Non-intrusive pipe internal pressure measurement

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FROM RESEARCH TO INDUSTRY

Non-intrusive pipe internal pressure measurement

15:20-15:50, the 4th of March, 2022 – NURETH19 Workshop – Fiber-optic sensors for thermal hydraulic measurements

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6 – 11 MARCH 2022, NURETH19, BRUSSELS, BELGIUM
19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics

EUROPEAN NUCLEAR SOCIETY

BEARN 2 pressure loop facility – CEA/Saclay

FROM RESEARCH TO INDUSTRY

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Non-intrusive pipe internal pressure measurement

Global context

- Why a non-intrusive pressure measurement ?

Non-intrusive pressure measurement and temperature compensation background

- Non-intrusive pressure measurement – Background
- Temperature cross-sensitivity compensation based on the same proof body – Background

Non-intrusive pressure measurement – Underlying principle and core theory

- Underlying principle leading to temperature cross-sensitivity compensation
- The infinitely long and straight pipe under hydrostatic pressure
- The FBG transducer – Some orders of magnitude
- Non-intrusive pressure ΔP_{int} measurement with direction-sensitive strain transducers
- Additional effects mitigation & application to other measurement techniques

Experimental validations – From simple to more severe conditions

- I – Mechanically isolated pipe section
- II – Air pressure loop
- III – Water pressure loop (NPP primary coolant circuit)
  - Hot-air gun experiment to estimate the non-intrusive pressure measurement robustness
  - No fluid flow, no temperature change
  - No fluid flow, but temperature changes due to heat conduction
  - Fluid flow with massive fluid flow change (from 14 m^3/h to zero) & temperature changes

Conclusion

Acknowledgements

Additional information – Data availability

FROM RESEARCH TO INDUSTRY

Global context

15:20-15:50, the 4th of March, 2022 – NURETH19 Workshop – Fiber-optic sensors for thermal hydraulic measurements

Non-intrusive pipe internal pressure measurement

Why a non-intrusive pressure measurement ?

- **No more pipe structural health damage due to sensor installation**
  - Does not require a hole per sensor
    - Measurement provided from pipe external surface, or even remotely
  - Sensors can be installed and removed on demand, without any downtime, nor requalification

e.g.: pressure equipment directive 97/23/EC from EU

- **No more contact with the fluid to monitor**
  - The pipe acts like the membrane of the traditional, but intrusive, sensor
    - But any undesired mechanical action on the pipe may introduce a measurement bias
    - Mitigation solution to be implemented to compensate for the effects of pure bending
- **A crucial measurement for the oil & gas industry**
  - First to prevent **hydrate-plugs** formation under specific **{P, T}** conditions (offshore)
  - Second to reduce the risk of pipe failure, and subsequent environmental consequences
- **Non-intrusive pressure sensors development mainly driven by the oil & gas industry**
  - Previous attempts mainly based on **ring sensors** (unsteady pressure), **surface strain measurements** or **acoustic waves**
    - Still suffer from **shortcomings**, with in general **poor temperature cross-sensitivity compensation**
  - Only one solution (Ekechukwu, 2021) based on both DAS and Raman DTS led to satisfactory results
- **New solution applicable to any fluid transportation if pipe cross-section is circular**
  - Temperature cross-sensitivity on pressure measurement intrinsically compensated / cancelled

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Non-intrusive pressure measurement and temperature compensation background

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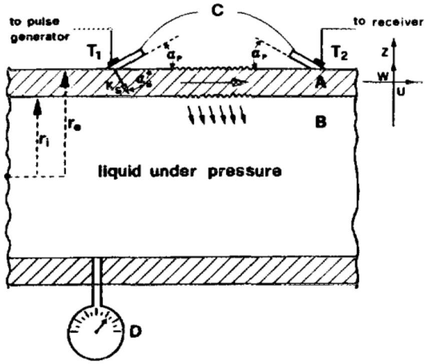
Non-intrusive pipe internal pressure measurement

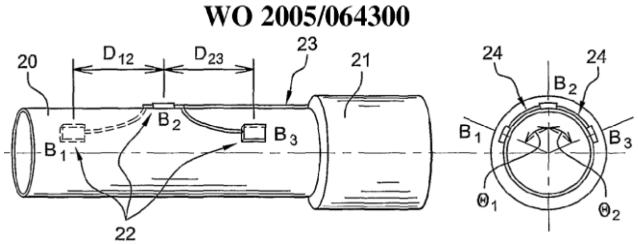
Non-intrusive pressure measurement – Background



Diodati, **1986**, **ultrasonics**

acoustic signal amplitude

→ dependency on fluid compressibility

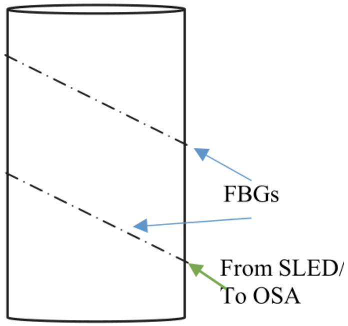


Magne *et al*, **2005**, **FBG** strain rosette

surface strain

→ temperature compensation issue

→ thin-shell theory approximation

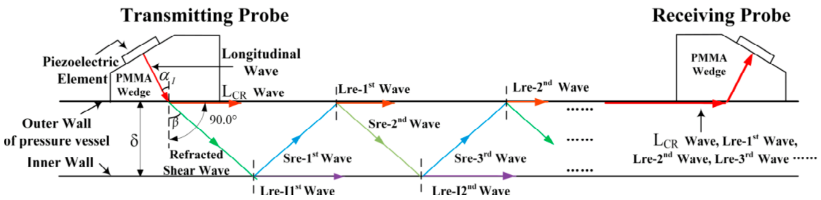


Meiring *et al*, **2016**, **FBG**

placed helically around the pipe

surface strain

→ temperature compensation issue

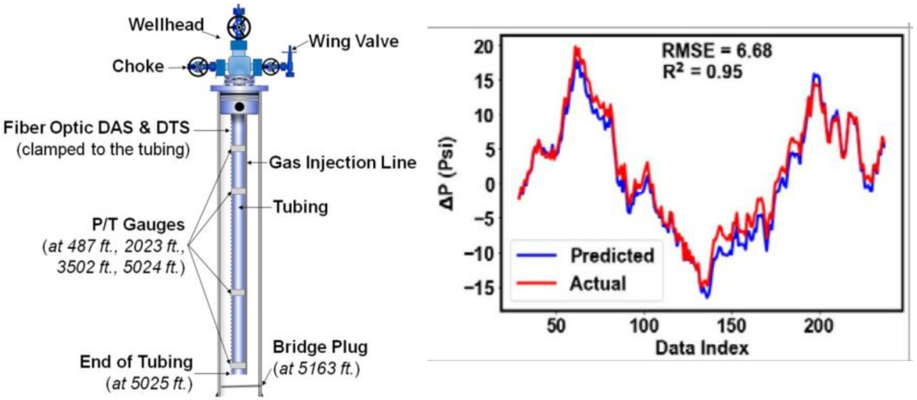


Zhou *et al*, **2016**, **ultrasonics**

propagation time of multiple longitudinal waves

→ temperature dependency requiring calibration

→ thin-shell theory approximation



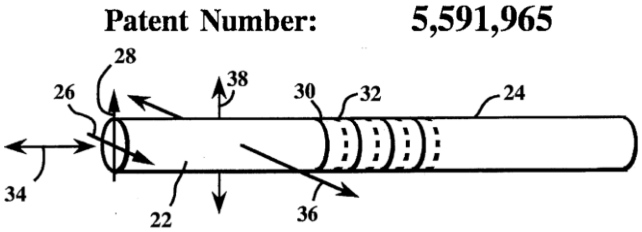
Ekechukwu *et al*, **2021**, **DAS & Raman DTS**

low-frequency DAS components

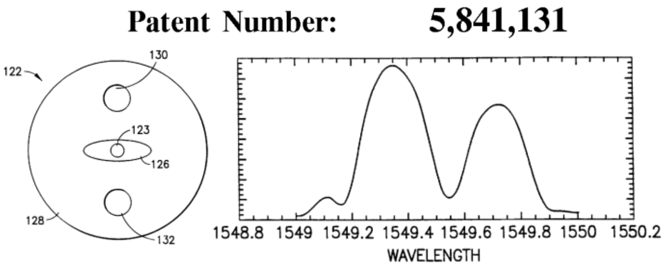
→ questionable if the fluid does not flow

