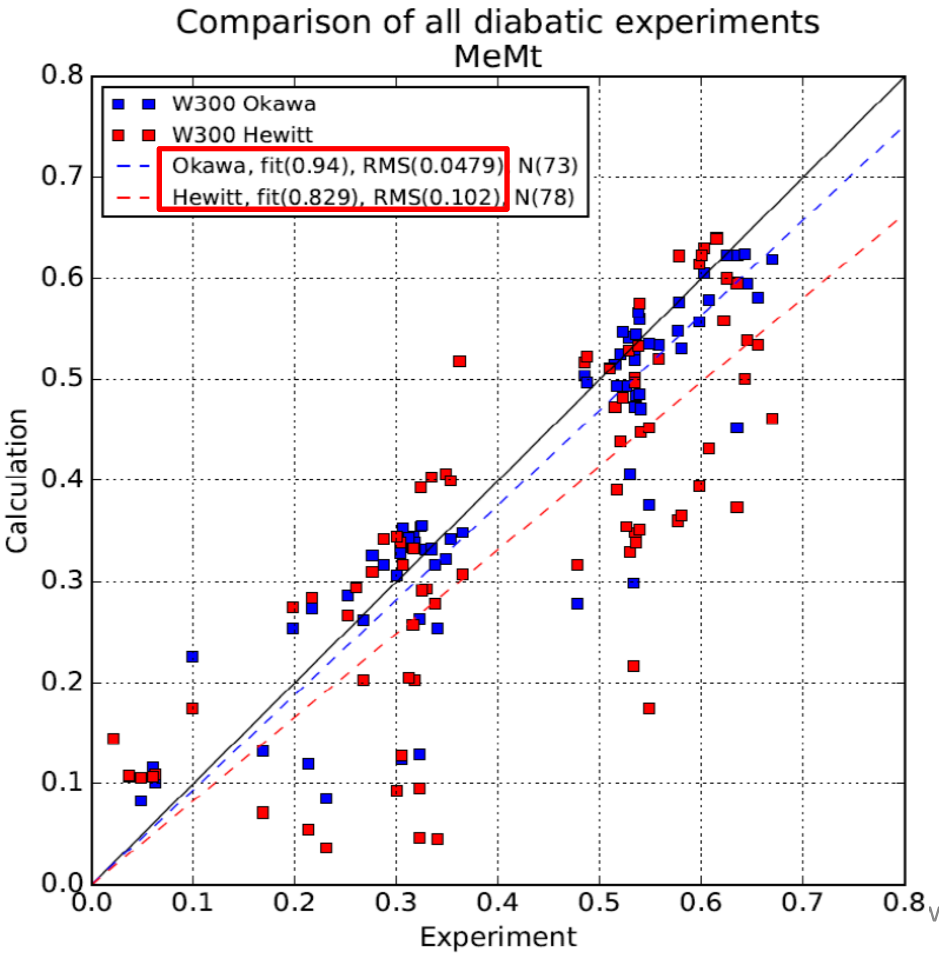
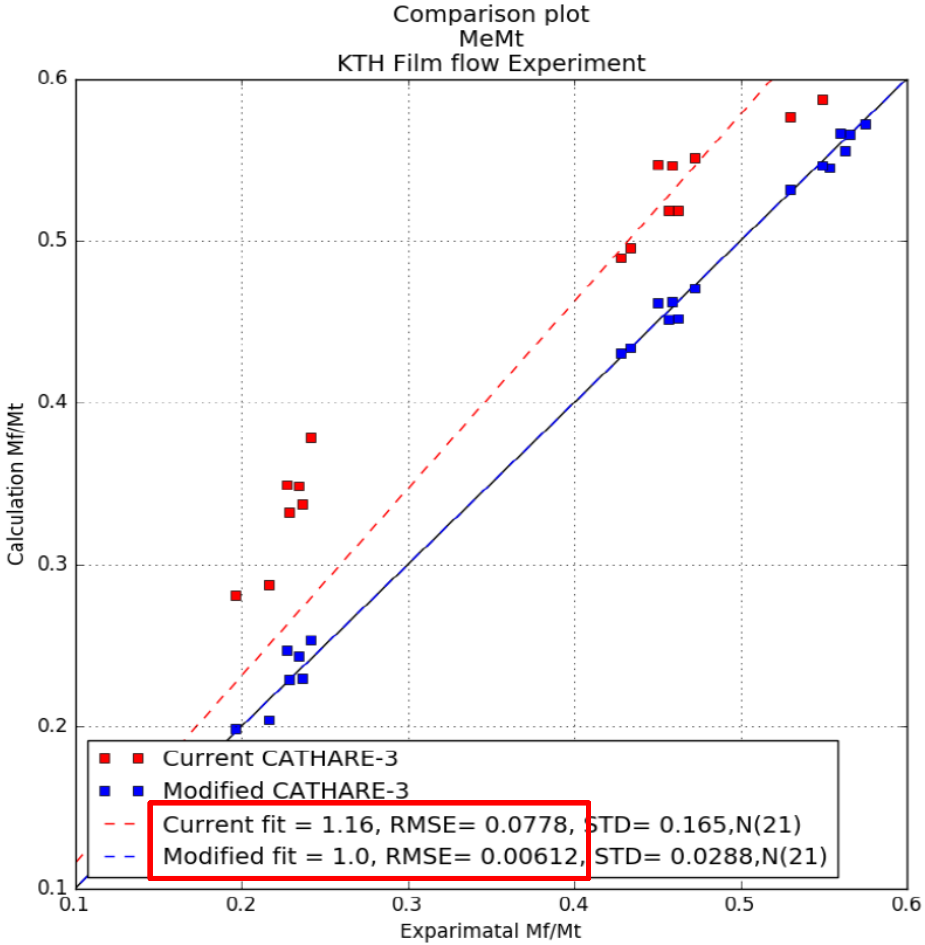
Experimental database

