Two-phase Flow Across Sudden Expansion/Contractions

Chi-Chuan Wang*, PhD (ccwang@mail.nctu.edu.tw)
Fellow ASME, Fellow ASHRAE

*Currently a professor @ Department of Mechanical Engineering, National Chiao Tung University, Hsinchu, Taiwan. The work was presented as a Keynote lecture in HEAT 2008 (the Fifth International Conference on Transport Phenomena in Multiphase Systems, June 30 - July 3, 2008, Bialystok, Poland) when the author was a senior lead researcher in Industrial Technology Research Institute.

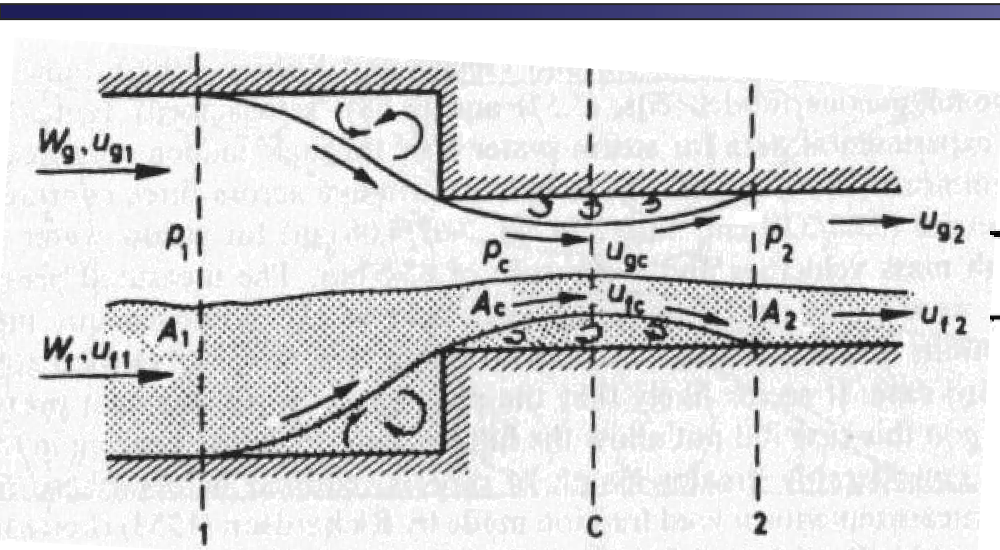
Outline

- Introduction
- Correlation Review
  - Two-phase pressure change across sudden enlargement
  - Two-phase pressure change across sudden contraction
- Experimental setup
- Results and Observations
- Correlation Assessment
- Conclusions

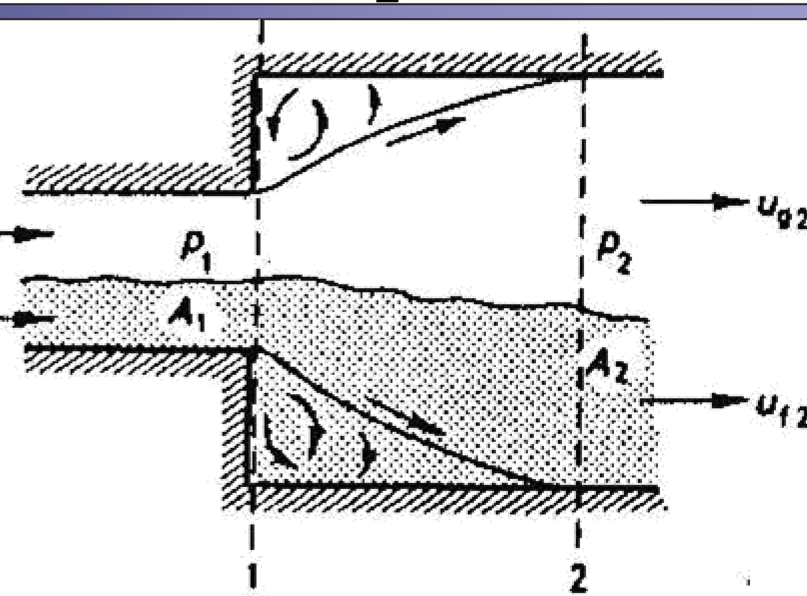
Introduction

- Fluid flow across singularity such as sudden expansion/contraction are is quite common in typical heat exchanging devices/piping connections. Irreversible pressure loss accompanies with these singularities.
- However, the pressure loss is recognized as minor loss when comparing to major frictional loss. This is often valid in macro tube systems but is questionable in mini/micro tube systems.
- For smaller heat exchanging device (e.g. micro heat exchangers). This loss becomes more pronounced and may be as high as 5-20% depending on the contraction ratio and flow rate. The loss becomes even worse for two-phase system (exceeds 35~40% in extreme cases).

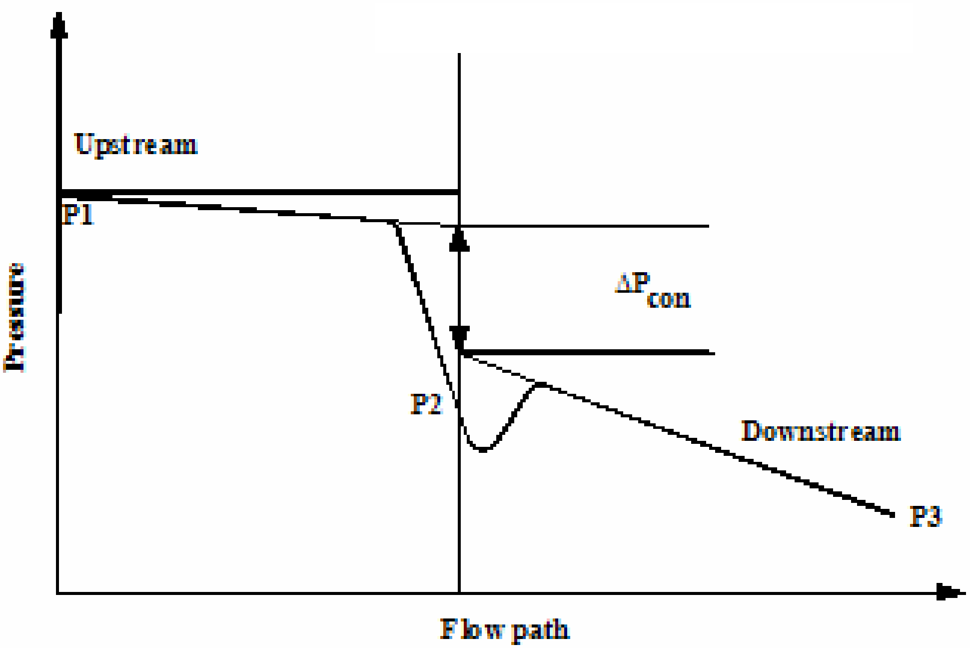
Two-phase flow across contractions/expansions

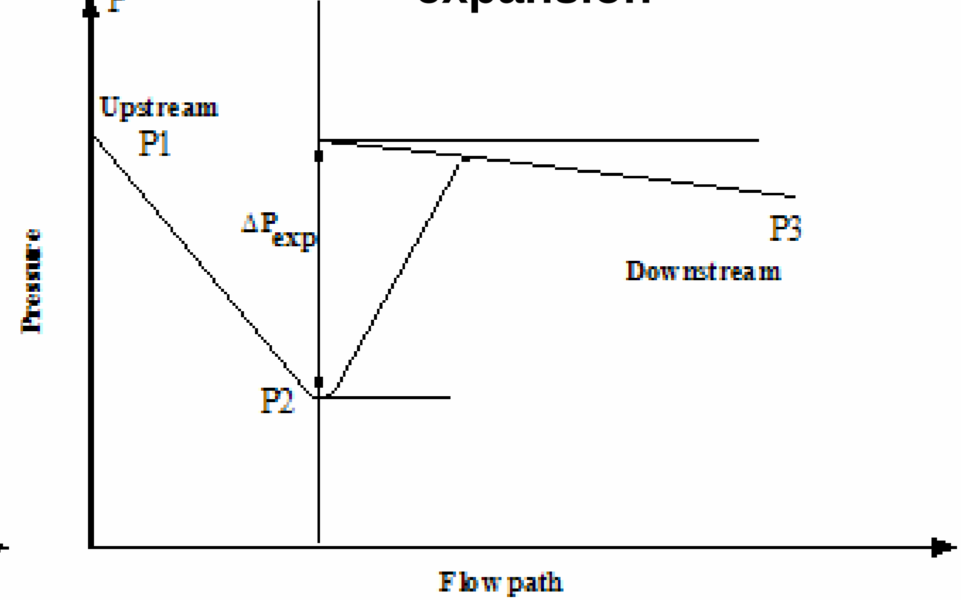


contraction



expansion





Motivations of this study

- Comparatively rare data subject to sudden area change in mini/micro channels.
- Therefore the objectives of this study includes:
  - To provide the new data in this range. (mini channels)
  - Assessment of the existing correlations.
  - To develop the a modified predictive method that is capable of predicting the present database and existing data.

Estimation of Pressure drop - Single phase flow

- By combining the pressure balance equation, the static pressure difference subject to the sudden expansion is related to the kinetic energy of the flow:

σ_A: contraction ratio

G: mass flux

$$\Delta P_e \Big/ \frac{G^2}{2\rho} = -2\sigma_A\left(1-\sigma_A\right)$$

- Sudden contraction is normally in terms of the contraction loss coefficient (K) and multiplication of kinetic energy of the fluid flow:

$$\Delta P_c \Big/ \frac{G^2}{2\rho} = K$$

Some correlations/models for 2-phase flow

◆ **Sudden Expansion**

※Schmidt and Friedel-1996

※Homogeneous Model

※Chisholm and Sutherland- 1969

※Wadle-1989

※Abdelall-2005

※Richardson-1958

※Lottes-1960

※Attou and Bolle-1997

※Romie-1958

◆ **Sudden Contraction**

※Schmidt and Friedel-1997

※Homogeneous Model

※Chisholm-1967

※Abdelall-2005

Correlations for sudden expansion

Attou and Bolle (1997)

$$\Delta P_e = -\sigma_A(1-\sigma_A)\theta_\sigma^r G^2\Phi + \frac{(1-\theta_\sigma^r)\sigma_A(1-\sigma_A)G^2}{\rho_L}$$

Abdelall et al. (2005)

$$\Delta P_e = \Delta P_{eI} - \Delta P_{eR} = 0.5\rho_L G^2\left[\frac{2\rho_L\sigma_A(\sigma_A-1)}{\rho'} - \frac{\rho_h\sigma_L(\sigma_A-1)}{\rho''^2}\right] - \frac{-0.5\rho_h G^2(1-\sigma_A^2)}{\rho''^2}$$

Chisholm and Sutherland (1969)

$$\Delta P_e = -G^2\sigma_A(1-\sigma_A)(1-x)^2\left[\frac{(1+C_h/X+1/X^2)}{\rho_L}\right]$$

Homogeneous Model

$$\Delta P_e = -G^2\sigma_A(1-\sigma_A)\left[\frac{(1-x)}{\rho_L}+\frac{x}{\rho_G}\right]$$

Lottes (1961)

$$\Delta P_e = \frac{-G^2\sigma_A(1-\sigma_A)}{\rho_L(1-\alpha)^2}$$

Richardson (1958)

$$\Delta P_e = -0.5G^2(1-\sigma_A^2)\left[\frac{\sigma_A(1-x^2)}{\rho_L(1-\alpha)}\right]$$

Romie (1958)

$$\Delta P_e = \frac{-G^2\sigma_A(1-\sigma_A)}{\rho_L}\left[\frac{(1-x)^2}{(1-\alpha)}+\frac{(\rho_L/\rho_G)x^2}{\alpha}\right]$$

Schmidt and Friedel (1996)

$$\Delta P_e = \frac{G^2\left[\frac{\sigma_A}{\rho_{eff}} - \frac{\sigma_A^2}{\rho_{eff}} - f_e\rho_{eff}\left(\frac{x}{\rho_G\alpha} - \frac{(1-x)}{\rho_L(1-\alpha)}\right)(1-\sqrt{\sigma_A})^2\right]}{1-\Gamma_e(1-\sigma_A)}$$

Wadle (1989)

$$\Delta P_e = -(1-\sigma_A^2)\frac{1}{2}\dot{m}^2K\left[\frac{(1-x)^2}{\rho_L}+\frac{x^2}{\rho_G}\right]$$

Correlations applicable for sudden contraction

Abdelall et al. (2005)

$$\Delta P_c = G^2 \left\{ \frac{\rho_h \left(\frac{1}{{C_C}^2} - {\sigma_A}^2 \right)}{2\rho''^2} + \frac{\left(1 - C_C\right)}{\rho'} \right\}$$

Chisholm (1983)

$$\Delta P_c = \Delta P_{cL} \left[1 + \left(\frac{\rho_L}{\rho_G} - 1 \right) (Bx\left(1 - x\right) + x^2) \right]$$

Homogeneous Model

$$\Delta P_c = \left(\frac{G^2}{2\rho_L} \right) \left[\left({C_C}^{-1} - 1 \right)^2 + \left(1 - {\sigma_A}^2 \right) \right] \left[1 + x\left(\frac{\rho_L}{\rho_G} - 1 \right) \right]$$

Schmidt and Friedel (1997)

$$\Delta p_c = \frac{G^2 [\frac{1}{\rho_{eff}} - \frac{\sigma_A}{\rho_{eff}} + f_{con}\rho_{eff} (\frac{x}{\rho_G \alpha} - \frac{1-x}{\rho_L (1-\alpha)})^2 (1 - {\sigma_A}^{1/2})^2]}{1 + \Gamma_{con} (\frac{1}{\sigma_A} - 1)}$$

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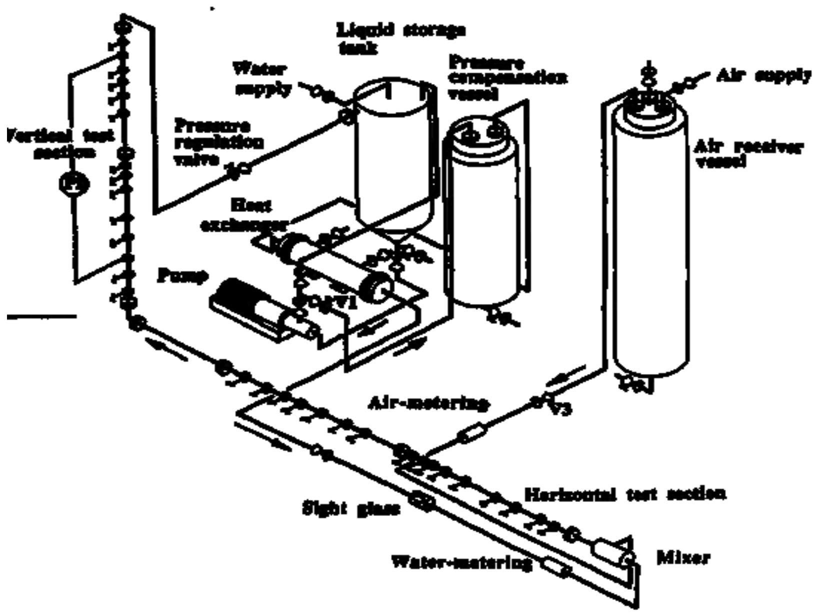
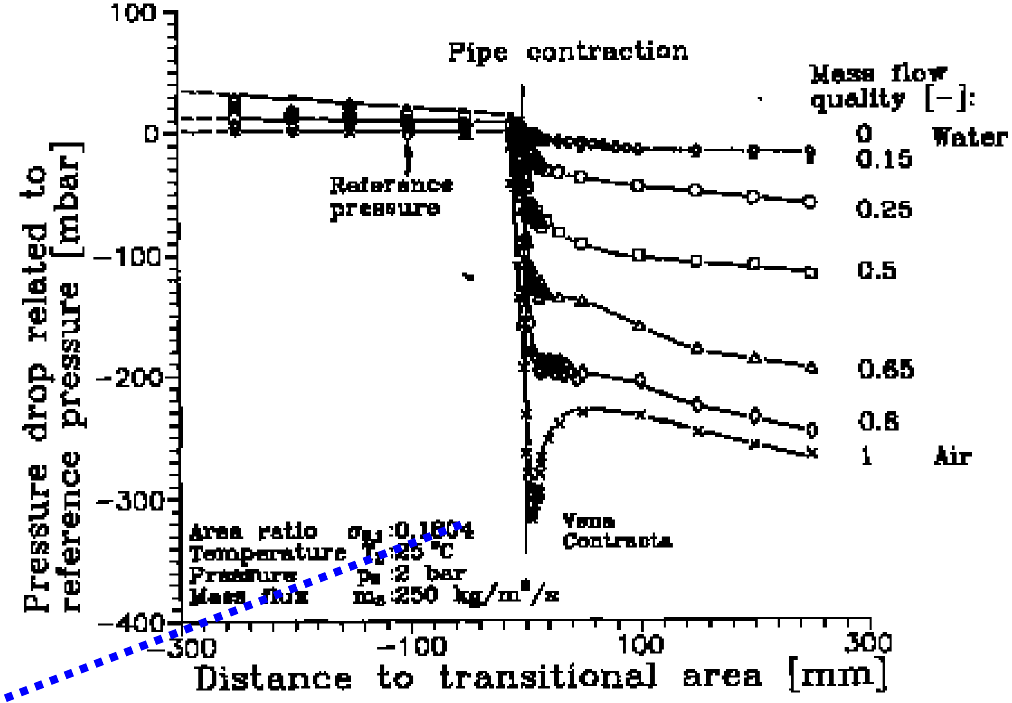
Sudden Contraction -Schmidt and Friedel



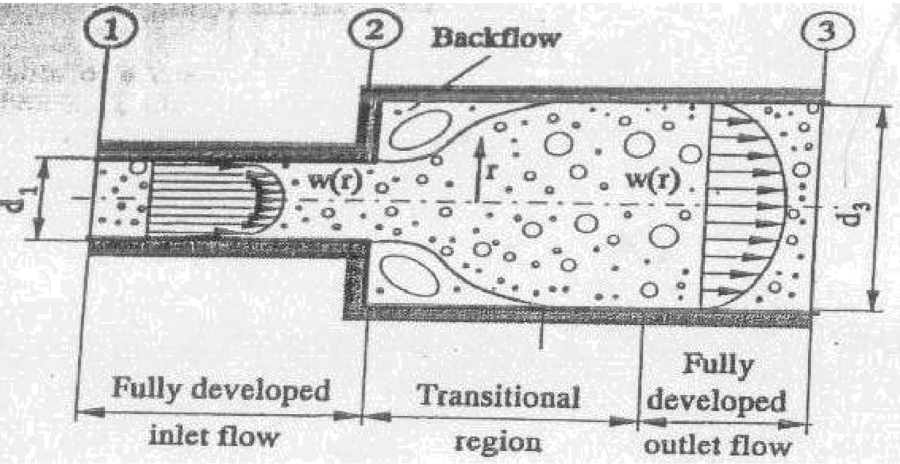


Area Ratio	Inner Pipe diameter	
	Inlet (mm)	Outlet (mm)
0.057	17.2	72.2
0.115	19.0	56.0
0.167	29.5	72.2
0.180	24.0	56.5
0.276	29.5	56.2
0.375	44.2	72.2
0.445	29.5	44.2
0.619	44.2	56.2

- ***Sudden Contraction***

$$\Delta p_{con} = \frac{G^2[\frac{1}{\rho_{eff}} - \frac{\sigma_A}{\rho_{eff}} + f_{con}\rho_{eff}(\frac{x}{\rho_G\alpha} - \frac{1-x}{\rho_L(1-\alpha)})^2(1-\sigma_A^{1/2})^2]}{1+\Gamma_{con}(\frac{1}{\sigma_A}-1)}$$

Sudden Expansion-Schmidt and Friedel



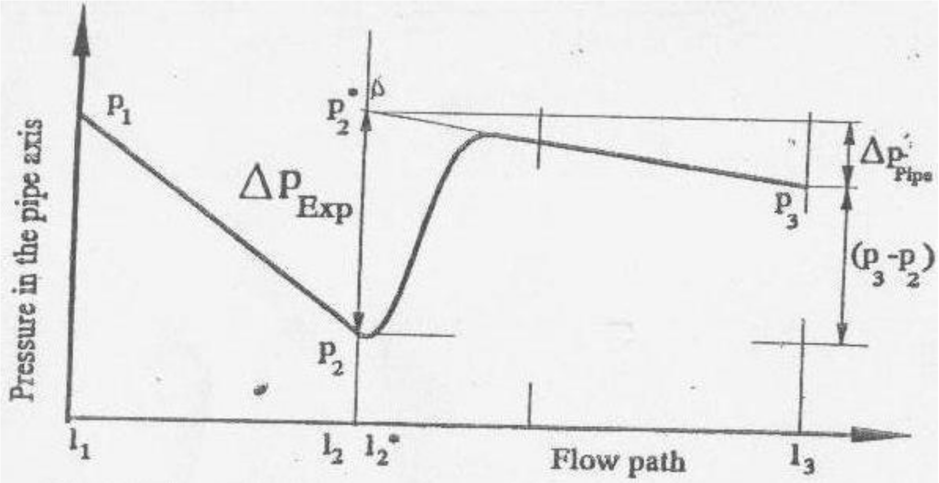


FIGURE 2.1 Idealized streamlines and static pressure in a pipe expansion.