Non-intrusive pipe internal pressure measurement

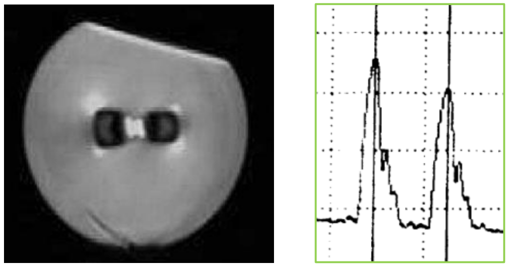
Temperature cross-sensitivity compensation based on the <u>same proof body</u> – Background



Udd, **1995**, **overlaid FBGs** at different wavelengths **in birefringent optical fiber**

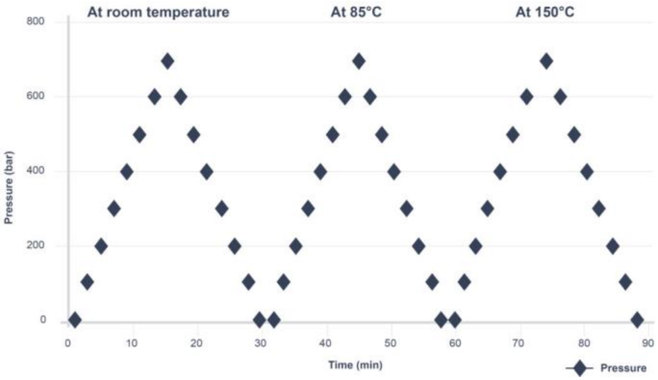


Schroeder *et al*, **1997** (Schlumberger™) **FBG in birefringent optical fiber**



Chen *et al*, **2003**, **Hi-Bi FBG**

Schlumberger™ **quartz** pressure sensor – Donzier *et al*, **2000**
from "*Techniques de l'Ingénieur*", vol. E 3 093
("*Capteurs microélectroniques*")
Pressure stability better than 0.01% Full Scale / Year



FBGS™ pressure sensor based on **Hi-Bi FBG**
https://fbgs.com/solutions/pressure-sensing/

FROM RESEARCH TO INDUSTRY

Non-intrusive pressure measurement Underlying principle and core theory

15:20-15:50, the 4th of March, 2022 – NURETH19 Workshop – Fiber-optic sensors for thermal hydraulic measurements

Non-intrusive pipe internal pressure measurement

Underlying principle leading to temperature cross-sensitivity compensation

- **Pipe behaviour under pressure <u>well-known for decades</u> – Formal models available**
  - **Materials' strength** recipes (Roark **1938**) → *averaged* values over pipe sections, thin *vs.* thick models
  - **Continuum mechanics** in the elastic range (Love **1927**, Timoshenko **1934**) → full & accurate solutions derived from Airy's potential – Temperature dependency to be taken into account
- **Exhibits different hoop *vs.* longitudinal stress sensitivities under hydrostatic pressure**
  - Balance of pipe wall internal forces *vs.* forces resulting from internal pressure P_{int} (closed pipe hypothesis)

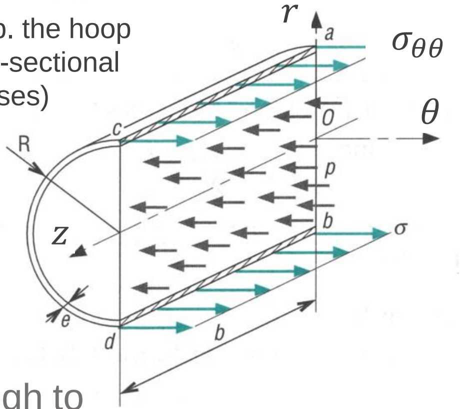
<u>hoop:</u> $2\sigma_{\theta\theta}.e.b \simeq P_{int}.2\mathrm{R.b}$ (*cylindrical cross-section balance*)

<u>longitudinal:</u> $\sigma_{zz}.e.2\pi R \simeq P_{int}.\pi R^2$ (*circular cross-section balance*)

($\sigma_{\theta\theta}$ and σ_{zz} are resp. the hoop & longitudinal cross-sectional *average* stresses)

$$P_{int} \simeq \frac{2\sigma_{\theta\theta}.e.b}{2R.b} \simeq \frac{\sigma_{zz}.e.2\pi R}{\pi R^2} \Rightarrow \boxed{\boldsymbol{\sigma_{\theta\theta} \simeq 2\sigma_{zz}}}$$

(thin-shell *approximation*)



modified from Fanchon, "*Guide de mécanique*", 1998

⇨ **<u>In the elastic range</u>, leads roughly to the same ratio between the *average* hoop $\varepsilon_{\theta\theta}$ and the longitudinal ε_{zz} mechanical strains, BUT …**

  ⇨ Poisson's transverse effect & pipe thickness *do* interfere *significantly*

  ⇨ Thin-shell model from material's strength approximation is not accurate enough to properly describe strains distribution within the pipe wall and on its surfaces

⇨ **Provides a clue for intrinsic temperature cross-sensitivity compensation** with <u>orientation-sensitive</u> strain transducers by simple **<u>subtraction</u>** <u>of 2 raw measurements</u>

  ➢ Requires a complete <u>thermo</u>mechanical & accurate model

    ➢ Expected better efficiency than the sole Poisson's transverse effect (Maurin *et al*, 2007)

  ⇨ **FBG transducers are good candidates for such implementation**

temperature compensation paradigm different from conventional solutions

Non-intrusive pipe internal pressure measurement

The infinitely long and straight pipe under hydrostatic pressure

Elastic strains hypothesis

- Hooke's law: $[\boldsymbol{\sigma}] = 2\mu[\boldsymbol{\varepsilon}]_{mec} + \lambda\,\mathrm{Tr}([\boldsymbol{\varepsilon}]_{mec})\,[\boldsymbol{I}]$
- *Linearized* Green-Lagrange strain tensor $[\boldsymbol{\varepsilon}]$ approximation: $\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \cancel{\sum_{k=1}^{k=3}\frac{\partial u_k}{\partial x_i}\frac{\partial u_k}{\partial x_j}}\right)$

Problem formulated in terms of displacements

- $\vec{u} = \vec{u}_\sigma + \vec{u}_T$: total displacement $\vec{u}$ (sum of mechanical $\vec{u}_\sigma$ and thermal $\vec{u}_T$ displacements)
- Homogeneous temperature in the pipe wall & no shear stress hypotheses
  - → the temperature does not generate any additional mechanical strain

Fundamental equation of dynamics for deformable bodies

$\mathrm{div}\,[\boldsymbol{\sigma}] + \rho(\vec{f} - \vec{\gamma}) = \vec{0} \Rightarrow \mathrm{div}\,[\boldsymbol{\sigma}] \simeq \vec{0}$ (static conditions)

⇩

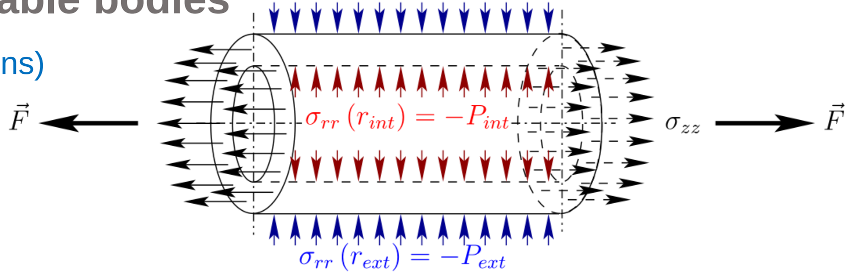
set of partial differential equations

⇩

formal solution valid *anywhere* in the pipe wall & pipe surfaces

displacement	$\vec{u} = f(K_1, L_1, L_2)$
strain tensor	$[\boldsymbol{\varepsilon}] = g(K_1, L_1, L_2)$
stress tensor	$[\boldsymbol{\sigma}] = h(K_1, L_1, L_2)$