Experiment	Length [m]	D_h[cm]	Pressure [bar]	Mass flux $[kg/m^2/s]$	quality $[\%]$	heat flux $[W/cm^2]$	Runs
Adiabatic tests							
Hewitt-Pulling	3.65	0.93	$2.39 \div 4.46$	297	$14 \div 75$	—	70
Keeys	3.66	1.26	$34.47 \div 68.94$	$1350 \div 2760$	$14 \div 68$	—	21
Singh(**new**)	2.54	1.252	68.94	$542 \div 949$	$30 \div 81$	—	8
Wurtz 200	9	1.0	$30 \div 90$	$500 \div 3000$	$8 \div 60$	—	72
Wurtz 600(**new**)	9	2.0	70	$500 \div 2000$	$20 \div 70$	—	21
Total	$2.54 \div 9$	$0.93 \div 2.0$	$2.39 \div 90$	$297 \div 3000$	$8 \div 81$	—	192
Diabatic tests							
Wurtz 300	4.02	1.0	70	$500 \div 3000$	$16 \div 80$	$50 \div 150$	21
Wurtz 300(**ext**)	$2 \div 6(0.1 \div 2)$	1.0	$30 \div 90$	$500 \div 3000$	$16 \div 80$	$50 \div 150$	78
KTH(**new**)	3.65	1.4	70	$750 \div 1750$	$40 \div 78$	$100 \div 200$	22
Total	$3.65 \div 6$	$1.0 \div 1.4$	$30 \div 90$	$500 \div 3000$	$16 \div 80$	$50 \div 200$	100


Comparison of high pressure adiabatic experiments
MeMt
Wurtz 200 Series
Singh
Wurtz 600 Series
Keeys
Okawa fit(0.981), RMS(0.0314), N(122)
Hewitt fit(0.841), RMS(0.0997), N(122)
Calculation
Experiment


Comparison of low pressure adiabatic experiment
MeMt
Modified
fit(0.76), RMS(0.0755), N(69)
Current
fit(1.11), RMS(0.0513), N(70)
Calculation
Experiment


Comparison of all diabatic experiments
MeMt
W300 Okawa
W300 Hewitt
Okawa, fit(0.94), RMS(0.0479) N(73)
Hewitt, fit(0.829), RMS(0.102) N(78)
Calculation
Experiment
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8


Comparison plot
MeMt
KTH Film flow Experiment
Current CATHARE-3
Modified CATHARE-3
Current fit = 1.16, RMSE= 0.0778, STD= 0.165,N(21)
Modified fit = 1.0, RMSE= 0.00612, STD= 0.0288,N(21)
Calculation Mf/Mt
Exparimatal Mf/Mt
0.1
0.2
0.3
0.4
0.5
0.6

Experimental database (cont.)

	Soderquist et al. (1992)	Becker et al. (1965)
Pressure $[MPa]$	2.9-10	2.9-10
Mass Flux $[kg/m^2s]$	500-6000	500-3000
Diameter $[m]$	0.008	0.014
Length $[m]$	1 - 6	9
Inlet Sub-cooling $[K]$	10-100	10
Heat-Flux $[MW/m^2]$	15-390	20-130
Boiling length $[m]$	1-5	2-6

Calculation results

- Statistical indicators

$$\xi = \frac{Q_{\mathrm{calc}}}{Q_{\mathrm{exp}}}$$

$$\Xi = \frac{Q_{\mathrm{calc}} - Q_{\mathrm{exp}}}{Q_{\mathrm{exp}}} = \xi - 1$$

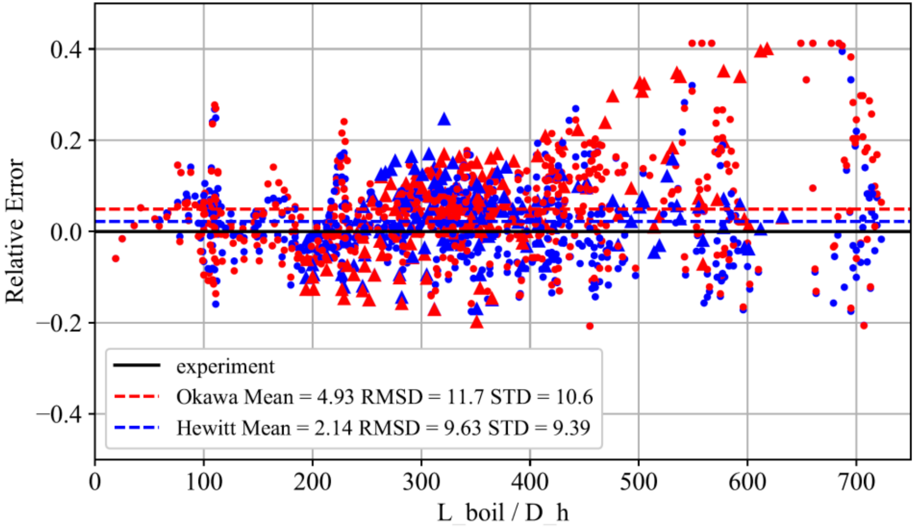
$$\mathrm{MEAN} = \overline{\Xi} = \frac{1}{N}\sum_{i}^{N} \Xi_i$$

