CFD of thermal striping in nuclear power plants

ERCOFTAC SIG 15.3

Richard Howard, EDF R&D

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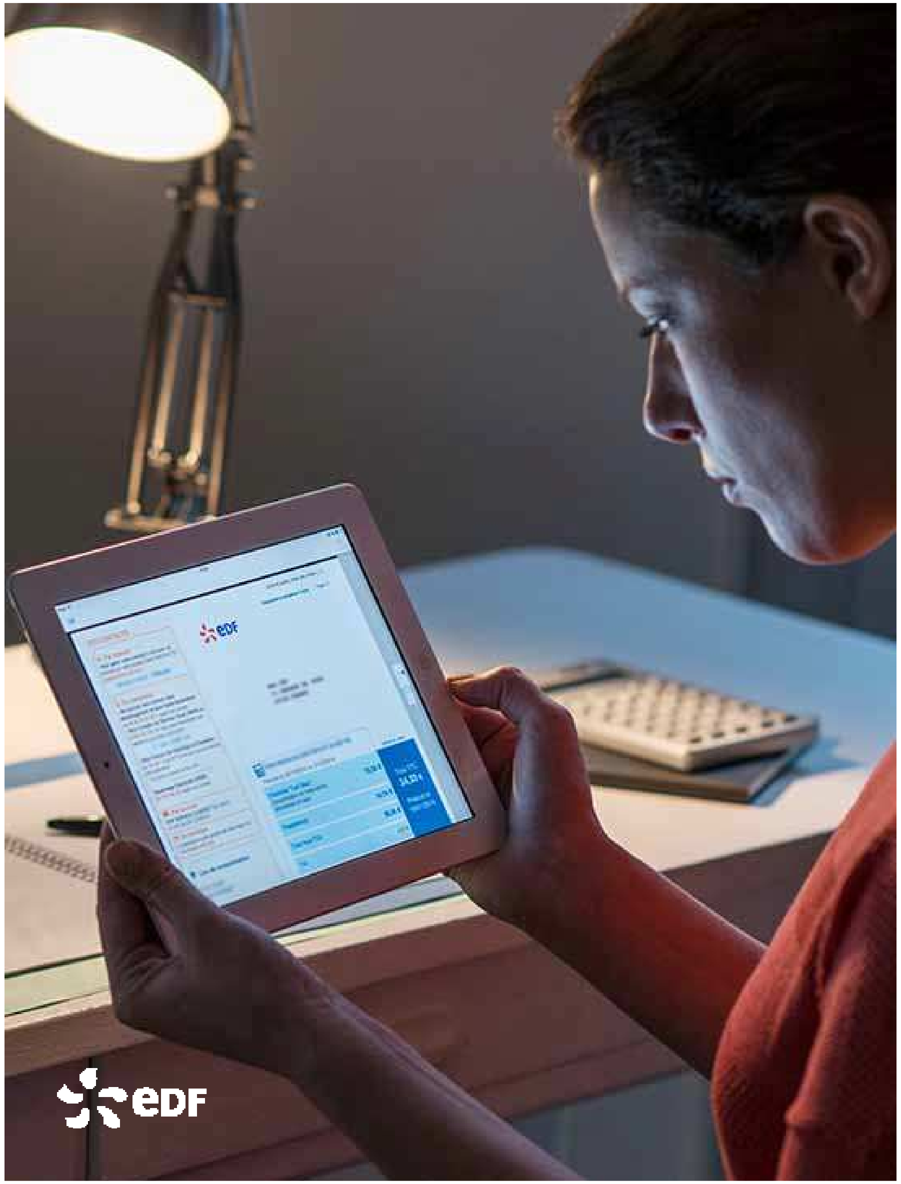

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Context : leaks due to high cycle thermal fatigue

Experiments of T junction flows

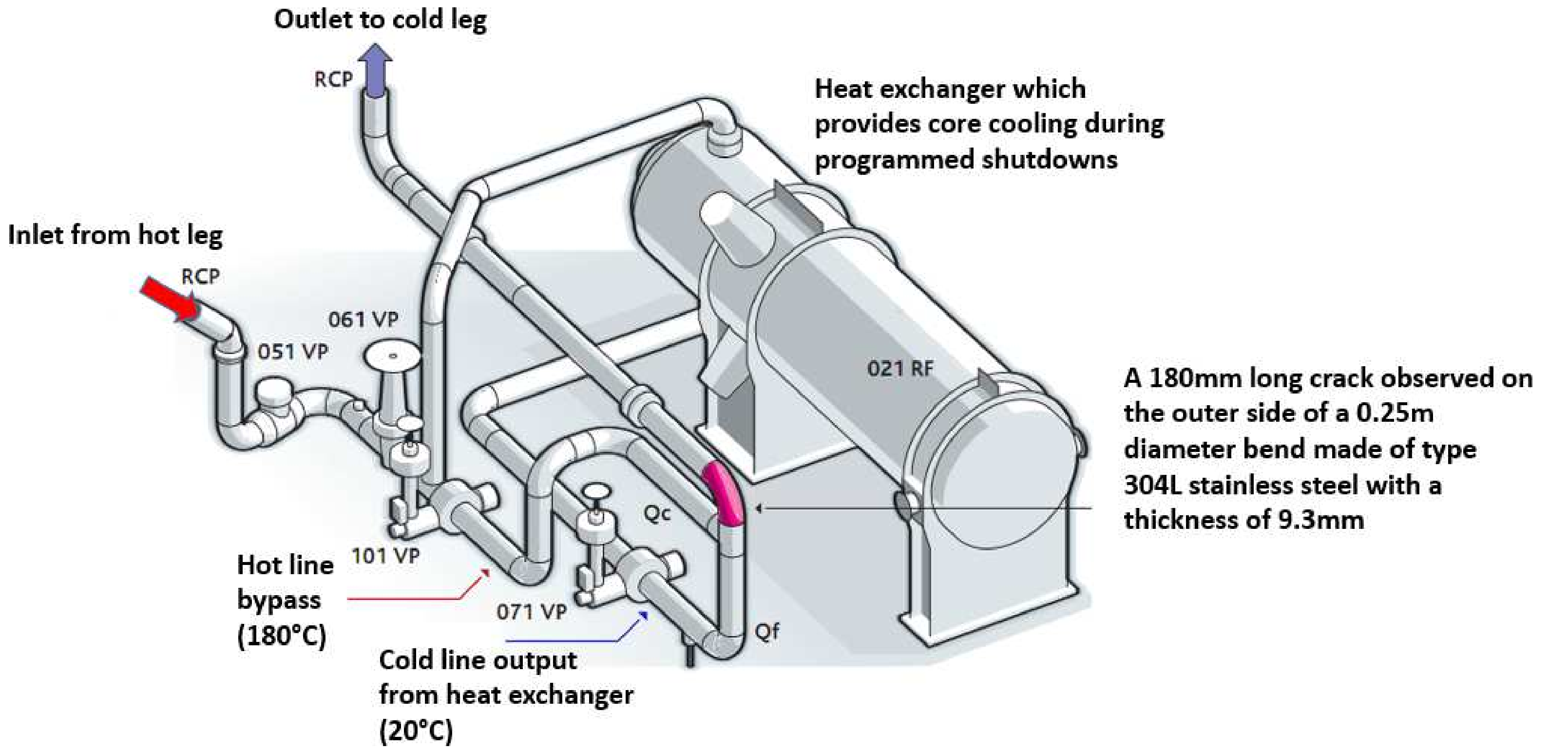
How thermal fluctations pass between a fluid and a solid

Challenges for CFD

Dead leg flows

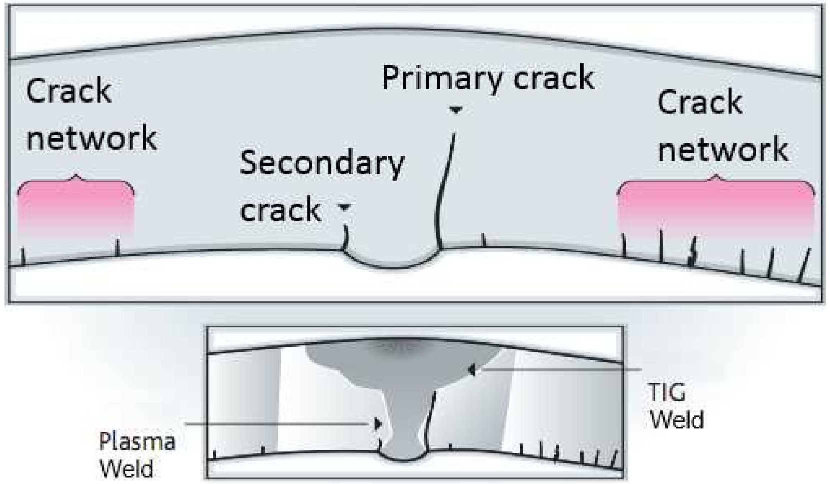
Civaux 1

- **PWR type N4 (1450MW) connected to the electricity network in 1997**
- **On 12th May 1998 a 30 m³/h leak is observed during a programmed shutdown**



