GDR TransInter – journées d'Aussois 2025

Etude expérimentale de la dynamique d'écoulements diphasiques eau/air au sein d'un canal de taille millimétrique

Jimmy Martin (CEA/DES/IRESNE/DTN/STCP/LTHC)

Yann Kervegant, Romuald Mallet, Sylvain Chareyre (CEA/DES/IRESNE/DTN/STCP/LETH)

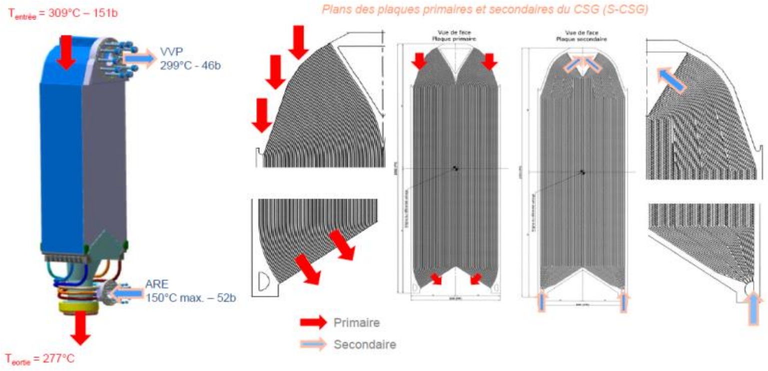
Aussois, 11 juin 2025

1. Context and motivations

A trend towards the miniaturization of nuclear systems in a context of nuclear energy revival

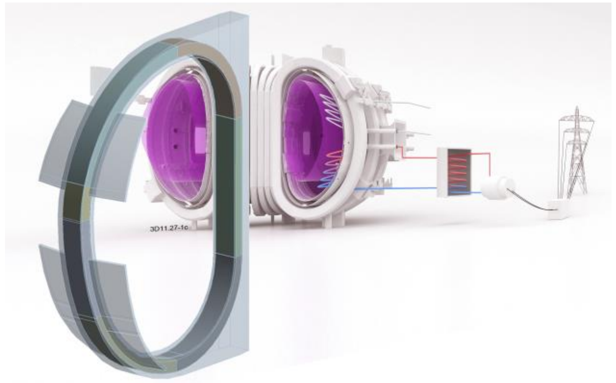
Applications such as **SMRs** or **nuclear fusion**

- R&D on compact steam generators for fission (CSG) or fusion reactors (studies carried out as part of the DEMO development
- Technical challenges:
  - Maximize steam production while minimizing the component's footprint
  - Limit fouling of the component's walls



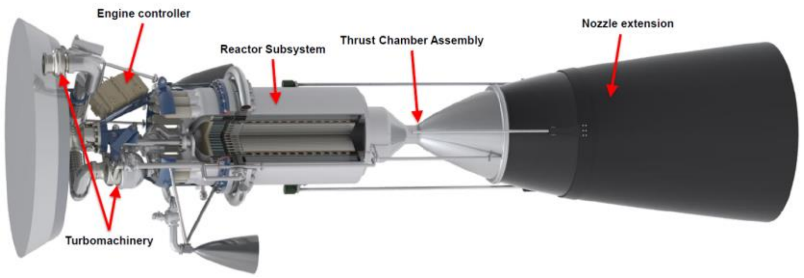
- High pressure, high temperature, and substantial flowrates are required to sustain **steam/water two-phase flow** conditions and maximize the thermodynamic efficiency of steam generation

  → Those strong constraints make the **millimetric scale** the **most appropriate**



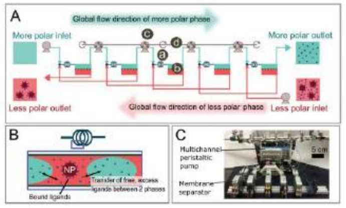
Space nuclear applications

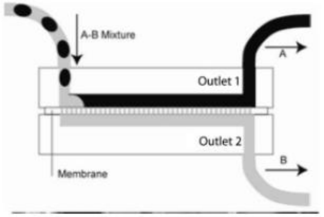
- Ongoing studies in France and abroad on concepts of nuclear reactors embedded for space exploration
- A CEA/CNES roadmap currently being drafted



Applications of the **nuclear fuel cycle**

- Ongoing R&D at CEA/ISEC in collaboration with a separation chemistry industry partner
- **Liquid-liquid two-phase flows, millimeter-scale imposed** by flow rate requirements / efficiency of chemical separation





How does two-phase flow behavior differ in millimeter-sized channels?

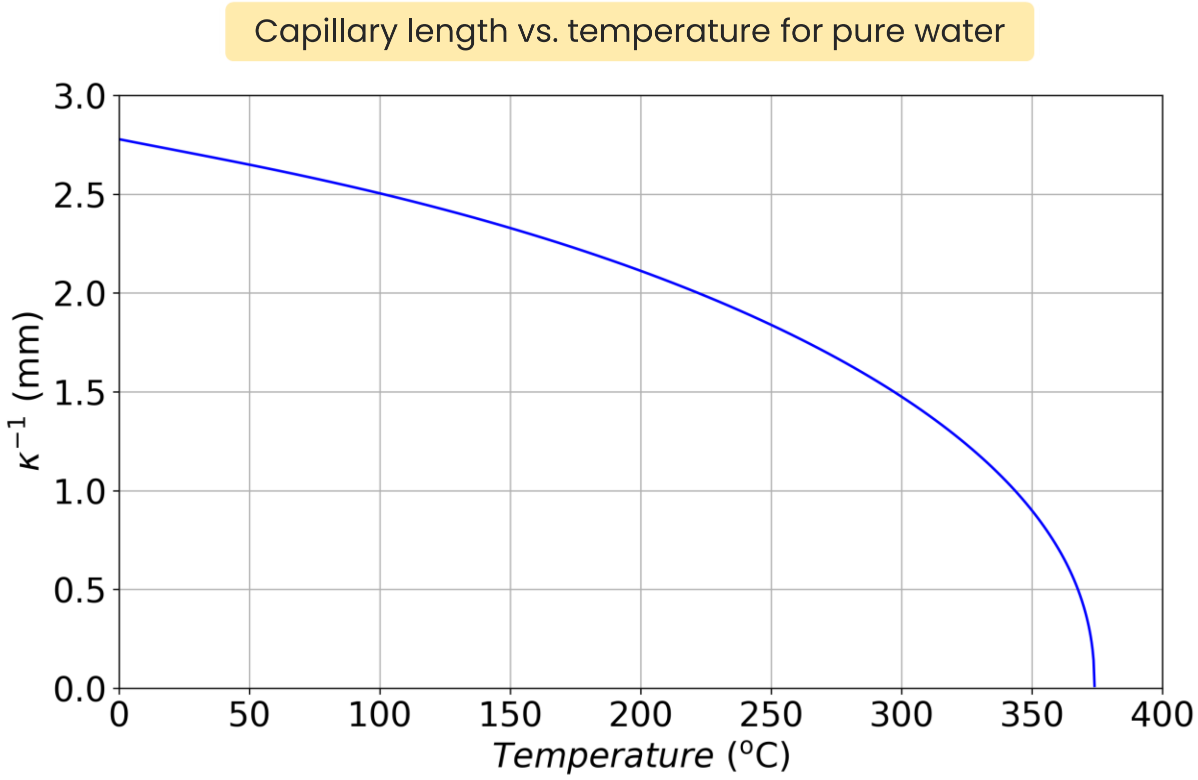
- An important length scale: the **capillary length**

$$\kappa^{-1} = \sqrt{\frac{\gamma}{g\,\Delta\rho}}$$

with γ, the gas/liquid surface tension, g, the gravitational acceleration, $\Delta\rho$, the liquid-to-gas density difference