Area Ratio	Inner Pipe diameter	
	Inlet (mm)	Outlet (mm)
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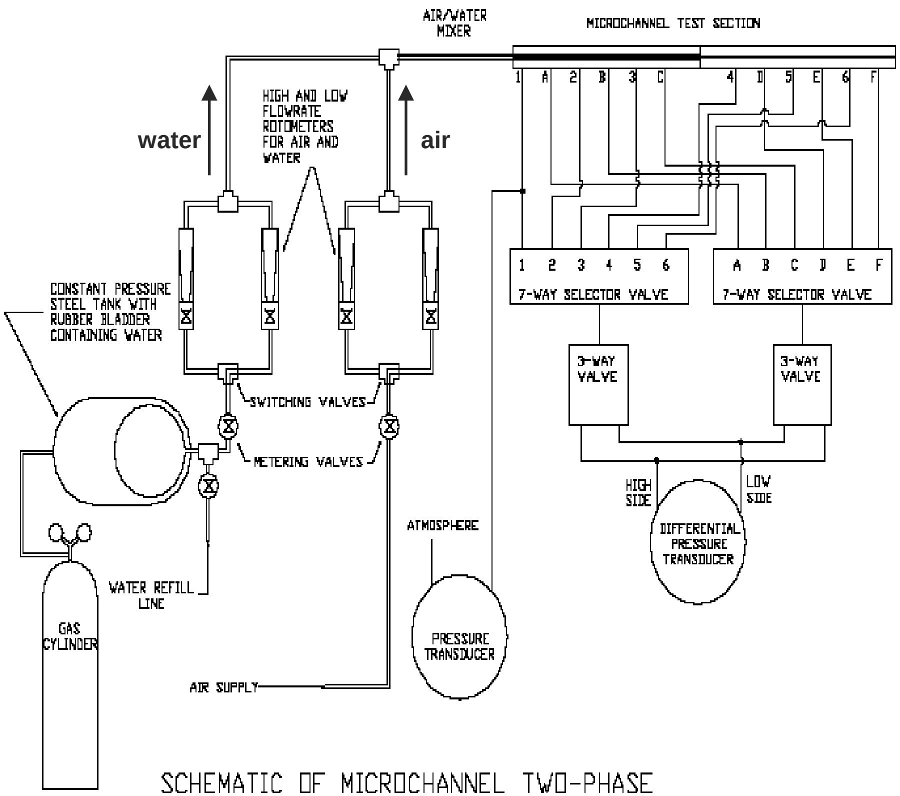
0.619	44.2	56.2

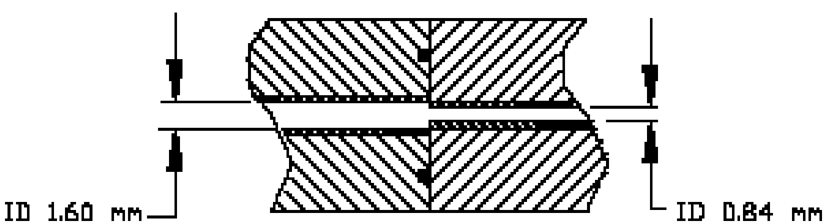
- ***Sudden Expansion***

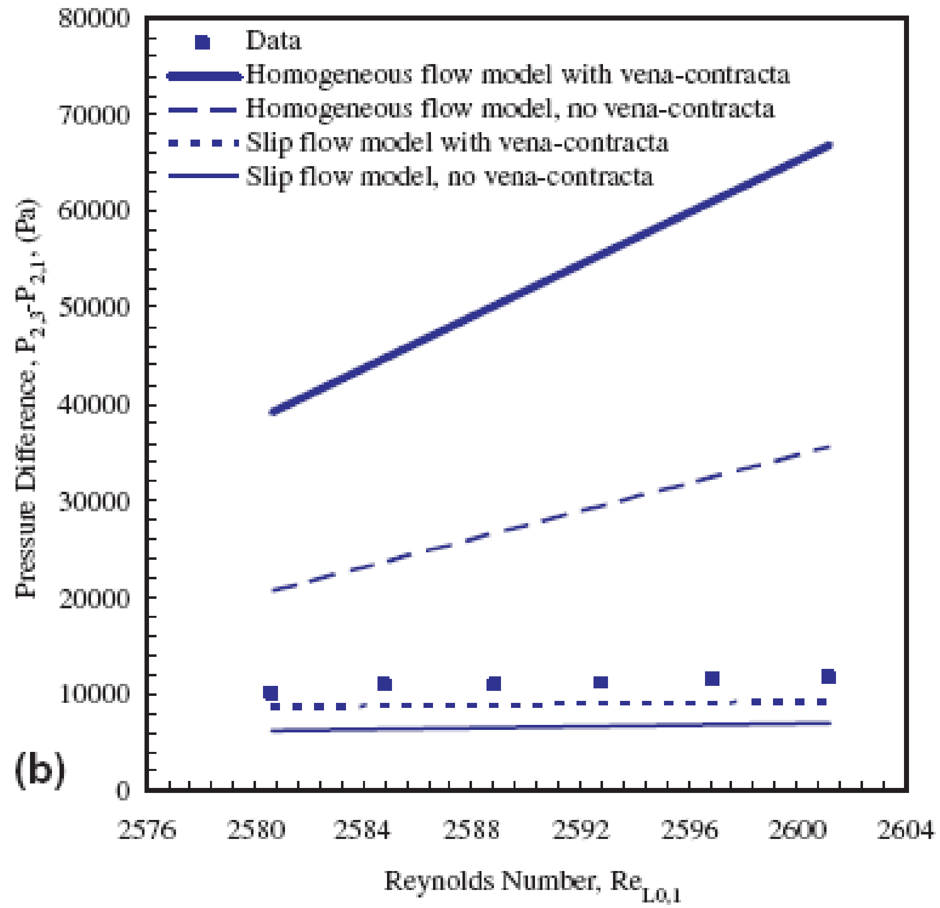
$$\Delta p_e = \frac{G^2\left[\frac{\sigma_A}{\rho_{eff}} - \frac{\sigma_A^2}{\rho_{eff}} - f_e \rho_{eff}\left(\frac{x}{\rho_G \alpha} - \frac{1-x}{\rho_L (1-\alpha)}\right)(1-\sigma_A^{1/2})^2\right]}{1-\Gamma_e(1-\sigma_A)}$$

Sudden Contraction-Abdelall Micro tubes



SCHEMATIC OF MICROCHANNEL TWO-PHASE PRESSURE DROP TEST FACILITY

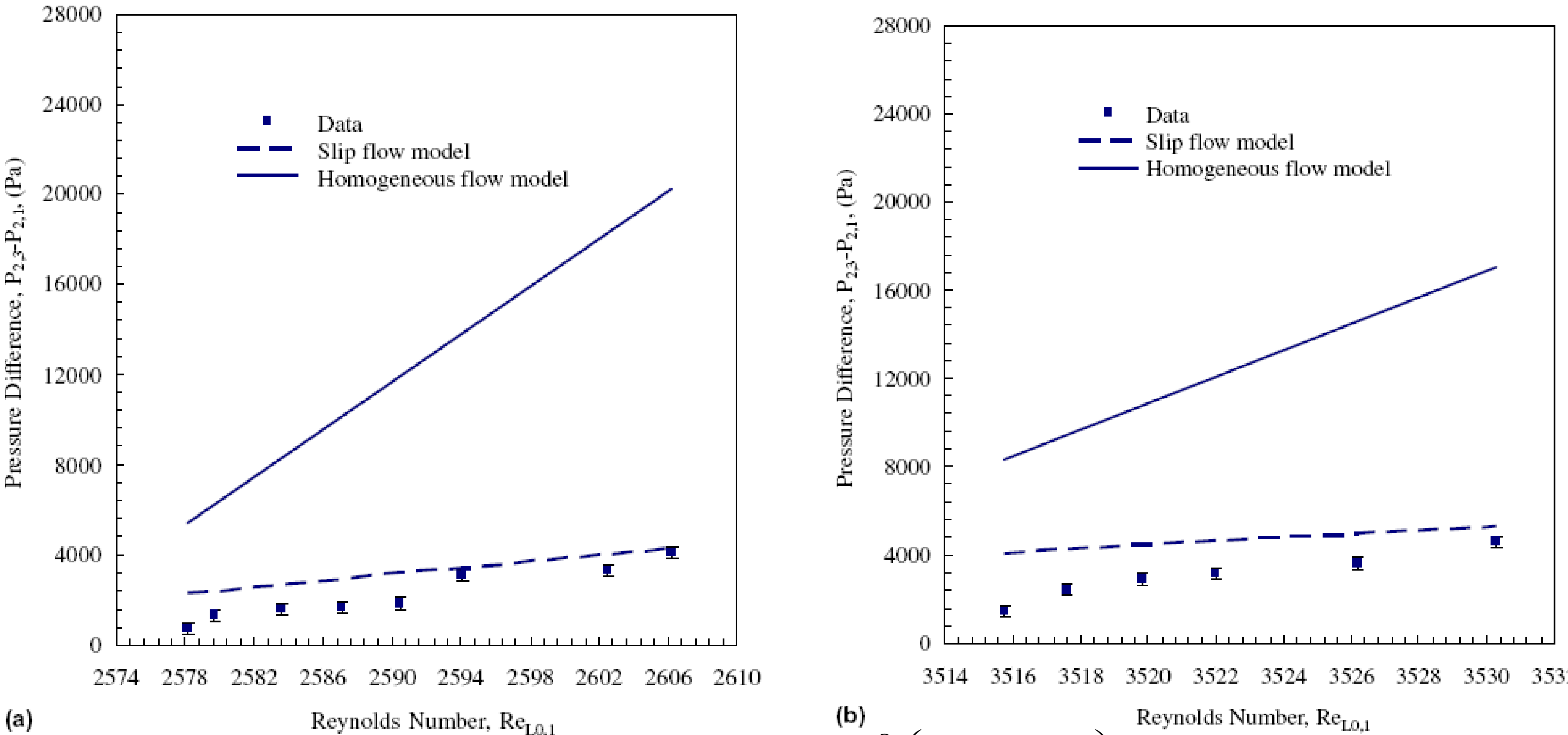




- ***Sudden Contraction***

$$\Delta P_c = G_1^2 \left\{ \frac{\rho_h}{2\rho'^2} \left(\frac{1}{C_c^2} - \sigma^2 \right) + \frac{1}{\rho'} (1 - C_c) \right\}$$

Sudden Expansion-Abdelall



- ***Sudden Expansion***

$$\Delta P_{e,R} = \frac{G^2}{2}\left(\frac{1}{\rho''^2} - \frac{\sigma_A}{\rho''^2}\right)$$

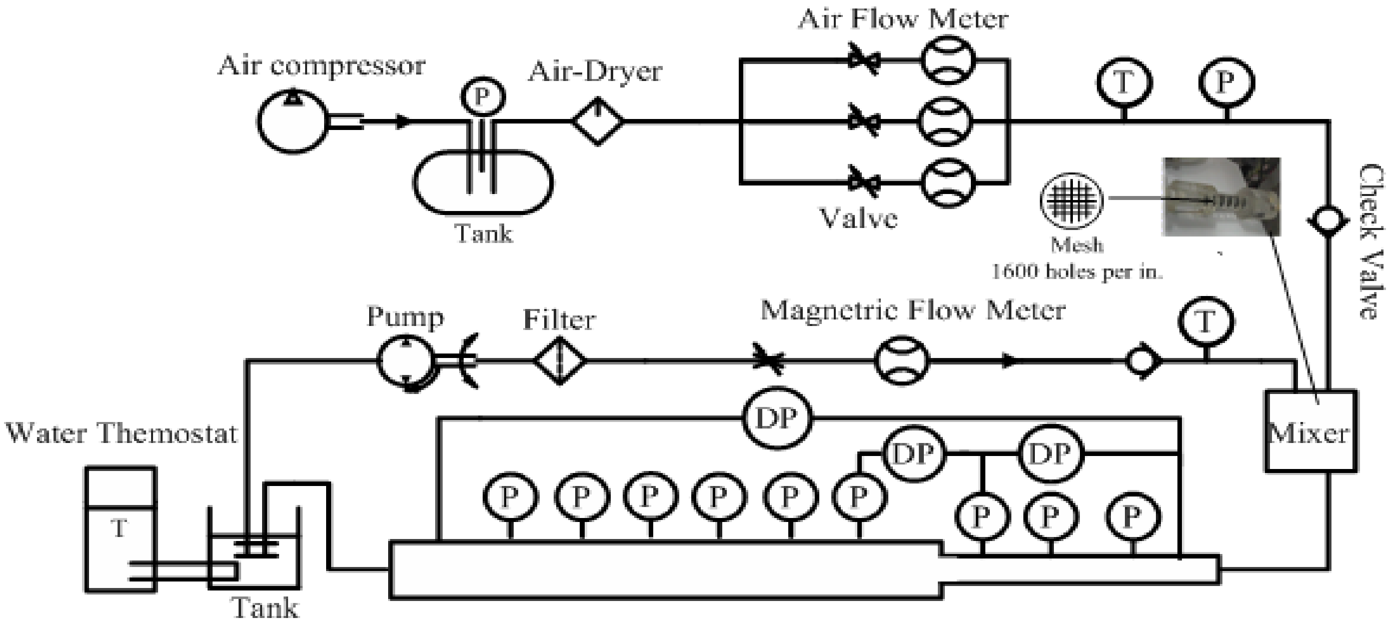
$$\Delta P_{e,I} = \frac{G^2}{2\rho_L}\left[\frac{2\rho_L\sigma_A(\sigma_A - 1)}{\rho'} - \rho_h\frac{\rho_L}{\rho''}(\sigma_A - 1)\right]$$

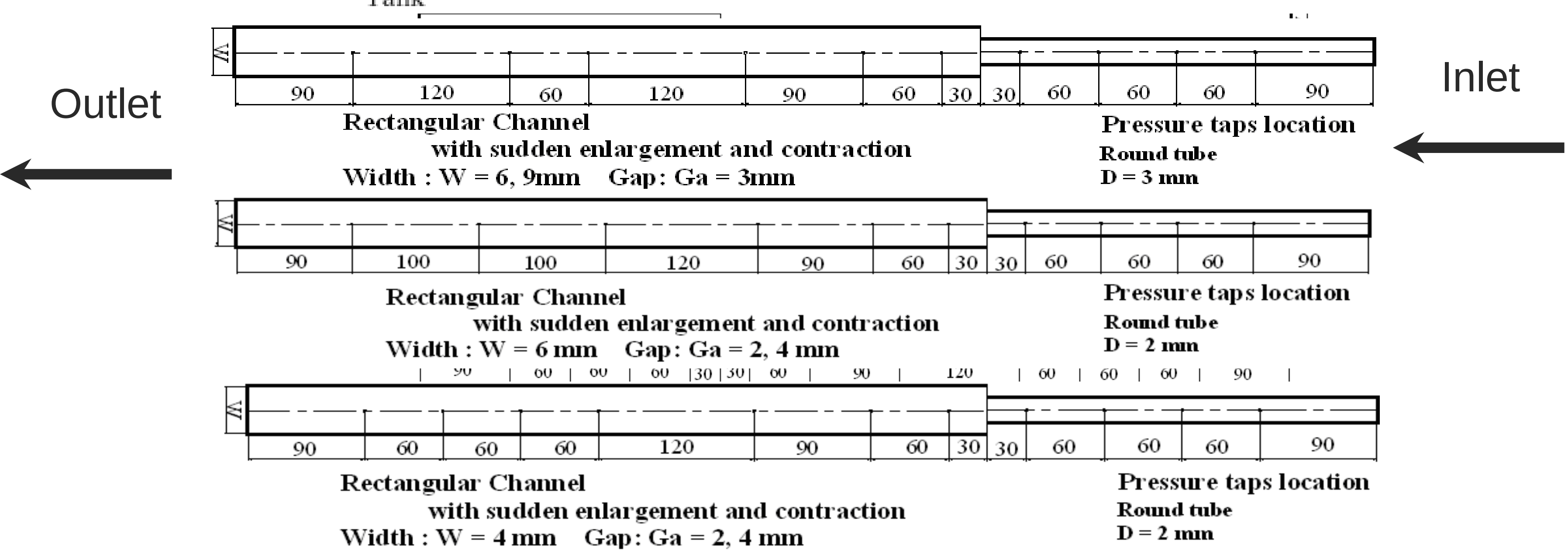
$$\Delta P_e = \Delta P_{eR} - \Delta P_{eI}$$

Some comments

- Correlations developed by previous researchers are generally applicable for their own database only. Extending the correlation outside their database are not recommended.
- A preliminary screening indicates the deviation for expansion amid different sources is much larger in association with data for contraction.