$$\mathrm{RMSD} = \sqrt{\frac{1}{N}\sum_{i}^{N} (\xi_i - 1)^2}$$

$$\mathrm{STD} = \sqrt{\frac{1}{N-1}\sum_{i}^{N} (\xi_i - \overline{\xi})^2}$$

Calculation results

P	Mass Flux	$\frac{L_{boil}}{d_h}$	Mean[%] Okawa	Mean[%] Hewitt	RMSD[%] Okawa	RMSD[%] Hewitt	STD[%] Okawa	STD[%] Hewitt
30	0-1000	400-	4.14	-1.7	7.29	5.55	5.99	5.28
		400+	3.77	-3.3	8.91	6.30	8.07	5.36
	1000-2000	400-	15.0	8.57	16.0	11.3	5.65	7.36
		400+	21.4	4.35	22.2	5.31	5.80	3.03
	2000-3000	400-	8.64	5.35	10.4	7.71	5.94	5.55
		400+	26.0	-0.6	27.5	4.57	9.04	4.52
	3000+	400-	0.65	2.12	3.24	4.51	3.17	3.98
		400+	7.44	-9.6	7.54	10.4	1.24	3.98
50	0-1000	400-	-0.0	-2.7	5.78	6.96	5.78	6.40
		400+	1.60	-3.0	10.4	11.2	10.3	10.8
	1000-2000	400-	9.62	9.29	10.3	10.0	3.82	3.76
		400+	13.7	5.58	14.0	5.96	3.14	2.11
	2000-3000	400-	6.41	8.16	7.80	9.71	4.44	5.26
		400+	15.8	1.67	16.2	4.12	3.52	3.77
	3000+	400-	2.17	3.05	3.49	4.45	2.73	3.23
		400+	5.94	-6.5	7.30	9.20	4.24	6.48
70	0-1000	400-	1.54	0.45	5.67	7.10	5.46	7.09
		400+	-0.9	-4.8	8.20	9.07	8.15	7.64
	1000-2000	400-	7.00	8.82	8.50	9.97	4.83	4.66
		400+	15.0	13.9	15.8	14.5	4.90	4.14
	2000-3000	400-	0.06	1.17	2.70	3.69	2.70	3.50
		400+	5.00	4.48	7.47	6.08	5.54	4.12
	3000+	400-	-1.0	-0.1	5.00	5.14	4.89	5.14
		400+	-3.2	-5.6	4.04	6.87	2.34	3.86
100	0-1000	400-	-0.5	0.15	5.82	6.45	5.79	6.45
		400+	9.43	8.48	20.3	20.1	18.0	18.2
	1000-2000	400-	-2.6	-0.1	6.30	5.59	5.70	5.59
		400+	27.3	28.6	29.5	30.4	11.1	10.2
	2000-3000	400-	-7.3	-5.4	9.38	8.23	5.88	6.17
		400+	14.5	15.4	17.4	18.1	9.48	9.57
	3000+	400-	-1.8	-0.9	7.98	7.82	7.75	7.76
		400+	-9.6	-9.7	9.98	10.1	2.62	2.85
TOTAL			4.93	2.14	11.7	9.63	10.6	9.39



Results in other publications

- Gimeno et al. (2015) have compared predictions obtained with three codes: MEFISTO-T, GRAMP and SCADOP. In all codes the Hewitt and Govan (1990) set of correlations for the deposition and entrainment rates has been used and a single value of **IEF = 0.7** has been selected.
- To check the universality of the results presented in Table, similar calculations have been performed with the CATHARE-3 code, using the Hewitt-Govan set of correlations and employing a single value of **IEF= 0.7**.
- If we „zoom in" into the details of these numer (for CATHARE-3 at least), we will see that for different pressures, we have an interesting trend. With rising pressure, the results traverse from underprediction to overprediction
- In order to „tune" results to match the experiment, different value of IEF should be applied for different pressures.

	MEFISTO-T	GRAMP	SCADOP	CATHARE-3
Mean error	−1.86%	−2.94%	−3.06%	−1%
RMS error	6.15%	6.41%	5.89%	5.7%
σ	3.95%	3.61%	3.73%	5.3%

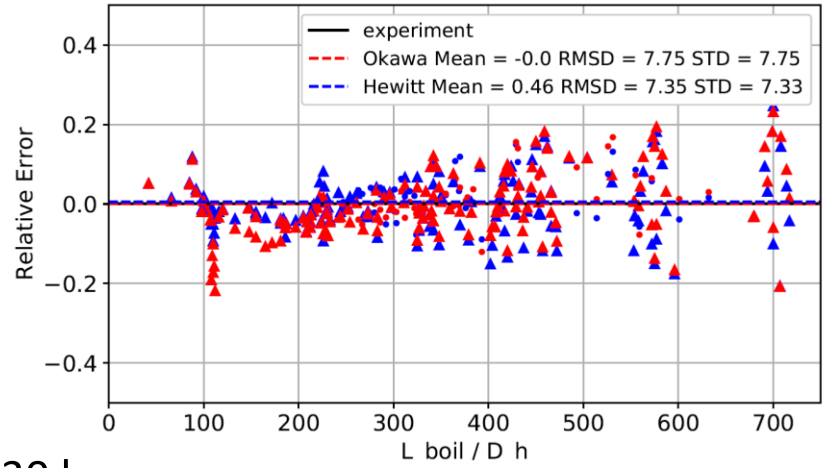
		Mean error [%]		
	IEF[%]	3 MPa	5 MPa	7 MPa
Hewitt-Govan	40	1.9	2.9	7.0
	50	**0.0**	**0.70**	6.4
	60	−2.5	−1.5	4.3
	70	−5.4	−3.3	3.5
	80	−6.6	−6.7	**0.53**
	90	−9.4	−9.1	−1.5
Okawa et al.	40	11.3	4.5	5.6
	50	7.8	3.5	4.8
	60	8.2	1.9	4.1
	70	5.6	**0.46**	3.1
	80	2.5	−2.3	**0.56**
	90	**-1.4**	−5.3	−1.7