- $\kappa^{-1} = 2.7\,mm$ for pure water at 20°C
- **Capillary effects are significant and gravity forces are less dominant** if hydraulic diameter or smallest channel transverse length < κ^{-1}

→ This remains true for water up to temperatures of 350°C (*i.e.* very close to the critical point): it largely encompasses the thermohydraulic operating conditions of a pressurized water nuclear reactor



How does two-phase flow behavior differ in millimeter-sized channels?

- An important dimensionless quantity: the **capillary number**

$$Ca = \frac{\mu V}{\gamma}$$

with γ, the gas/liquid surface tension, V, a characteristic velocity, μ, the liquid dynamic viscosity

- In the case of wetting surfaces with capillary numbers $Ca < 1$, the presence of a **triple line at the fluid–fluid–solid interface is possible**

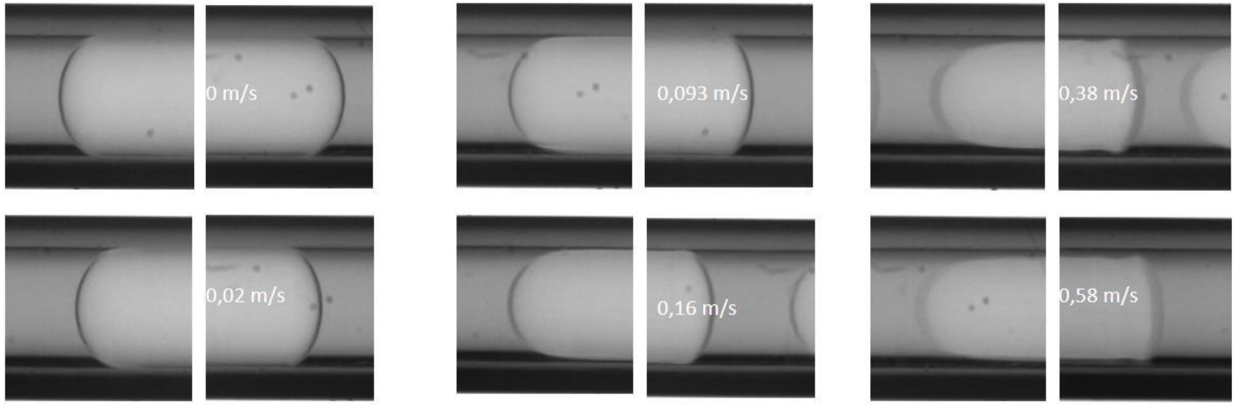
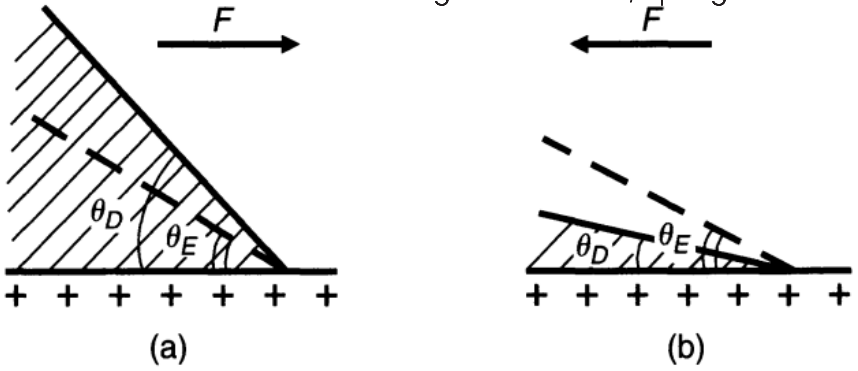
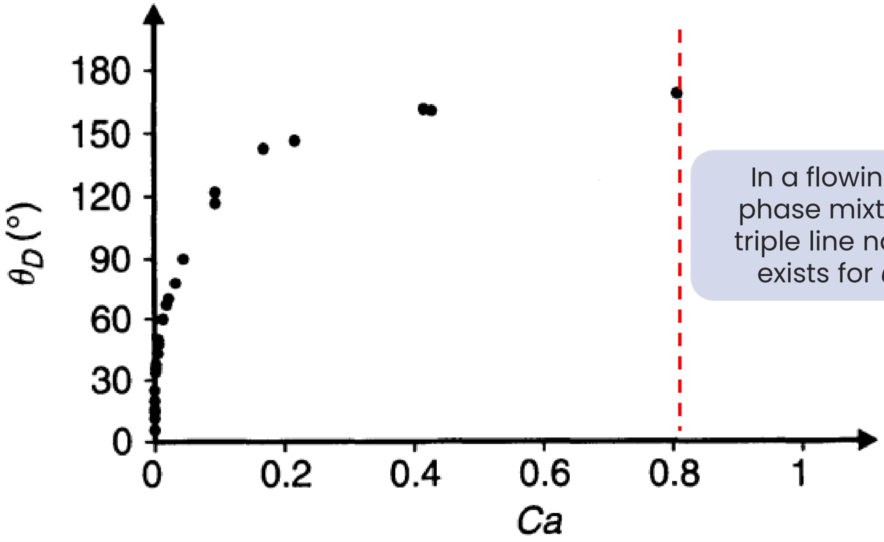


Illustration of a water/Isane184 liquid/liquid two-phase flow within a PTFE channel of an inner diameter of 750 µm (courtesy of F. Lamadie, CEA/ISEC)

Source: P.-G. De Gennes *et al.* (2004). "Capillarity and Wetting Phenomena", Springer



Non-equilibrium force F exerted on the triple line, with θ_E the so-called static contact angle and θ_D the dynamic contact angle