- ➢ linear relationship with hydrostatic pressures
- ➢ quadratic relationship with temperature



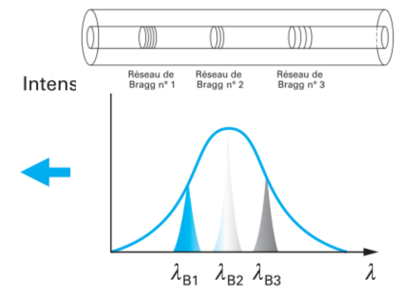
boundary conditions applied on the straight pipe section

$\boldsymbol{K_1}, \boldsymbol{L_1}, \boldsymbol{L_2}$ are integration parameters depending on:

- pipe thermomechanical properties,
- pipe inner $r_{0_{int}}$ & outer $r_{0_{ext}}$ radiuses,
- longitudinal pulling force $\vec{F}$,
- inner P_{int} & outer P_{ext} hydrostatic pressures,
- surface temperature T.

Non-intrusive pipe internal pressure measurement

The FBG transducer – Some orders of magnitude



from Ferdinand, "*Capteurs à fibres optiques à réseaux de Bragg*", "*Techniques de l'Ingénieur*", vol. R 6 735 v2, 2018

- **Temperature & strain measurements with the FBG transducer**
  - $\lambda_B = 2n_{eff}\Lambda \Rightarrow \frac{d\lambda_B}{\lambda_B} = (\kappa_T + \kappa_\varepsilon.\Delta\alpha).dT + \kappa_\varepsilon.d\varepsilon_{mec}$

    temperature dependency

    mechanical strain dependency
  - $\kappa_\varepsilon.\Delta\alpha$: additional temperature sensitivity when attached to pipe surface
    - Detached from the structure: $\Delta\lambda_B = 1\,pm \leftrightarrow 0.1°C \leftrightarrow 1\,\mu m/m$ $(@\ 1550\ nm)$
    - **Once attached to pipe surface**: $\Delta\lambda_B = 1\,pm \leftrightarrow 0.04°C \leftrightarrow 1\,\mu m/m$
      - Typically **2.3 times more sensitive** to temperature
  - Typical mechanical strain amplitude of a **Ø 4″ NPS Sch. 160 metallic pipe** under hydrostatic pressure
    - $\Delta P_{int} = 1\,bar \Rightarrow \Delta\varepsilon_{mec} \simeq 1\,\mu m/m \Rightarrow \boxed{\delta P_{int} = 1\,bar\text{ resolution } \leftrightarrow 0.04°C\text{ max temperature discrepancy}}$

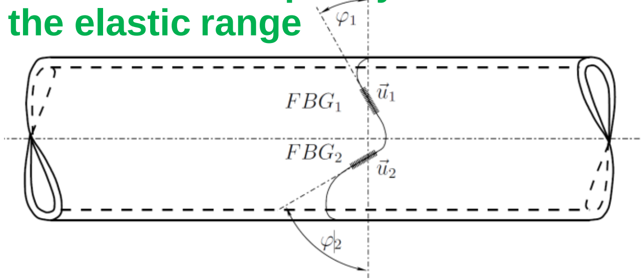
⇨ Temperature cross-sensitivity compensation is critical to reach $\delta P_{int} = 1\,bar$ resolution

(typical performance target)

- **FBG temperature is mainly weighted by the pipe thermal effusivity**
  - **Temperature discrepancy** between 2 transducers attached to the pipe surface **remains very small**
  - The **subtraction** between two raw measurements can therefore be assimilated to a **purely mechanical information, in direct relationship with the internal pressure in the elastic range**
    - λ_1 and λ_2 are the Bragg wavelengths of the FBG transducers attached to the pipe external surface

$$\boxed{\Delta P_{int} \simeq f_{\Delta\varepsilon}(\Delta\lambda_1 - \Delta\lambda_2)}$$

$f_{\Delta\varepsilon}$: linear function



Non-intrusive pipe internal pressure measurement

Non-intrusive pressure ΔP_{int} measurement with direction-sensitive strain transducers

- **Non-intrusive pressure measurement on a straight and closed pipe section**
  - Internal pressure ΔP_{int} and surface temperature ΔT variations are two independent information
    - Temperature variation ΔT also based on pipe mechanical properties (Young’s modulus E & Poisson’s ratio ν)
      - **Time delayed information** (due to heat diffusion) **to be considered with limited confidence**

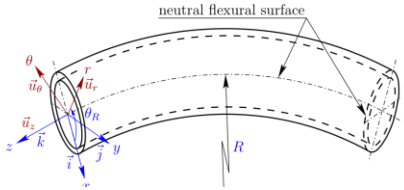
$$\left\{\begin{aligned}\Delta P_{int} &= \Delta P_{ext} + \frac{r_{0_{ext}}^2 E\boxed{(\underline{\Delta\Psi}_1 - \underline{\Delta\Psi}_2)}}{\kappa_\varepsilon(1+\nu)[\cos^2(\varphi_1) - \cos^2(\varphi_2)]}\left(\frac{1}{r_{0_{int}}^2} - \frac{1}{r_{0_{ext}}^2}\right) + \frac{\delta F}{\pi r_{0_{int}}^2}\\ \Delta T &= \frac{1}{\kappa_T}\left[\frac{1-2\nu}{1+\nu}\frac{\underline{\Delta\Psi}_1 - \underline{\Delta\Psi}_2}{\cos^2(\varphi_2) - \cos^2(\varphi_1)} + \frac{\underline{\Delta\Psi}_1\cos^2(\varphi_2) - \underline{\Delta\Psi}_2\cos^2(\varphi_1)}{\cos^2(\varphi_2) - \cos^2(\varphi_1)}\right.\\ &\quad\left. + \frac{\kappa_\varepsilon(1-2\nu)}{E}\Delta P_{ext} - \frac{1}{\pi E}\frac{2\kappa_\varepsilon(1-\nu)}{r_{0_{ext}}^2 - r_{0_{int}}^2}\delta F\right]\end{aligned}\right.$$

$\underline{\Delta\Psi}$ the transducer true relative variation measurement

$$\underline{\Delta\Psi} = \ln\left(1 + \frac{\Delta\lambda_B}{\lambda_B}\right) \underset{0}{\sim} \frac{\Delta\lambda_B}{\lambda_B}$$

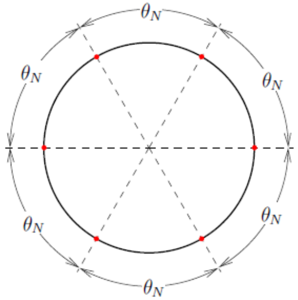
δF is the unexplained residual longitudinal force

$$|\varphi_1| \neq |\varphi_2| \mod \pi$$



- **Bending mitigation by simple averaging**
  - Requires $N \geq 2$ sensors evenly distributed in ring position around the pipe

$$\left\{\begin{aligned}\Delta P_{int} &= \Delta P_{ext} + \frac{r_{0_{ext}}^2 E\boxed{\frac{1}{N}\sum_{k=1}^{k=N}(\underline{\Delta\Psi}_{1_k} - \underline{\Delta\Psi}_{2_k})}}{\kappa_\varepsilon(1+\nu)[\cos^2(\varphi_1) - \cos^2(\varphi_2)]}\left(\frac{1}{r_{0_{int}}^2} - \frac{1}{r_{0_{ext}}^2}\right) + \frac{\delta F}{\pi r_{0_{int}}^2}\\ \Delta T &= \frac{1}{\kappa_T}\left[\frac{1-2\nu}{1+\nu}\frac{\frac{1}{N}\sum_{k=1}^{k=N}(\underline{\Delta\Psi}_{1_k} - \underline{\Delta\Psi}_{2_k})}{\cos^2(\varphi_2) - \cos^2(\varphi_1)} + \frac{\frac{1}{N}\sum_{k=1}^{k=N}[\underline{\Delta\Psi}_{1_k}\cos^2(\varphi_2) - \underline{\Delta\Psi}_{2_k}\cos^2(\varphi_1)]}{\cos^2(\varphi_2) - \cos^2(\varphi_1)}\right.\\ &\quad\left. + \frac{\kappa_\varepsilon(1-2\nu)}{E}\Delta P_{ext} - \frac{1}{\pi E}\frac{2\kappa_\varepsilon(1-\nu)}{r_{0_{ext}}^2 - r_{0_{int}}^2}\delta F\right]\end{aligned}\right.$$