Model	P [MPa]	IEF [%]	Mean [%]	RMSD	STD
Hewitt	3	30	−0.1	6.19	6.19
	5	40	0.0	6.94	6.94
	7	70	0.46	7.35	7.33
	total		0.11	6.89	6.89
Okawa	3	99	2.6	13.7	13.4
	5	90	−0.2	8.38	8.38
	7	90	0.0	7.75	7.75
	total		0.71	10.0	10.0

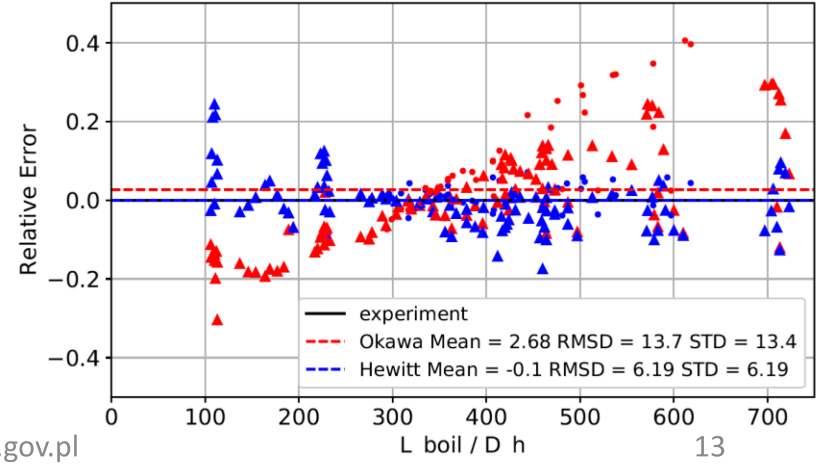
Error compensation

- Underprediction in one part compensates for overprediction on different part.
- This happened when „good” mean error was achieved for Okawa et al.
- Good global mean error can hide bad results
- This compensation can occur in other plots.
  - vs mass flux
  - vs pressure

P = 70 bar

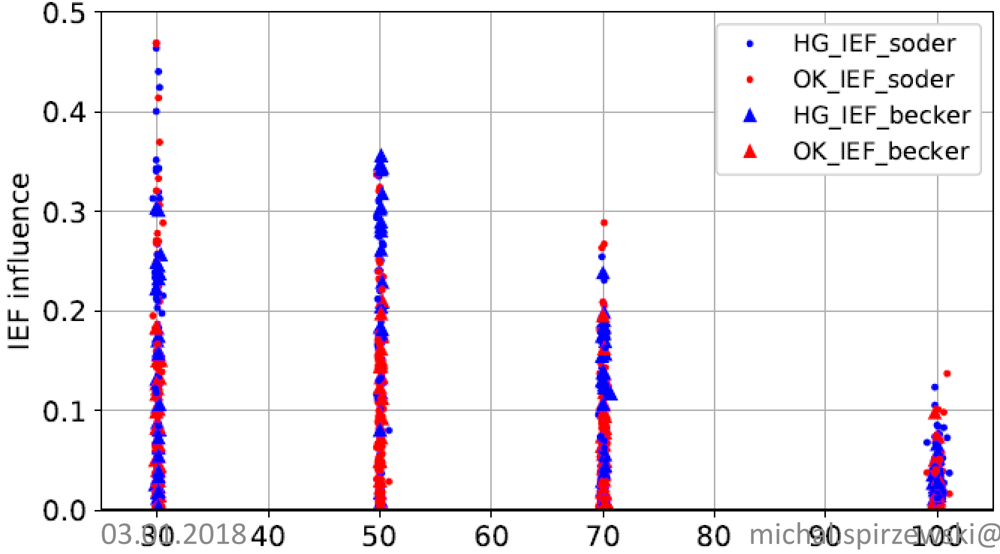


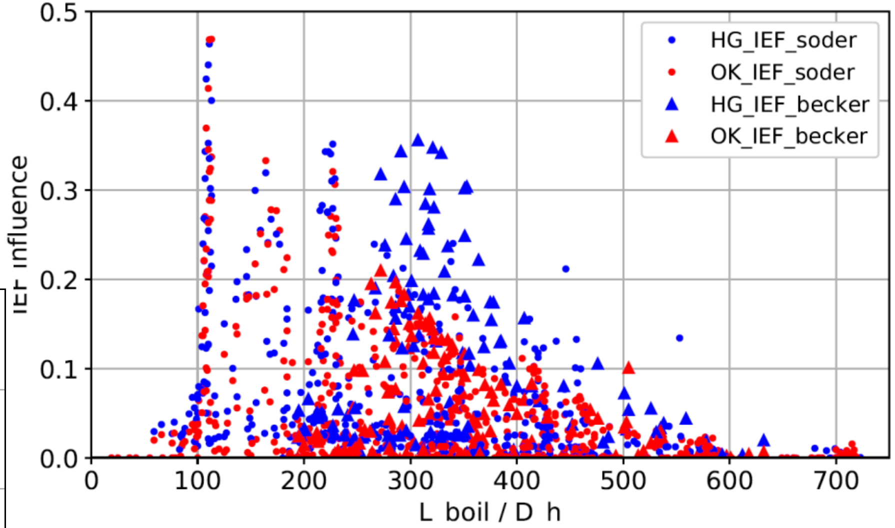
P = 30 bar



Sensitivity to Initial Entrained Fraction

$$\Delta\xi_{\mathrm{IEF}} = \xi|_{\mathrm{IEF}=0} - \xi|_{\mathrm{IEF}=0.99}$$
$$= \frac{Q_{calc,\mathrm{IEF}=0} - Q_{calc,\mathrm{IEF}=0.99}}{Q_{\exp}}$$