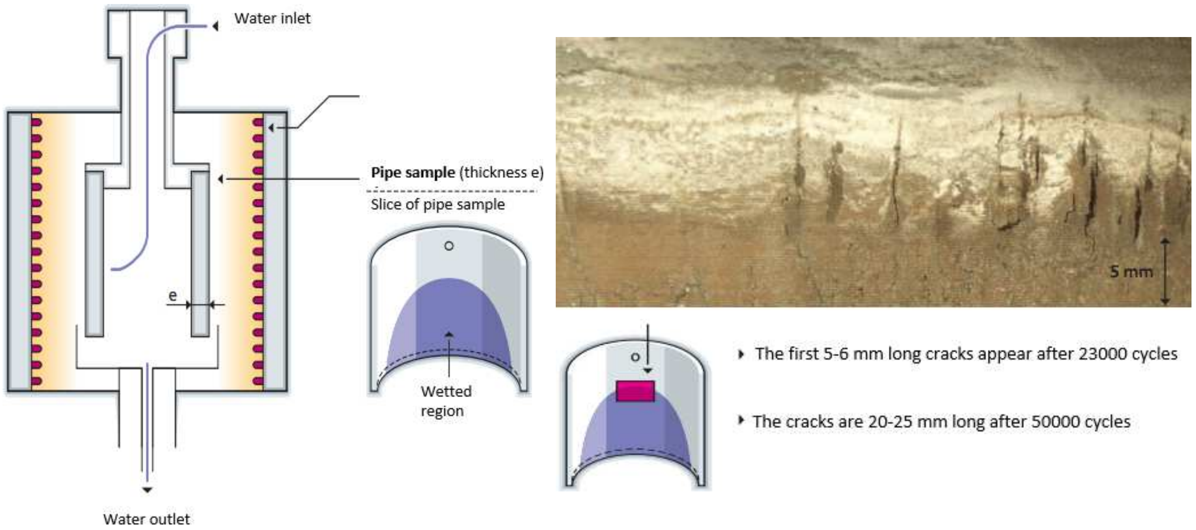
Civaux 1

- **All four reactors of this type observed to have similar levels of degradation (Chooz B1, B2 and Civaux 2)**
- **Expert analysis suggested thermal fatigue due to thermohydraulic mixing:**
  - duration of the forcing
  - large temperature differences
  - the state of the surface
  - different forcing regimes
- **Initial modelling incomplete**
  - Unable to identify the exact location
  - Unable identify the correct level of degradation



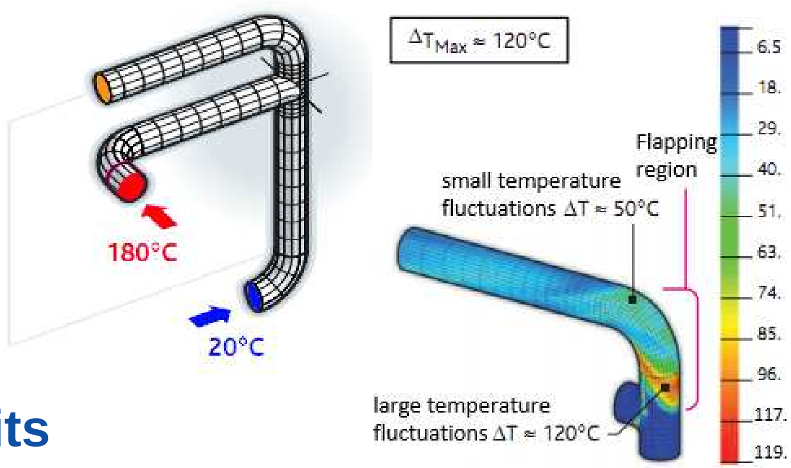
Civaux 1

- **R&D programme initiated**
  - EDF R&D
  - AREVA (today FRAMATOME)
  - CEA
  - IRSN (Safety Authority)



- **Reproduce the same type of crack in experiments FAT3D**

- **Evaluate the forcing in numerical simulations**

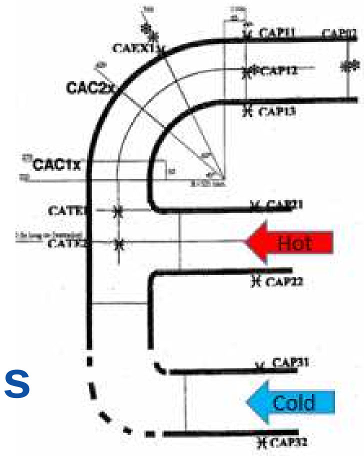


- **Screen all the mixing zones in all circuits**

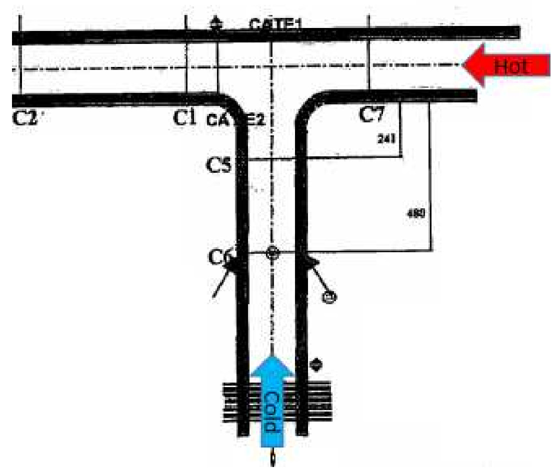
Civaux 1

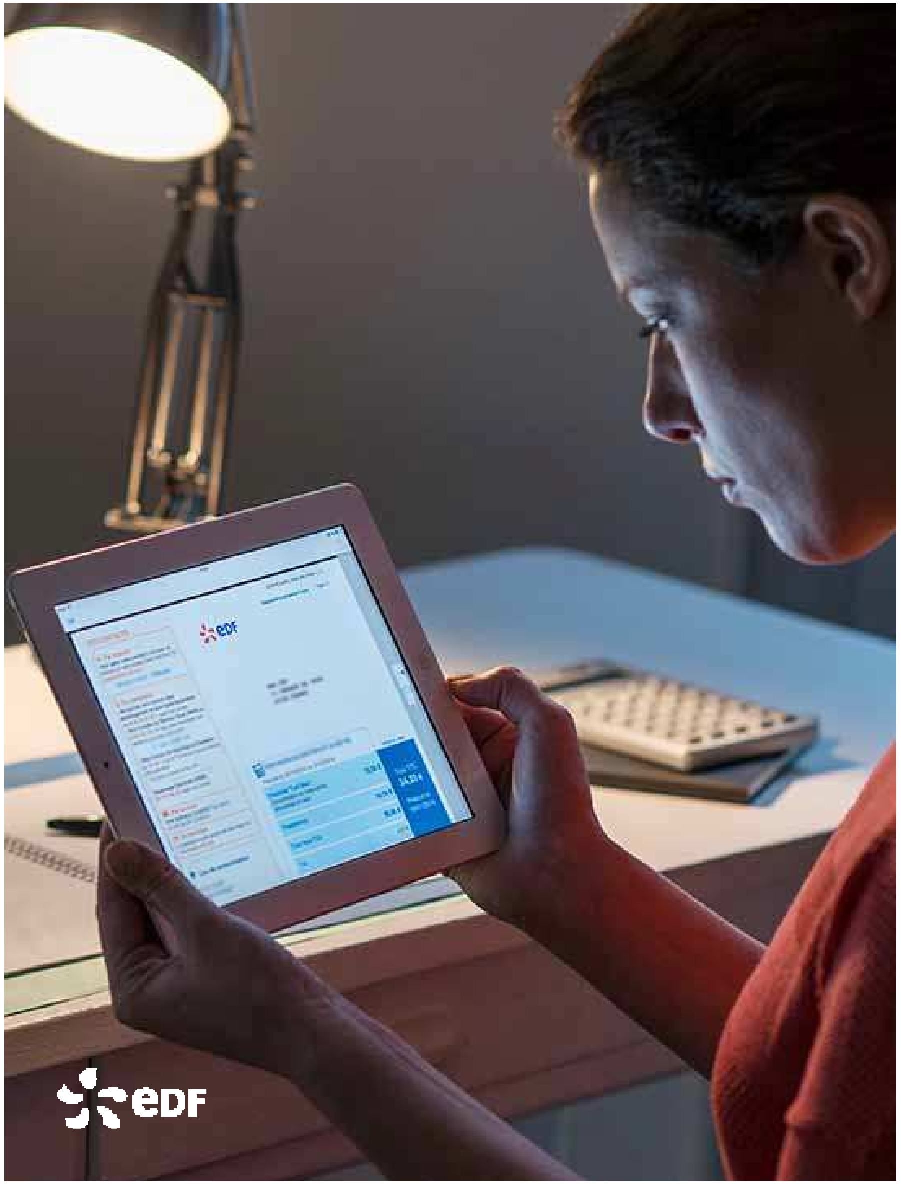
- **R&D programme extended**
- **Screening procedure more strict**
  - Temperature differences of 50°C instead of 80°C
- **Modification of the mixing zone circuit**
- **Increase in the frequency of inspections**
- **Regular replacement of certain T junctions**

