ADAPTATION OF THE NUCLEAR SAFETY CODE CATHARE3 TO SUPERCRITICAL HELIUM FLOW

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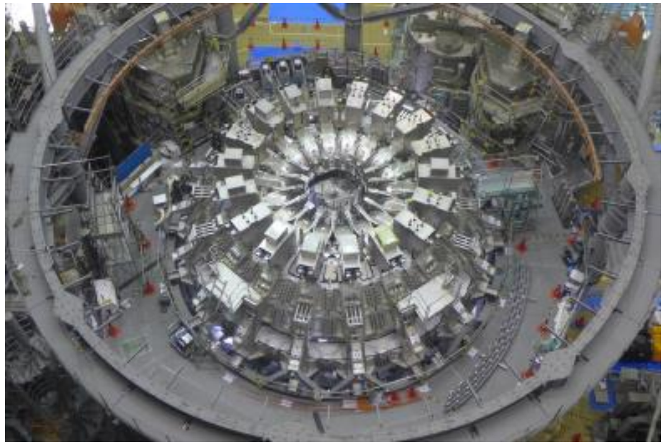
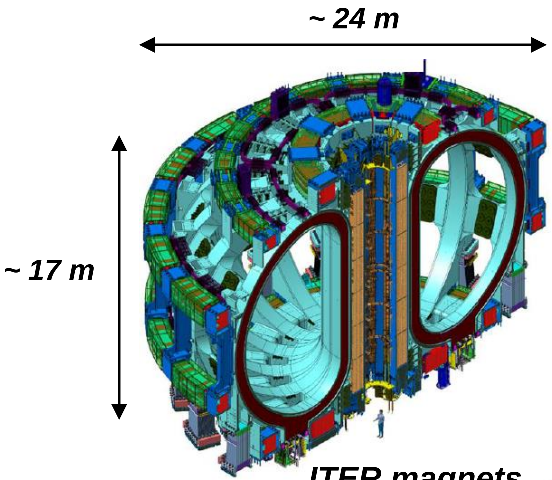
CONTEXT

CONTEXT AND OBJECTIVE

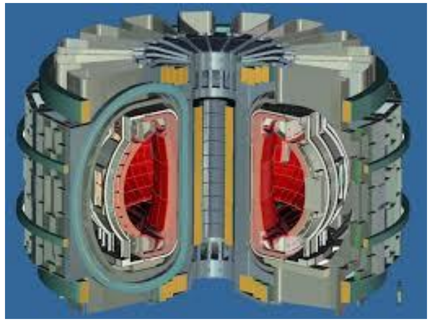
- Several projects on **nuclear fusion: JT-60SA, ITER, DEMO**
- Tokamak reactors need specific cryogenic systems
- **Fields of application :**
  - Superconducting magnets cooled by supercritical helium to 4.5 K
  - Cryogenic lines and liquid helium bath
  - Cryopump operated at 3.6 K
- Some thermal hydraulic codes are available for **sizing calculations** of helium cooling system, but it is necessary to develop calculation tools **for nuclear safety evaluation**.



JT-60SA



ITER magnets



DEMO

Tokamak fusion reactors

CONTEXT AND OBJECTIVES

- Current status : no **scientific calculation tool** qualified to perform safety evaluation of fusion reactor

- **CATHARE** : Reference tool for safety evaluation of Pressurized Water Reactor

➪ THESAURUS project : Adapt the CATHARE code to supercritical helium flow

to obtain a qualified tool for safety analysis on fusion reactor

- **CATHARE code introduction**
  - Properties of supercritical helium
  - Development in CATHARE to model supercritical helium flow
  - Verification and validation methodology of CATHARE

- **First application related to safety**
  - Dynamic thermal-hydraulic modelling of a JT60-SA TFC Cable in Conduit
  - Helium discharge line : “*Cryostat soupape*” experiment

THE CATHARE SYSTEM CODE

THE CATHARE SYSTEM CODE (1/2)

- Developed by CEA, FRAMATOME, EDF and IRSN

- 2-fluid and 6 equation model
  - Thermal and mechanical non equilibrium between the 2 phases
  - 3 equation for each phase,
  - 6 main hydraulic variables : P, H_l, H_g, a, V_l, V_g
  - Taking into account all the flow regimes, mass and heat transfer between each phase or fluid and structure

- Mass balance equation

$$A\frac{\partial}{\partial t}(\alpha_k\,\rho_k) + \frac{\partial}{\partial x}(A\,\alpha_k\,\rho_k V_k) = A\,\Gamma_{i,k}$$

- Momentum balance equation

$$A\frac{\partial}{\partial t}(\alpha_k\,\rho_k V_k) + \frac{\partial}{\partial x}(A\,\alpha_k\,\rho_k {V_k}^2) + A\alpha_k\frac{\partial P}{\partial x} = -\chi\tau_{p,k} + A\alpha_k\,\rho_k g_z + AI_{i,k}$$