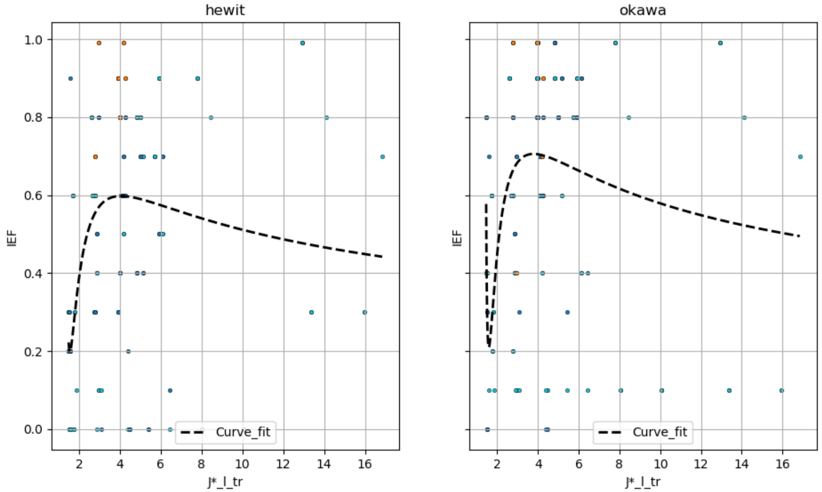
Proposed IEF correlation

$$IEF = A \cdot (J^*_{l,tr})^B + C \cdot (J^*_{g,tr} - J_{g,0})^D$$

$$J^*_k = J_k \sqrt{\frac{\rho_k}{g D_h (\rho_l - \rho_g)}}$$

- Dataset selection
  - smallest value of L_b/D_h parameter for each possible combination of
    - Pressure
    - mass flux
    - hydraulic diameter

- For each of aforementioned combination an optimal IEF is estimated from IEF sensitivity.



Models	Parameters				
	A	B	C	D	$J_{g,0}$
Hewitt	−4.946	−1.8926	1.0222	−0.2982	1.346
Okawa	−7.5	−2.185	1.1368	−0.3	1.4

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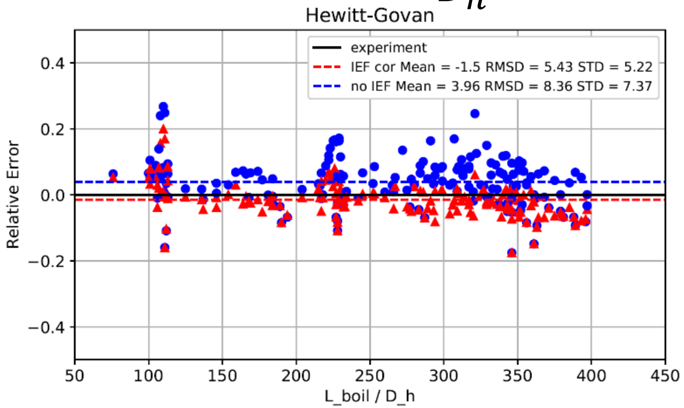
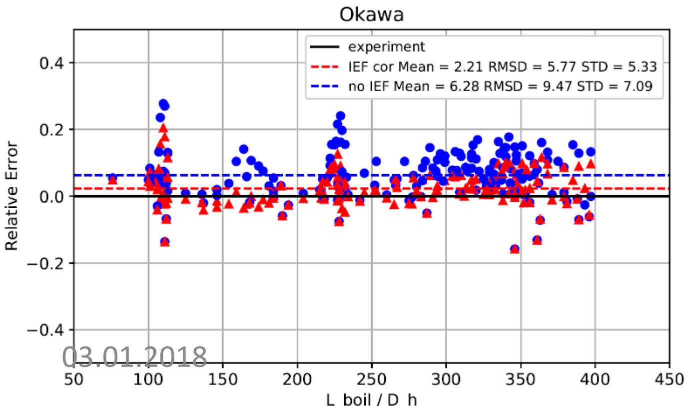
Improvement

- Values of mean relative error for experiments with $\frac{L_b}{D_h} < 400$





		Hewitt		Okawa	
P	Mass Flux	IEF=0	new IEF	IEF=0	new IEF
3	0-1000	−1.8	−3.5	4.14	1.29
	1000-2000	8.57	−0.2	15.0	7.04
	2000-3000	5.35	−3.1	8.64	5.08
	3000+	2.12	−2.5	0.65	−0.3
	subtotal	3.84	−2.2	8.80	4.10
5	0-1000	−2.7	−5.2	−0.0	−3.2
	1000-2000	9.14	1.04	9.65	3.01
	2000-3000	8.16	0.54	6.41	3.38
	3000+	3.05	1.15	2.17	1.54
	subtotal	4.04	−0.9	4.48	0.89
7	0-1000	0.45	−2.1	1.54	−1.0
	1000-2000	8.82	4.81	7.00	4.08
	2000-3000	1.17	−0.6	0.06	−0.9
	3000+	−0.1	−1.2	−1.0	−1.4
	subtotal	2.90	0.41	2.26	0.29
10	0-1000	0.15	−1.2	−0.5	−2.1
	1000-2000	−0.1	−2.2	−2.6	−3.6
	2000-3000	−5.4	−7.2	−7.3	−7.6
	3000+	−0.9	−1.8	−1.8	−1.9
	subtotal	−1.7	−3.4	−3.4	−4.1