Schematic for Experimental setup for expansion

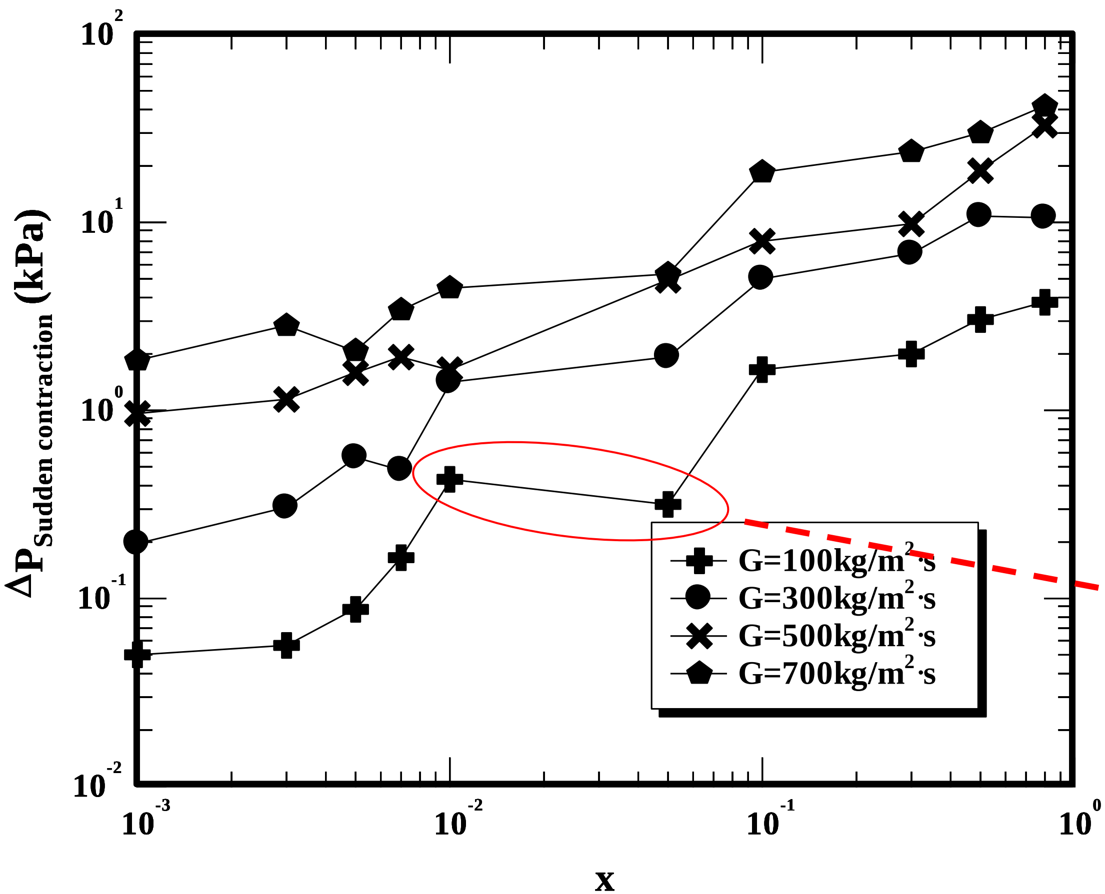




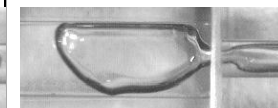
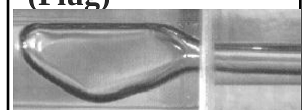
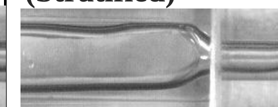
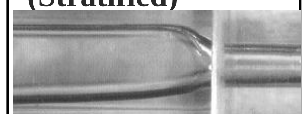
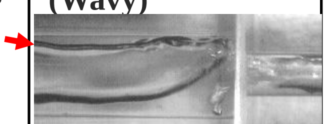
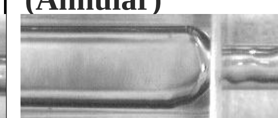
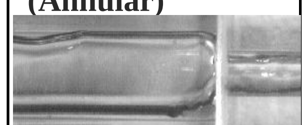
Some database collected for comparisons - contractions

Researchers	Geiger(1964) 3 tubes	McGee(1966) 2 tubes	Schmidt & Friedel(1997) 1 tube	Abdellal (2005) 1 tube	Present Data 6 tubes
Mass flux (kg/m^2s)	①2313-8116 ②4013-12682 ③6941-21448	①3251-6471 ②1778-4421	①500-4000	①2700-6200	100-700
Quality	①0.0117-0.265 ②0.0001-0.245 ③0.0001-0.159	①0-0.981 ②0-0.323	①0.01-0.90	①$1.9x10^{-4}$-$1.6x10^{-3}$	0.001-0.8
Working fluid	Steam-Water at 194-241 °C	Steam-Water at 141-195 °C	Air-Water at 25 °C	Air-Water at 25 °C	Air-Water at 25 °C
Hydraulic Diameter (mm)	①9.70-25.53 ②12.88-25.53 ③16.10-25.53	①8.64-11.68 ②11.68-14.99	①17.2-72.2	①0.84 -1.6	①2-2.67 ②2-4 ③2-3 ④2-4.8 ⑤3-4 ⑥3-4.5
Contraction ratio	①0.144 ②0.253 ③0.398	①0.546 ②0.608	①0.057	①0.26	①0.39 ②0.19 ③0.26 ④0.13 ⑤0.39 ⑥0.26
Bond number	7-19	15-55	9.988	0.024	0.13-0.29
Test Points	210	44	77	26	240
Mean Deviation (%) by Homogenous Model	①19.90 ②24.34 ③15.56	①20.43 ②19.43	①43.64	①468.79	①33.82 ②30.39 ③41.42 ④47.61 ⑤54.27 ⑥60.84

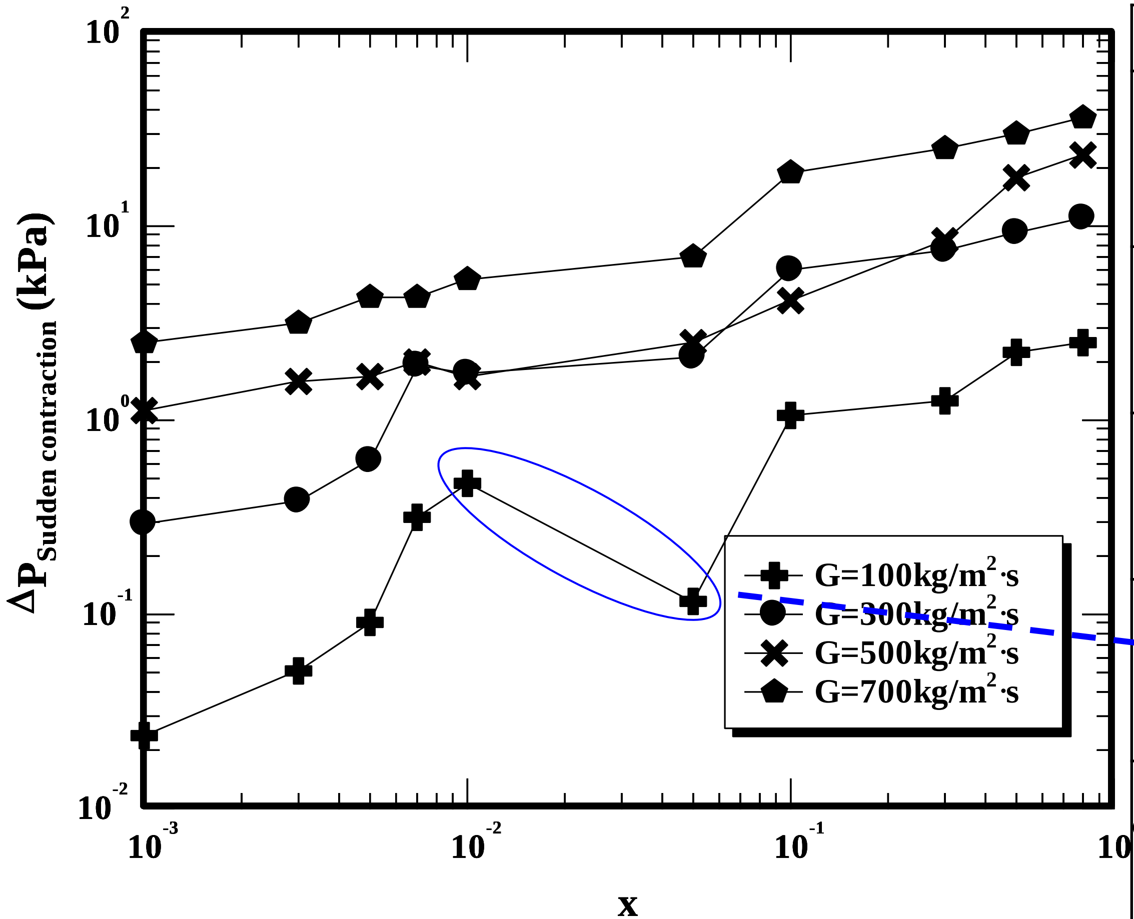
Pressure drops for sudden contraction
6×3 rectangular channel into 3 mm tube

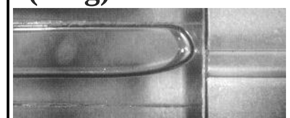
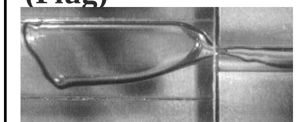
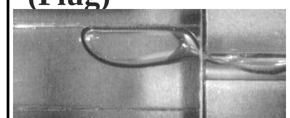
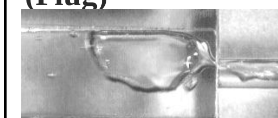
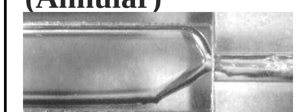


*6 × 3 mm **rectangular** channel to 3 mm tube*

6x3	G=100 kg/m^2·s	G=500 kg/m^2·s
0.001	(Plug) 	(Plug) 
0.005	(Plug) 	(Stratified) 
0.01	(Stratified) 	(Annular) 
0.05	(Wavy) 	(Annular) 
0.1	(Annular) 	(Annular) 

Pressure drops for sudden contraction 9×3 rectangular channel into 3 mm tube



9x3	G=100 kg/m²·s	G=300 kg/m²·s
0.001	(Plug) 	(Plug) 
0.005	(Plug) 	(Plug) 
0.01	(Stratified) 	(Annular) 
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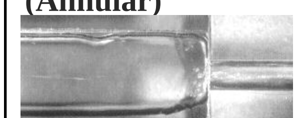
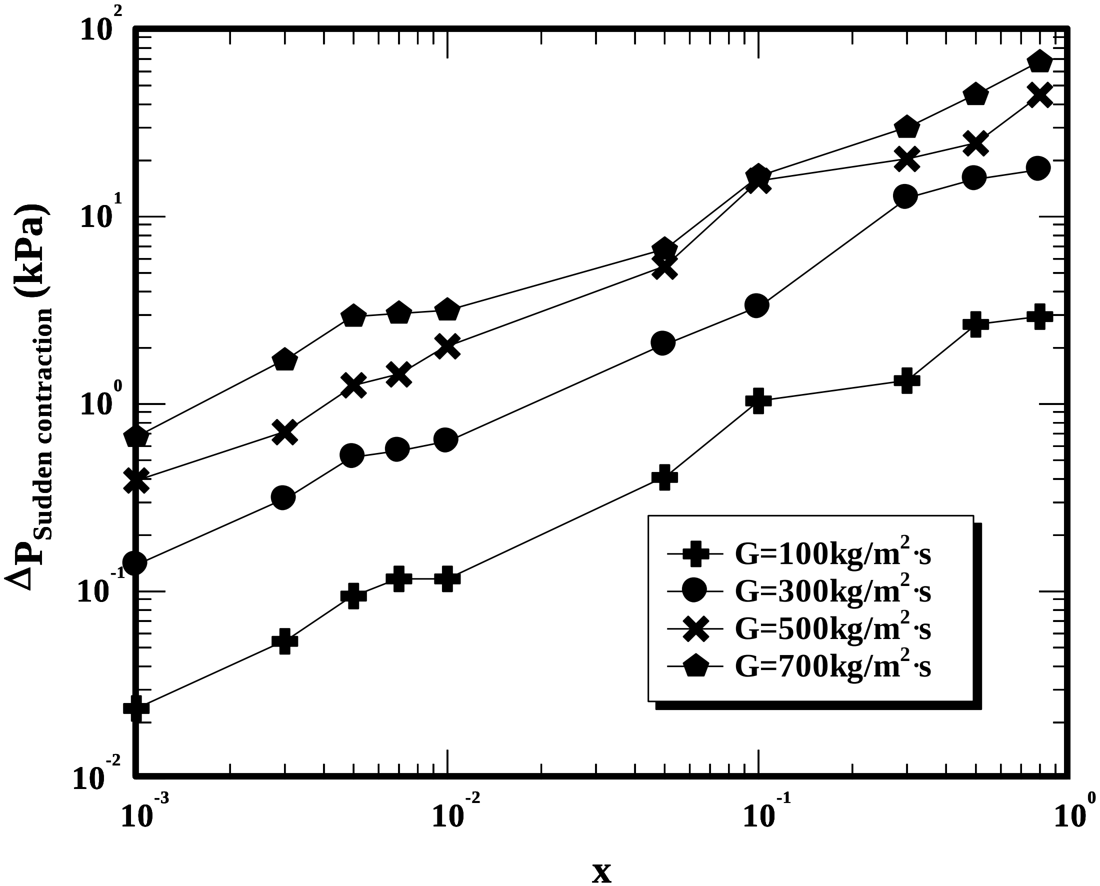
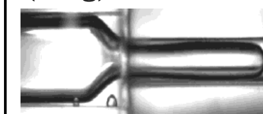
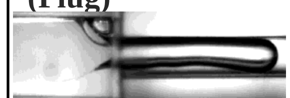
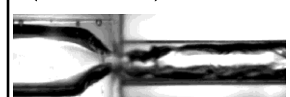
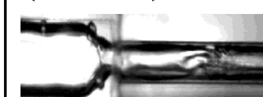
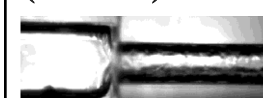
0.1	(Annular) 	(Annular) 

9 × 3 mm ***rectangular*** *channel to 3 mm tube*

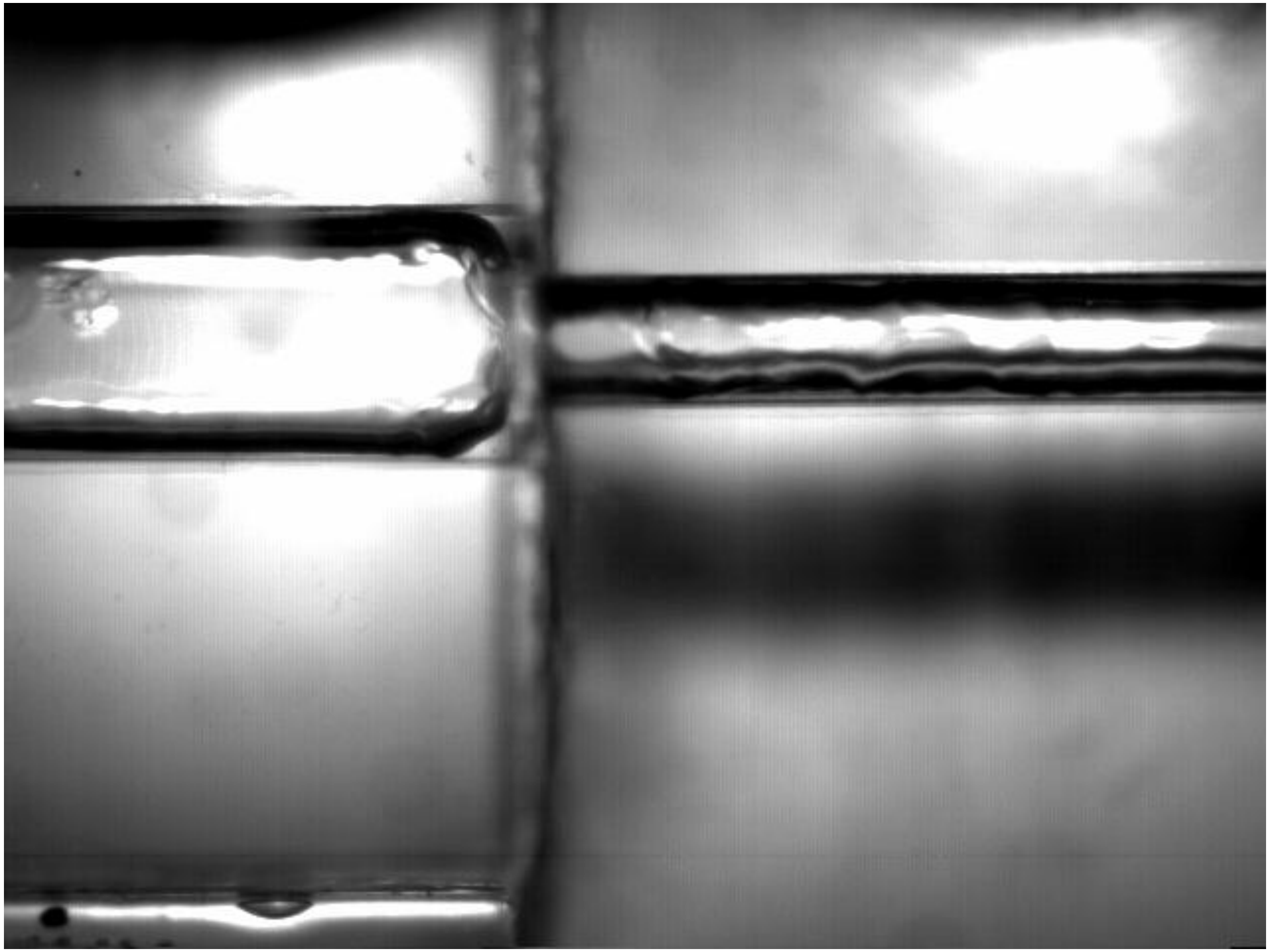
Pressure drops for sudden contraction
4×2 rectangular channel into 2 mm tube



4 ×2 mm ***rectangular*** *channel to 2 mm tube*

4x2	G=100 kg/m²·s	G=500 kg/m²·s
0.001	(Plug) 	(Plug) 
0.005	(Plug) 	(Plug) 
0.01	(Annular) 	(Annular) 
0.05	(Annular) 	(Annular) 
0.1	(Annular) 	(Annular) 

Contraction: 4×2 rectangular tube into a 2mm tube



G = 300 kg/m$^{2}\cdot$s, x =0.05

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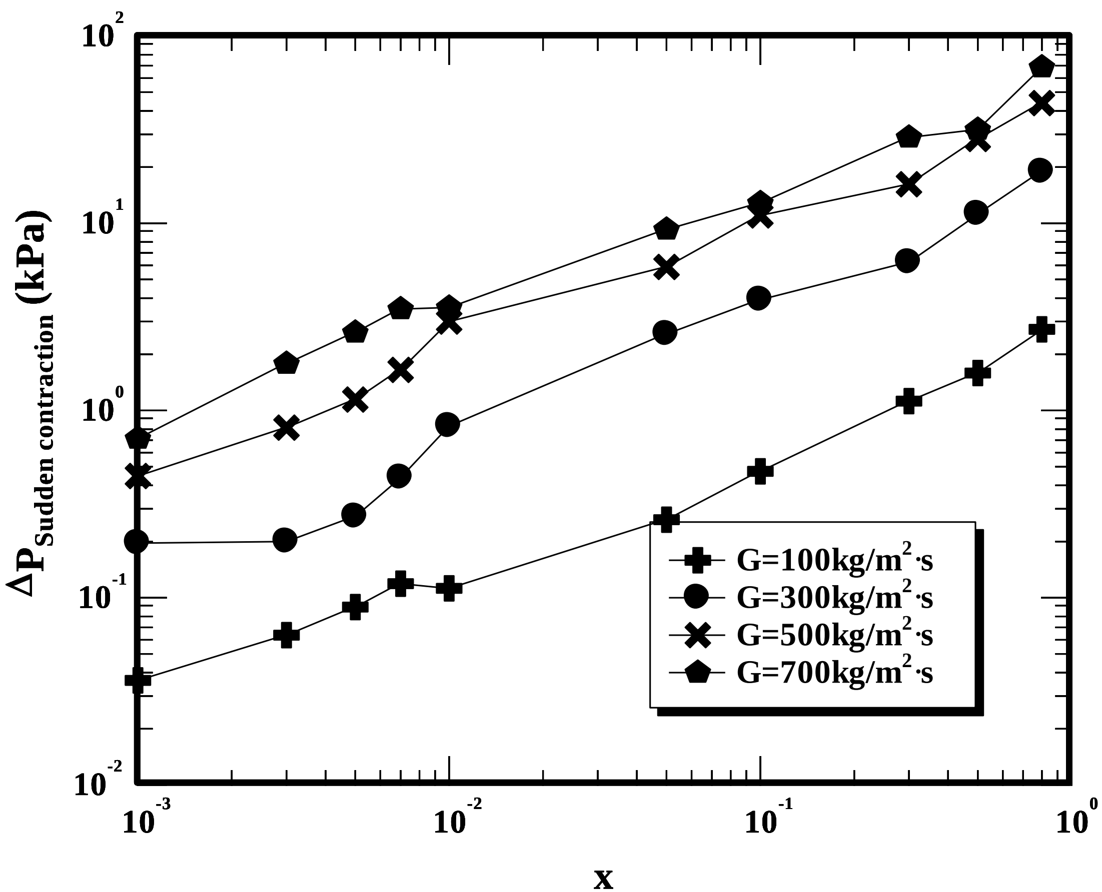
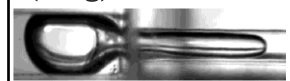
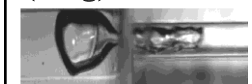
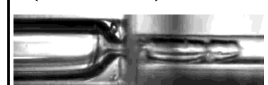
Pressure drops for sudden contraction 4×4 rectangular channel into 2 mm tube



4 × 4 mm ***rectangular*** *channel to 2 mm tube*

4x4	$G=100\ kg/m^2\cdot s$	$G=500\ kg/m^2\cdot s$
0.001	(Plug) 	(Plug) 
0.005	(Plug) 	(Plug) 
0.01	(Plug) 	(Annular) 
0.05	(Annular) 	(Annular) 
0.1	(Annular) 	(Annular) 