- Energy balance equation

$$A\frac{\partial}{\partial t}(\alpha_k\,\rho_k\,(H_k + {V_k}^2/2)) + \frac{\partial}{\partial x}(A\,\alpha_k\,\rho_k V_k(H_k + {V_k}^2/2)) - A\alpha_k\frac{\partial P}{\partial t} = A\phi_{i,k} + \chi_{p,k}$$

$$+ A\alpha_k\,V_k\,\rho_k g_z + A\,\Gamma_{i,k}\,(H_k + {V_k}^2/2)$$

THE CATHARE SYSTEM CODE (2/2)

- Modular code with 3 main hydraulic modules :
  - Axial 1-D : fluid flow in one main direction
  - Volume 0-D : high capacity volume with low flowrates
  - Threed 3-D : elements with multidirectional flows
  - Many thermal and hydraulic sub-modules (thermal wall, safety valve, pump, boundary condition, source, sink …)

- The default fluid is two-phase water but other option are available :
  - Perform calculation in single phase
  - Thermodynamic and transport properties of more than 100 fluids are available including helium (REFPROP database developed by the NIST)
  - Additional closure law can be developed

- CATHARE qualified only on the pressure and temperature range encountered in normal or accidental operation of PWR
  - 0,1 Mpa < P < 25 MPa and 2 °C < T < 2000 °C

- Fundamentals of the CATHARE validation :
  - Separate Effect Test : Based on experiment to study a particular physical phenomenon
  - Integral Effect Test : Performed in experimental Loop to check the abilities of the code to model all physic effects and interaction between different phenomena

NEW CLOSURE LAWS IN CATHARE

- **There is no electrical law avaible, no Joule effect**
- New correlations have been implemented to performed thermal-hydraulic calculation in bundle region

Cross section CICC in TFC JT-60SA

- Heat exchange transfert between fluid and structure

Correlation	Colburn Reynolds analogy
Equation	$N_u = \frac{f}{2} Re Pr^{\frac{1}{3}}$

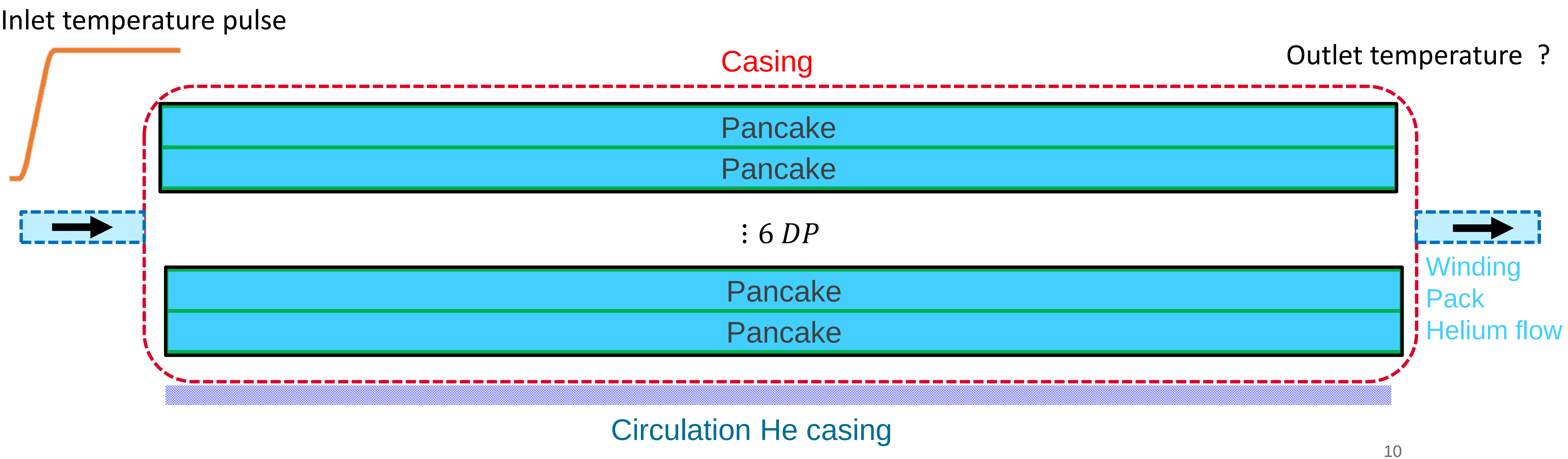
- Pressure drop in the bundle region

Correlations :	Darcy-Forchheimer	Emperical fit determined on the OTHELLO test facility (CEA Cadarache)
φ	$\sim 0{,}32$	Specific TFC JT-60SA
Equation	$f_D = \varphi^2 . C_F . \frac{D_h}{2. K^{0,5}} + \varphi . \frac{{D_h}^2}{2. K} . \frac{1}{Re}$ $\frac{C_F}{\sqrt{K}} = \frac{2{,}42}{\varphi^{5{,}80}}\,;\; K = 19{,}9.10^{-9} \frac{\varphi^3}{(1-\varphi)^2}$ **K : Permeability** **Cf : Drag Factor**	$f_D = \alpha + \beta Re^{\gamma}$ α, β et γ determined for each DP