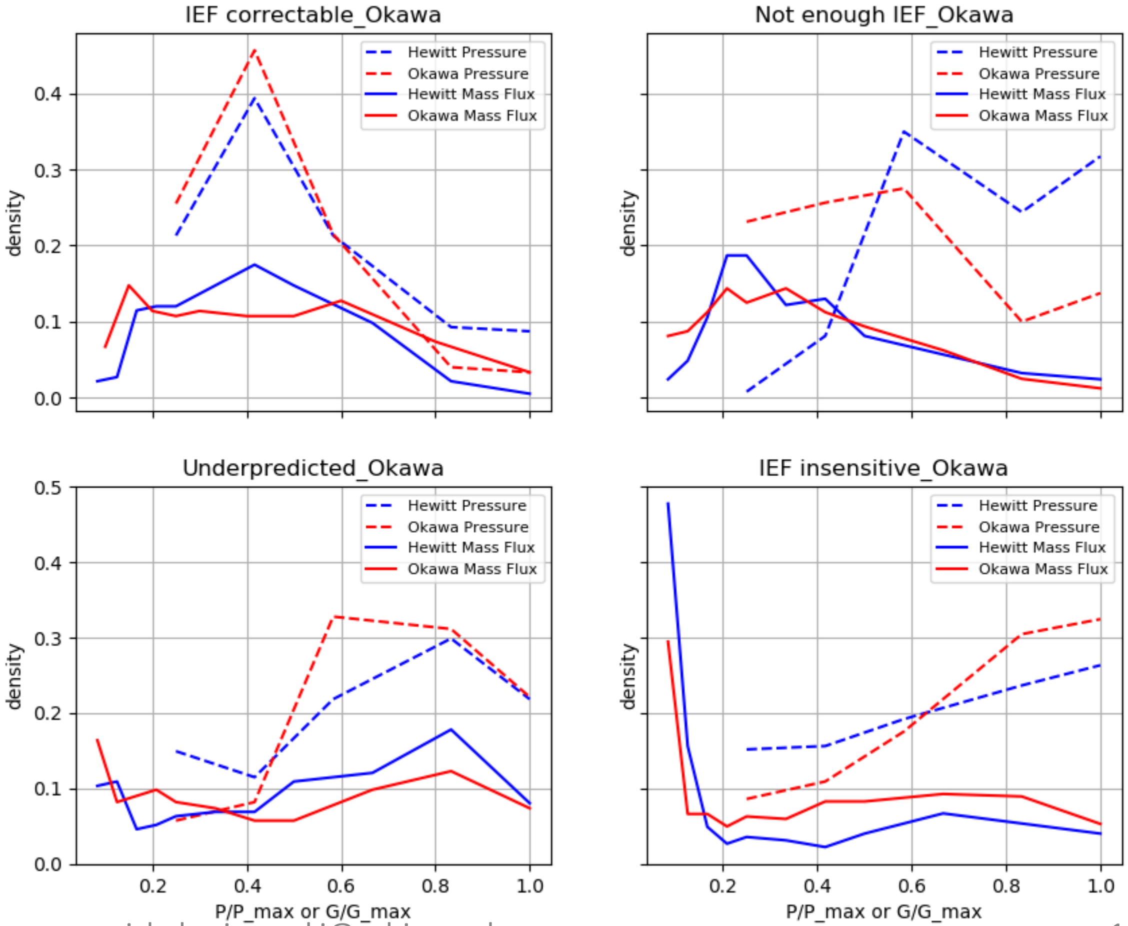
4 group classification

1. Prediction error can be eliminated by choosing an optimal IEF **(IEF correctable).**
2. $\Delta IEF > 0$ but it is insufficient to match Q_{exp} thus, Q_{calc} is always over-predicted **(Always over-predicted).**
3. Q_{calc} is always under-predicted **(Always under-predicted)**.
4. Predicted critical power is insensitive to IEF (**IEF insensitive**).

- Group 1 Area of current work
- Group 2 contains cases where error elimination partially depends on IEF modication and partially on (E-D) rates models. However, the inuence of the latter is dominant.
- Groups 3 and 4 represent cases where implementation of IEF would not improve results.
- This indicates that other models should be employed.

Group	Hewitt-Govan		Okawa et al.	
	Soderquist	Becker	Soderquist	Becker
IEF correctable	183 (26%)	68 (43%)	149 (20%)	46 (29%)
Always overpredicted	123 (17%)	31 (20%)	160 (22%)	39 (24%)
Always underpredicted	174 (25%)	45 (28%)	122 (17%)	23 (14%)
IEF insensitive	224 (32)	16 (10%)	302 (41%)	53 (33%)