Contraction: 4×4 rectangular tube into a 2mm tube

$G = 300\ kg/m^{2}\cdot s$, $x = 0.01$

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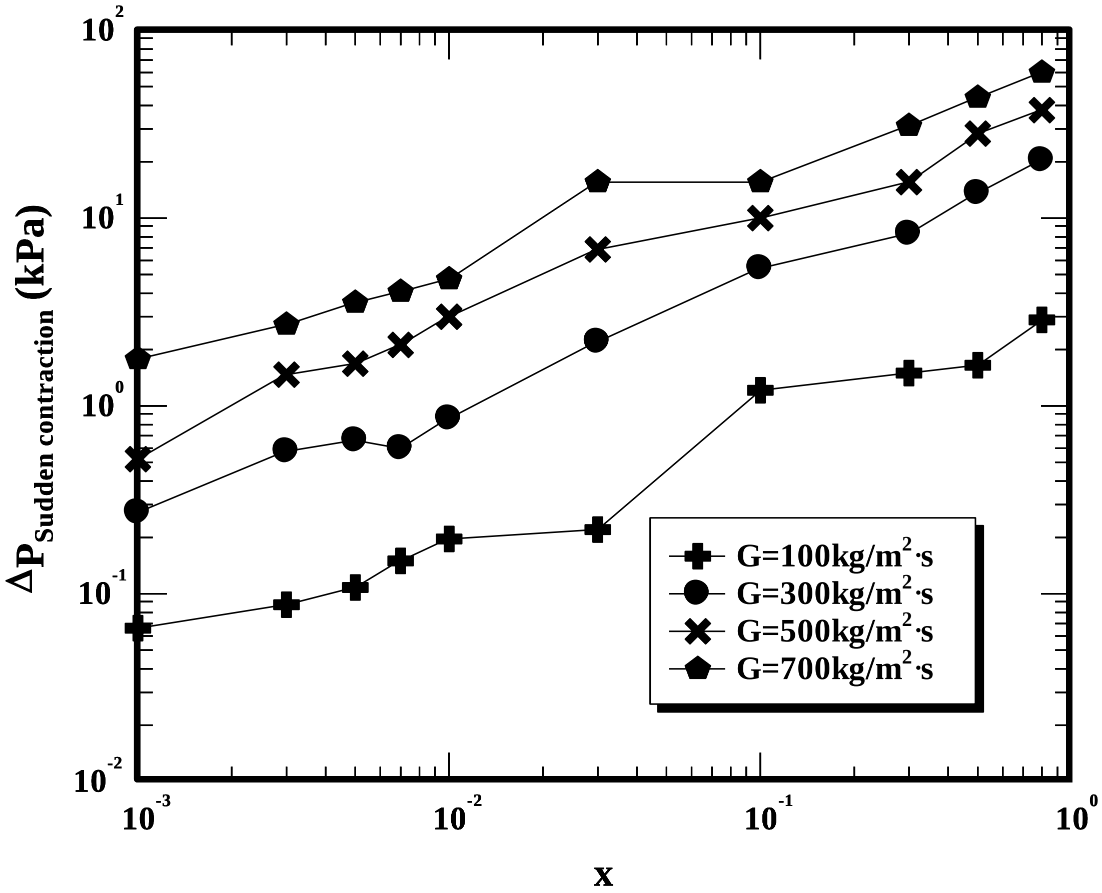
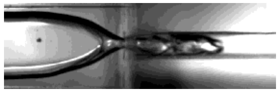
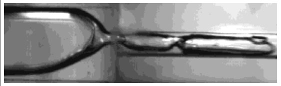
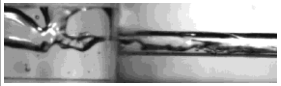
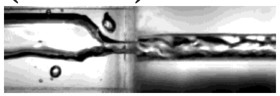
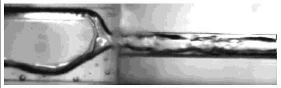
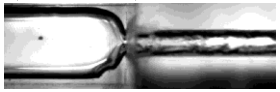
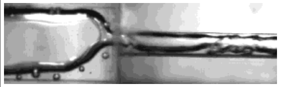
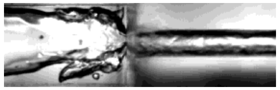
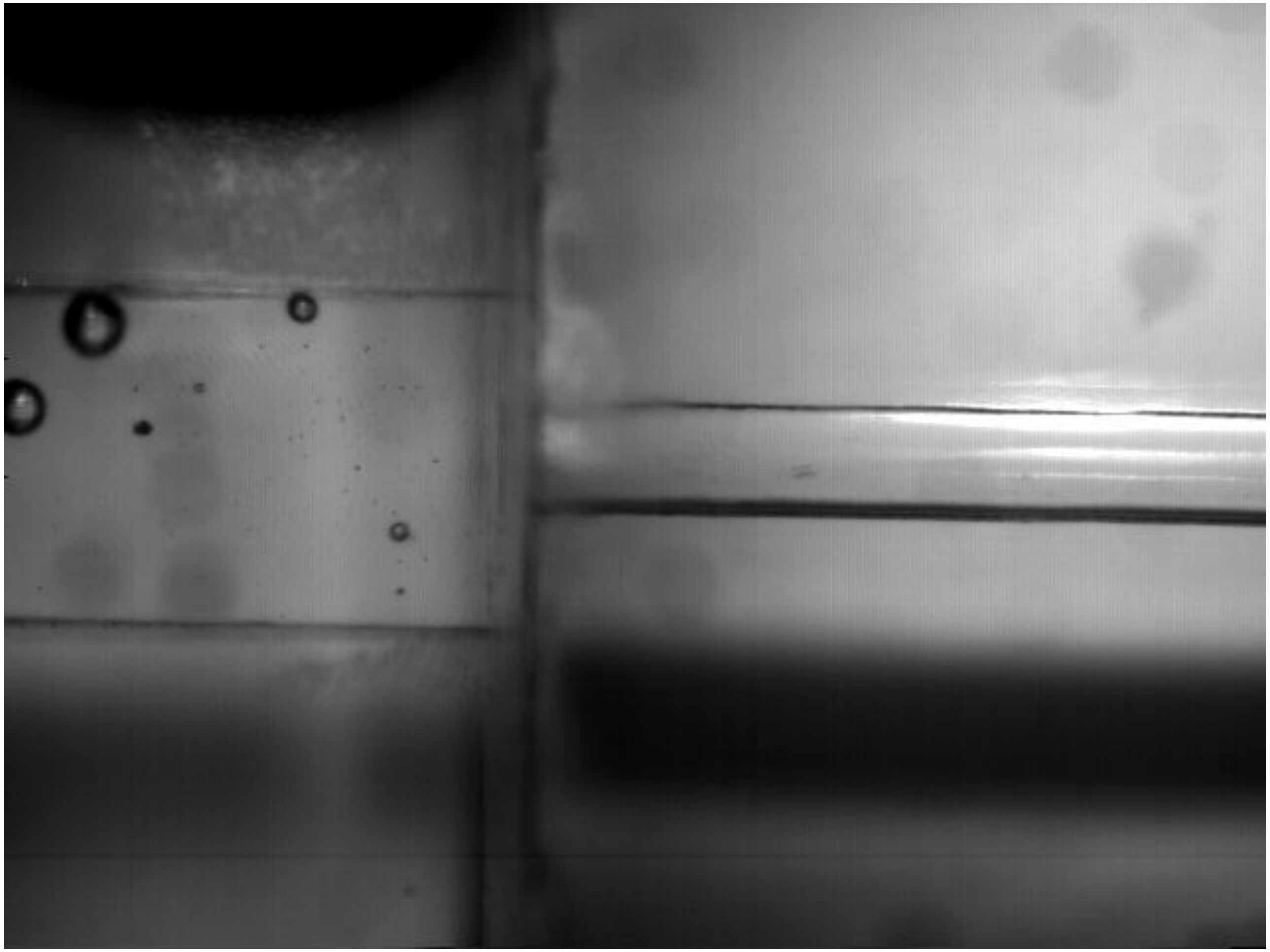
Pressure drops for sudden contraction 6×2 rectangular channel into 2 mm tube



6x2	G=300 kg/m²·s	G=700 kg/m²·s
0.001	(Plug) 	(Plug) 
0.005	(Plug) 	(Annular) 
0.01	(Annular) 	(Annular) 
0.05	(Annular) 	(Annular) 
0.1	(Annular) 	(Annular) 

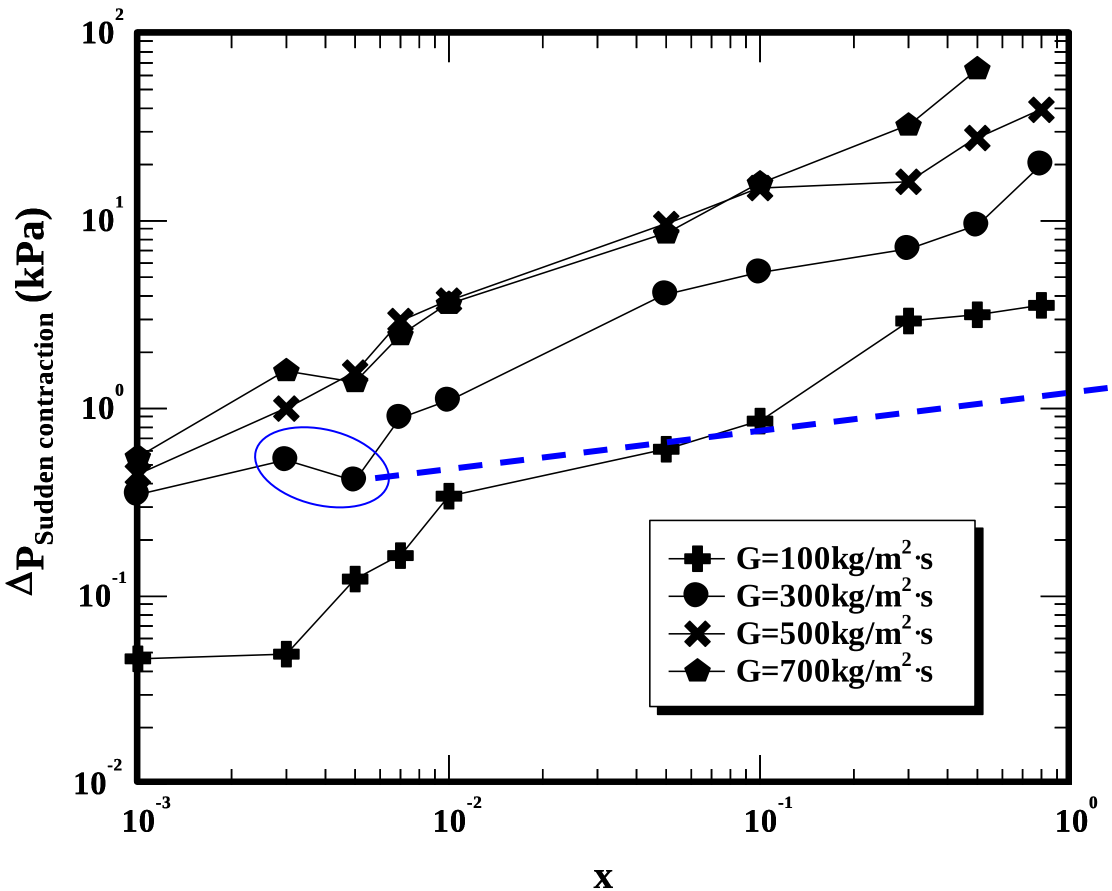
6 ×2 mm ***rectangular*** *channel to 2 mm tube*

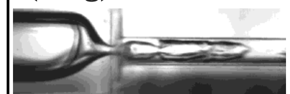
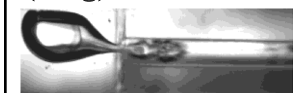
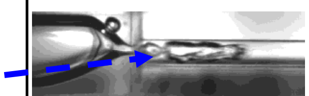
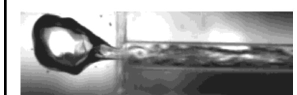
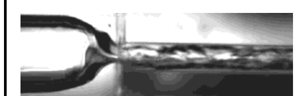
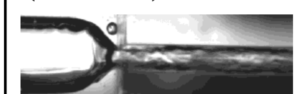
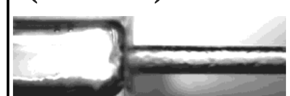
Contraction: 6×2 rectangular tube into a 2mm tube



$G = 300\ kg/m^2 \cdot s,\ x = 0.05$

Pressure drops for sudden contraction 6×4 rectangular channel into 2 mm tube



6x4	G=300 kg/m²·s	G=700 kg/m²·s
0.001	(Plug) 	(Plug) 
0.005	(Plug) 	(Annular) 
0.01	(Plug) 	(Annular) 
0.05	(Annular) 	(Annular) 
0.1	(Annular) 	(Annular) 

6 × 4 mm ***rectangular*** *channel to 2 mm tube*

Contraction: 6×4 rectangular tube into a 2mm tube

G = 300 kg/m^{2}·s, x =0.005

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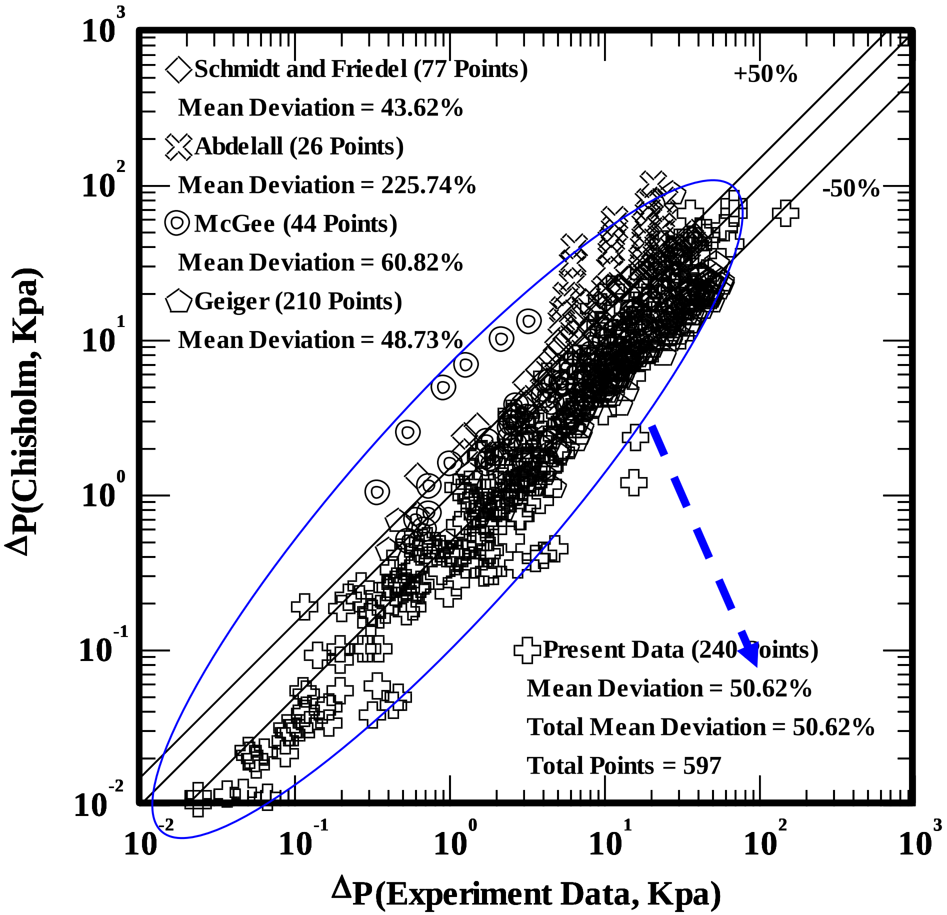
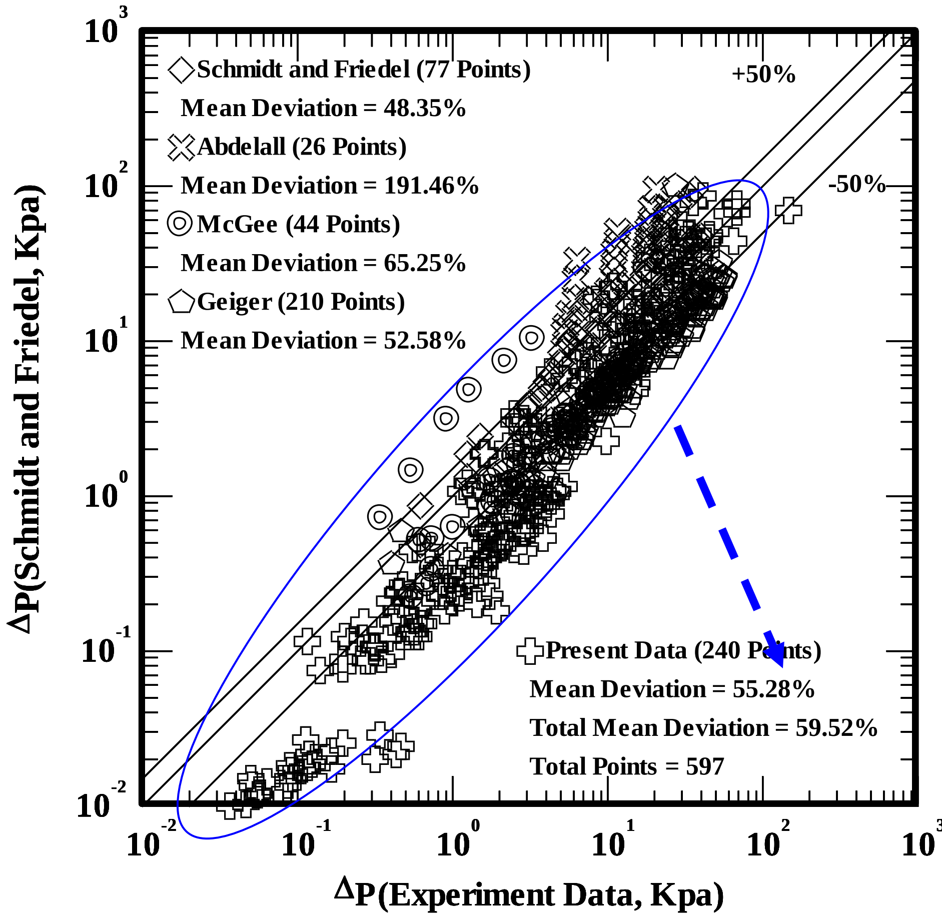
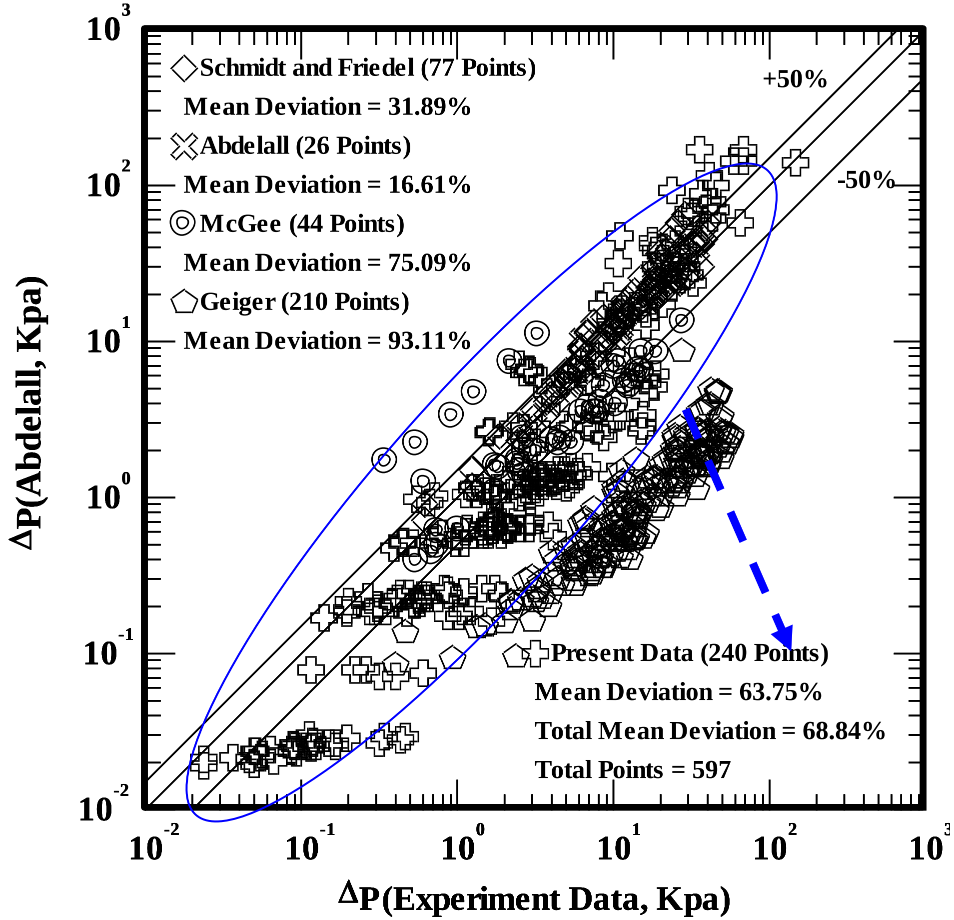
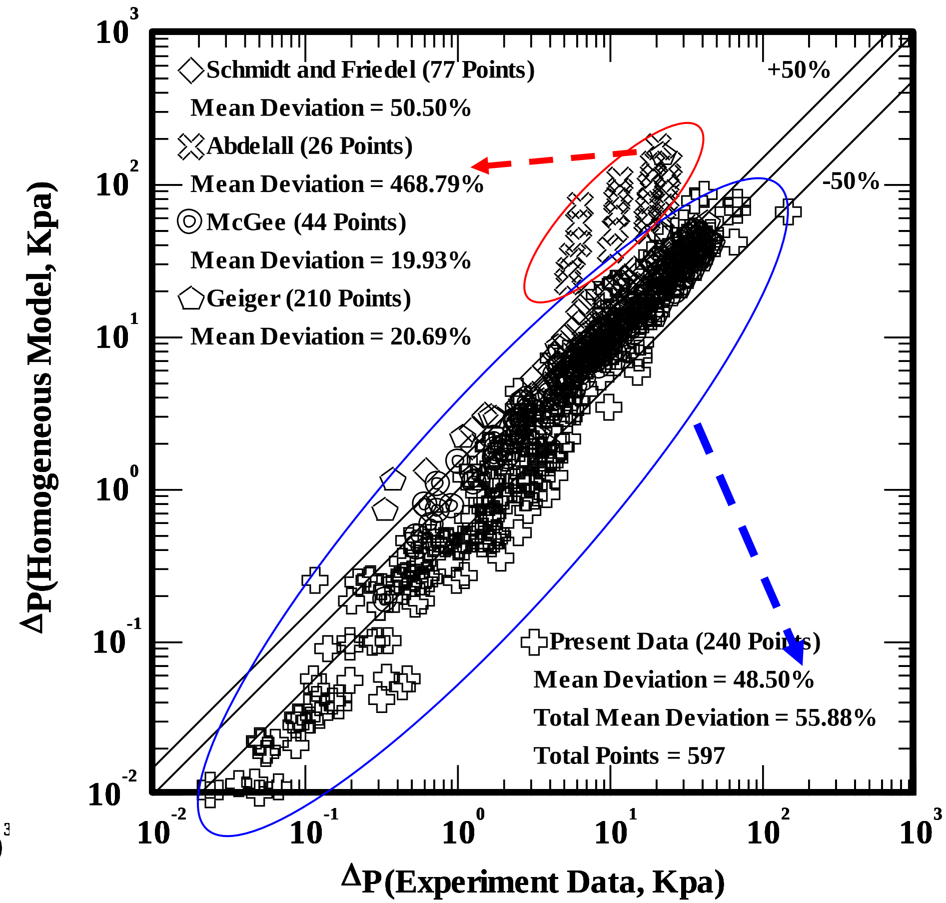
Correlation Assessment