Initial design



New design





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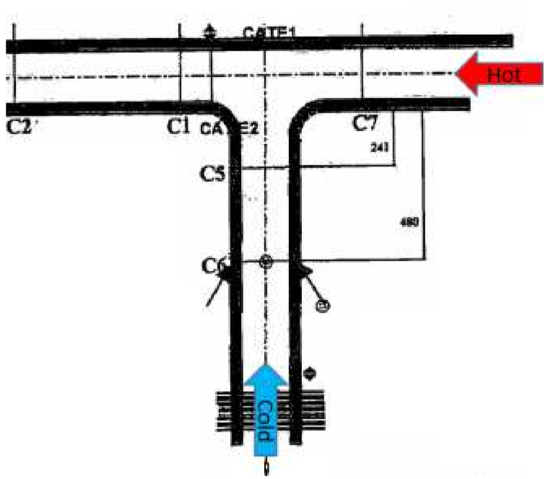
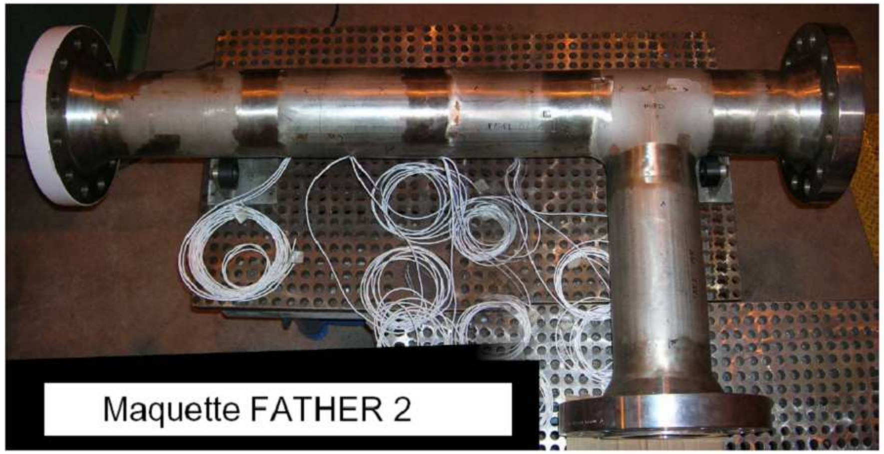
FATHER

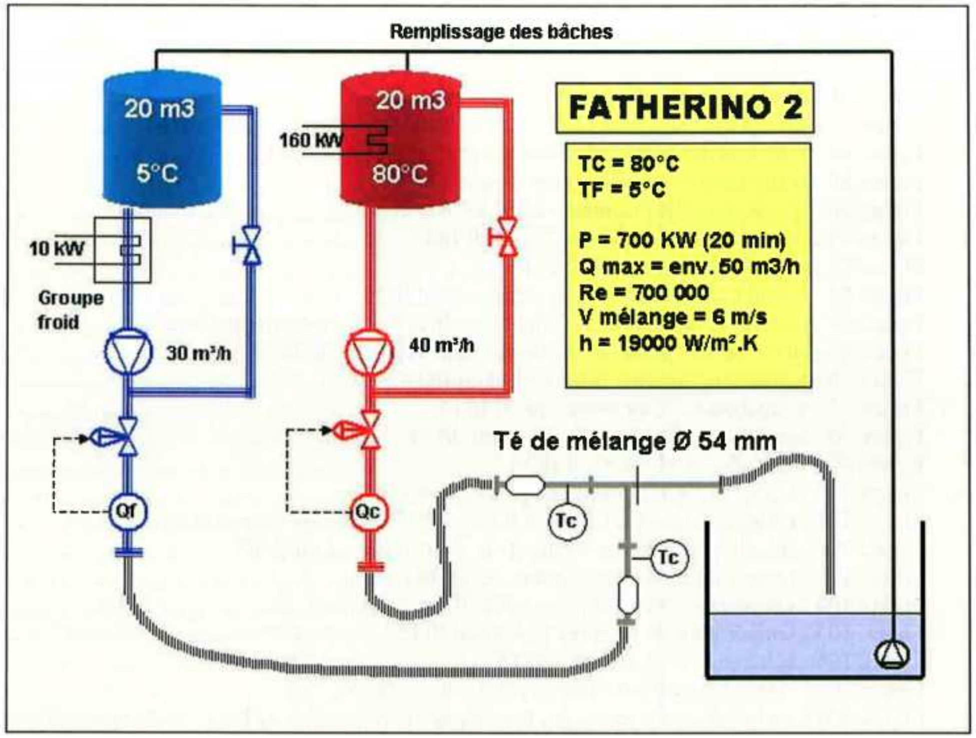
- **Temperature difference 160°C**
- **Diameter 154mm**
- **Pressure up to 50 bars**
- **Flow rate up to 1000m³/h**