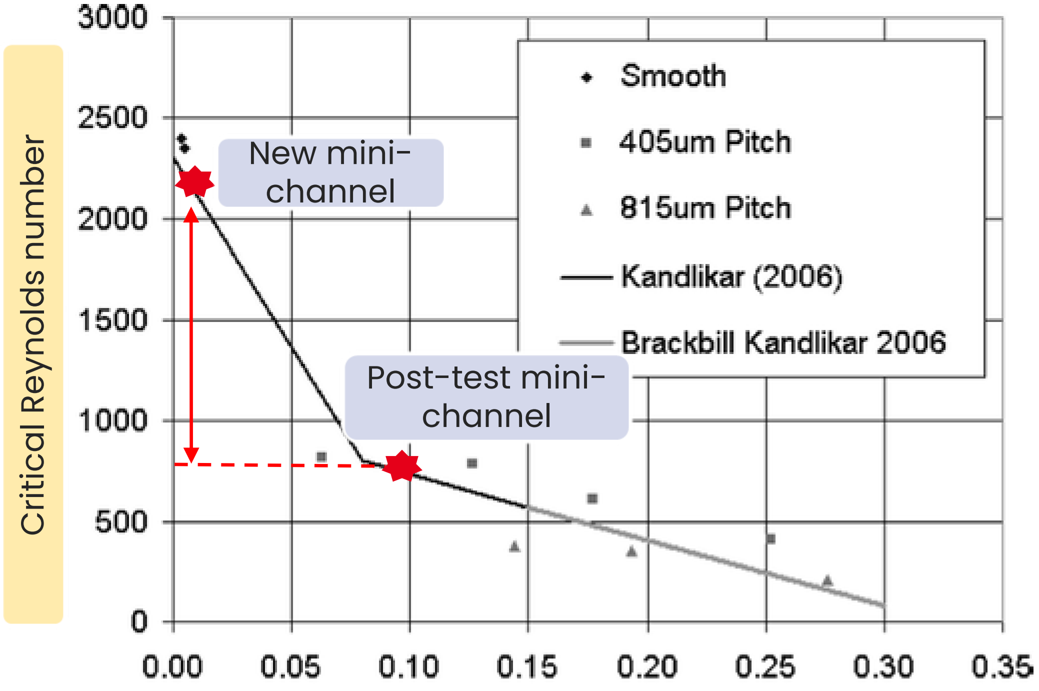


In a flowing two-phase mixture, the triple line no longer exists for $Ca \gg 1$

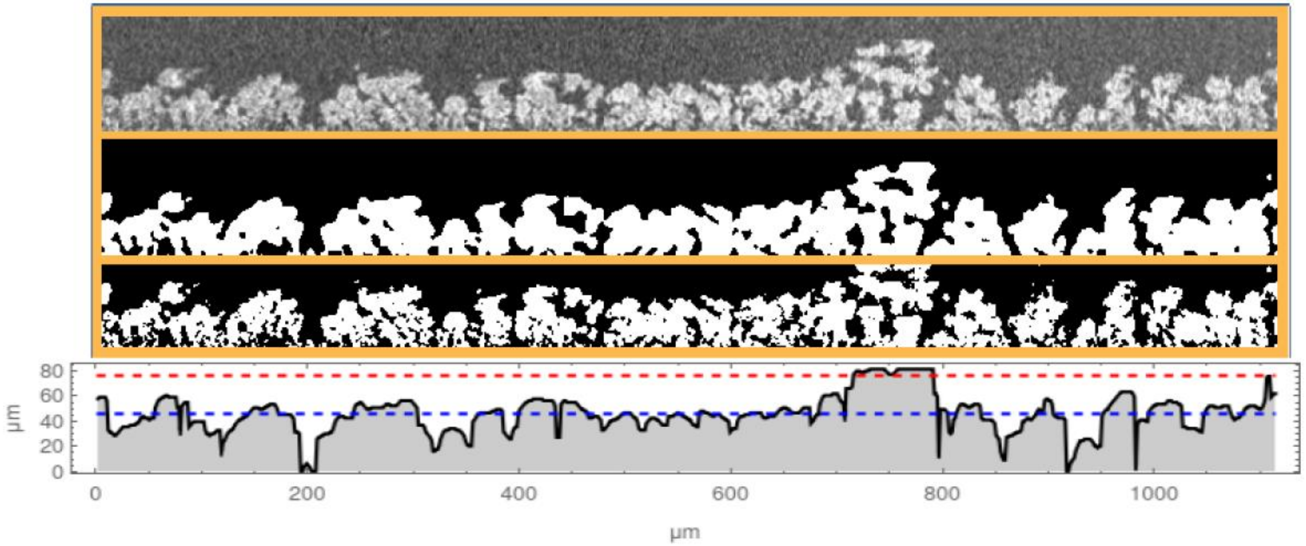
Variations of the dynamic contact angle θ_D as a function of the capillary number for several oils in a glass channel (Hoffmann, 1975)

How does two-phase flow behavior differ in millimeter-sized channels?

- The wall roughness strongly matters!
  - The wall friction impacts the laminar/turbulent regime transition in an unusual way
  - Millimetric-scale channels are prone to fouling, leading to significant variations in wall roughness over time (*e.g.* +50µm magnetite deposit after about 2 months at 60 bar / 300°C in a titanium cylindrical channel with an inner diameter of 1.4 mm during a CEA IRESNE test)



SEM image of a cross-section of the titanium mini-channel and its magnetite deposit after a fouling test at CEA IRESNE



Source: S.G. Kandlikar *et al.* (2014). "Heat Transfer and Fluid Flow in Minichannels and Microchannels – Second Edition", Butterworth-Heinemann Elsevier

How does two-phase flow behavior differ in millimeter-sized channels?

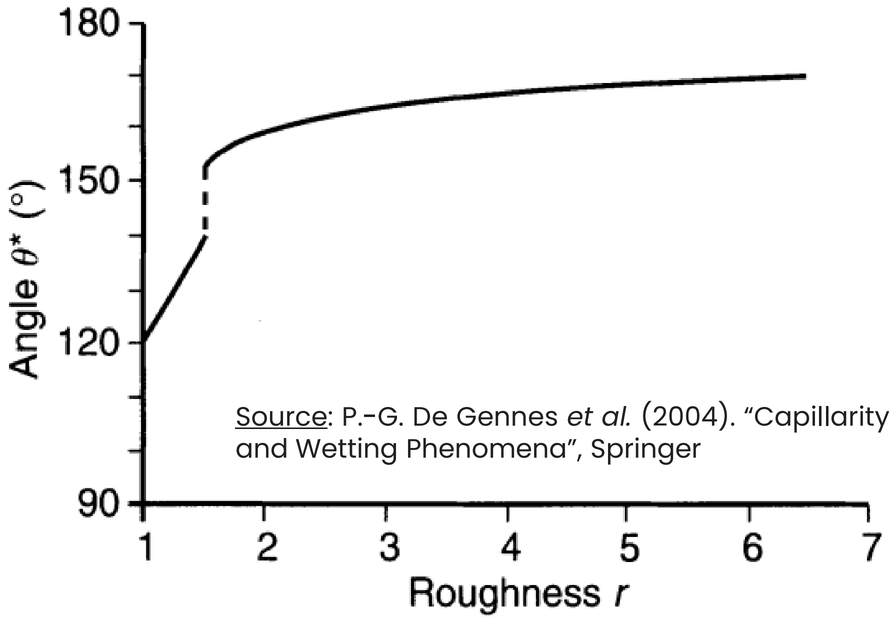
- The wall roughness strongly matters!
  - The wall friction impacts the wettability properties of the channel and hence the triple line dynamics
    - **Wenzel's law**: rough surfaces tend to exaggerate the intrinsic wetting characteristics of a material, making hydrophilic surfaces more hydrophilic and hydrophobic surfaces more hydrophobic