Correlation Assessment



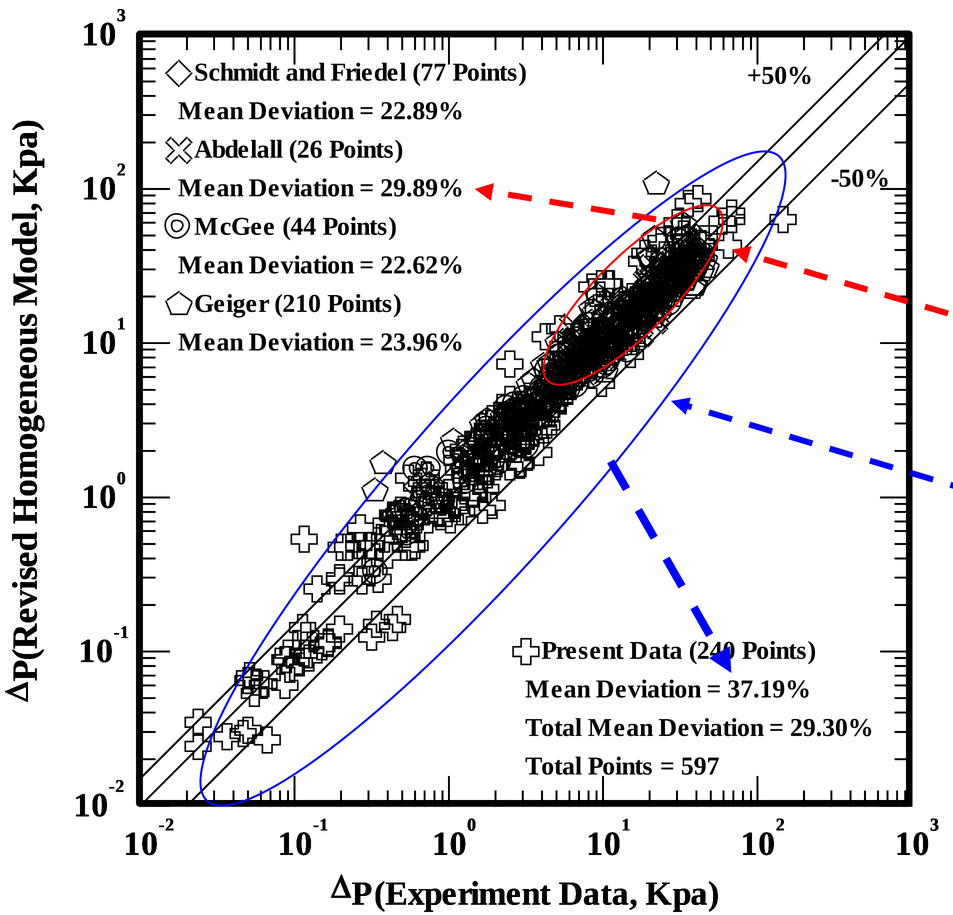


Further examination of the existing Data and Some critical parameters

Researchers	Geiger(1964) 3 tubes	McGee(1966) 2 tubes	Schmidt & Friedel(1997) 1 tube	Abdellal (2005) 1 tube	Present Data 6 tubes
Mass flux (kg/m^2s)	①2313-8116 ②4013-12682 ③6941-21448	①3251-6471 ②1778-4421	①500-4000	①2700-6200	100-700
Quality	①0.0117-0.265 ②0.0001-0.245 ③0.0001-0.159	①0-0.981 ②0-0.323	①0.01-0.90	①$1.9x10^{-4}$-$1.6x10^{-3}$	0.001-0.8
Working fluid	Steam-Water at 194-241 °C	Steam-Water at 141-195 °C	Air-Water at 25 °C	Air-Water at 25 °C	Air-Water at 25 °C
Hydraulic Diameter (mm)	①9.70-25.53 ②12.88-25.53 ③16.10-25.53	①8.64-11.68 ②11.68-14.99	①17.2-72.2	①0.84 -1.6	①2-2.67 ②2-4 ③2-3 ④2-4.8 ⑤3-4 ⑥3-4.5
Contraction ratio	①0.144 ②0.253 ③0.398	①0.546 ②0.608	①0.057	①0.26	①0.39 ②0.19 ③0.26 ④0.13 ⑤0.39 ⑥0.26
Bond number	7-19	15-55	9.988	0.024	0.13-0.29
Test Points	210	44	77	26	240
Mean Deviation (%) by Homogenous Model	①19.90 ②24.34 ③15.56	①20.43 ②19.43	①43.64	①468.79	①33.82 ②30.39 ③41.42 ④47.61 ⑤54.27 ⑥60.84

A rational modification to the Homogeneous Model

$$\Delta P_{Modified} = \Delta P_H \times \left[1 + e^{\left(\frac{-0.1Bo}{C}\right)}\left(-0.92 + 2.13\left(Bo'\right)^{-0.072}\right)\right]\left[1 + 0.28\left(-1.1 + e^{-10Bo}\right)^{-1}\right]$$



$$C = 1 + 100e^{(-\sigma_A)}$$

$$Bo' = We \times Bo \times \sigma_A$$

$$Bo = \frac{g(\rho_L - \rho_G)(D/2)^2}{\sigma}$$

$$We = G^2 x^2 \frac{d}{\rho_G \sigma} \frac{\left(\rho_L - \rho_G\right)}{\rho_G}$$

Short summary – Contraction

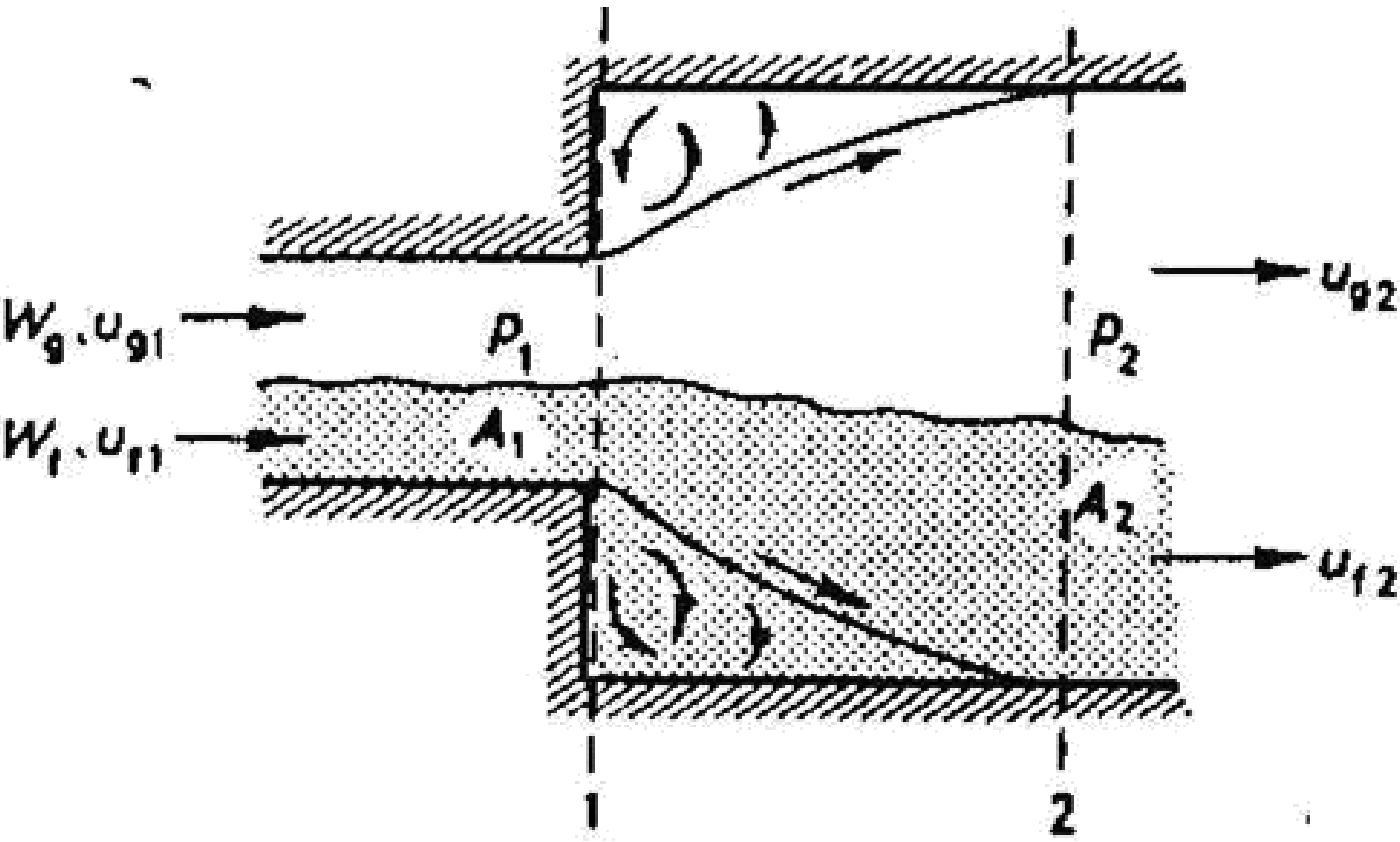
- **At a rather low mass flux where the upstream/downstream flow patterns are wavy flow or a "*Liquid like vena contracta*" *occurring at a certain mass flux/quality may lead to a fall-off contraction pressure drop.***

- ***The "Liquid like vena contracta" seems to occur in front of the contraction.***

- ***Correlation/model assessment indicates that the homogeneous model gives the best predictive ability with a mean deviation of 57.45%.***

- ***By introducing a correction factor, a modified homogeneous correlation is proposed. The correction factor takes into account the influence of Bond number with a mean deviation of 29.30%.***

Expansion



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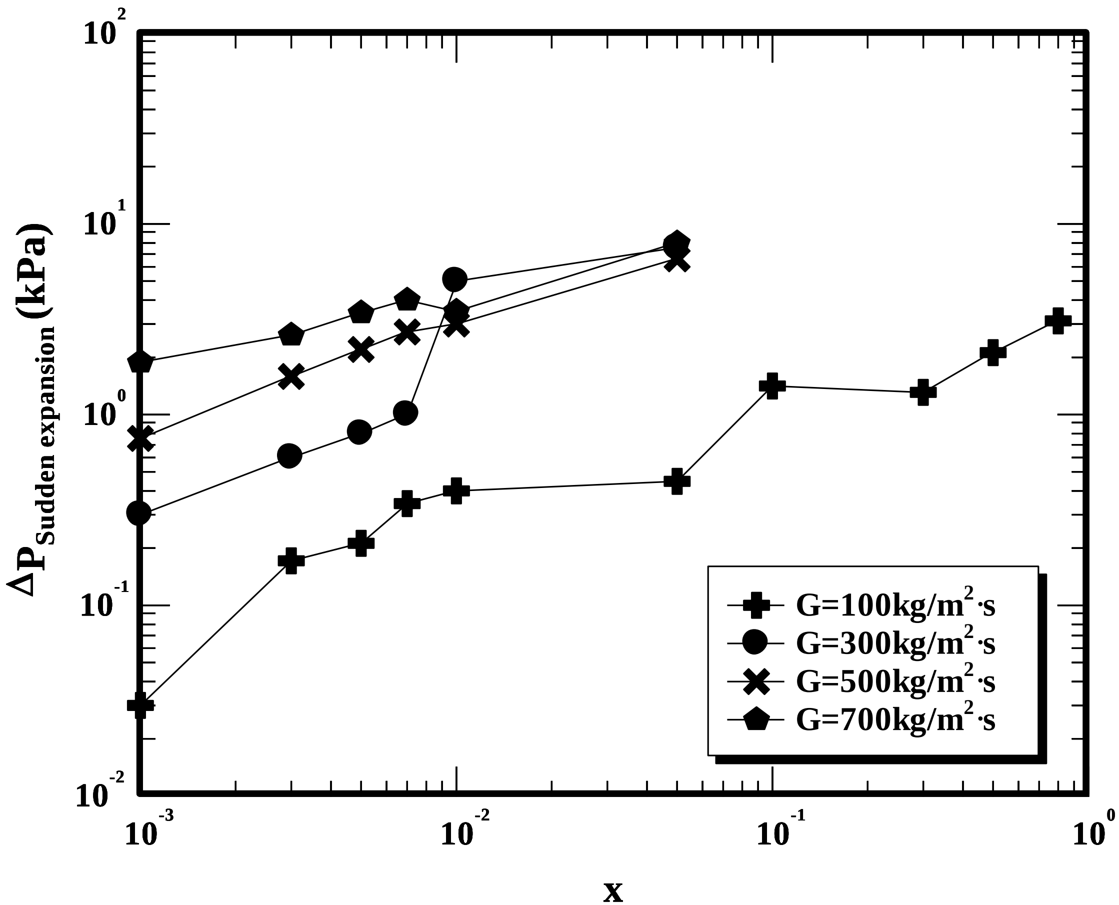
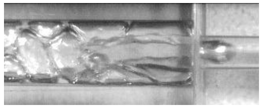
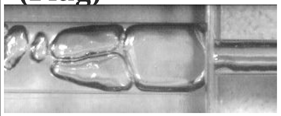
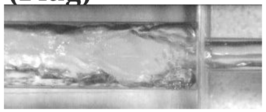
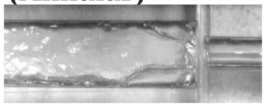
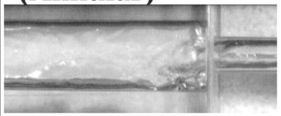
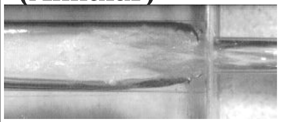
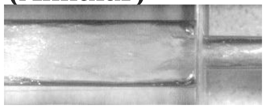
Test Results for sudden expansion 3 mm tube into 6×3 rectangular channel



3 mm tube to 6 × 3 mm ***rectangular*** *channel*

6x3	G=100 kg/m^2·s	G=500 kg/m^2·s
0.001	(Plug) 	(Slug) 
0.005	(Plug) 	(Plug) 
0.01	(Annular) 	(Annular) 
0.05	(Annular) 	(Annular) 
0.1	(Annular) 	(Annular) 