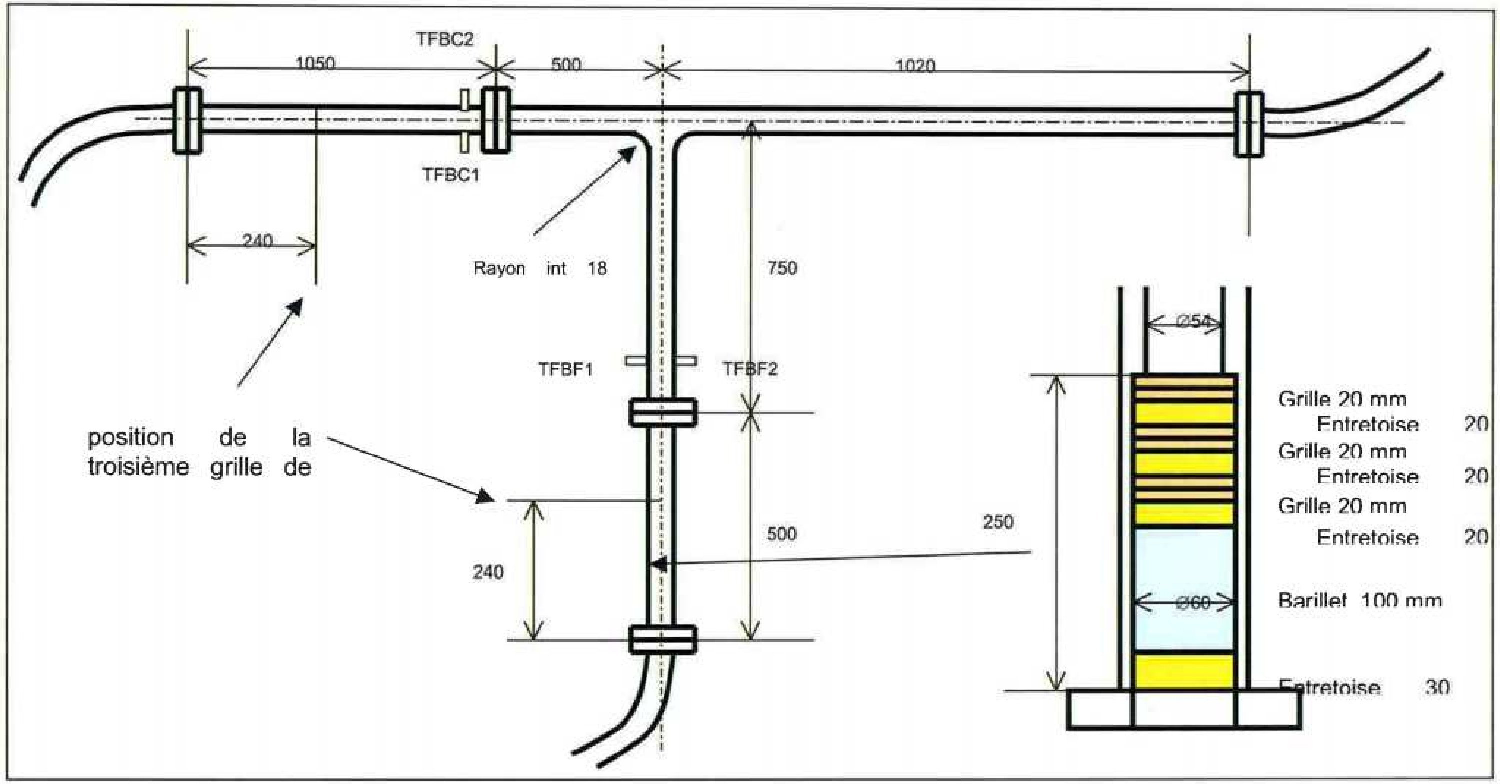
THE FATHERINO EXPERIMENT

More than ten minutes of useful results each time the containers are emptied.



Courtesy of Olivier Braillard, Commissariat of Atomic Energy (CEA) Cadarache, France

THE FATHERINO EXPERIMENT



Courtesy of Olivier Braillard, Commissariat of Atomic Energy (CEA) Cadarache, France

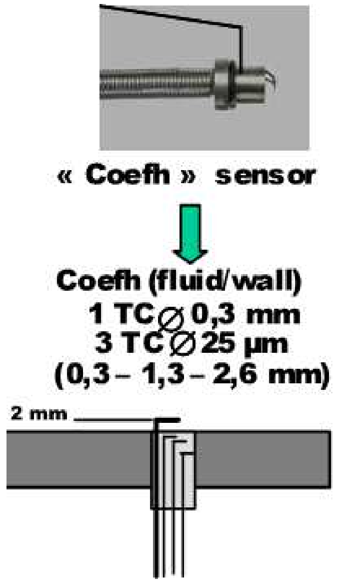
THE FATHERINO EXPERIMENT

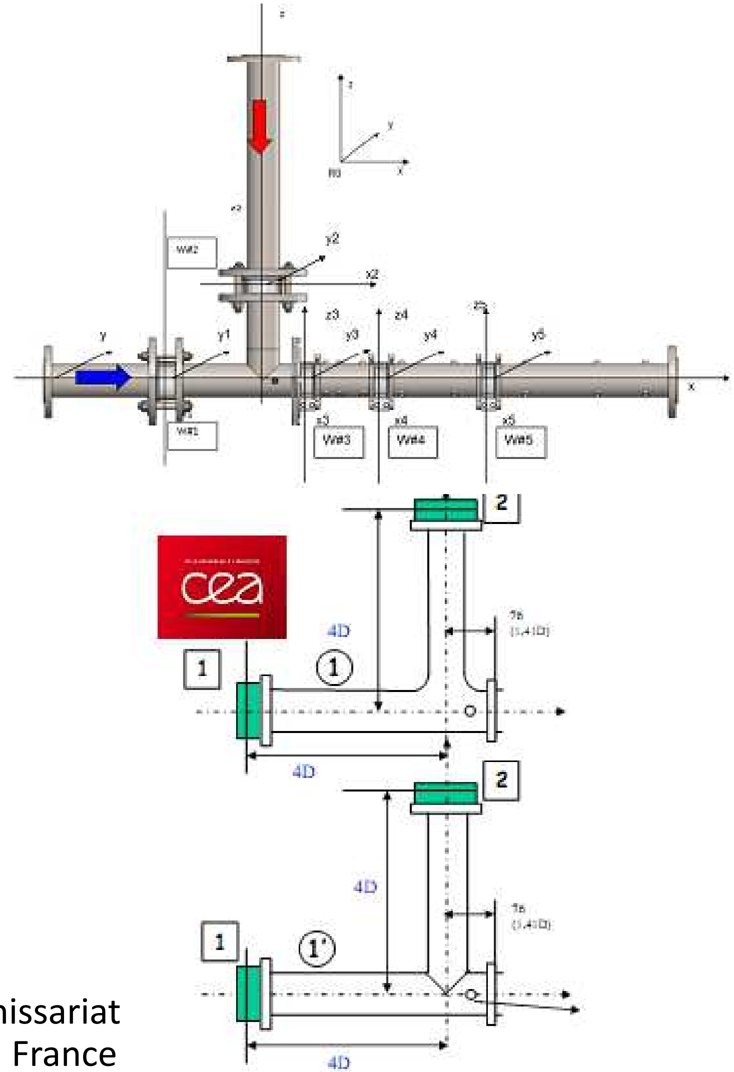
Courtesy of Olivier Braillard, Commissariat of Atomic Energy (CEA) Cadarache, France

Infra red camera which can be used to measure mean and variances of the temperature

THE MOTHER EXPERIMENT

- **Sharp and rounded corners**
- **Stainless steel with plexiglass windows for LDV**
  - CoefH sensor
- **Brass model**