$$\cos \theta^* = r \times \cos \theta_E$$

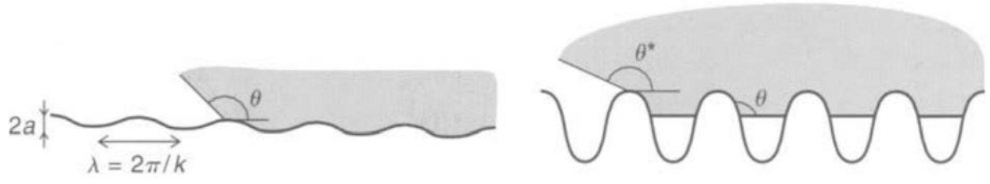
with θ_E the static contact angle of a smooth solid surface, θ^* the static contact angle of its rough counterpart, r the *ratio* between the actual surface area and the projected (or apparent) surface area

    - For very rough surfaces, **air trapping** is likely to occur and can affect surface wettability
    - On rough surfaces, **microscopic defects and asperities can pin the triple contact line**, hindering its motion

Variations of the static contact angle θ^* of a rough solid surface as a function of a roughness estimator r

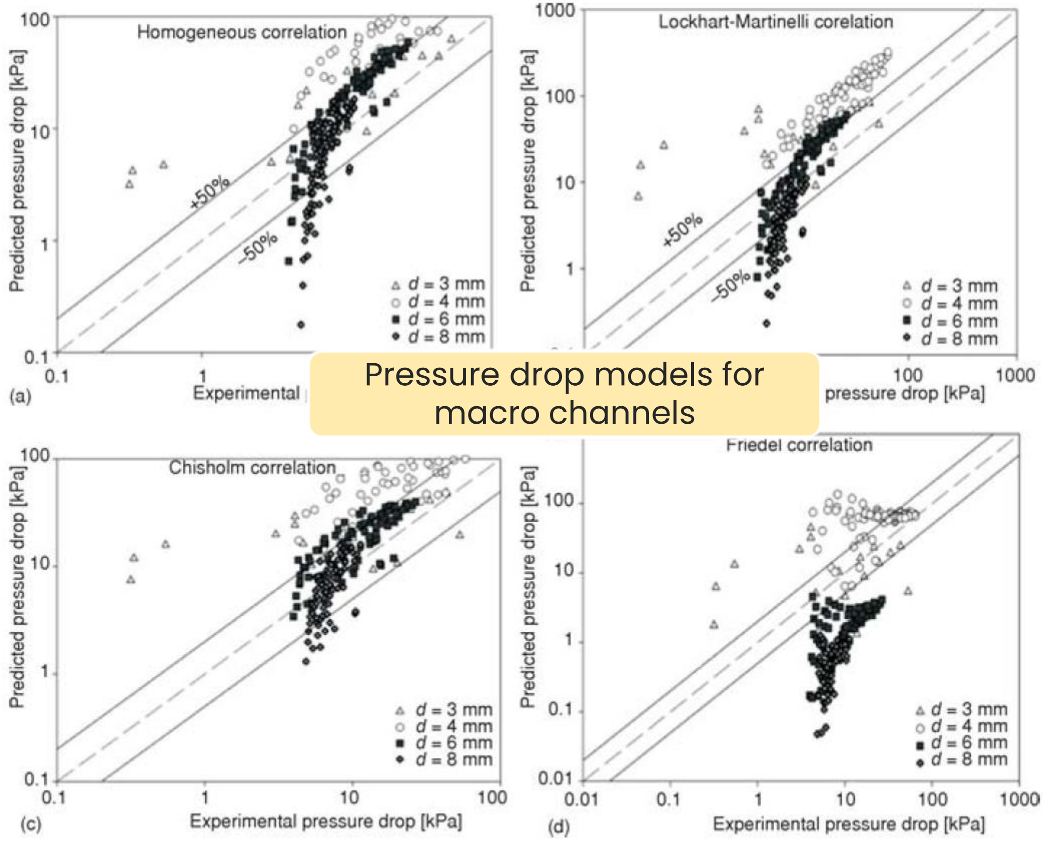


Source: P.-G. De Gennes *et al.* (2004). "Capillarity and Wetting Phenomena", Springer

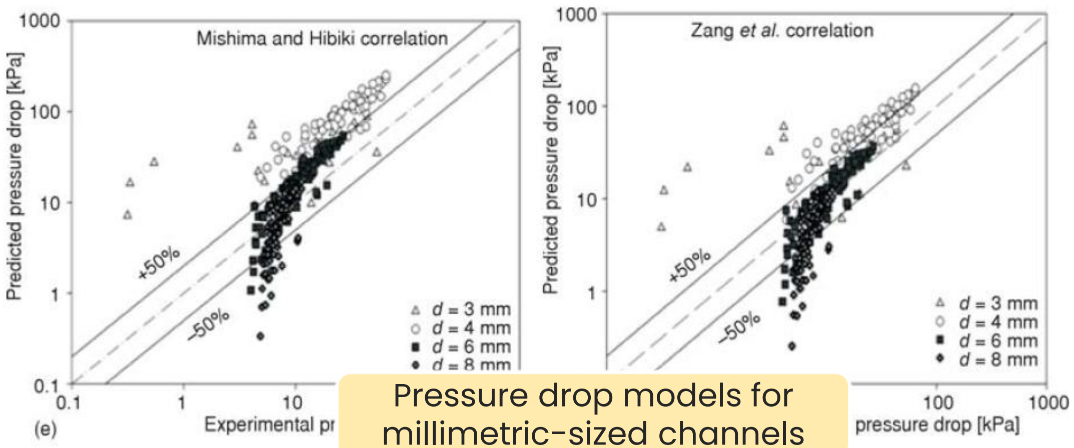


Challenges and limitations from an operational perspective

- Due to the complex physical effects discussed earlier, current models for two-phase pressure drop remain difficult to establish in the specific case of mini-channel applications and still involve significant uncertainties
- Two-phase pressure drop models are not yet mature enough for applications in mini-channels, highlighting the **need for experimental data to support their development and validation (purpose of this first study)**