N sensors evenly arranged in ring position around the pipe

1 sensor = 1 pair of FBGs

$|\varphi_1| \neq |\varphi_2| \mod \pi$

Non-intrusive pipe internal pressure measurement

Additional effects mitigation & application to other measurement techniques

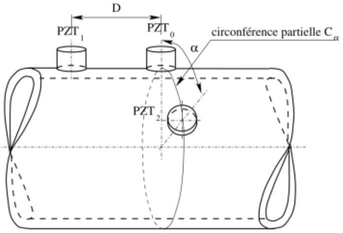
- **The subtraction compensation process leads to a purely mechanical information**
  - Temperature influence on pressure measurement is intrinsically cancelled
    - Transducers sensitivity to temperature must be equal
  - Any additional effect, different from purely mechanical, should also be optimally mitigated
    - *e.g.*: nuclear radiations influence on FBGs (responsible for Bragg wavelength shifts)
  - The temperature ΔT information should therefore be considered as a global influence parameter
    - Including temperature, but also *any* additional non-mechanical influence on the transducers

- **Application to other direction-sensitive surface strain or length measurement techniques**
  - The longitudinal mechanical strain variation $\Delta\varepsilon$ is nothing else but a relative length variation

$$\Delta\varepsilon = \ln\left(1 + \frac{\Delta L}{L}\right) \underset{0}{\sim} \frac{\Delta L}{L}$$

(true longitudinal strain variation definition)

  - Every measurement technique capable to measure length variations ΔL on pipe surface should also be able to perform non-intrusive pressure measurement
  - Examples of candidate measurement techniques:
    - Ultrasonics with PZT transducers
    - Non-contact cross-correlation technique with video cameras for remote pressure monitoring (if sensitivity OK with regards to strain ranges)



example of PZT transducers configuration distributed on pipe surface & dedicated to non-intrusive temperature self-compensated pressure measurement

FROM RESEARCH TO INDUSTRY

Experimental validations – From simple to more severe conditions

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CEA - www.cea.fr

6 – 11 MARCH 2022, NURETH19, BRUSSELS, BELGIUM
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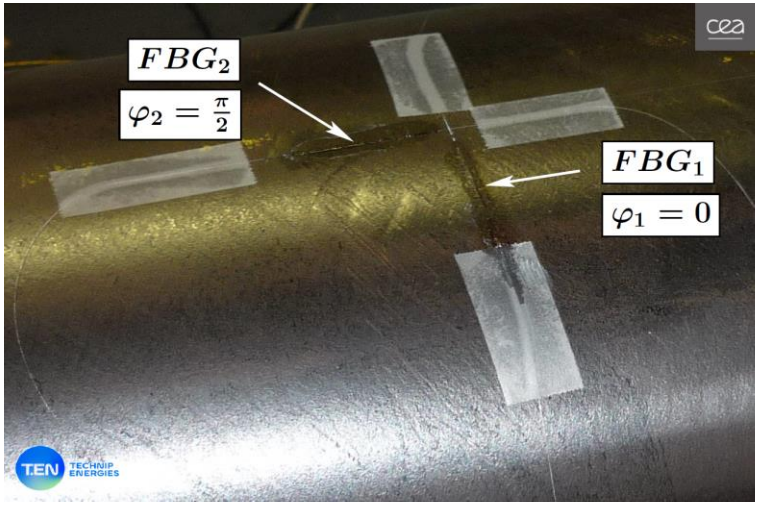
EUROPEAN NUCLEAR SOCIETY

Non-intrusive pipe internal pressure measurement

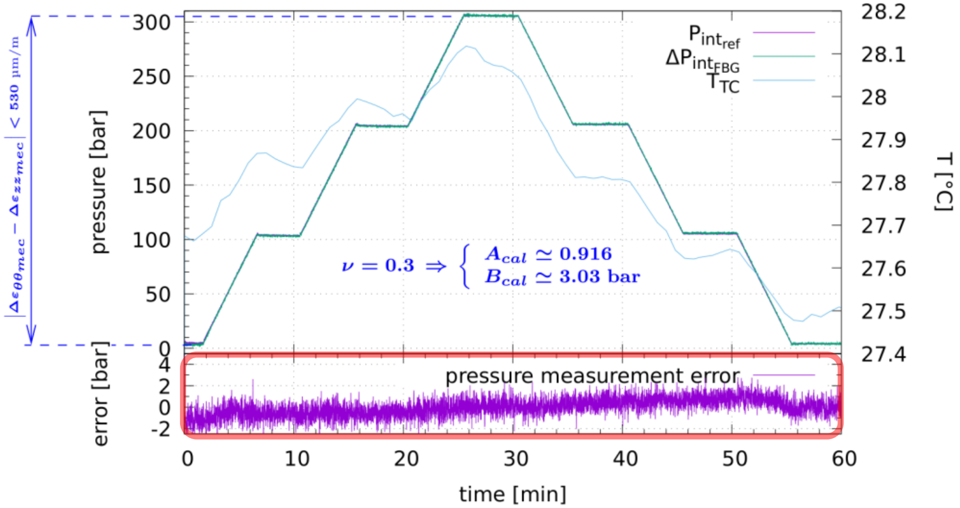
Technip Energies, Marseille, FR
July 2019

I – Mechanically isolated pipe section

- **Pipe section filled with pressurized water**
  - No external force applied on the pipe – Room temperature
  - Inflating pressure up to 300 bar
  - Pipe length greater than 5 times its diameter
    - FBG transducers in the middle of the pipe section to be free from side effects



one non-intrusive FBG-based pressure sensor made of two FBG transducers in hoop and longitudinal configurations (best sensitivity configuration, also insensitive to torsion)



non-intrusive pressure measurement error **better than 0.54% Full Scale** at 2σ after calibration – **5 Hz** measurement rate

A_{cal}: calibration scale factor (*i.e.*: the gauge factor)

B_{cal}: calibration pressure offset

measurement performed without delay (in real-time)

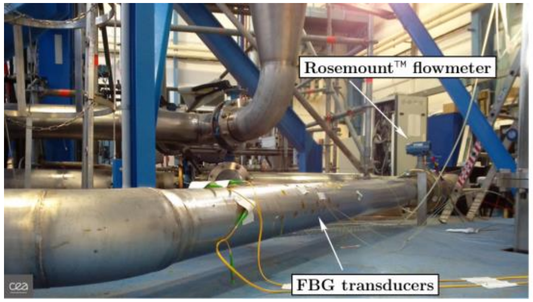
Non-intrusive pipe internal pressure measurement

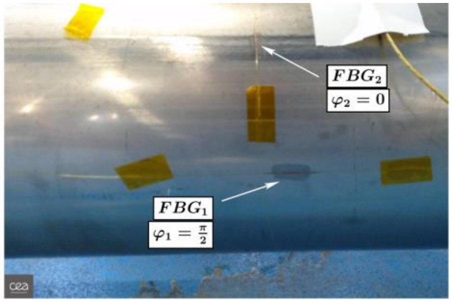
CEA, DES, Mercure facility, Cadarache, FR
IRESNE, *Research Institute for Nuclear Systems for Low Carbon Energy Production*
October 2019