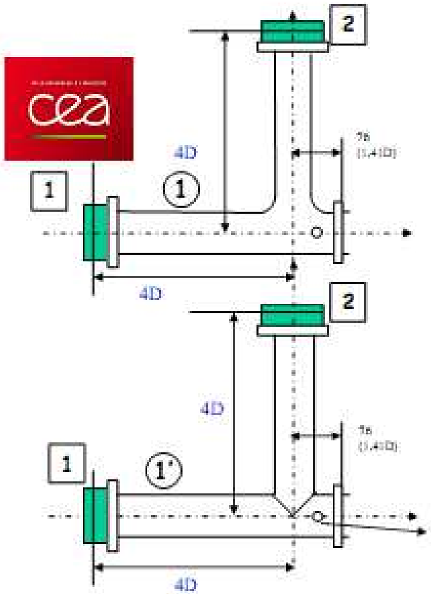


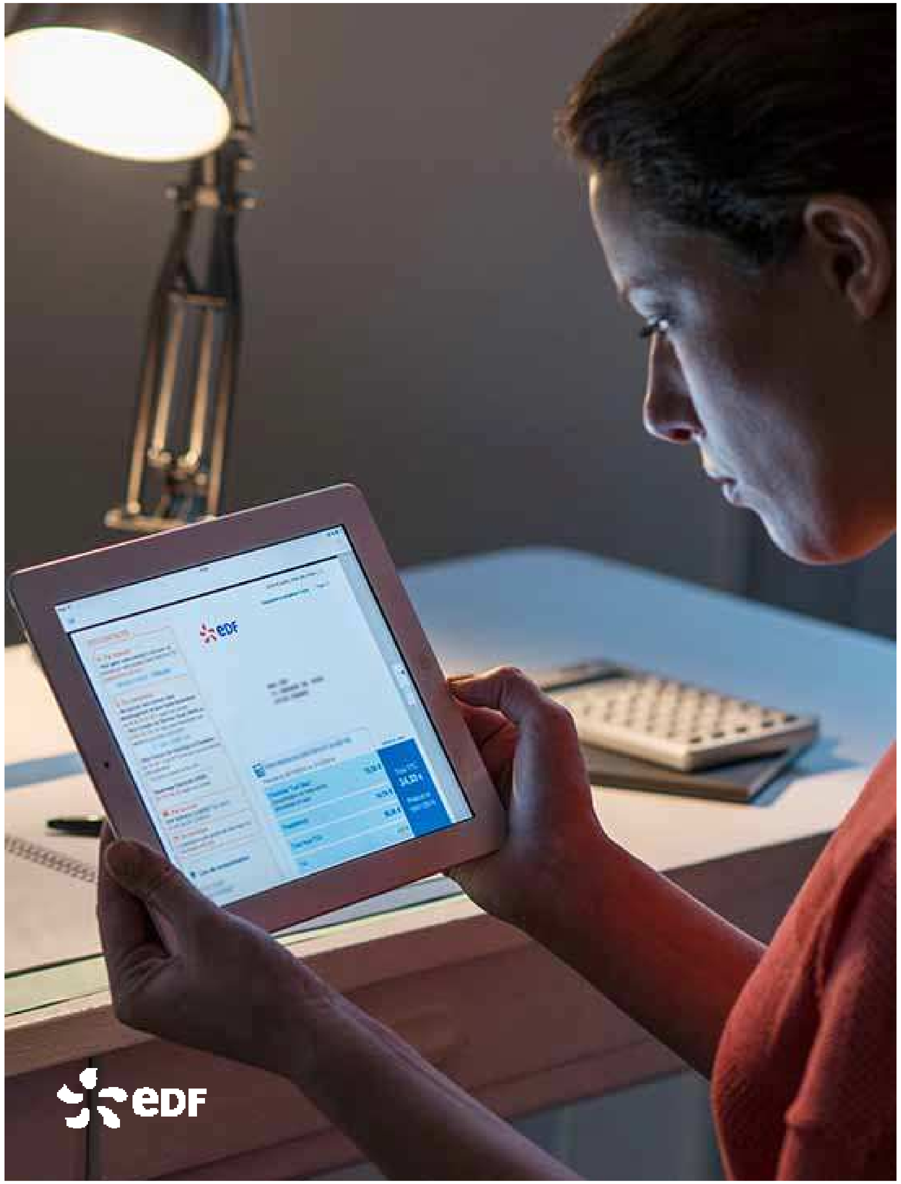


Courtesy of Olivier Braillard, Commissariat of Atomic Energy (CEA) Cadarache, France

THE MOTHER EXPERIMENT

- **Experiment demonstrated (Braillard et al 2018) that the sharp corner provokes a flow instability at St=0.5**
  - This phenomenon does not occur for the round corner T junction
- **CFD synthesis exercise (Shams et al 2018) showed**
  - The sharp corner case was easier to model
  - LES more reliable than RANS
  - Prediction of the solid field required long convergence times





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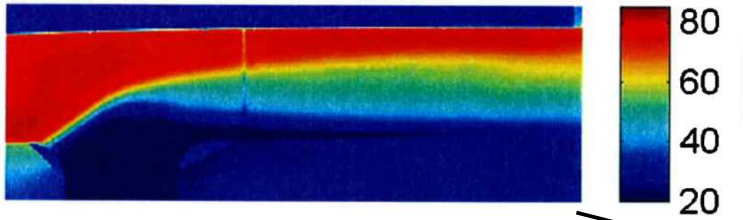
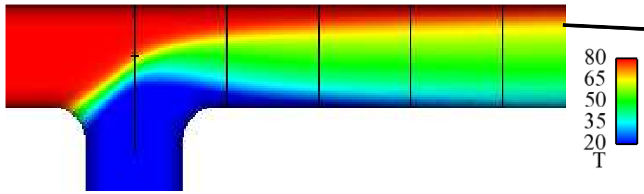
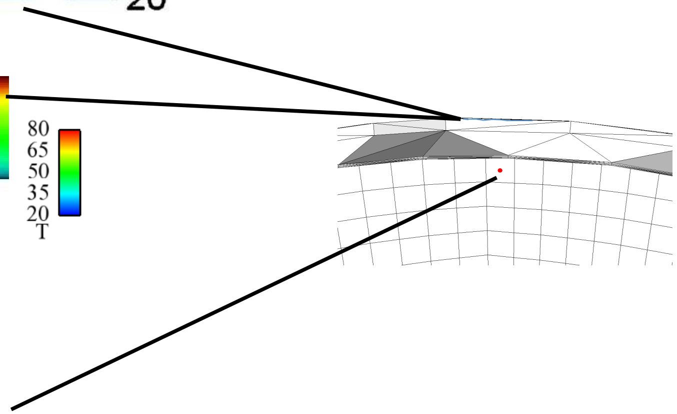
AVERAGE TEMPERATURE

Experiment, temperature at the outer skin of the brass

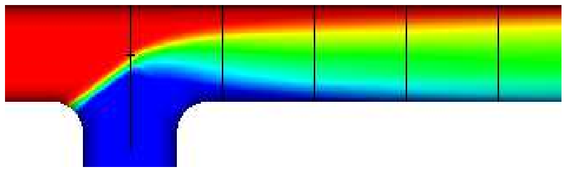


Simulation, temperature at the outer skin of the brass

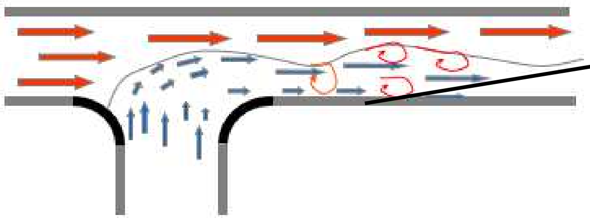




Simulation, fluid temperature at the first wall grid cell



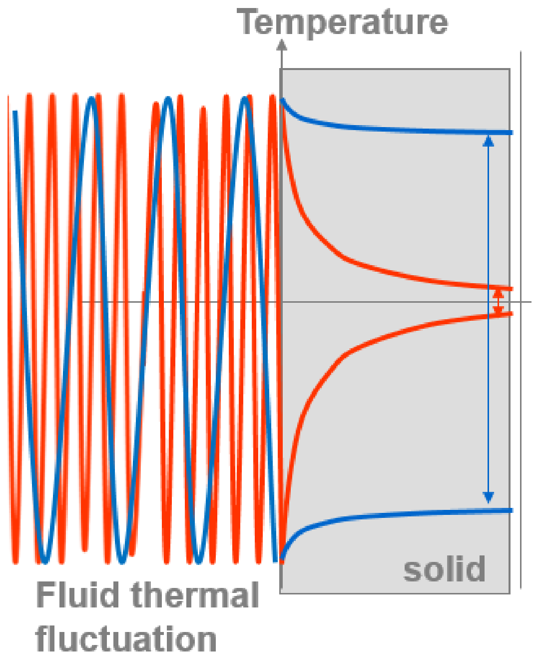
BASIC PRINCIPLES



Mechanical forcing in the solid is due to thermal fluctuations in the fluid

The frequency of the fluid fluctuations dictates whether they can penetrate into the solid

Classic RANS cannot provide information about the frequency.



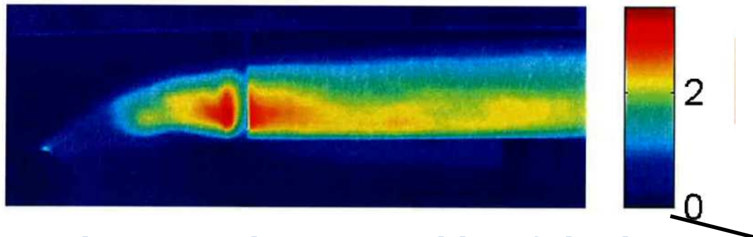
Low frequencies penetrate the solid

High frequencies are rapidly damped and can only effect the surface

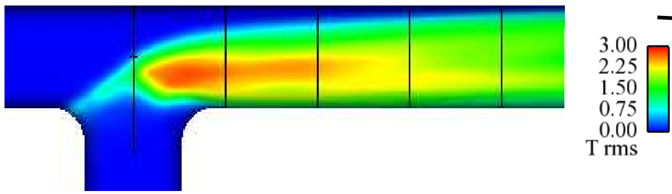
- Hence most CFD studies of thermal fatigue use LES

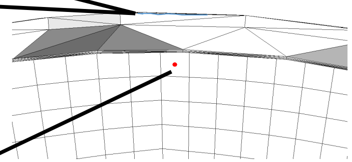
RMS TEMPERATURE FLUCTUATIONS

Experiment, rms temperature variance at the outer skin of the brass

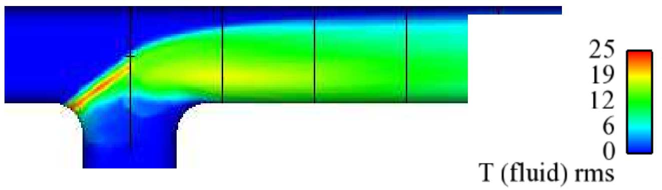


Simulation, rms temperature variance at the outer skin of the brass





Simulation, rms fluid temperature variance at the first wall grid cell



THEORETICAL BASIS

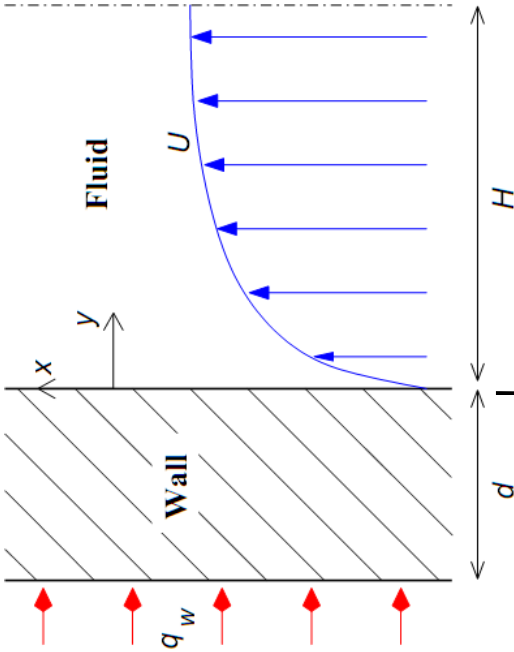
Turbulence, Heat and Mass Transfer 6
K. Hanjalić, Y. Nagano and S. Jakirlić (Editors)