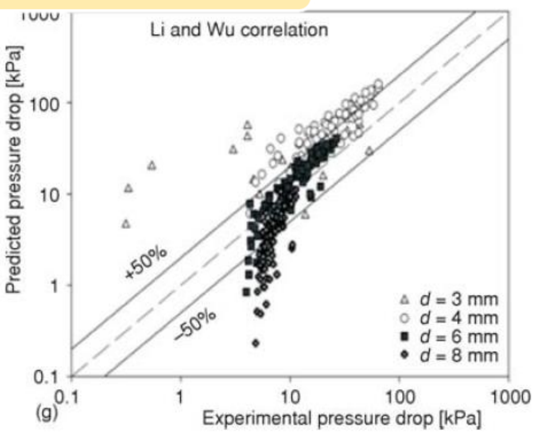


Pressure drop models for macro channels



Pressure drop models for millimetric-sized channels

Source: A. Autee *et al.* (2014). “Experimental study on two-phase pressure drop of air-water in small diameter tubes at horizontal orientation”, Thermal Science, Vol. 18, No. 2, pp. 521-532



2. Description of BICHE test device

The BICHE test device allows experiments for better understanding the heat and mass transfers in millimetric-scale channels

Overview of BICHE analytical test bench

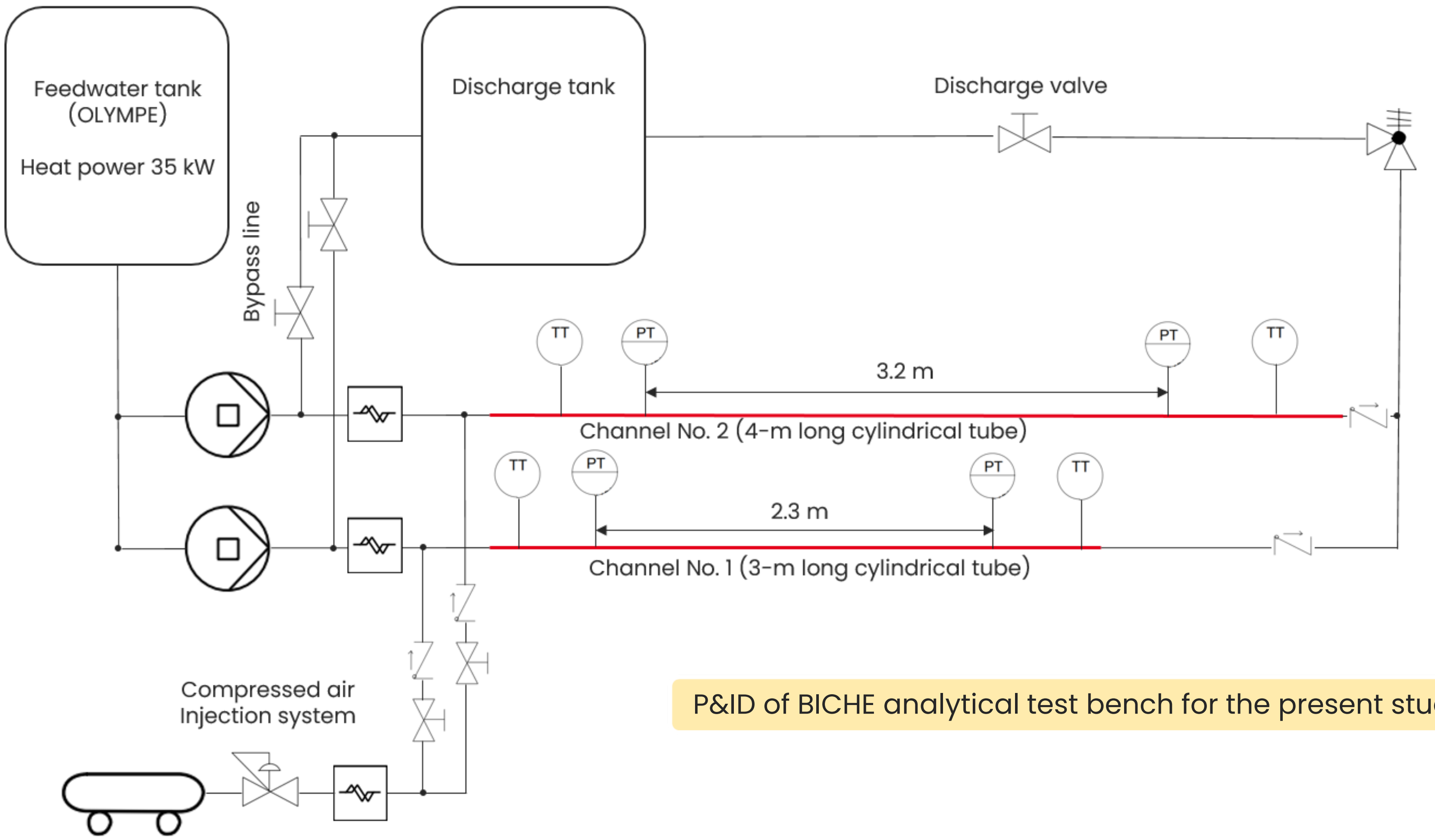
- BICHE: an analytical loop for investigating the pressure losses and two-phase flow regimes, focusing on mini-channel flow dynamics

- Loop design:
  - Two independent hydraulic circuits with volumetric pumps (0.5–200 g/s, 1–10 bar discharge pressures)
  - Water supply from OLYMPE tank (demineralized, non-degassed)
  - Heating system in OLYMPE to set feedwater temperature up to 80°C (35 kW max)
  - Compressed air injection (0–3 g/s) for each circuit

- Instrumentation:
  - Pressure and temperature at the inlet/outlet
  - Mass flow rate at the inlet for each phase
  - Void fraction and bubble velocity using optical sensors

J. Martin, R. Mallet, Y. Kervegant, S. Chareyre, "A characterization of the two-phase frictional pressure drop within a cylindrical mini-channel in the laminar and turbulent regimes," *21st International Topical Meeting on Nuclear Reactor Thermal Hydraulics*, Busan, Korea (2025)

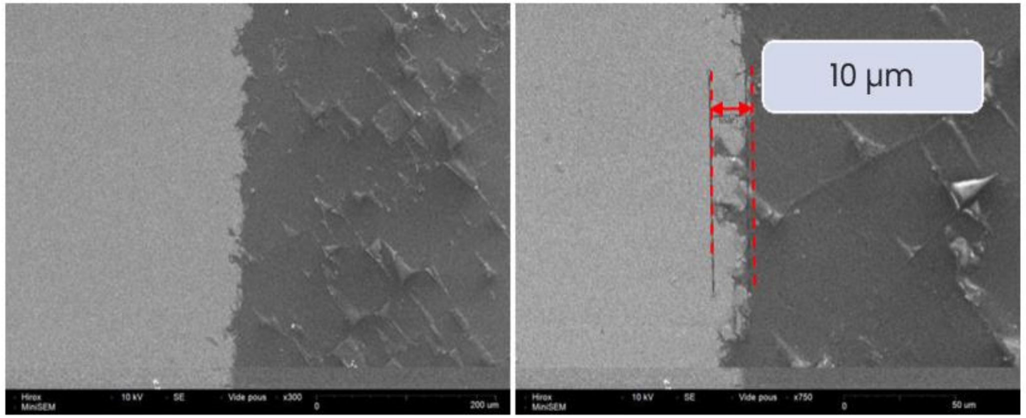
The BICHE test device allows experiments for better understanding the heat and mass transfers in millimetric-scale channels