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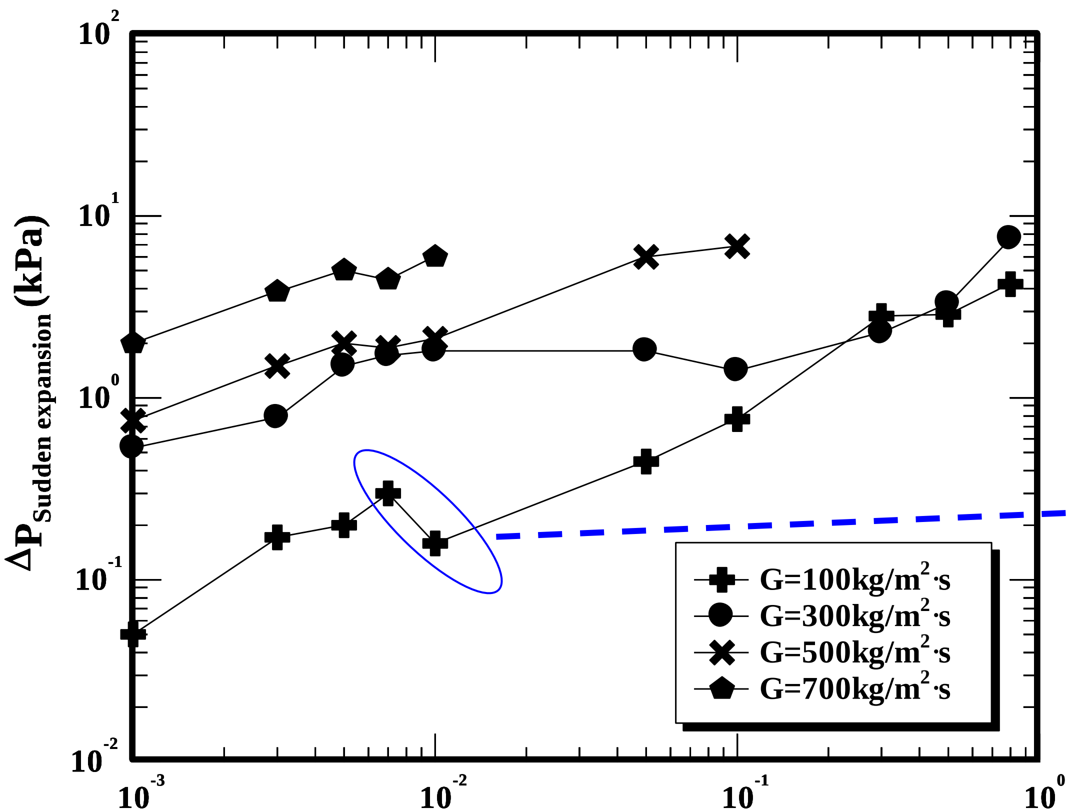
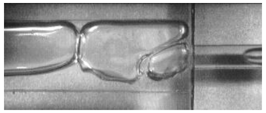
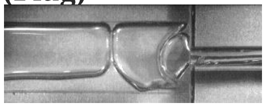
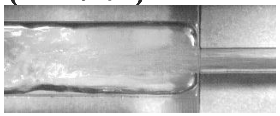
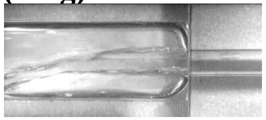
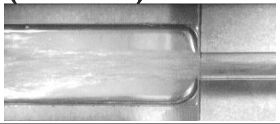
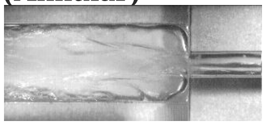
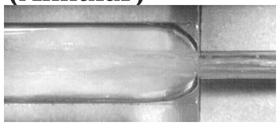
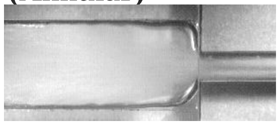
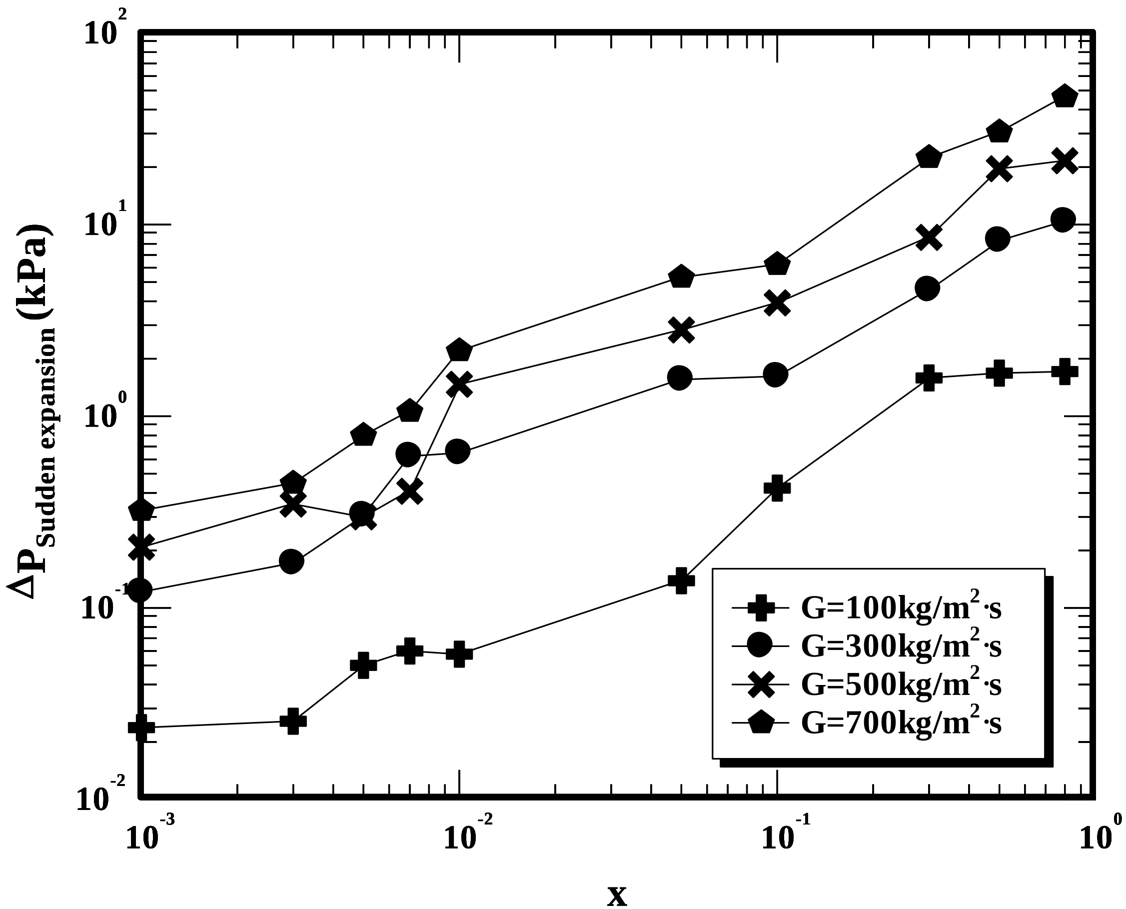
Test Results for sudden expansion
3 mm tube into 9×3 rectangular channel



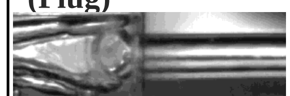
*3 mm tube to 9 × 3 mm **rectangular** channel*

9x3	G=100 kg/m^2·s	G=500 kg/m^2·s
0.001	(Plug) 	(Slug) 
0.005	(Plug) 	(Annular) 
0.01	(Plug) 	(Annular) 
0.05	(Annular) 	(Annular) 
0.1	(Annular) 	(Annular) 

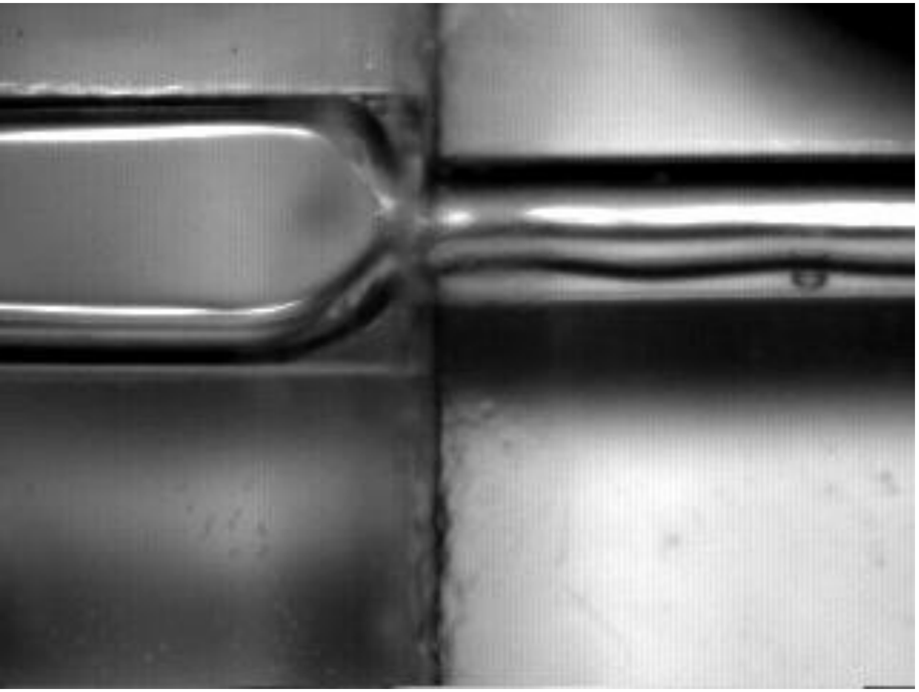
Test Results for sudden expansion 2 mm tube into 4×2 rectangular channel



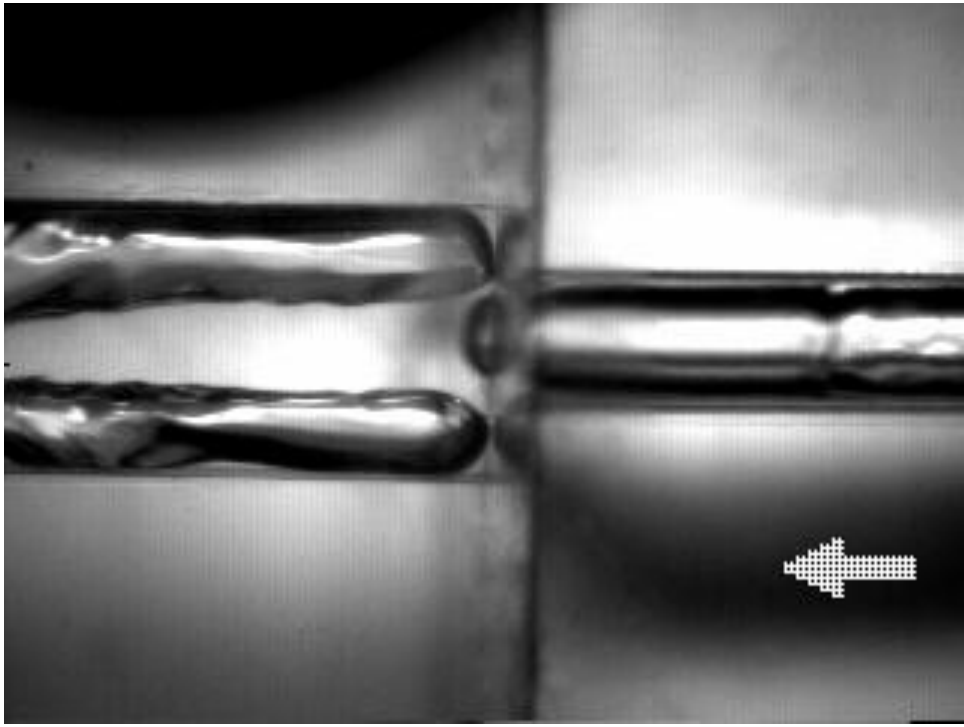
2 mm tube to 4×2 mm ***rectangular*** *channel*

4x2	G=100 kg/m²·s	G=500 kg/m²·s
0.001	(Slug) 	(Slug) 
0.005	(Slug) 	(Plug) 
0.01	(Plug) 	(Annular) 
0.05	(Annular) 	(Annular) 
0.1	(Annular) 	(Annular) 

Expansion: 2 mm tube into 4×2 rectangular cross section



G = 100 kg/m²·s, x =0.01



G = 300 kg/m²·s, x =0.005

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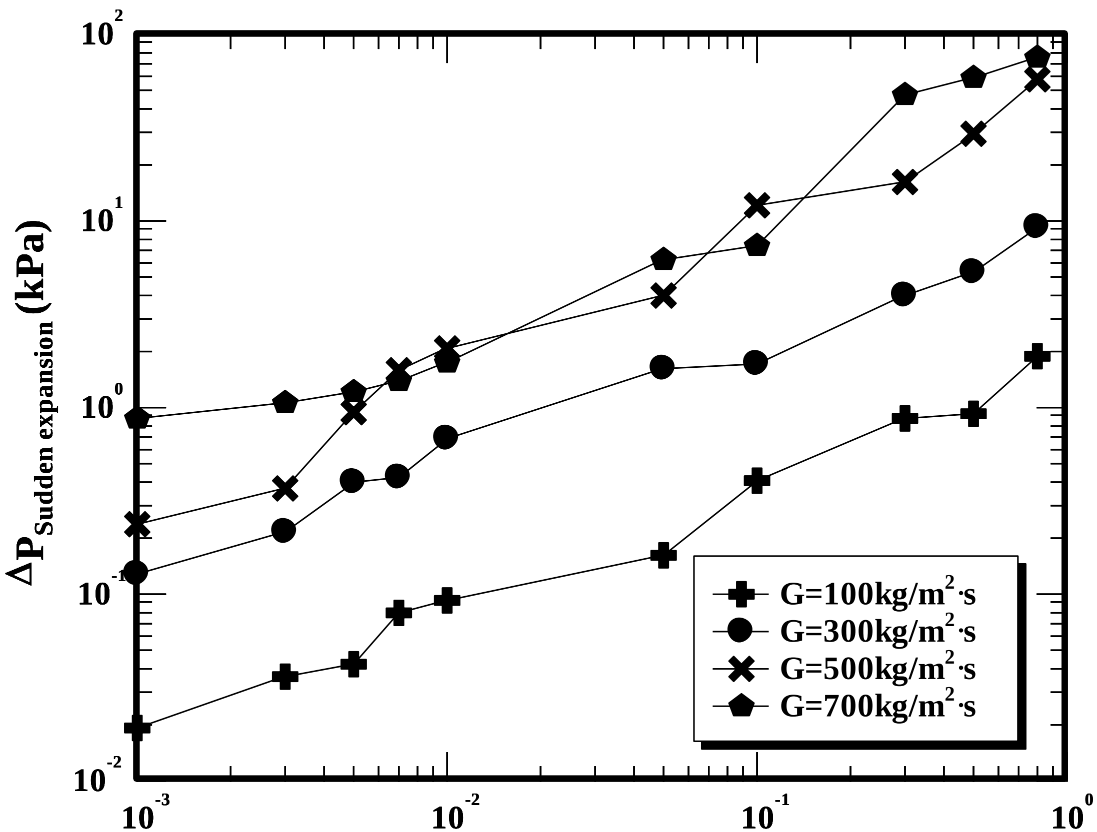
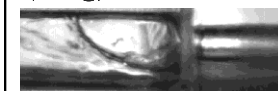
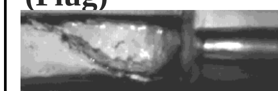
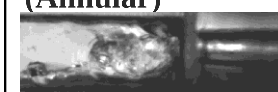
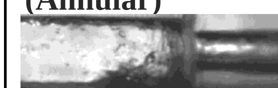
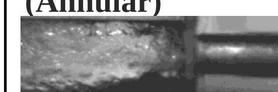
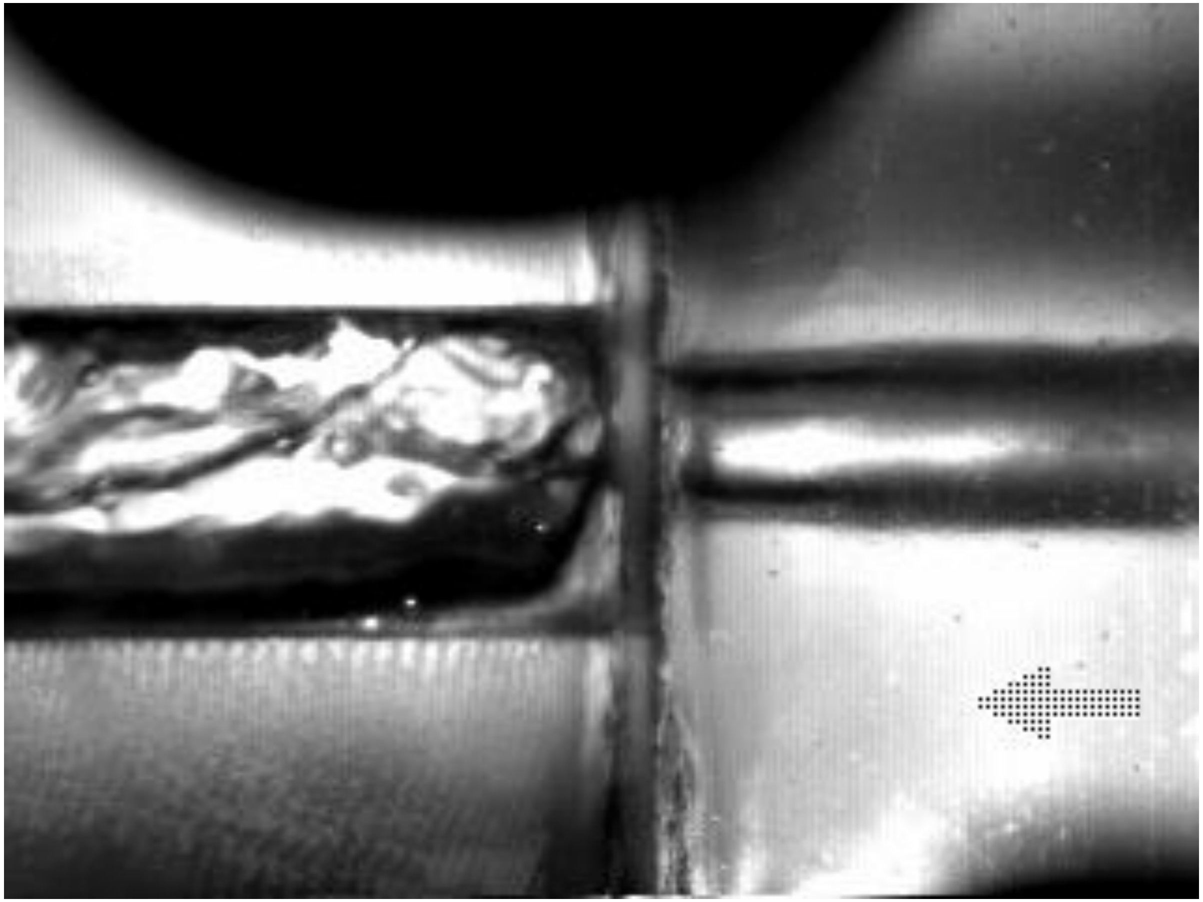
Test Results for sudden expansion 2 mm tube into 4×4 rectangular channel



*2 mm tube to 4×4 mm **rectangular** channel*

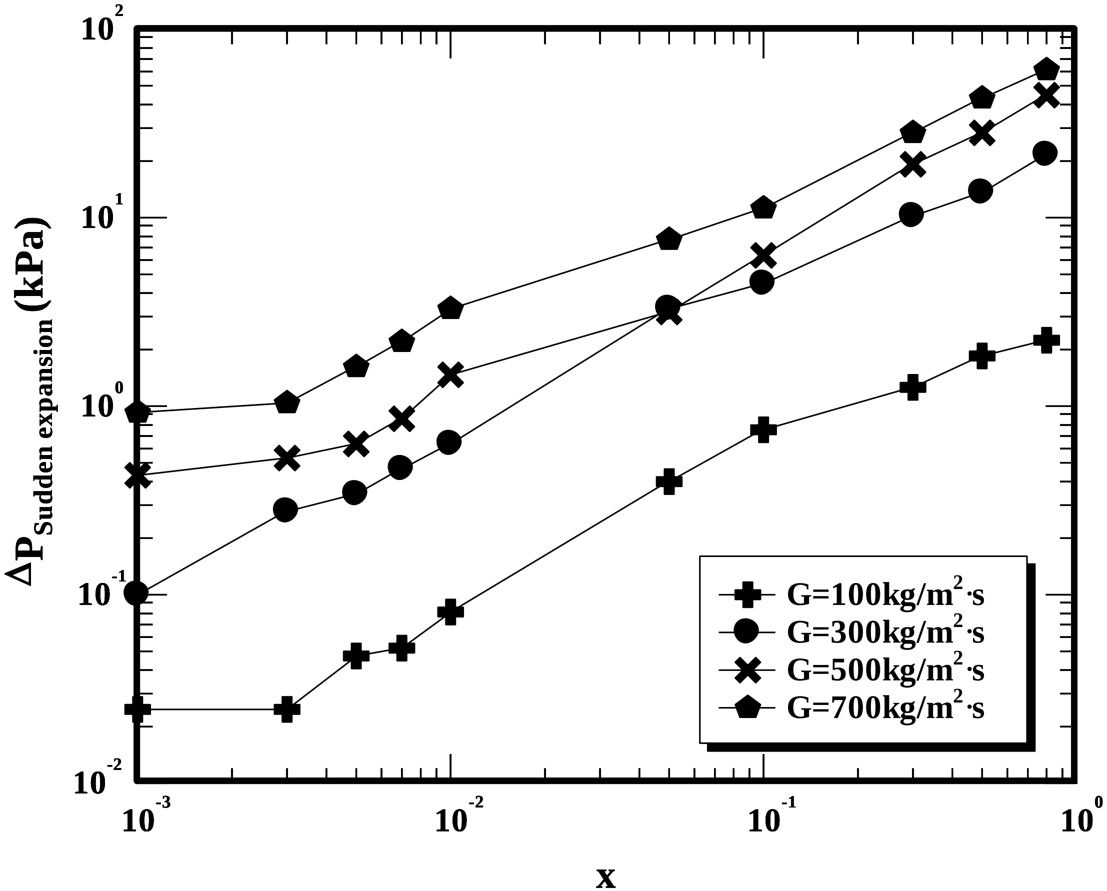
4x4	G=100 kg/m^2·s	G=500 kg/m^2·s
0.001	(Slug) 	(Plug) 
0.005	(Slug) 	(Plug) 
0.01	(Plug) 	(Annular) 
0.05	(Plug) 	(Annular) 
0.1	(Annular) 	(Annular) 

Expansion: 2 mm tube into 4×4 rectangular cross section

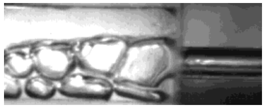
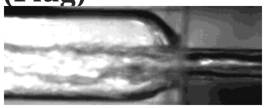
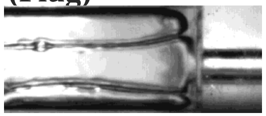
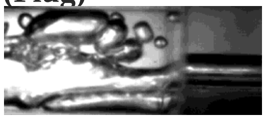
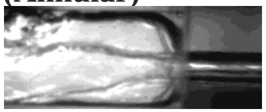
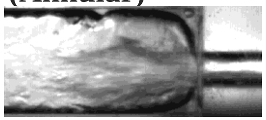
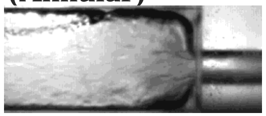