Towards the Development of RANS Models for Conjugate Heat Transfer

T.J. Craft, H. Iacovides, S. Uapipatanakul

$$\varepsilon_\theta = \tilde{\varepsilon}_\theta + \alpha\left(\partial \overline{\theta^2}^{1/2} / \partial x_j\right)^2$$

$$\alpha = \nu / Pr$$



$$\frac{D(\rho c_p \overline{\theta^2})}{Dt} = 2\rho c_p P_\theta - 2\rho c_p \varepsilon_\theta + \frac{\partial}{\partial x_j}\left[c_p\left(\frac{\mu}{Pr} + \frac{\mu_t}{\sigma_t}\right)\frac{\partial \overline{\theta^2}}{\partial x_j}\right]$$

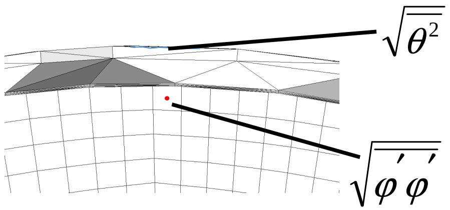
$$\frac{D(\rho c_p \tilde{\varepsilon}_\theta)}{Dt} = c_{\varepsilon_\theta 1}\rho c_p \frac{P_k \tilde{\varepsilon}_\theta}{k} + c_{\varepsilon_\theta 3}\rho c_p \frac{P_\theta \tilde{\varepsilon}_\theta}{\overline{\theta^2}} - c_{\varepsilon_\theta 4}\rho c_p \frac{\tilde{\varepsilon}_\theta^2}{\overline{\theta^2}} - c_{\varepsilon_\theta 2}\rho c_p f_{\varepsilon_\theta}\frac{\tilde{\varepsilon}\tilde{\varepsilon}_\theta}{k}$$
$$+ \frac{\partial}{\partial x_j}\left[c_p\left(\frac{\mu}{Pr} + \frac{\mu_t}{\sigma_t \sigma_{\varepsilon_\theta}}\right)\frac{\partial \tilde{\varepsilon}_\theta}{\partial x_j}\right] + \rho c_p E_\theta$$

$$\frac{\partial(\rho c_p \overline{\theta^2})}{\partial t} = -2\rho c_p \varepsilon_\theta + \frac{\partial}{\partial x_j}\left[c_p \frac{\mu}{Pr}\frac{\partial \overline{\theta^2}}{\partial x_j}\right]$$

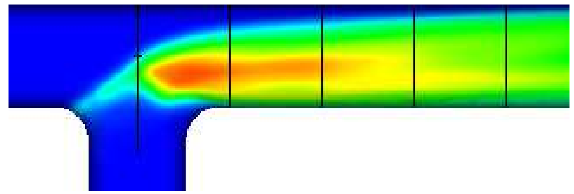
$$\frac{\partial(\rho c_p \tilde{\varepsilon}_\theta)}{\partial t} = -c_{\varepsilon_\theta 4}\rho c_p \frac{\tilde{\varepsilon}_\theta \tilde{\varepsilon}_\theta}{\overline{\theta^2}} + \frac{\partial}{\partial x_j}\left[c_p \frac{\mu}{Pr}\frac{\partial \tilde{\varepsilon}_\theta}{\partial x_j}\right]$$

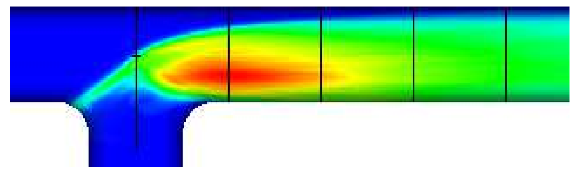
EDF

TRANSFER OF THERMAL FLUCUATIONS IN PRACTICE



- Temperature variance at the outer skin of the brass
- Thermal flux variance (fluid) at the first wall grid cell





- Thermal flux variance: $\sqrt{\overline{\varphi'\varphi'}} = \sqrt{\left(\frac{\lambda}{\rho c_p}\right)^2 \left(\overline{\left.\frac{\partial\theta}{\partial y}\right|_{wall}^2}\right)}$ is associated with the dissipation of the temperature variance: $\varepsilon_\theta = 2\left(\frac{\lambda}{\rho c_p}\right)\left(\overline{\left.\frac{\partial\theta}{\partial y}\right|_{wall}^2}\right)$
- It is effectively ε_θ which determines $\overline{\theta^2}$ in the solid:

Equations within the solid

$$\frac{\partial(\rho c_p \overline{\theta^2})}{\partial t} = -2\rho c_p \varepsilon_\theta + \frac{\partial}{\partial x_j}\left[c_p \frac{\mu}{Pr} \frac{\partial \overline{\theta^2}}{\partial x_j}\right]$$

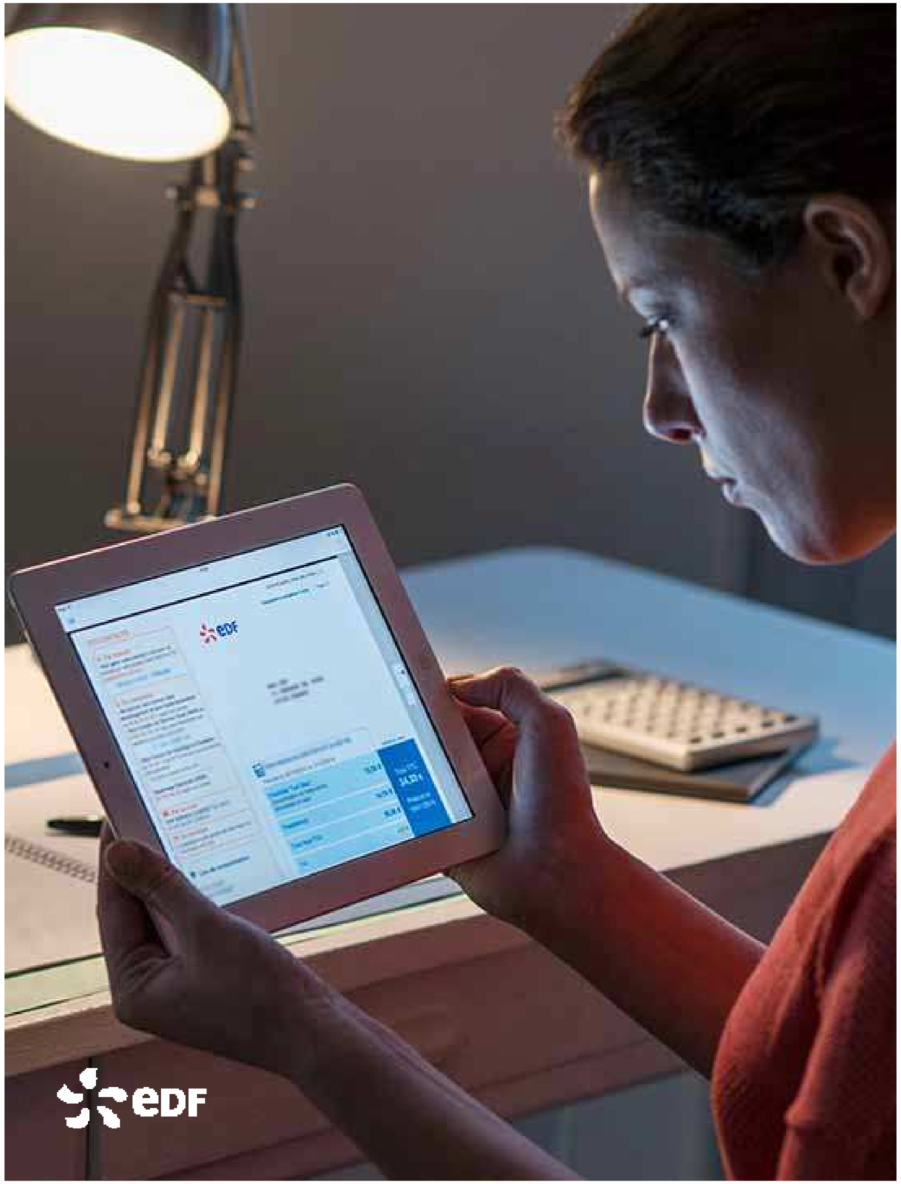
$$\frac{\partial(\rho c_p \tilde{\varepsilon}_\theta)}{\partial t} = -c_{\varepsilon_\theta 4}\rho c_p \frac{\tilde{\varepsilon}_\theta \tilde{\varepsilon}_\theta}{\overline{\theta^2}} + \frac{\partial}{\partial x_j}\left[c_p \frac{\mu}{Pr} \frac{\partial \tilde{\varepsilon}_\theta}{\partial x_j}\right]$$