4 group classification – Soderquist PDF’s



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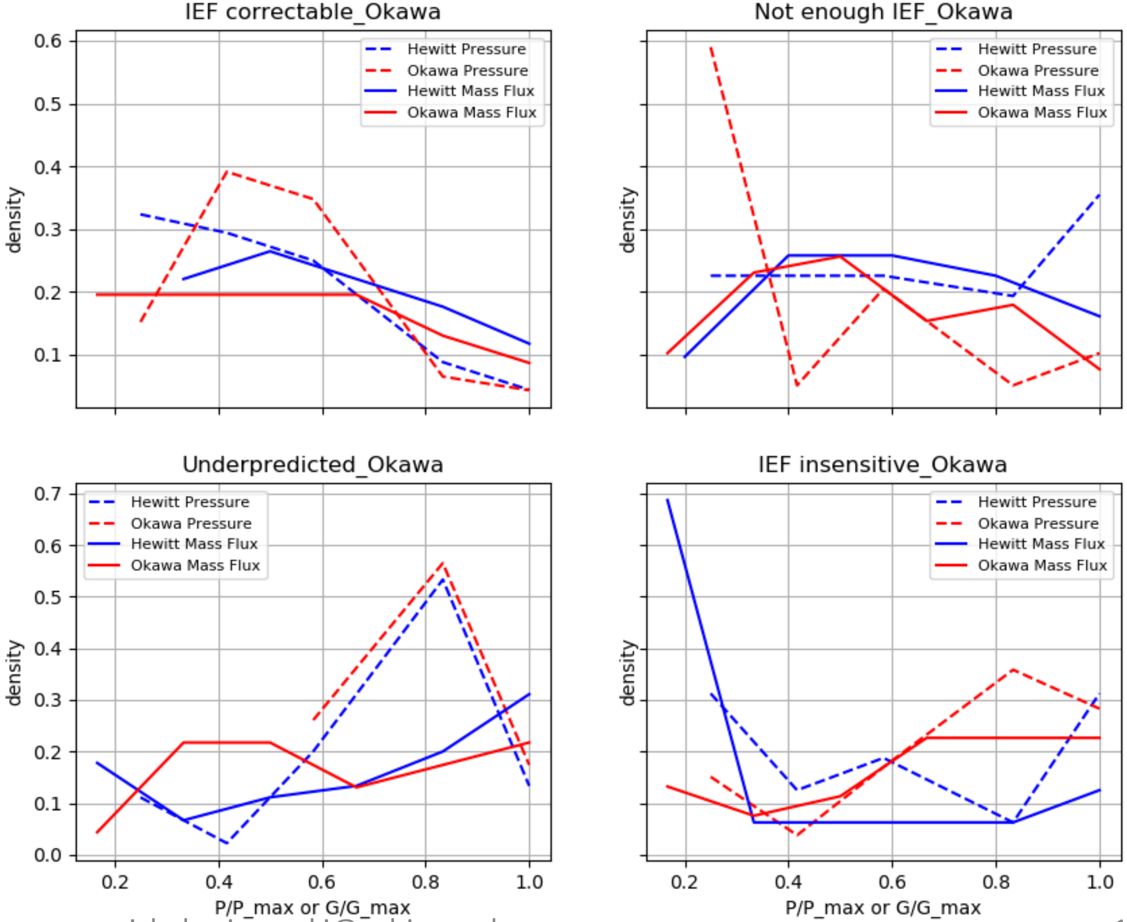
4 group classification – Becker PDF’s



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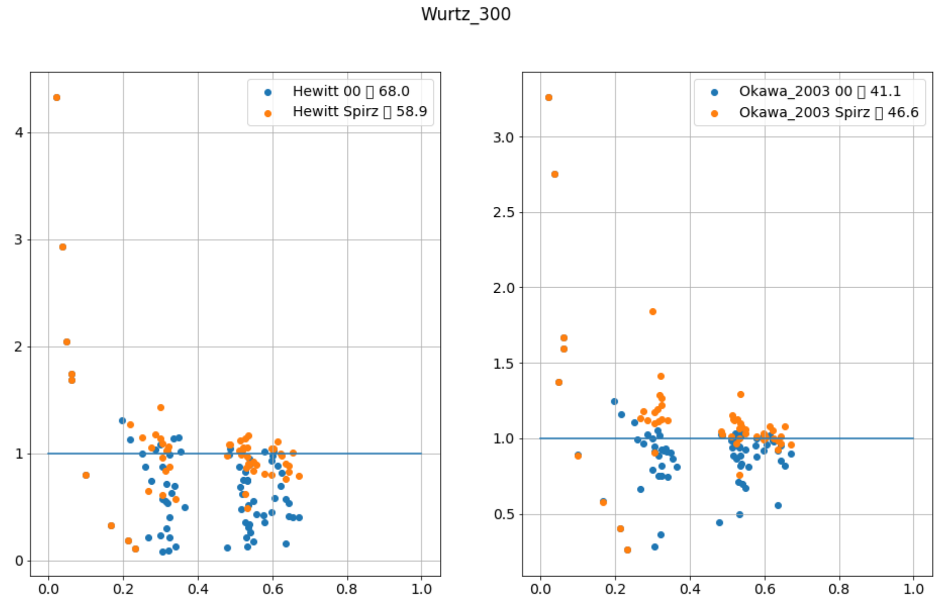
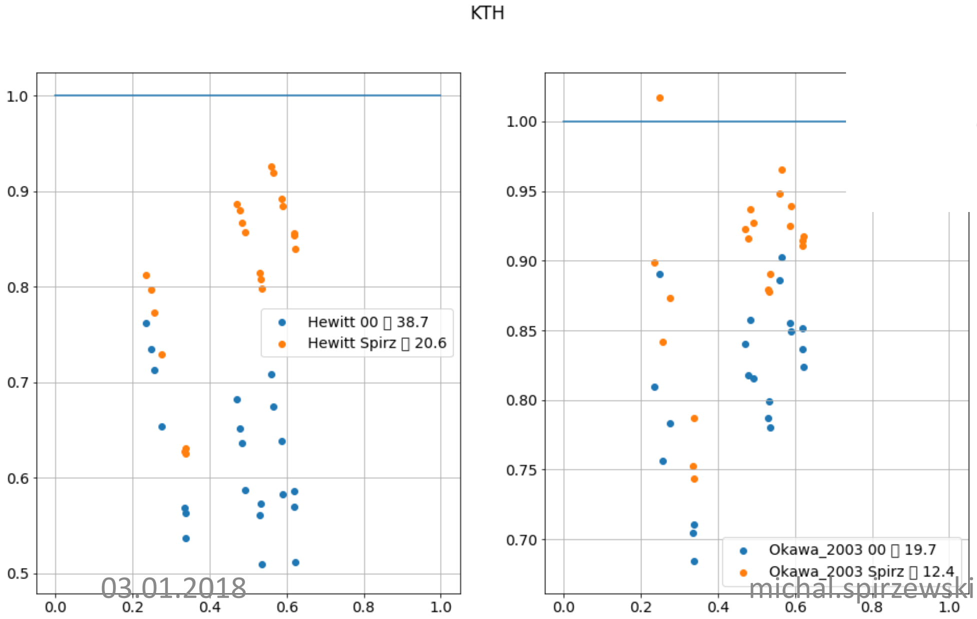
Wurtz 300 / KTH validation