G = 100 kg/m^2·s, x =0.01

Test Results for sudden expansion 2 mm tube into 6×2 rectangular channel



2 mm tube to 6×2 mm ***rectangular*** *channel*

6x2	G=300 kg/m²·s	G=700 kg/m²·s
0.001	(Slug) 	(Plug) 
0.005	(Plug) 	(Plug) 
0.01	(Plug) 	(Annular) 
0.05	(Annular) 	(Annular) 
0.1	(Annular) 	(Annular) 

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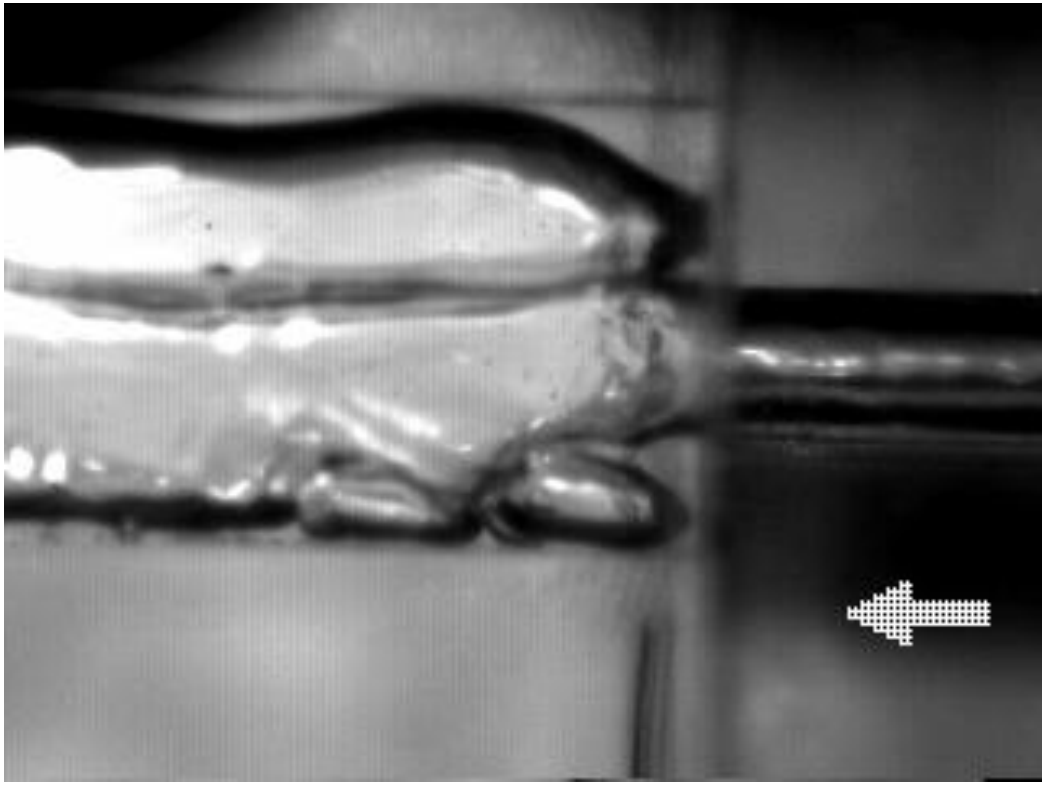
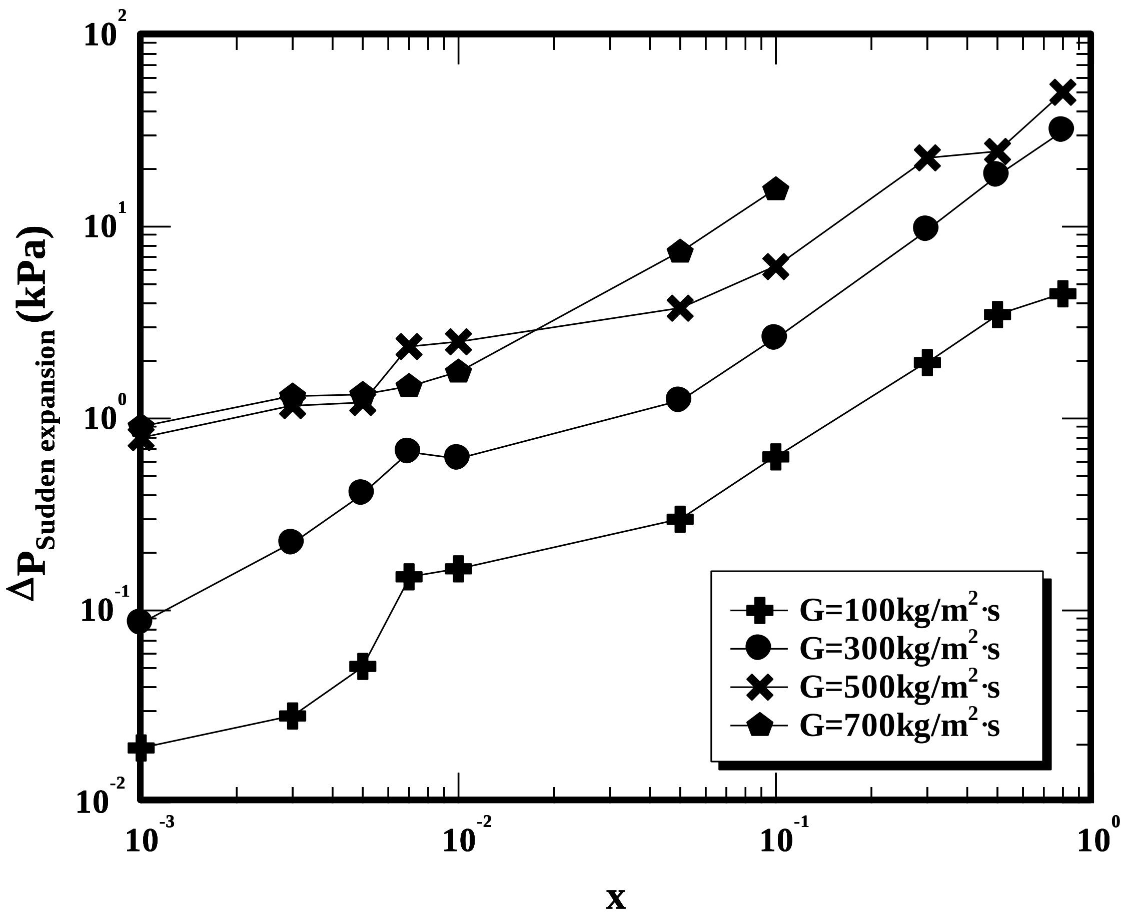
Expansion: 2 mm tube into 6×2 rectangular cross section



G = 300 kg/m²·s, x =0.005

Test Results for sudden expansion 2 mm tube into 6×4 rectangular channel

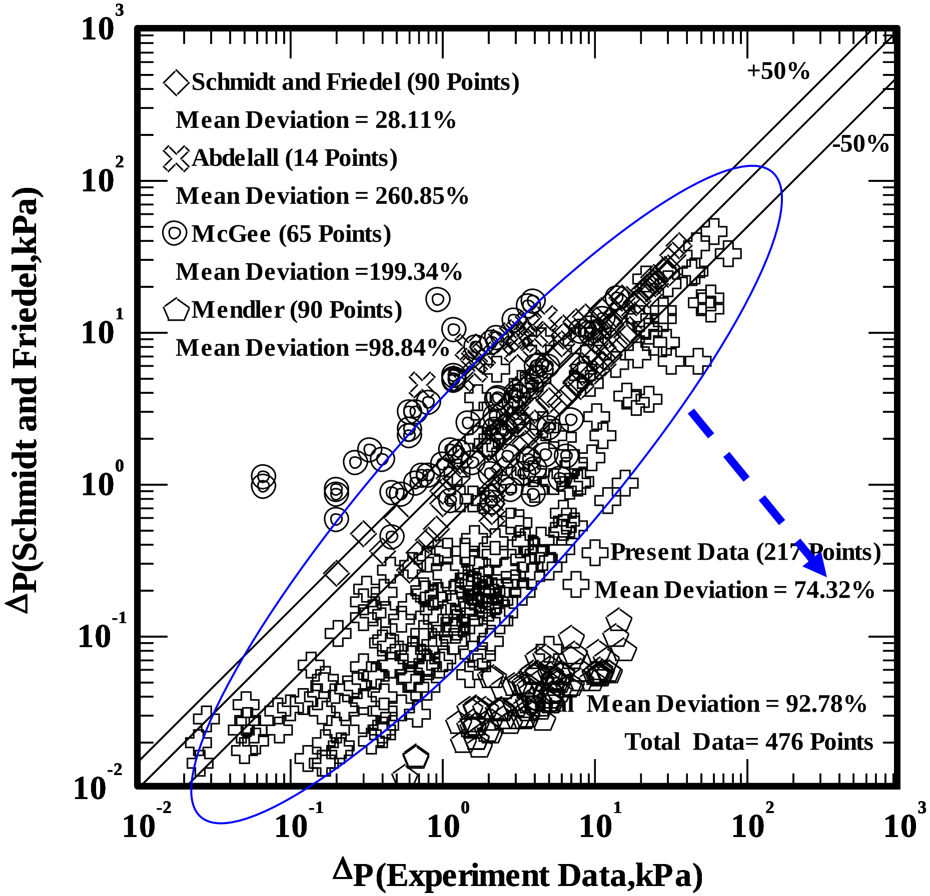


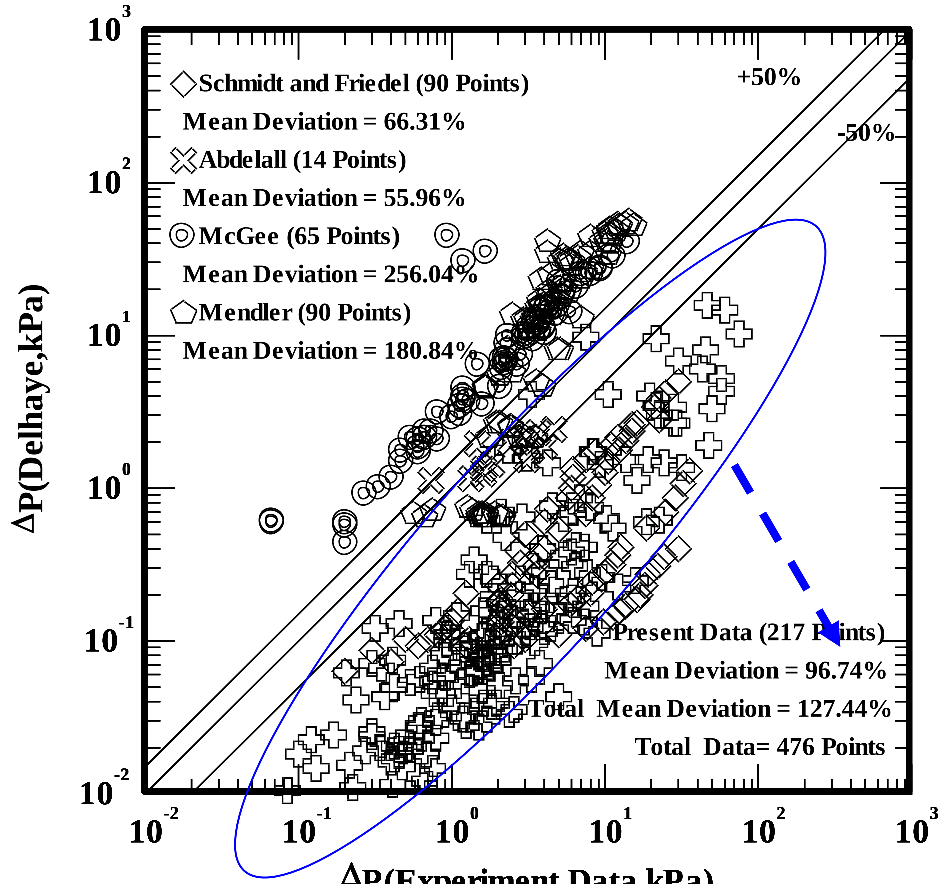
*2 mm tube to 6 × 4 mm **rectangular** channel*

Collected dData for comparison/development

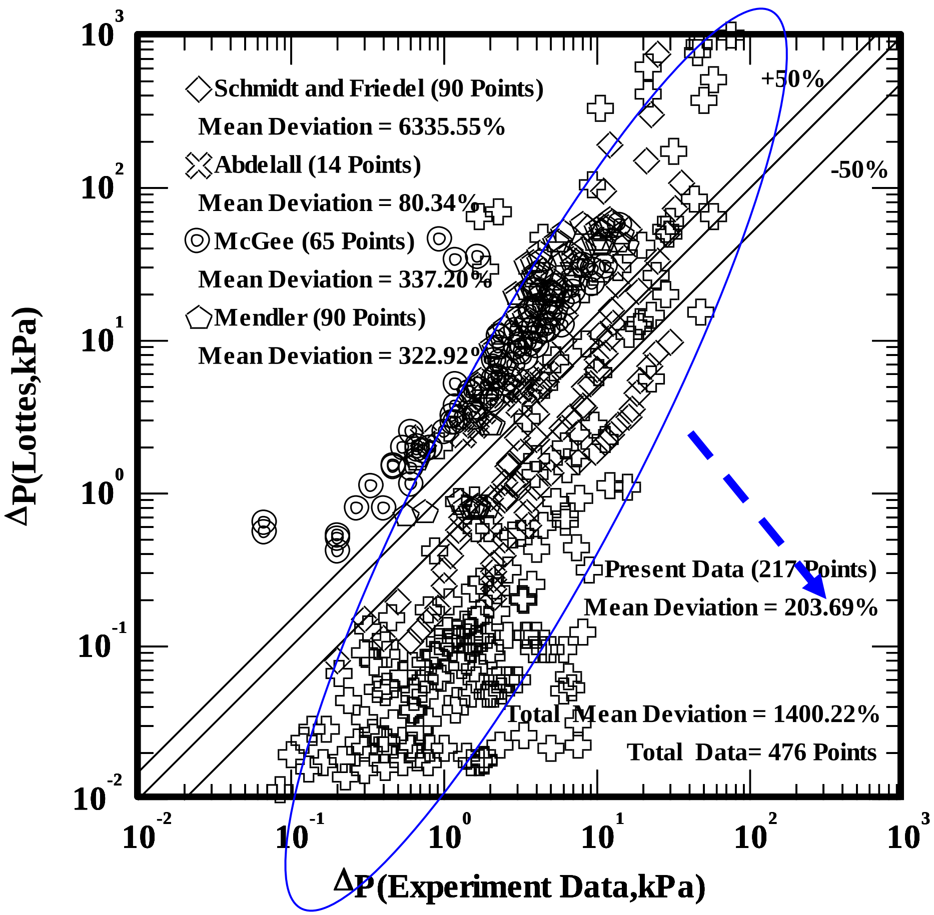
Researchers	Abdellal	Mendler	McGee	Schmidt & Friedel	Present study
Mass flux (kg/m^{2}s)	①3000-5000	①8928-18480 ②4528-11280 ③2304-4576	①1778-4416 ②3248-6464 ③3248-8096	①1000 ②1000-3000	100-700
Quality	①0.0022-0.006	①0.032-0.139 ②0.040-0.181 ③0.037-0.185	①0-0.304 ②0-0.249 ③0-0.229	①0.01-0.99 ②0.01-0.99	0.001-0.8
Working fluid	Air-Water at 25 °C	Steam-Water at 194-252 °C	Steam-Water at 141-195 °C	Air-Water at 25 °C	Air-Water at 25 °C
Hydraulic Diameter (mm)	①0.84 -1.6	①9.55-25.09 ②12.90-25.09 ③17.63-25.09	①11.43-14.99 ②8.636-14.99 ③8.636-11.68	①17.2-72.2 ②19.0-62.1	①2-2.67 ②2-4 ③2-3 ④2-4.8 ⑤3-4 ⑥3-4.5
Contraction ratio	①0.26	①0.145 ②0.264 ③0.493	①0.608 ②0.332 ③0.546	①0.0568 ②0.0937	①0.39 ②0.19 ③0.26 ④0.13 ⑤0.39 ⑥0.26
Bond number	0.024	7-30	7-20	①9.988 ②12.188	0.13-0.29
Total Points	14	90	65	90	240