T.J. Craft, H. Iacovides, S. Uapipatanakul
THMT 09

IMPLICATION FOR MECHANICAL STRESSES

- One can solve for $\overline{\theta^2}$ and ε_θ in the solid using boundary conditions from the fluid
  - It is not necessary to know the spectrum of the fluid thermal forcing to calculate $\overline{\theta^2}$ and ε_θ in the solid
- A RANS approach which includes reliable modelling of $\overline{\theta^2}$ will provide a reliable solution for ε_θ in the solid

- This suggests that studies of the mechanical stress should seek a solution for the variance of the stress $\overline{\sigma'\sigma'}$
  - This quantity can be found when $\overline{\theta^2}$ and ε_θ are known.
- It is the variance of the mechanical stress $\overline{\sigma'\sigma'}$ which gives the intensity of the forcing for high cycle thermal fatigue



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Challenges for CFD

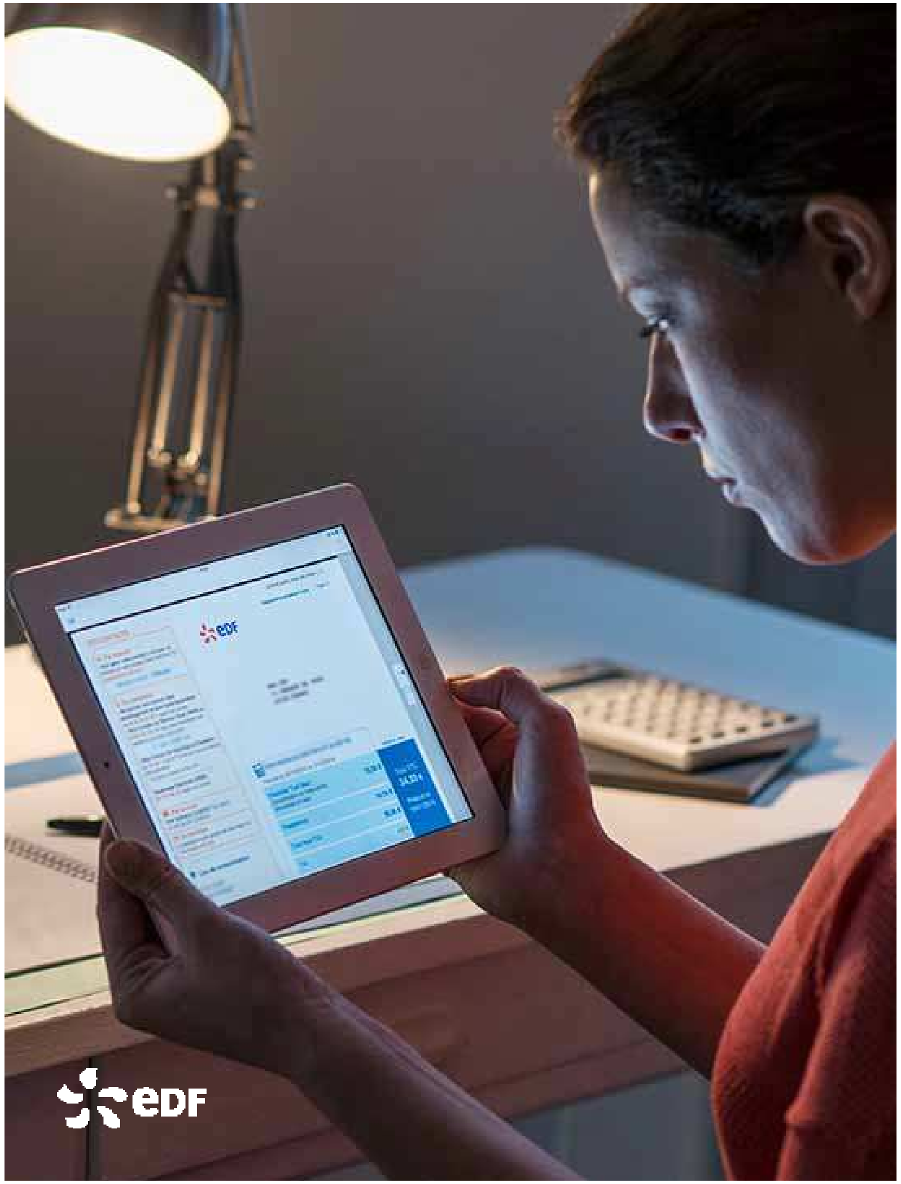
Dead leg flows

SENSITIVITY TO FRICTION VELOCITY

- Heat transfer coefficient depends on the friction velocity
- Wall temperature depends on the friction velocity
- Bulk flowfield resolution depends on pressure gradient, convection and turbulence as well
- Errors in the friction velocity can have a minor effect on the bulk flow resolution and a major effect on the heat transfer resolution

ACCURATE MODELLING OF ε_θ

- **One of the most difficult terms to model in RANS modelling**
- **Enhanced resolution is needed to resolve scalar dissipation (Vreman & Kuerten 2014)**
  - Roughly two times finer in each spatial direction (Flageul & Tiselj 2017)
- **In DNS it is a term used to assess the quality of the resolution**
  - it tends to degrade before the the velocity field is affected



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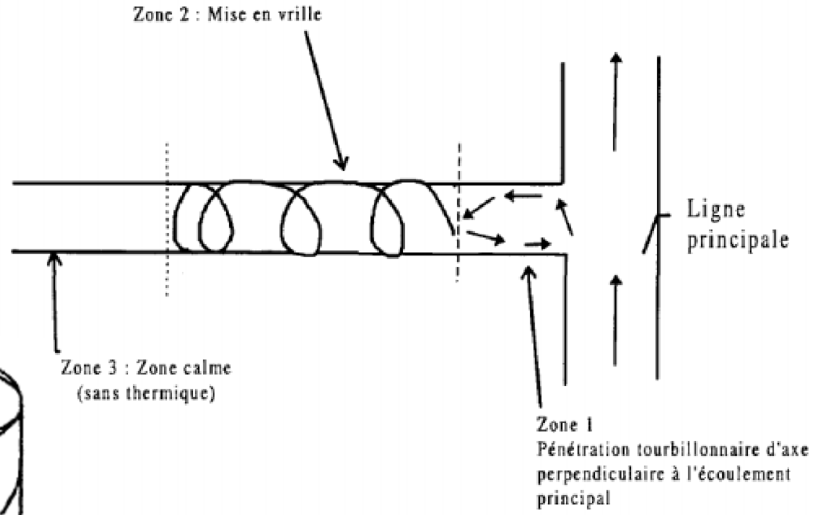
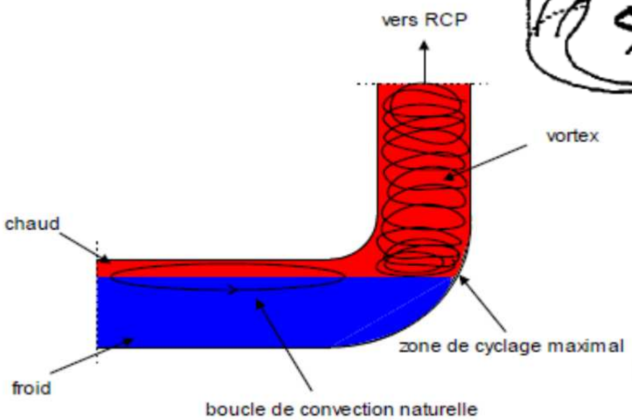
DEAD LEG FLOWS