II – Air pressure loop

- **Air pressure loop including several bends**
  - FBG transducers in the middle of a 5 m long pipe section – Complex pipe layout with many bends
  - Air flow rate steps up to $300\ m^3/h$ – Room temperature

complex pipe layout including several bends and attachments

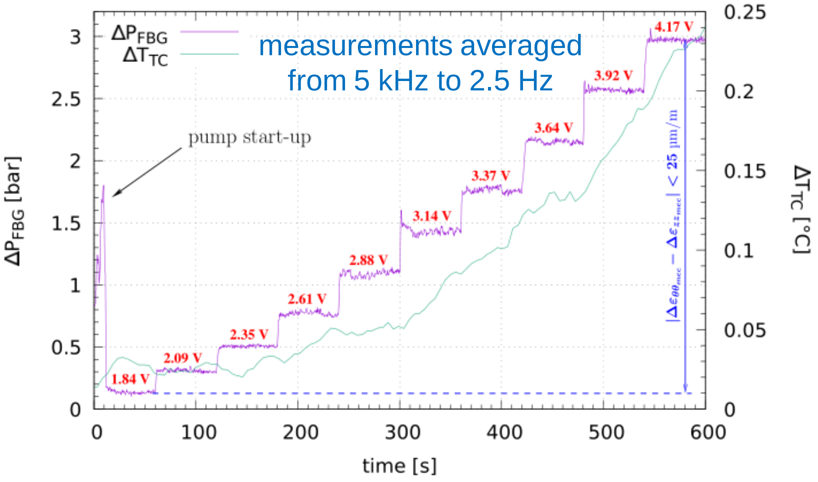




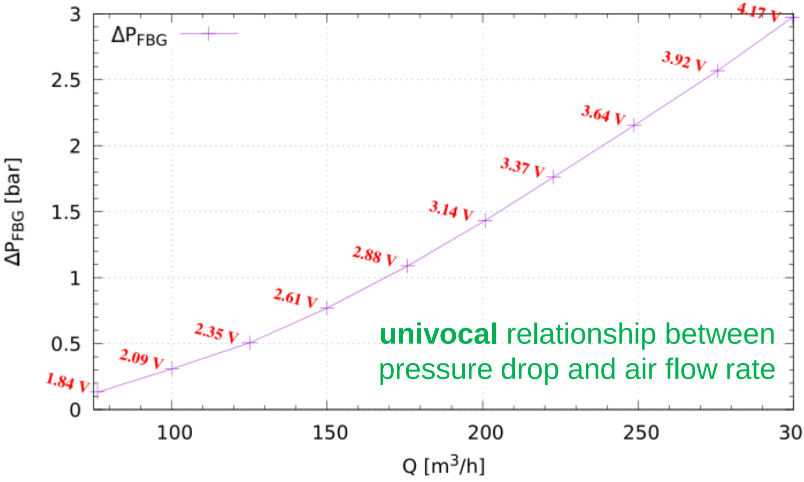
one non-intrusive pressure sensor made of two FBG transducers in hoop and longitudinal configurations (best sensitivity configuration, also insensitive to torsion)

thermocouples on pipe surface for reference temperature

Rosemount™ air flow rate Q: $Q_{[\mathrm{m^3/h}]} = 3600 \times \left(0.02661\, V_{[\mathrm{V}]} - 0.02778\right)$



measurements averaged from 5 kHz to 2.5 Hz



univocal relationship between pressure drop and air flow rate

Non-intrusive pipe internal pressure measurement

CEA, DES, BEARN 2 facility, Saclay, FR
2020

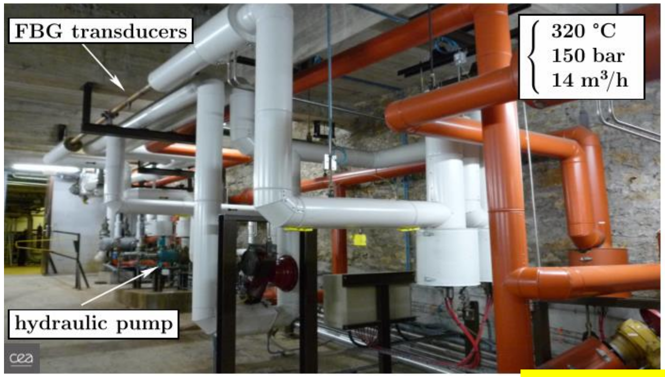
III – Water pressure loop (NPP primary coolant circuit)

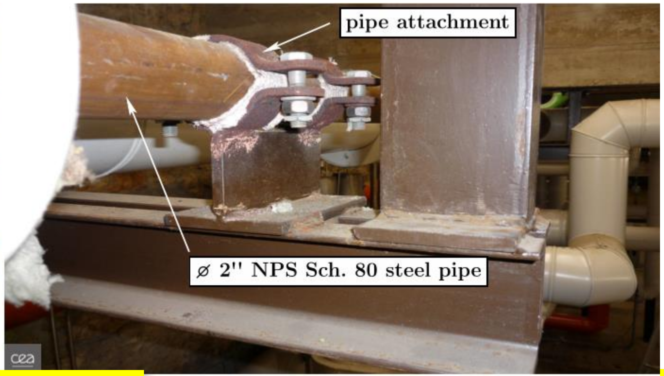
- BEARN 2 water pressure loop (up to 320°C – 150 bar – 14 m^3/h)
  - FBG transducers installed on **Ø 2" NPS Sch. 80** and **Ø 4" NPS Sch. 160** pipe sections
  - Non-intrusive sensors made of pairs of FBG transducers in hoop & longitudinal configurations
    - Rings configurations to mitigate bending effects

complex pipe layout including several bends and attachments

inline heaters and hydraulic pumps

valves to isolate pipe sections from fluid flow



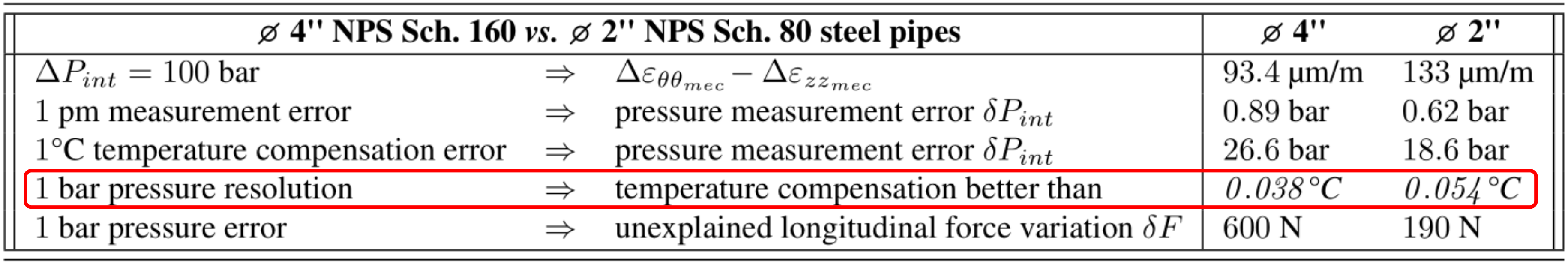


Ø 2" NPS Sch. 80

typical pipe attachment

Ø 4" NPS Sch. 160

- **Typical orders of magnitude** (see also page 12)



⌀ 4'' NPS Sch. 160 *vs.* ⌀ 2'' NPS Sch. 80 steel pipes			⌀ 4''	⌀ 2''
$\Delta P_{int} = 100$ bar	$\Rightarrow$	$\Delta\varepsilon_{\theta\theta_{mec}} - \Delta\varepsilon_{zz_{mec}}$	93.4 µm/m	133 µm/m
1 pm measurement error	$\Rightarrow$	pressure measurement error δP_{int}	0.89 bar	0.62 bar
1°C temperature compensation error	$\Rightarrow$	pressure measurement error δP_{int}	26.6 bar	18.6 bar
1 bar pressure resolution	$\Rightarrow$	temperature compensation better than	*0.038 °C*	*0.054 °C*
1 bar pressure error	$\Rightarrow$	unexplained longitudinal force variation δF	600 N	190 N