Okawa 2004 correlation

$$\pi_e = \frac{f_i \rho_g J_g^2}{(\sigma/\delta)}$$

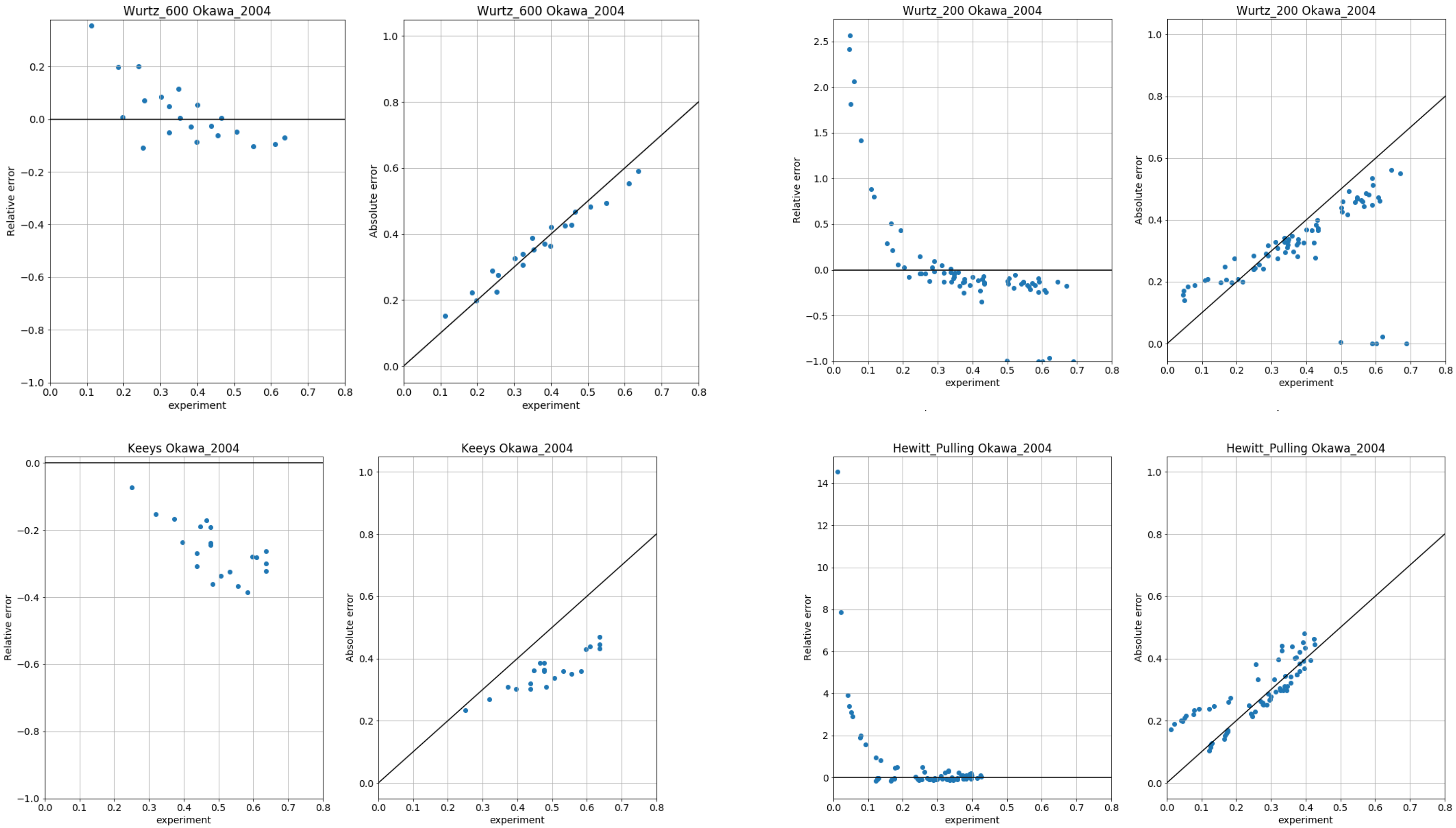
$$m_{es} = k_e \rho_l \pi_e^n$$

- It will undergo the same validation procedure as the one presented

$$k_e = 3.1 \times 10^{-2}\ \text{m/s and } n = 2.3 \quad \text{for } \pi_e < 0.0675$$

$$k_e = 1.6 \times 10^{-3}\ \text{m/s and } n = 1.2 \quad \text{for } 0.0675 < \pi_e < 0.295$$

$$k_e = 6.8 \times 10^{-4}\ \text{m/s and } n = 0.5 \quad \text{for } \pi_e > 0.295$$


Wurtz_600 Okawa_2004
Relative error
experiment
Wurtz_600 Okawa_2004
Absolute error
experiment
Wurtz_200 Okawa_2004
Relative error
experiment
Wurtz_200 Okawa_2004
Absolute error
experiment
Keeys Okawa_2004
Relative error
experiment
Keeys Okawa_2004
Absolute error
experiment
Hewitt_Pulling Okawa_2004
Relative error
experiment
Hewitt_Pulling Okawa_2004
Absolute error
experiment

Further work

- Further
  - IEF sensitivity for Okawa et al. 2004 and IEF correlation development.
  - More detailed analysis of 4 group classification
  - Other entrainment and deposition models to be analysed
  - Influence of hydraulic diameter on IEF needs to be analysed.

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