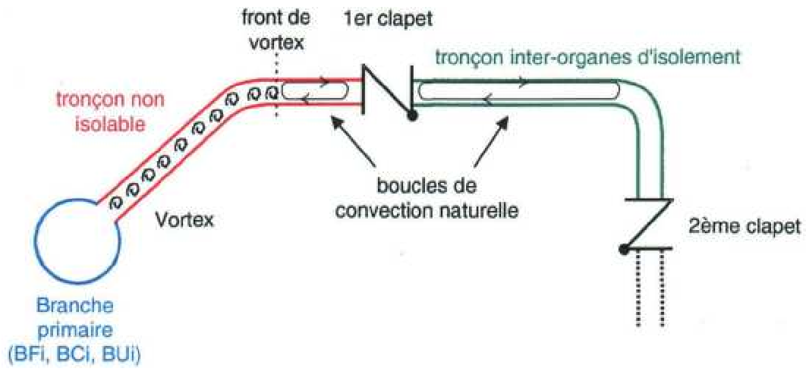
- Nuclear reactors contain many auxiliary lines that branch off the main primary (or secondary) circuit so that additional water can be added or extracted from the primary circuit as and when required
- When flow is not required in an auxiliary line it is sealed from the main circuit by a closed valve
- Dead leg flows occur in branch lines which lead up to closed valves
- Dead leg flows can induce thermal cycling and have been responsible for leaks in several nuclear plants
  - Japan (Mihama)
  - USA (Farley)
  - Belgium (Tihange)
- All PWR operators need to both understand and mitigate for dead leg flows

DEAD LEG FLOWS

- **High velocity high temperature in the main line**
- **Formation of a high temperature vortex in the dead leg**
- **Penetration of the vortex along the dead leg**
- **Stratification at the end of the dead leg**





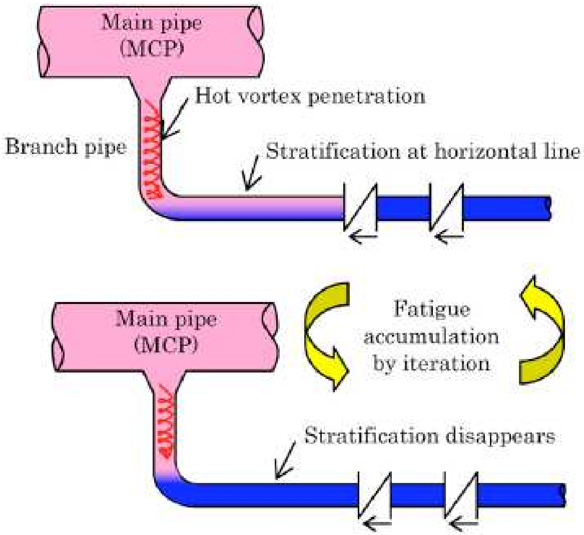


DEAD LEG FLOWS

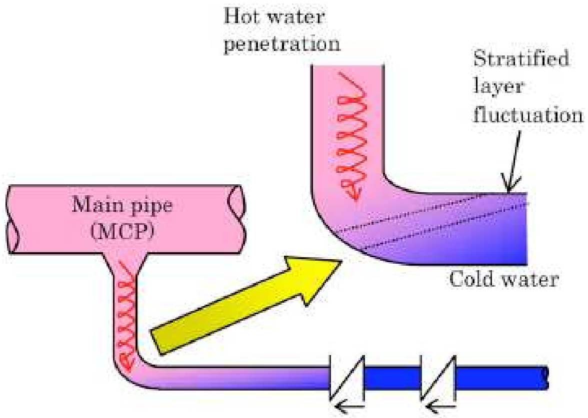
When the vortex moves close to the elbow bend a large stratification can enter the horizontal line

If the vortex cycles periodically across the bend thermal fatigue can accumulate

The temperature changes can be large (of the order of 100°C)



(a) Cavity flow front is located at the upper portion of the horizontal line



(b) Cavity flow front is located at the central portion of the elbow

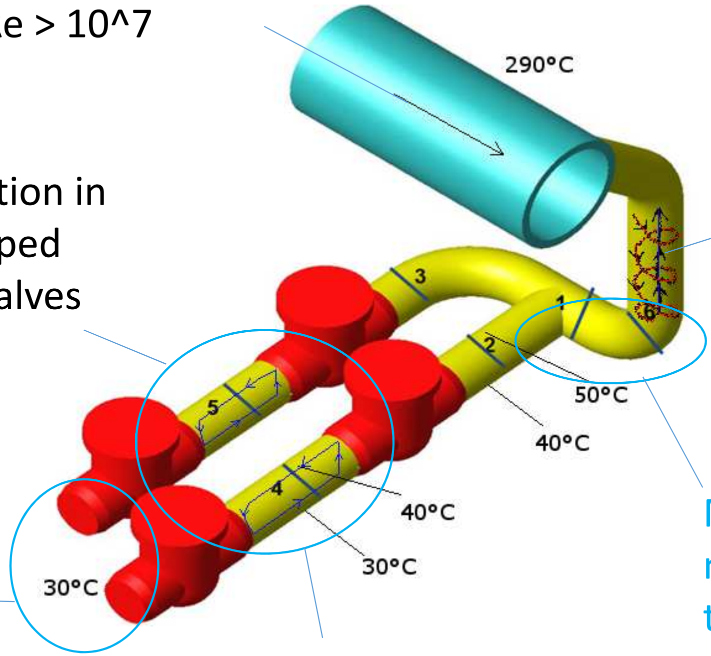
DEAD LEG FLOWS

High flow rates in the main branch : Re > 10^7

Heat transfer along the pipe network and at the valves

Natural convection in the region trapped between two valves

Vortex pénétration (at an unknown flow rate) with colder flow returning via the center of the vortex



Weak natural convection flow behind the valves

Mixed convection zone dominated by natural convection if the vortex stops above the bend and forced convection if the vortex « inserts » below the bend

Natural convection (Re < 100)

DEAD LEG FLOWS

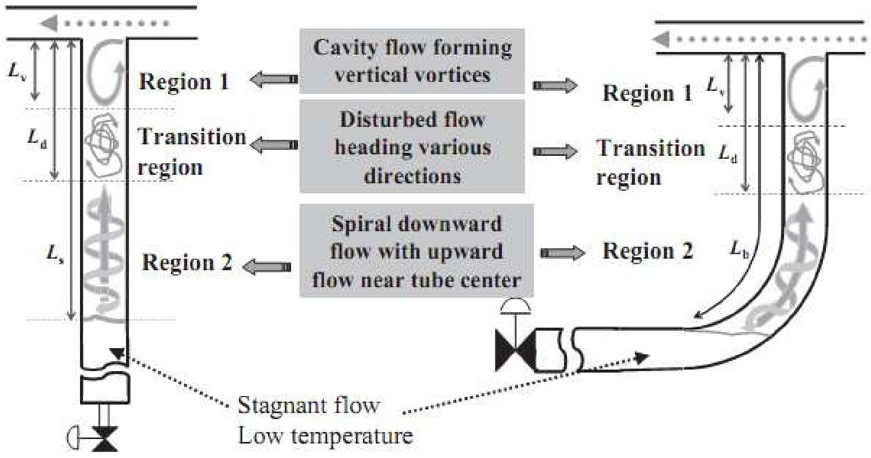
- **Nakamura et al conducted an important experiment of a dead leg flow under two temperature environments**
  - isothermal and a 50°C temperature difference

- **Further experiments are required**
  - to classify dead leg flow phenomena
  - to provide a wide range of temperature differences
  - to assess whether CFD can be used as a predictive tool for this sort of flow

Temperature fluctuation phenomena in a normally stagnant pipe connected downward to a high velocity and high temperature main pipe

Akira Nakamura[a,*], Koji Miyoshi[a], Toru Oumaya[b], Nobuyuki Takenaka[c], Shigeo Hosokawa[c], Daisuke Hamatani[c], Masatsugu Hase[c], Daisuke Onojima[c], Yasuhiro Yamamoto[c], Atsushi Saito[c]

Nuclear Engineering and Design 269 (2014) 360–373



(a) Straight pipe (b) Bent pipe with horizontal section