P&ID of BICHE analytical test bench for the present study

Tested mini-channels and instrumentation

- For this experimental study, two cylindrical mini-tubes made of titanium alloy were used: the first with a length of 2.3 m and the second 3.2 m. Both have a hydraulic diameter of 1.38 mm and an outer diameter of 2 mm
- The tubes were placed horizontally (no significant two-phase stratification expected)
- Prior to testing, the internal surface condition of these mini-tubes was characterized using a scanning electron microscope



Scanning electron microscope images of the internal surface state of a mini-tube made of titanium alloy used in the BICHE device

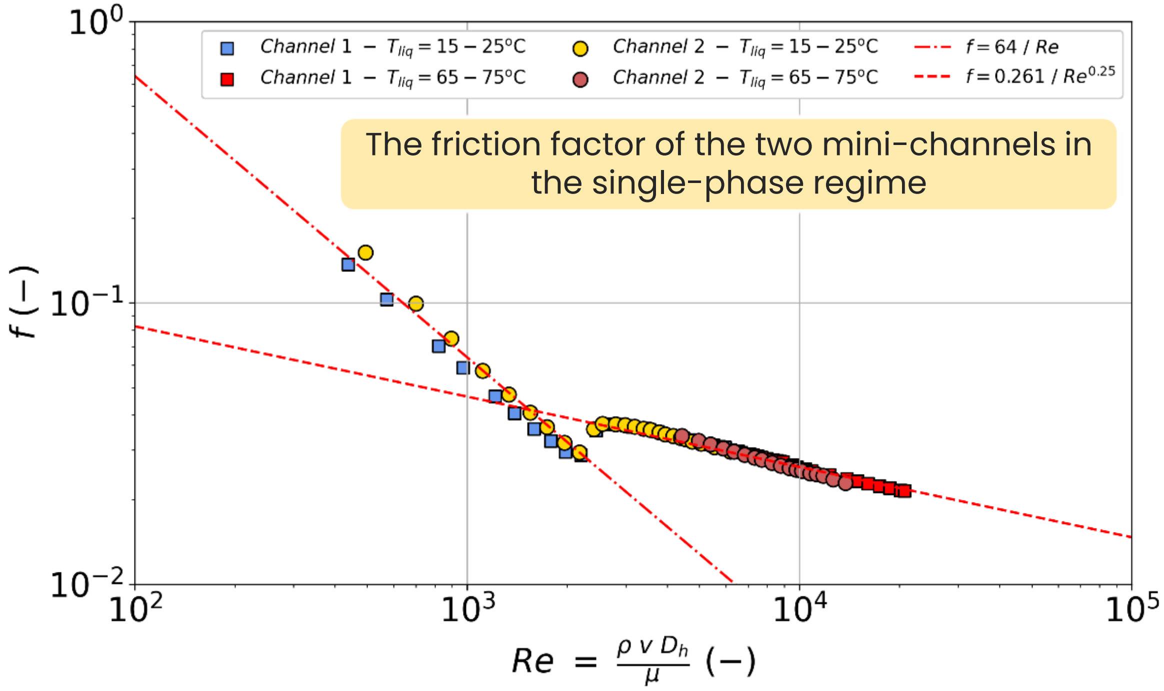
Measurement	Sensor	Range	Precision (k=2)
Channels No.1-2 inlet liquid mass flow rate	Coriolis flow meter, Elite series (MICROMOTION)	0 – 200 g/s	±0.1 % measurement
Injected air mass flow rate	Coriolis flow meter, Elite series (MICROMOTION)	0 – 5 g/s	±0.1 % measurement
Inlet/outlet temperature	Pt-100 1/10e DIN probe	0 – 100°C	±0.15 K
Inlet/outlet pressure	Pressure transducer EMERSON 3051	0 – 10 bar	±0.2 % measurement

Instrumentation of BICHE experimental setup

3. An experimental study of the pressure losses in a smooth millimetric-sized channel made of titanium

A prior estimate of the single-phase pressure drop

- Before analyzing pressure drops in a two-phase configuration, the single-phase liquid pressure drops were first characterized for the studied mini-channels
- A total of 100 tests were conducted (52 for channel No.1, 48 for channel No.2), with liquid mass flow rates ranging from 0.5 to 9 g/s and inlet liquid temperatures between 15 and 75°C, yielding liquid Reynolds numbers Re between 400 and 21,000
- Data reduction through the form of a regular friction factor f and a liquid Reynolds number Re



- Results in agreement with the literature (*i.e.* no shift in the critical Reynolds number)
- The following friction laws were obtained:

$$f = \frac{64}{Re} \qquad for\ Re \lesssim 2300$$

$$f = \frac{0.261}{Re^{0.25}} \qquad for\ 2300 \lesssim Re < 21{,}000$$

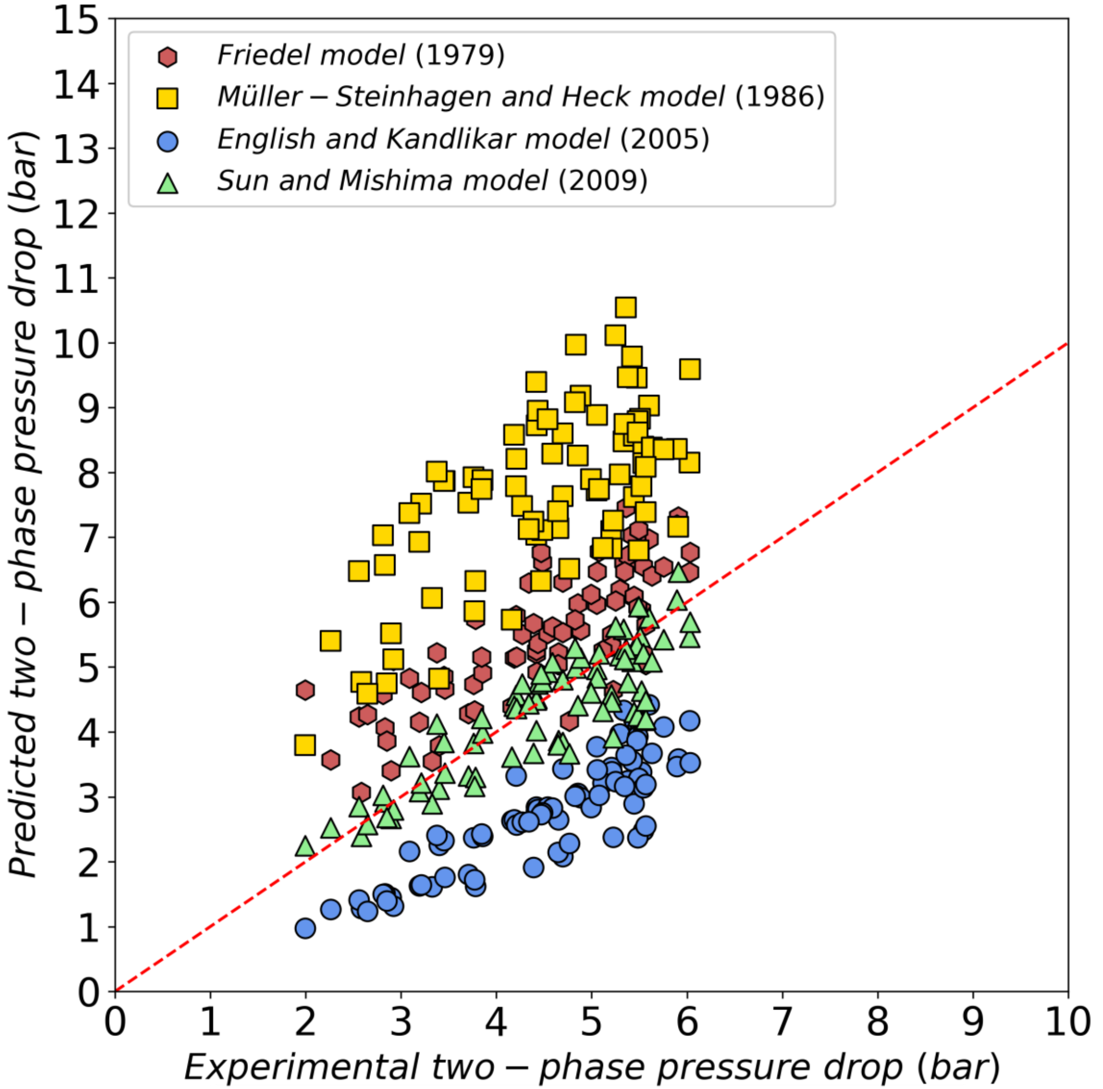
Where one can recognize a Blasius-type law corresponding to the so-called turbulent smooth regime