Non-intrusive pipe internal pressure measurement

CEA, DES, BEARN 2 facility, Saclay, FR
2020

III – Water pressure loop (Ø 4" NPS Sch. 160 section)

Hot-air gun experiment to estimate the non-intrusive pressure measurement robustness

- Measurements performed on Ø 4" NPS Sch. 160 metallic pipe section
- Hot-air temperature *estimated* greater than 100°C to generate asymmetrical temperature distribution around the pipe (hot spot)
- Typically 5 cm distance between FBG transducers in hoop & longitudinal configurations
  - Temperature difference between FBG transducers *estimated* greater than 40°C

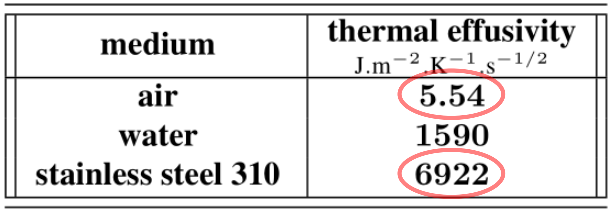
→ Pressure bias smaller than **5 bar**

→ **Without compensation**, the measurement error would have probably been greater than **1000 bar**

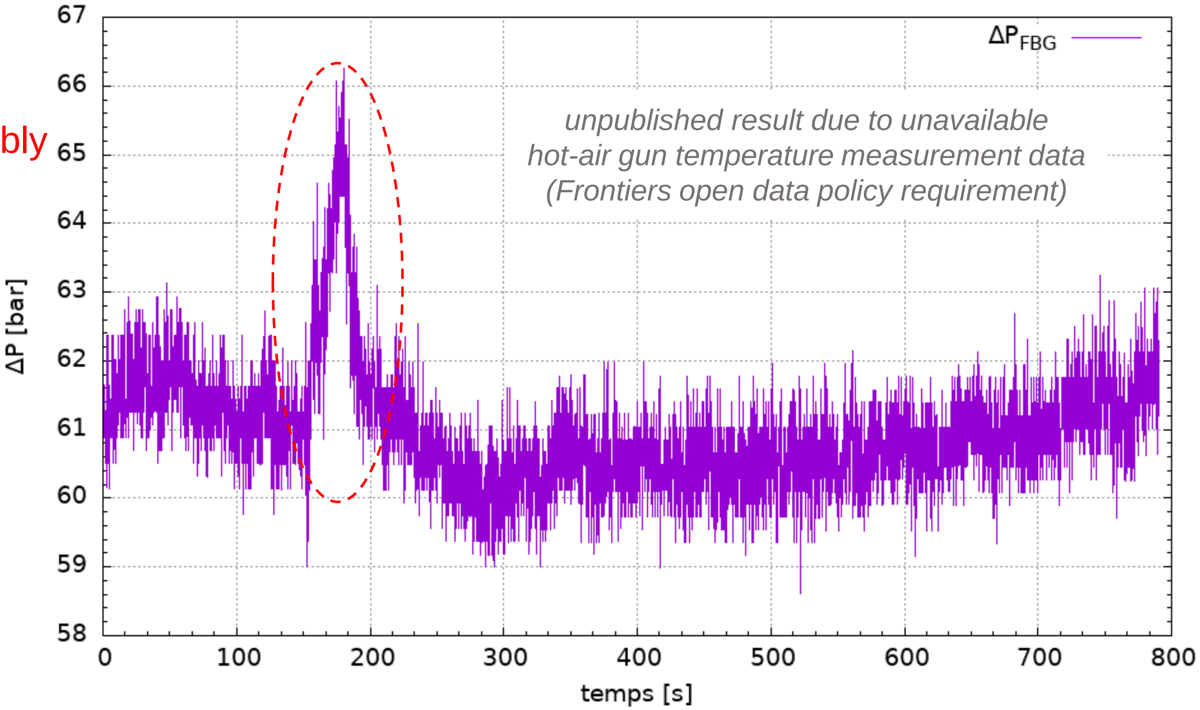
$$T_{(1|2)} = \frac{a_1 T_1 + a_2 T_2}{a_1 + a_2}$$

a thermal effusivity

$T_{(1|2)}$ FBG surface temperature



medium	thermal effusivity $J.m^{-2}.K^{-1}.s^{-1/2}$
air	5.54
water	1590
stainless steel 310	6922



unpublished result due to unavailable hot-air gun temperature measurement data (Frontiers open data policy requirement)

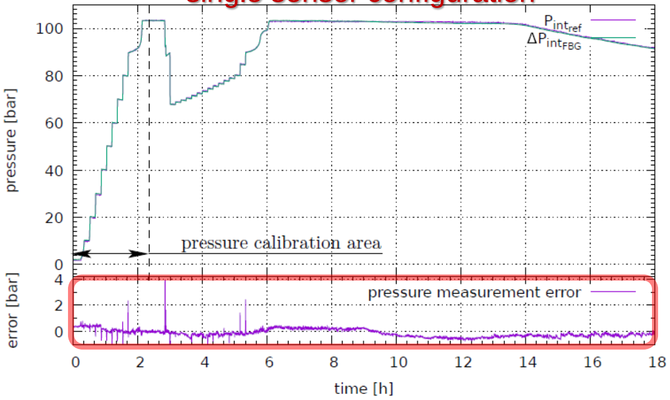
Non-intrusive pipe internal pressure measurement

CEA, DES, BEARN 2 facility, Saclay, FR
2020

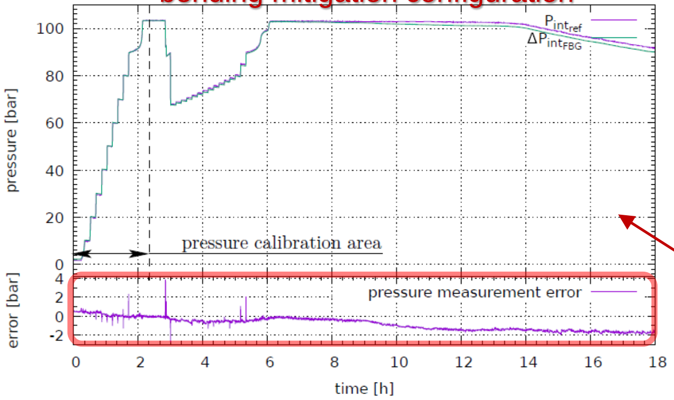
III – Water pressure loop (Ø 4" NPS Sch. 160 section)

▶ No fluid flow, no temperature change

single sensor configuration



bending mitigation configuration



reference intrusive pressure sensor

FBG pressure average error
1.36 bar (2 σ)

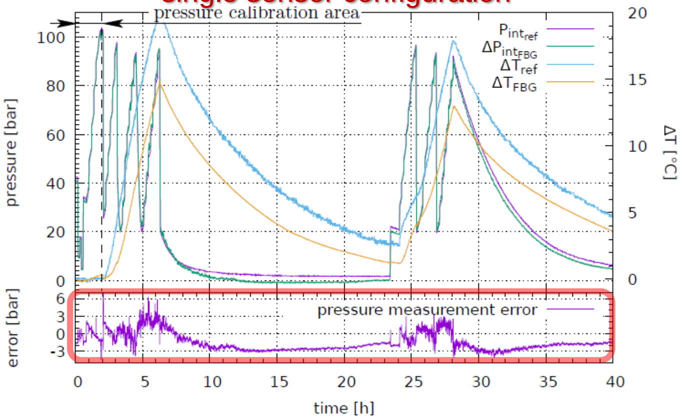
bending mitigation with
3 FBG-based sensors (⇨ 3×2 = 6 FBGs)
in ring configuration