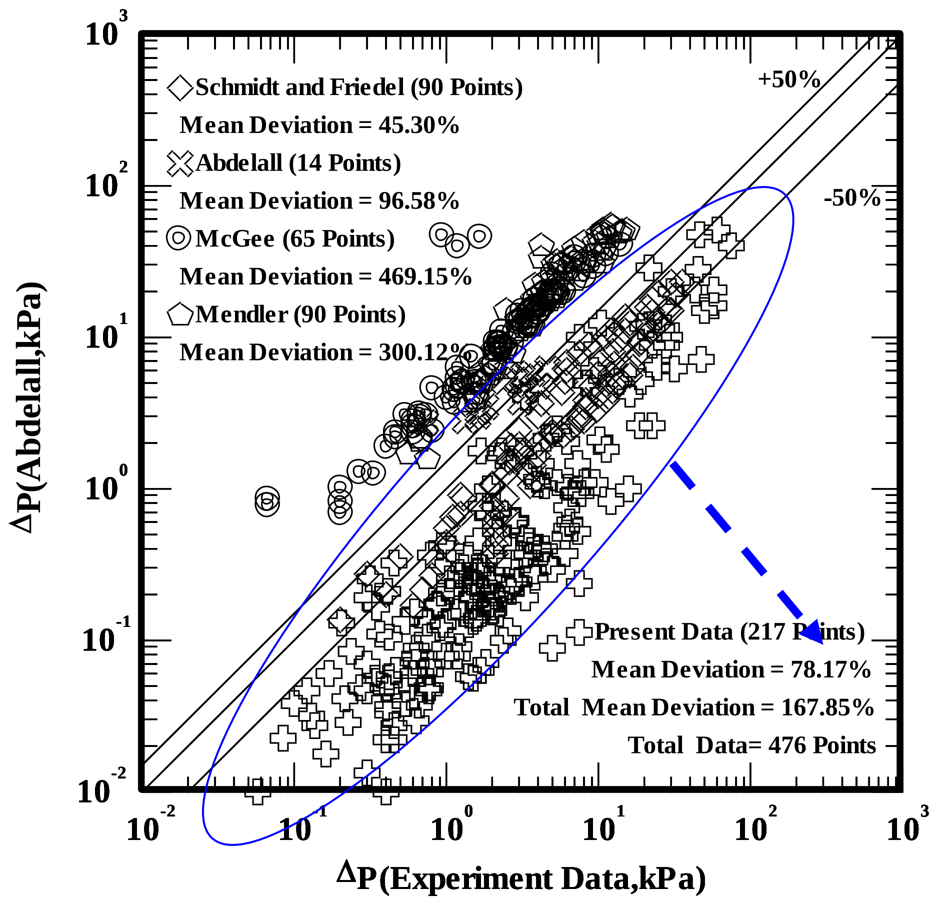
Correlation assessment



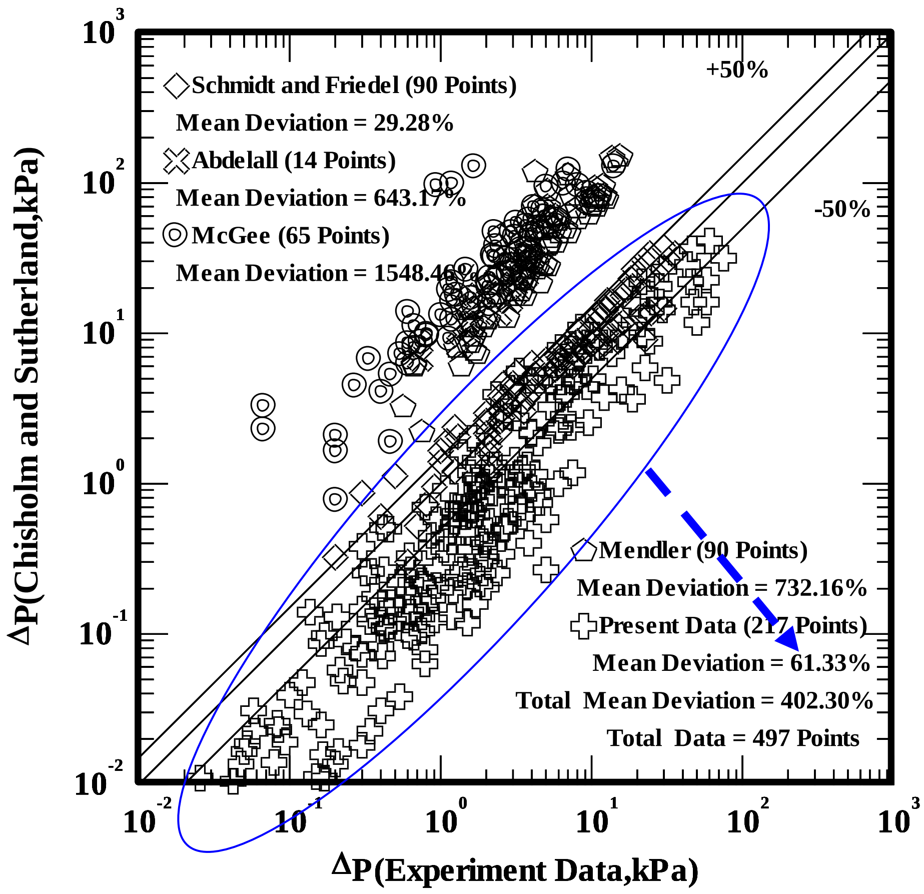


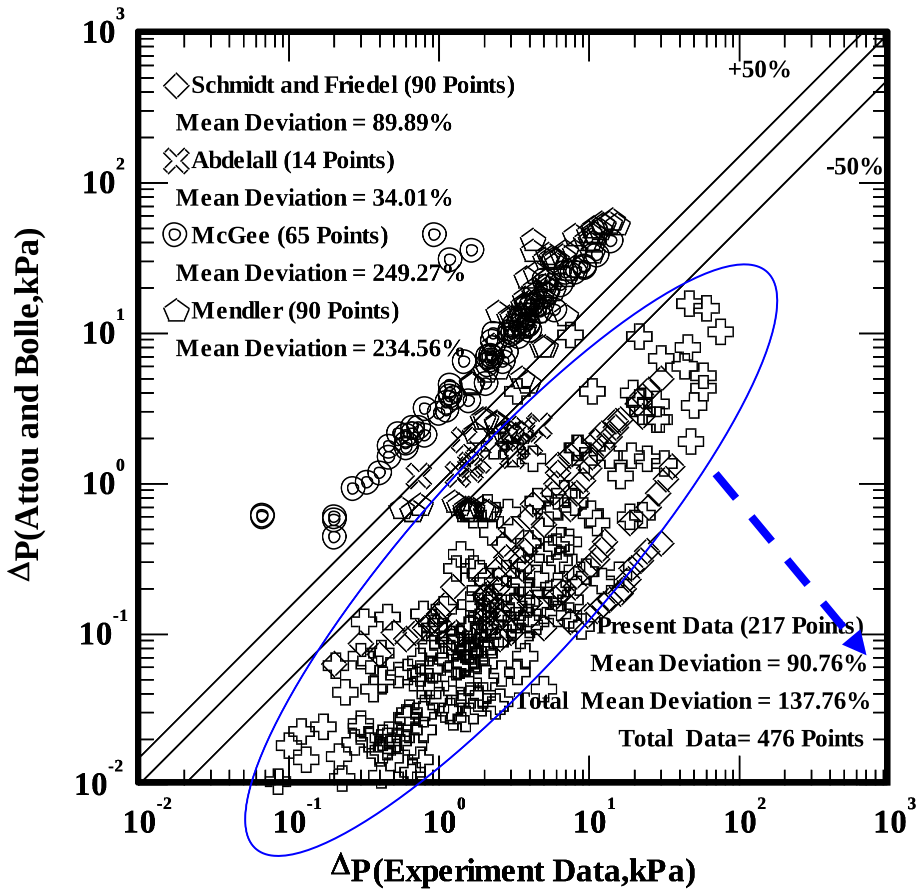
Correlation assessment





Correlation assessment





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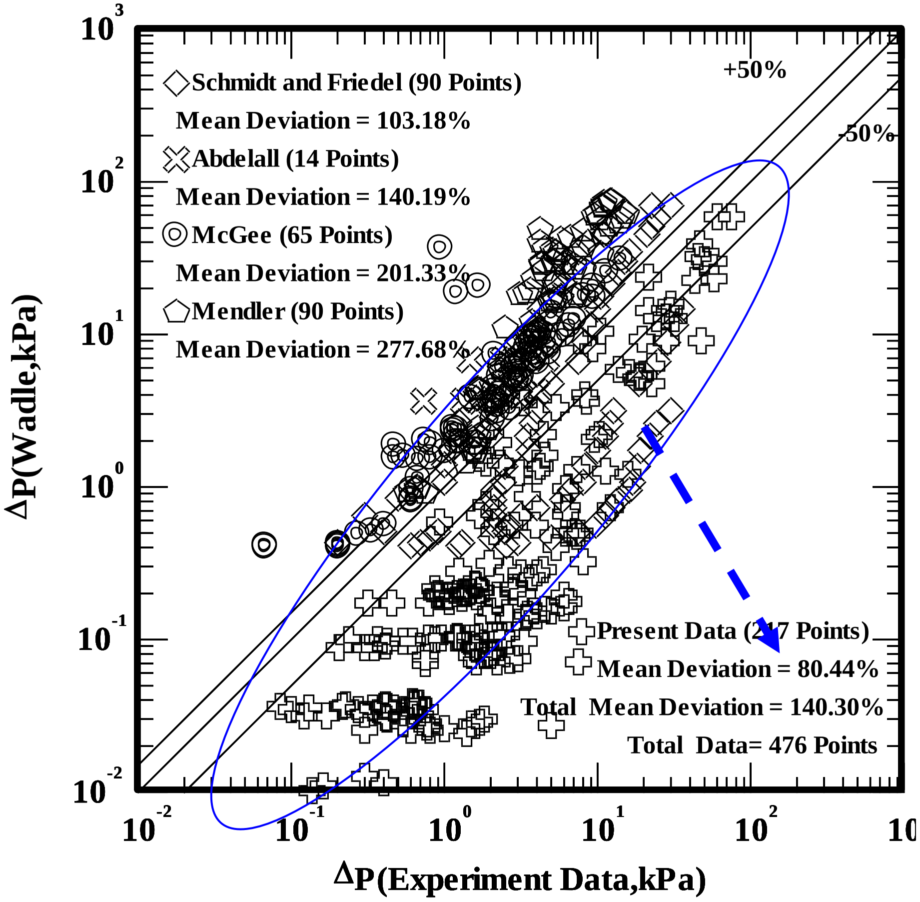

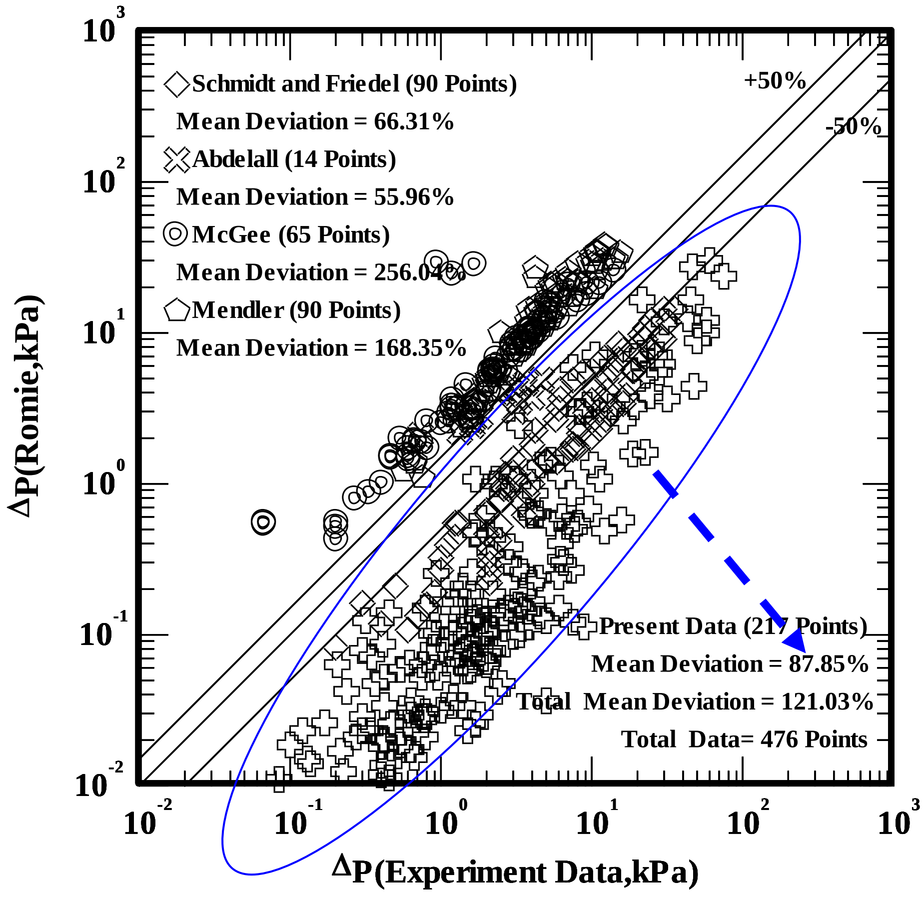

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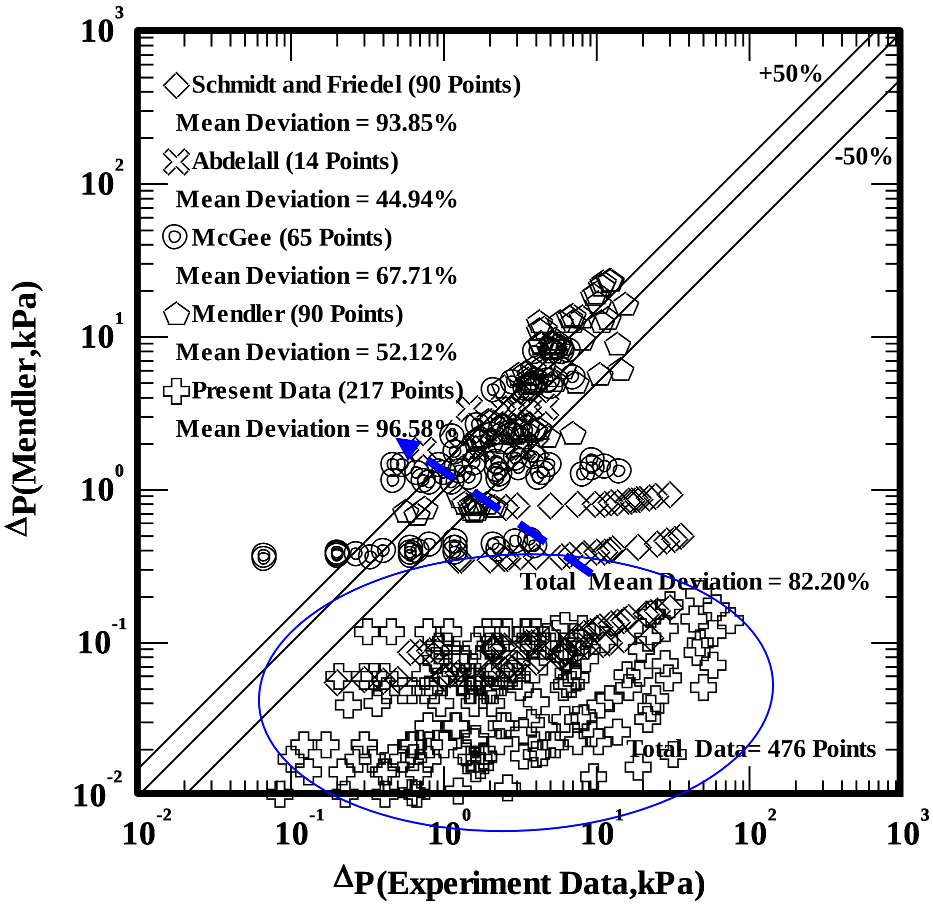
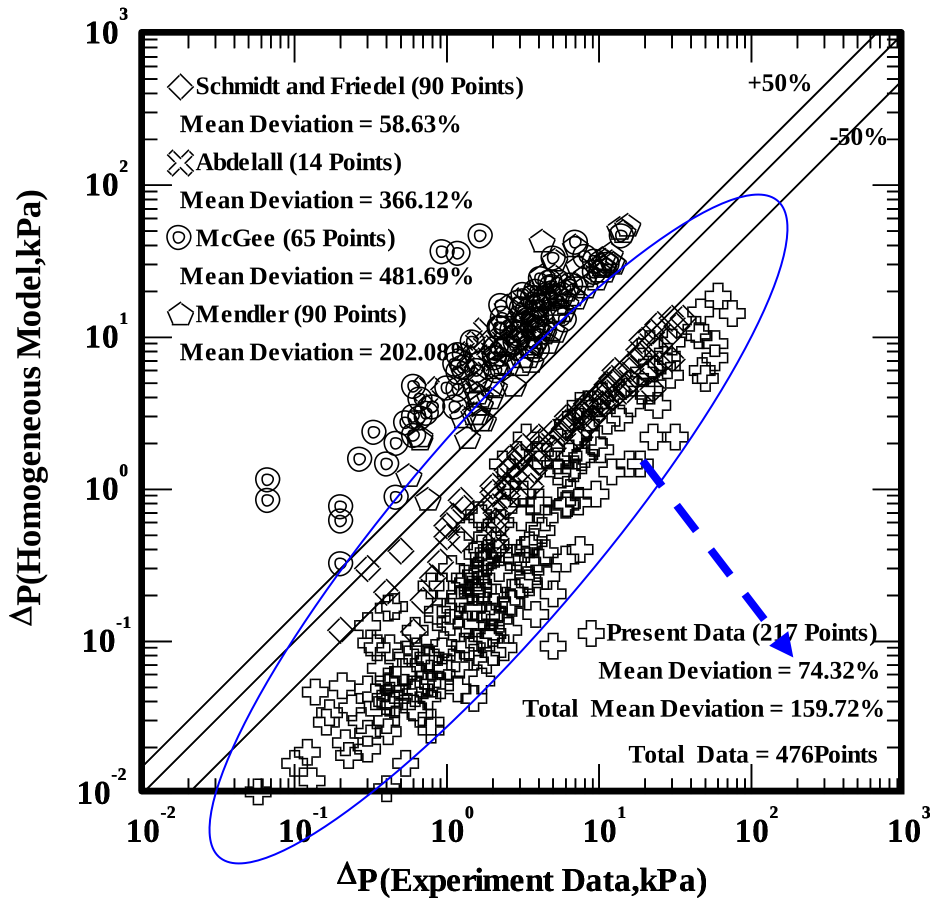
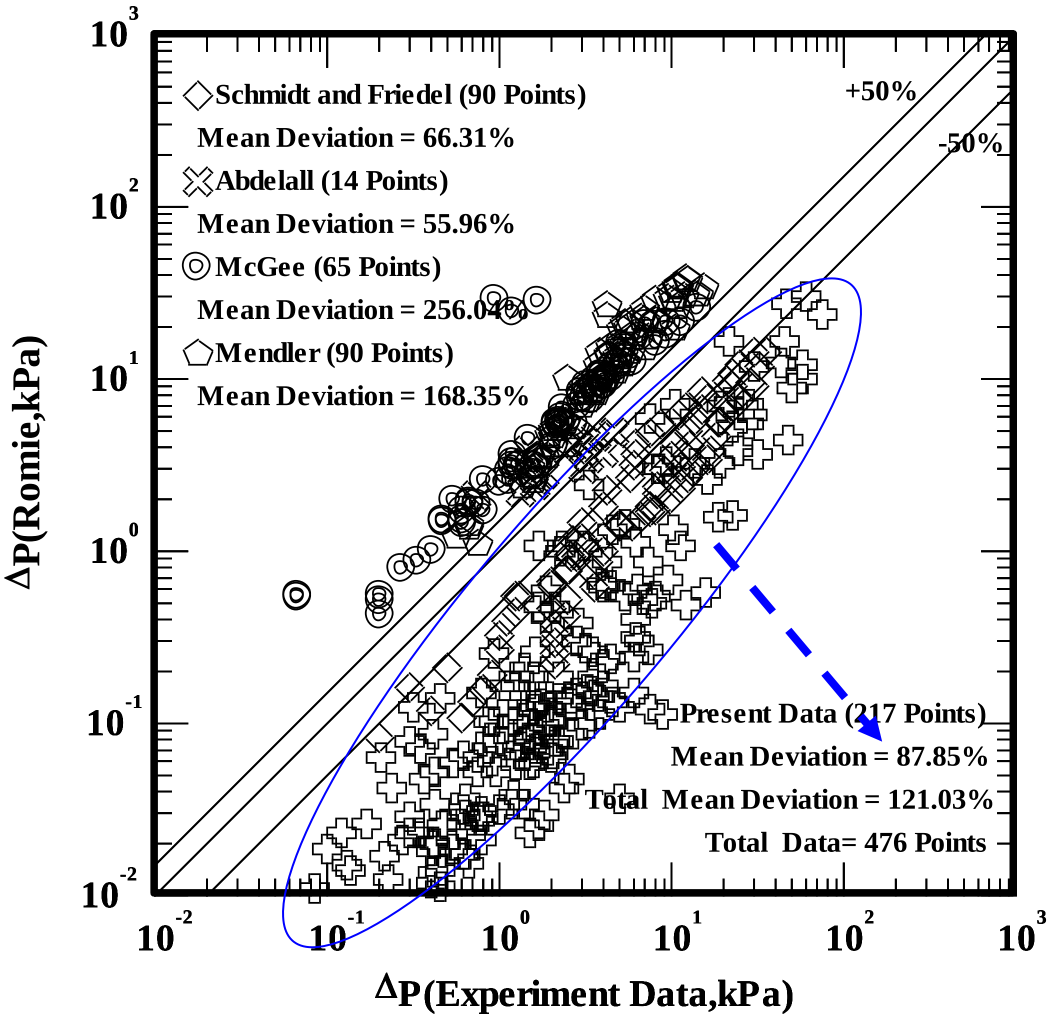




Correlation assessment



$$\Delta P_e = \frac{G^2\left(1-\sigma_A^2\right)}{2}\left(\frac{\sigma_A\left(1-x\right)^2}{\rho_L\left(1-\alpha\right)}\right)$$

Mean Deviation

ref	Present Data	Schmidt and Friedel	Abdelall	McGee	Mendler
Schmidt and Friedel	92.78%	28.11%	260.85%	199.34%	98.84%
Homogeneous Model	74.32%	58.63%	366.12%	481.69%	202.08%
Abdelall	78.17%	45.30%	96.58%	469.15%	300.12%
Richardson	83.72%	95.54%	29.55%	58.10%	35.81%
Romie	87.85%	66.31%	55.96%	256.04%	168.35%
Chisholm and Sutherland	61.33%	29.28%	643.17%	1548.47%	732.15%
Lottes	203.69%	6335.54%	80.34%	337.20%	322.92%
Wadle	80.44%	103.18%	140.19%	201.33%	277.68%
Attou and Bolle	90.76%	89.89%	34.01%	249.27%	234.56%
Mendler	96.58%	93.85%	44.94%	67.71%	52.12%
Delhaye	96.74%	66.31%	55.96%	256.04%	180.84%

Conclusions-Sudden expansion

- ''Liquid jet-like flow pattern'' at a very low quality and mass flux region may lead to a fall-off of pressure drop.
- Elongated bubble becomes the dominate flow pattern when vapor quality or the mass flux is small.
- The total mean deviations of the relevant predictions to all the data are 92.78%, 159.72%, 1400.52%, 82.20%, 71.80%, 137.76%, 140.30%, 121.03%, 167.85%, 127.44%, 402.30% by Schmidt and Friedel correlation , Homogeneous model, Lottes, Mendler, Richardson, Attou and Bolle, Wadle, Romie,Abdelall et al. correlation , Delhaye and Chisholm and Sutherland.
- Development of suitable correlation applicable for expansion is still in progress

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- Graduate Students: ***Chu, M. C. & Lin Y. S.***

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Thanks for your attention

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Experimental setup - expansion