Results and discussion for an air/water two-phase flow

- For investigating the two-phase frictional pressure drop at the scale of a mini-channel, a total of 82 tests were conducted (53 for channel No.1, 29 for channel No.2)
  - Liquid mass flow rates ranging from 0.7 to 4.8 g/s
  - Gas mass flow rates between 0.01 and 0.14 g/s.
  - The experiments were performed at an inlet liquid temperature of approximately 20°C (*i.e.* to avoid any gas solubility effect)

- Liquid Reynolds numbers between 500 and 4,000 and gas Reynolds numbers ranged from 600 to 8,000

- A comparison of experimental data with four different two-phase pressure drop models among the most recommended for mini-channels was carried out



Two-phase data comparison with four relevant pressure loss models

Results and discussion for an air/water two-phase flow

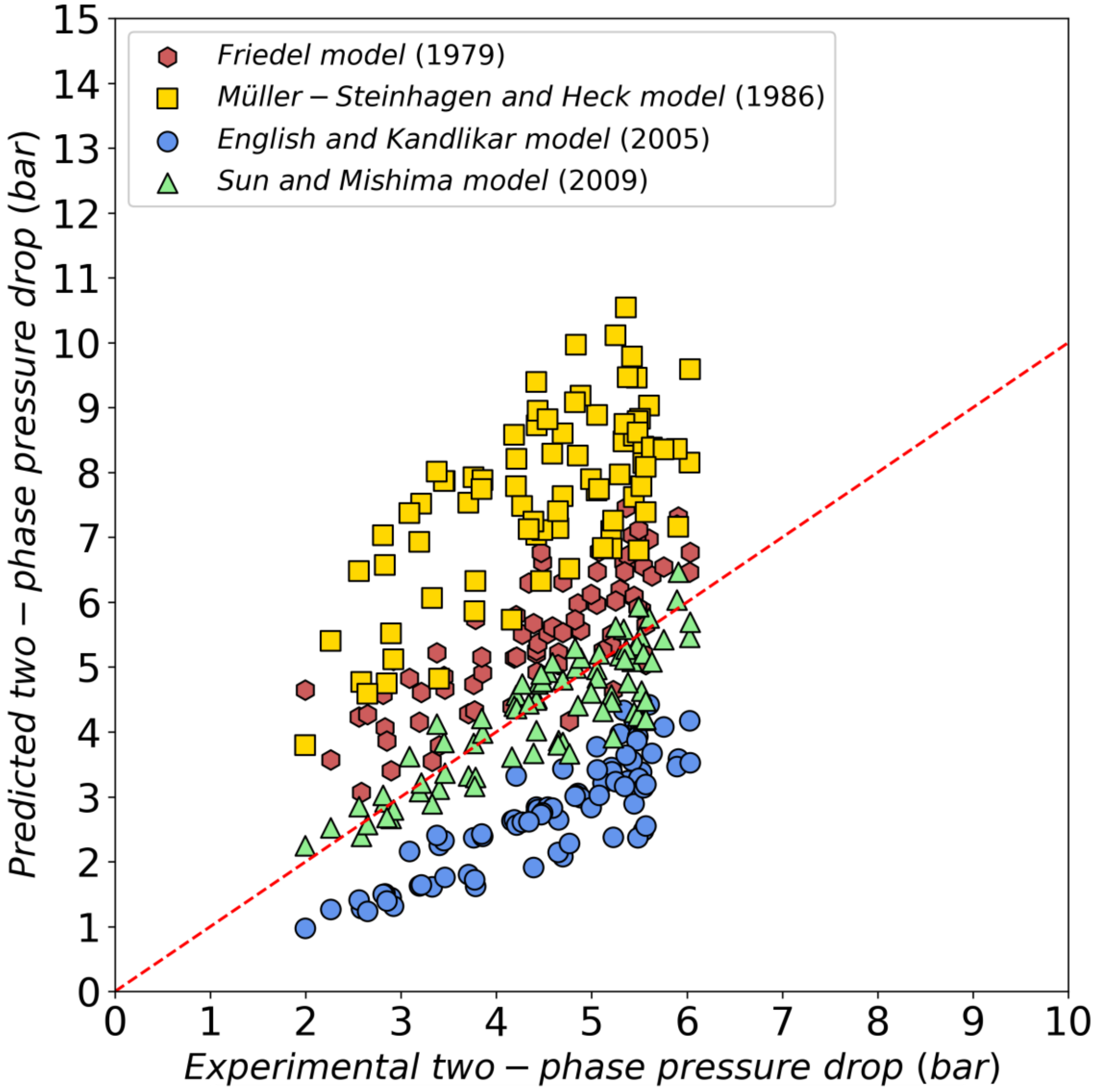
- Among the tested models, **the Sun and Mishima model (2009) best predicts the experimental data**, in agreement with the recommendations of the literature

Source: Y. Xu *et al.* (2012). "Evaluation of frictional pressure drop correlations for two-phase flow in pipes", Nuclear Engineering and Design, Vol. 253, pp. 86-97