⇨ no significant improvement *vs.* single sensor measurement

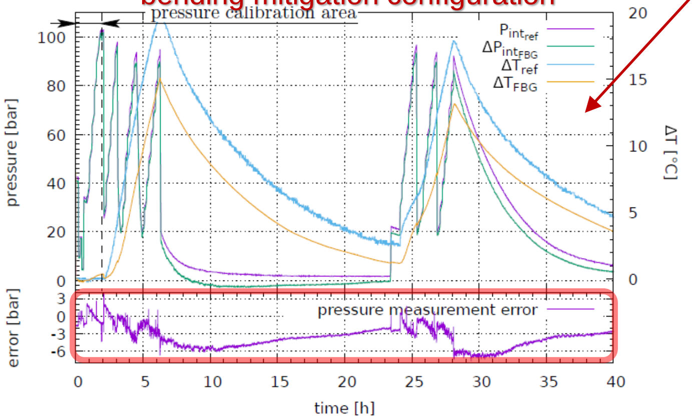
▶ No fluid flow, but temperature changes due to heat conduction

- Closed instrumented section – Fluid flowing in the other part of the loop

single sensor configuration



bending mitigation configuration



$\Delta T_{max} \simeq 19°C$

FBG pressure average error
2.12 bar (2 σ)

similar FBG surface temperature evolution than reference sensor

Non-intrusive pipe internal pressure measurement

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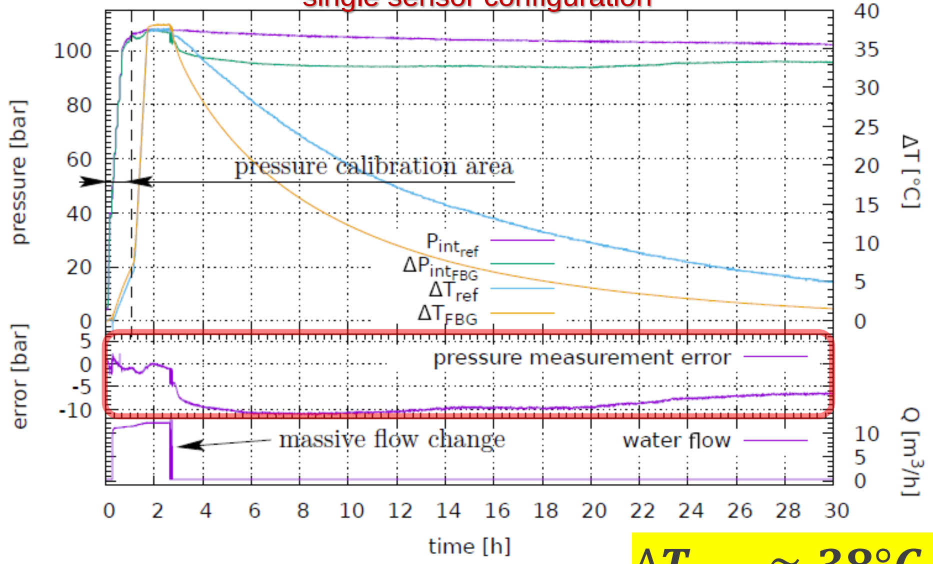
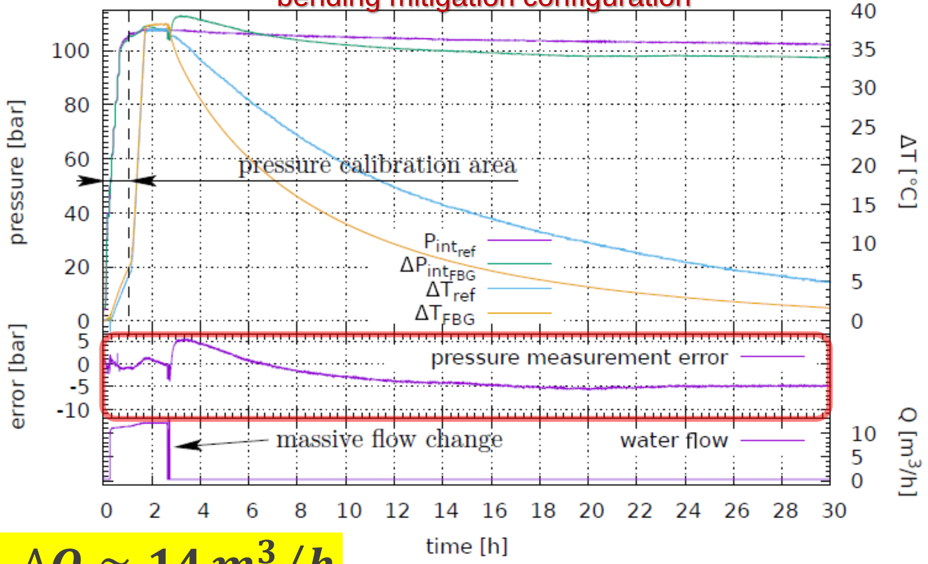
2020

III – Water pressure loop (Ø 2" NPS Sch. 80 section)

▶ Fluid flow with massive fluid flow change (from 14 m³/h to zero) & temperature changes


single sensor configuration

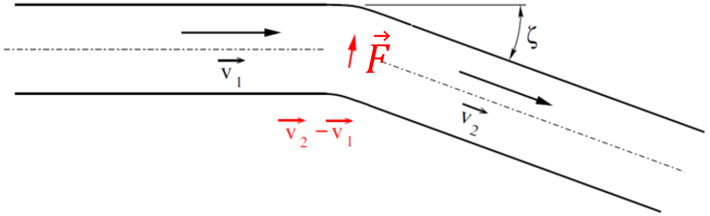

bending mitigation configuration

$$\Delta T_{max} \simeq 38°C - \Delta Q \simeq 14\,m^3/h$$

- pressure calibration performed **during** important flow ΔQ and temperature ΔT changes
- FBG pressure average error during calibration close to **2 bar** (2 σ)
- **similar** FBG surface temperature evolution than reference sensor

bending mitigation with 2 FBG-based sensors (⇨ 2×2 = 4 FBGs) in ring configuration

⇨ **maximum pressure error roughly reduced by a factor of two** *vs.* single sensor measurement, **from -8.6 bar to -5 bar**



$$\vec{F} = \frac{d(m\vec{v})}{dt}$$

massive flow change, combined with fluid flow direction changes (bends), may generate significant bending forces $\vec{F}$ on the pipe

FROM RESEARCH TO INDUSTRY

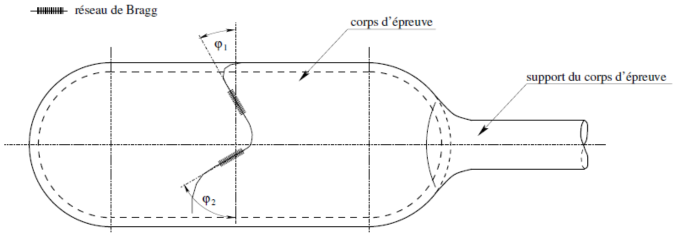
Conclusion

15:20-15:50, the 4th of March, 2022 – NURETH19 Workshop – Fiber-optic sensors for thermal hydraulic measurements

Non-intrusive pipe internal pressure measurement

Conclusion

- **Optimal temperature cross-sensitivity compensation is a key parameter for a reliable pressure measurement**
- **The closed pipe with circular cross-section provides an intrinsic mean to compensate for the transducers temperature cross-sensitivity with the same proof body**
  - The subtraction of two true relative raw measurements of direction-sensitive strain transducers is a purely mechanical information
    - Demonstrated by the linearized formal model for pipes with circular cross-section
      - Can probably be extended to other pipe cross-section shapes, but much more complicated to establish a dedicated formal model for demonstration…
    - In the elastic range, this information is proportional to the pipe internal pressure variation ΔP_{int}
  - The pipe surface temperature variation ΔT is an additional, but time delayed (due to heat diffusion in the pipe wall) information provided by the formal model, independently from the pressure information
- **Any additional non-mechanical effect can theoretically be intrinsically compensated**
  - *e.g.:* nuclear radiations on Bragg wavelengths for FBG transducers (but additional work necessary…)
- **Can be extended to any direction-sensitive surface strain or distance measurement**
  - Ultrasonics with PZT transducers
  - Non contact cross-correlation techniques (remote sensing)
- **Opens the way to new kinds of temperature self-compensated hydrostatic pressure sensors, based on a closed proof body with circular cross-section**
  - From tens to hundreds of bar in pressure ranges
    (depending of proof body mechanical properties and dimensions)



example of new kind of temperature self-compensated hydrostatic pressure sensor for ***external*** **pressure** P_{ext} **monitoring**