- Mean relative deviations between predictions and experimental results obtained for each model:

	Friedel (1979)	Müller-Steinhagen & Heck (1986)	English & Kandlikar (2005)	Sun & Mishima (2009)
Mean relative deviation	-26%	-75%	+40%	**+3%**

… but what happens in the case of a rough channel surface? This issue is left as a direction for future research…



Two-phase data comparison with four relevant pressure loss models

Seeking a power law to reduce further the scatter in experimental data

- In order to reduce the obtained data, two well-known quantities are computed:
  - The dimensionless pressure drop Φ_L^2
  - The so-called Martinelli parameter X^2

- Those quantities read:

$$\Phi_L^2 = \frac{\Delta P_{fric}}{\left(\Delta P_{fric}\right)_L} \qquad X^2 = \frac{\left(\Delta P_{fric}\right)_L}{\left(\Delta P_{fric}\right)_G}$$

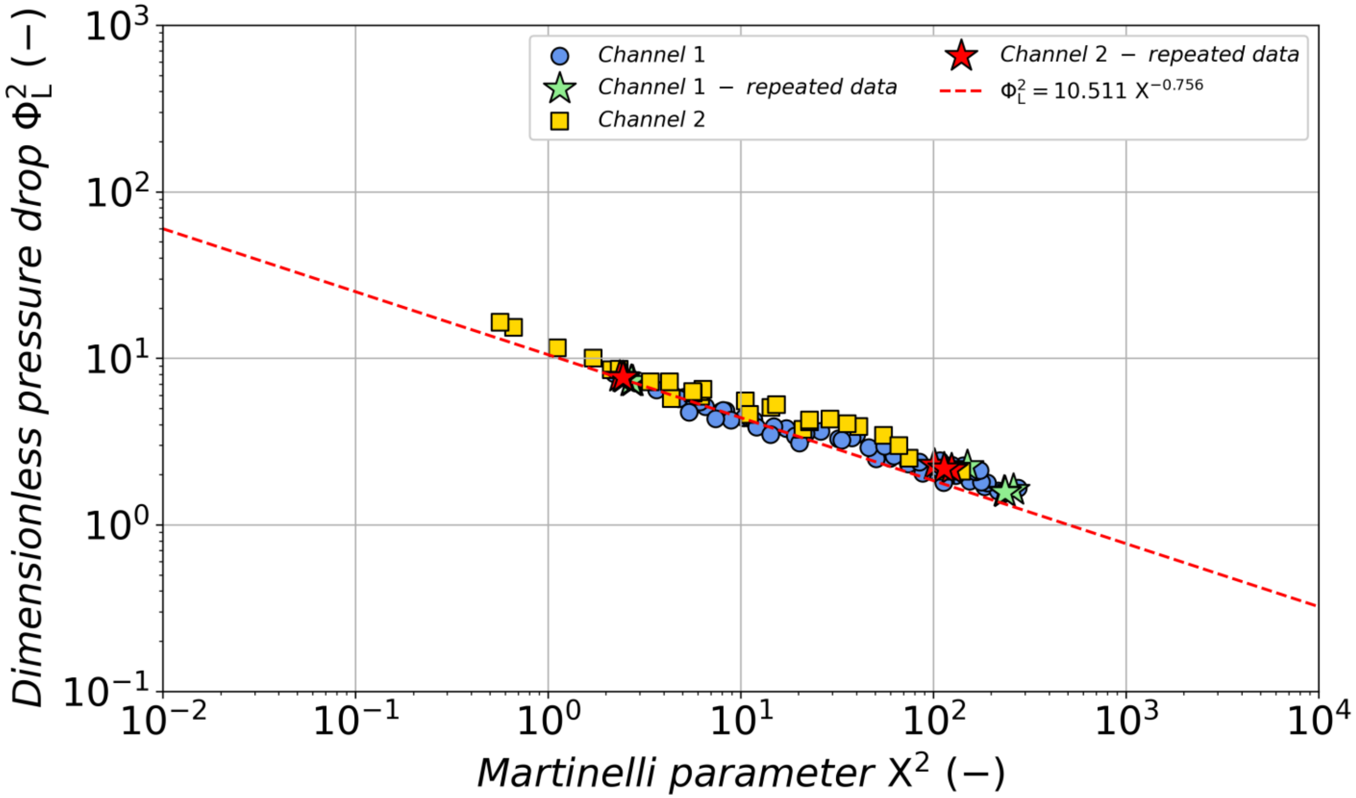
where one assumes $\Delta P_{fric} \approx \Delta P$, the measured pressure difference in the two-phase case and with $(\Delta P_{fric})_L$ and $(\Delta P_{fric})_G$, respectively the pressure drop of the liquid and gas phases alone, whose value is computed on the basis of the prior estimate of the channel's friction laws in the single-phase regime

Seeking a power law to reduce further the scatter in experimental data

- A power law relating Φ_L^2 to X^2 fits the experimental data well!

$$\Phi_L^2 = 10.511\ X^{-0.756}$$

with a regression coefficient $R^2 = 0.94$, a pre-factor equal to $10.511 \pm 0.520\ (k = 2)$ and an exponent equal to $-0.756 \pm 0.055\ (k = 2)$



4. Conclusions and perspectives

Some conclusions

- This experimental study **characterized the frictional pressure drop** in **two-phase flow** within cylindrical **mini-smooth channels of millimeter-scale diameter**, made of titanium

- The results demonstrate that the most recommended correlation to data in the field, namely the *Sun and Mishima* model (2009), accurately reproduce the experimental data, with a limited mean relative deviation between predictions and empirical results of +3%

- The tests covered a wide range of Reynolds numbers for both liquid and gas phases, revealing a clear trend in the relationship between the well-known dimensionless pressure drop Φ_L^2 and the Martinelli parameter X^2

- A power law relating Φ_L^2 to X^2 has been derived from the achieved tests and further reduces the scatter in experimental data

- The strong repeatability of the results reinforces their reliability and confirms that channel length has no significant influence on the observed trends (*i.e.* no unwanted “entrance effect”)

What's next?

- **Submission of an ANR PRC project proposal** in fall 2025 in order to go beyond those first results and better understand the various roughness effects on the two-phase flow dynamics at millimetric scale

- **Additional experiments will be conducted**, with wide variations in:
  - The used couples of flowing fluids (*e.g.* air/water, organic fluid/water, etc.)
  - The material of the channel walls (*i.e.* for changing significantly the static contact angle of the channel surface)
  - The roughness of the channel walls (*i.e.* by means of controlled substrate deposits)

- **Modeling activities will be conducted using both CMFD and LBM frameworks**, with upscaling efforts aimed at deriving macroscopic models for two-phase pressure drops

Thank you for your attention

CEA CADARACHE
DES/IRESNE/DTN/STCP/LTHC
13115 Saint-Paul-lez-Durance, France
jimmy.martin@cea.fr
+ 33 4 42 25 63 96