Acknowledgements

Additional information – Data availability

Non-intrusive pipe internal pressure measurement

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- **M. Daniel Mabily** from **Technip Energies** for the kind permission to publish the data and the results from the pressure test held in **Marseille** in July 2019
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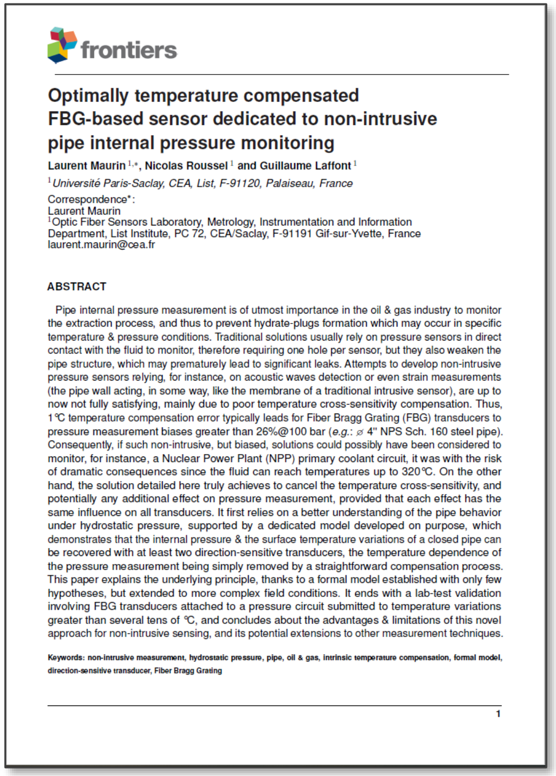
- **Prof. Patrice Mégret** from the **University of Mons** for the invitation to NURETH19 workshop

Non-intrusive pipe internal pressure measurement

Additional information – Data availability

- This topic is published in *Frontiers in Sensors*, “Recent Advances in Optical Fiber Sensors”
  - https://www.frontiersin.org/research-topics/23029/recent-advances-in-optical-fiber-sensors
  - Original paper available at: https://www.frontiersin.org/articles/10.3389/fsens.2022.835140



frontiers

Optimally temperature compensated FBG-based sensor dedicated to non-intrusive pipe internal pressure monitoring

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ABSTRACT

Pipe internal pressure measurement is of utmost importance in the oil & gas industry to monitor the extraction process, and thus to prevent hydrate-plugs formation which may occur in specific temperature & pressure conditions. Traditional solutions usually rely on pressure sensors in direct contact with the fluid to monitor, therefore requiring one hole per sensor, but they also weaken the pipe structure, which may prematurely lead to significant leaks. Attempts to develop non-intrusive pressure sensors relying, for instance, on acoustic waves detection or even strain measurements (the pipe wall acting, in some way, like the membrane of a traditional intrusive sensor), are up to now not fully satisfying, mainly due to poor temperature cross-sensitivity compensation. Thus, 1 ℃ temperature compensation error typically leads for Fiber Bragg Grating (FBG) transducers to pressure measurement biases greater than 26%@100 bar (*e.g.*: ⌀ 4" NPS Sch. 160 steel pipe). Consequently, if such non-intrusive, but biased, solutions could possibly have been considered to monitor, for instance, a Nuclear Power Plant (NPP) primary coolant circuit, it was with the risk of dramatic consequences since the fluid can reach temperatures up to 320 ℃. On the other hand, the solution detailed here truly achieves to cancel the temperature cross-sensitivity, and potentially any additional effect on pressure measurement, provided that each effect has the same influence on all transducers. It first relies on a better understanding of the pipe behavior under hydrostatic pressure, supported by a dedicated model developed on purpose, which demonstrates that the internal pressure & the surface temperature variations of a closed pipe can be recovered with at least two direction-sensitive transducers, the temperature dependence of the pressure measurement being simply removed by a straightforward compensation process. This paper explains the underlying principle, thanks to a formal model established with only few hypotheses, but extended to more complex field conditions. It ends with a lab-test validation involving FBG transducers attached to a pressure circuit submitted to temperature variations greater than several tens of ℃, and concludes about the advantages & limitations of this novel approach for non-intrusive sensing, and its potential extensions to other measurement techniques.

Keywords: non-intrusive measurement, hydrostatic pressure, pipe, oil & gas, intrinsic temperature compensation, formal model, direction-sensitive transducer, Fiber Bragg Grating

1

- Publication in open access, with open data
  - Open data will be made available in the CEA HAL open archive: https://hal-cea.archives-ouvertes.fr/cea-03541365

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Optimally temperature compensated FBG-based sensor dedicated to non-intrusive pipe internal pressure monitoring

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DM2I - Département Métrologie Instrumentation & Information : DRT/LIST/DM2I

Abstract : Pipe internal pressure measurement is of utmost importance in the oil & gas industry to monitor the extraction process, and thus to prevent hydrate-plugs formation which may occur in specific temperature & pressure conditions. Traditional solutions usually rely on pressure sensors in direct contact with the fluid to monitor, therefore requiring one hole per sensor, but they also weaken the pipe structure, which may prematurely lead to significant leaks. Attempts to develop non-intrusive pressure sensors relying, for instance, on acoustic waves detection or even strain measurements (the pipe wall acting, in some way, like the membrane of a traditional intrusive sensor), are up to now not fully satisfying, mainly due to poor temperature cross-sensitivity compensation. Thus, 1°C temperature compensation error typically leads for Fiber Bragg Grating (FBG) transducers to pressure measurement biases greater than 26%@100 bar (e.g.: Ø4" NPS Sch. 160 steel pipe). Consequently, if such non-intrusive, but biased, solutions could possibly have been considered to monitor, for instance, a Nuclear Power Plant (NPP) primary coolant circuit, it was with the risk of dramatic consequences since the fluid can reach temperatures up to 320°C. On the other hand, the solution detailed here truly achieves to cancel the temperature cross-sensitivity, and potentially any additional effect on pressure measurement, provided that each effect has the same influence on all transducers. It first relies on a better understanding of the pipe behavior under hydrostatic pressure, supported by a dedicated model developed on purpose, which demonstrates that the internal pressure & the surface temperature variations of a closed pipe can be recovered with at least two direction-sensitive transducers, the temperature dependence of the pressure measurement being simply removed by a straightforward compensation process. This paper explains the underlying principle, thanks to a formal model established with only few hypotheses, but extended to more complex field conditions. It ends with a lab-test validation involving FBG transducers attached to a pressure circuit submitted to temperature variations greater than several tens of °C, and concludes about the advantages & limitations of this novel approach for non-intrusive sensing, and its potential extensions to other measurement techniques.

Keywords : non-intrusive sensor | Hydrostatic Pressure | Pipe | Oil & gas | Surface temperature | intrinsic temperature compensation | bending mitigation | Formal model | Iterative algorithm | direction-sensitive transducer | FBG sensor | experimental validation | Pressure Loop | instrumentation | sensor | Optical Fiber Sensor | Fiber Bragg Grating | Distributed and Quasi-distributed sensing

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EXPORTER

BibTeX | TEI | DC | DCterms | EndNote

PARTAGER

MÉTRIQUES

Consultations de la notice

12

much more information about this sensor can be found in this article

this presentation will also be made available in the CEA HAL open archive

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Thank you for your attention

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