DYNAMIC THERMAL-HYDRAULIC MODELLING OF A JT60-SA TF COILS CABLE IN CONDUIT WITH CATHARE

MODELLING OF AN EXPERIMENTAL THERMAL-HYDRAULIC TEST (1/3)

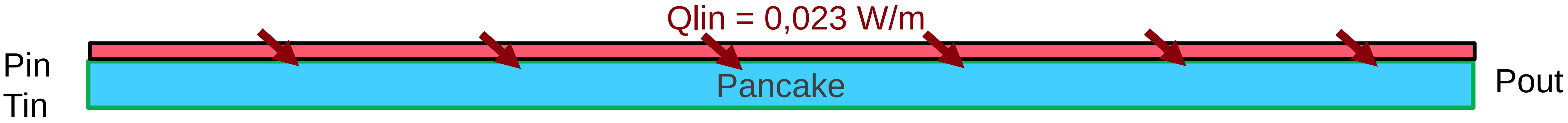
- Thermal-hydraulic experimental test on a TF Coil of JT60-SA without current
- Study the heat propagation longitudinally along the helium flow and transversally in the structures
- Pulsed scenarios, using heater at the inlet of the TF
- 4 different mass flows (reduced = 1 g/s, nominal = 2 g/s, increased = 3 g/s & 4 g/s on each pancake)

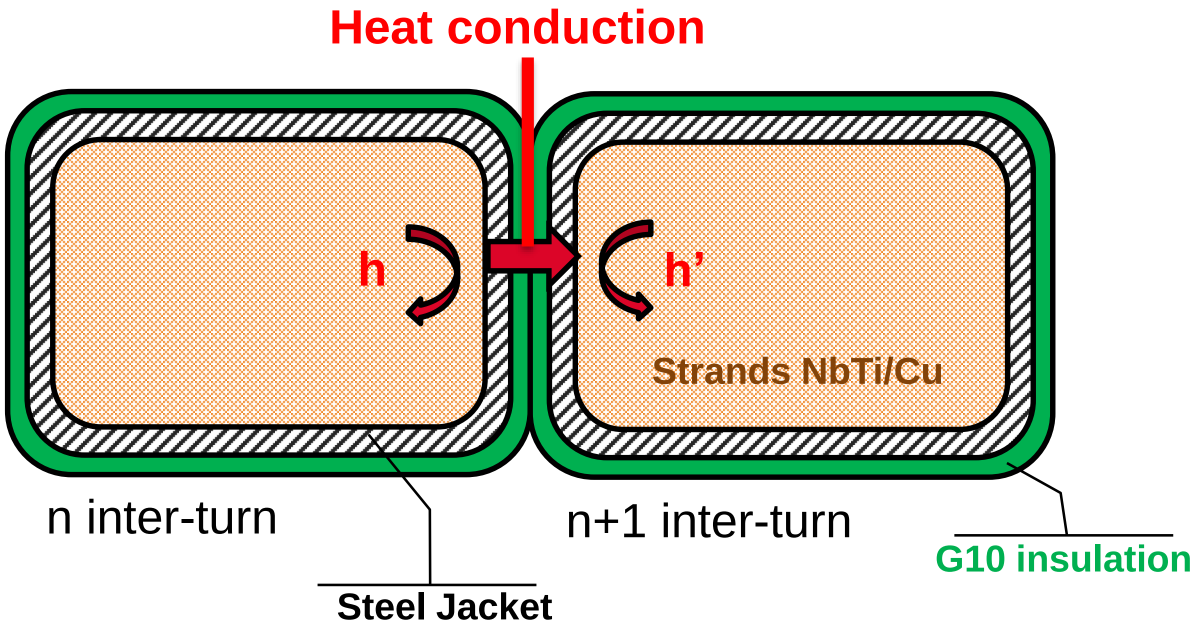


MODELLING OF AN EXPERIMENTAL THERMAL-HYDRAULIC TEST (2/3)

- Model of **one single** pancake of JT-60SA have been built in CATHARE :
  - Casing not considered
  - Impact of the inter-turn thermal coupling

- Boudary Conditions : Exp. Inlet/Outlet pressure, Exp. Inlet temperature + additionnal linear heat flux Qlin = 0,023 W/m (31W for the whole Coil)





Friction factor : Empirical fit on the DP1 TFC02 :

$$f_D = \alpha + \beta Re^{\gamma}$$

Heat exchange coefficients (h and h') : Colburn Reynolds analogy

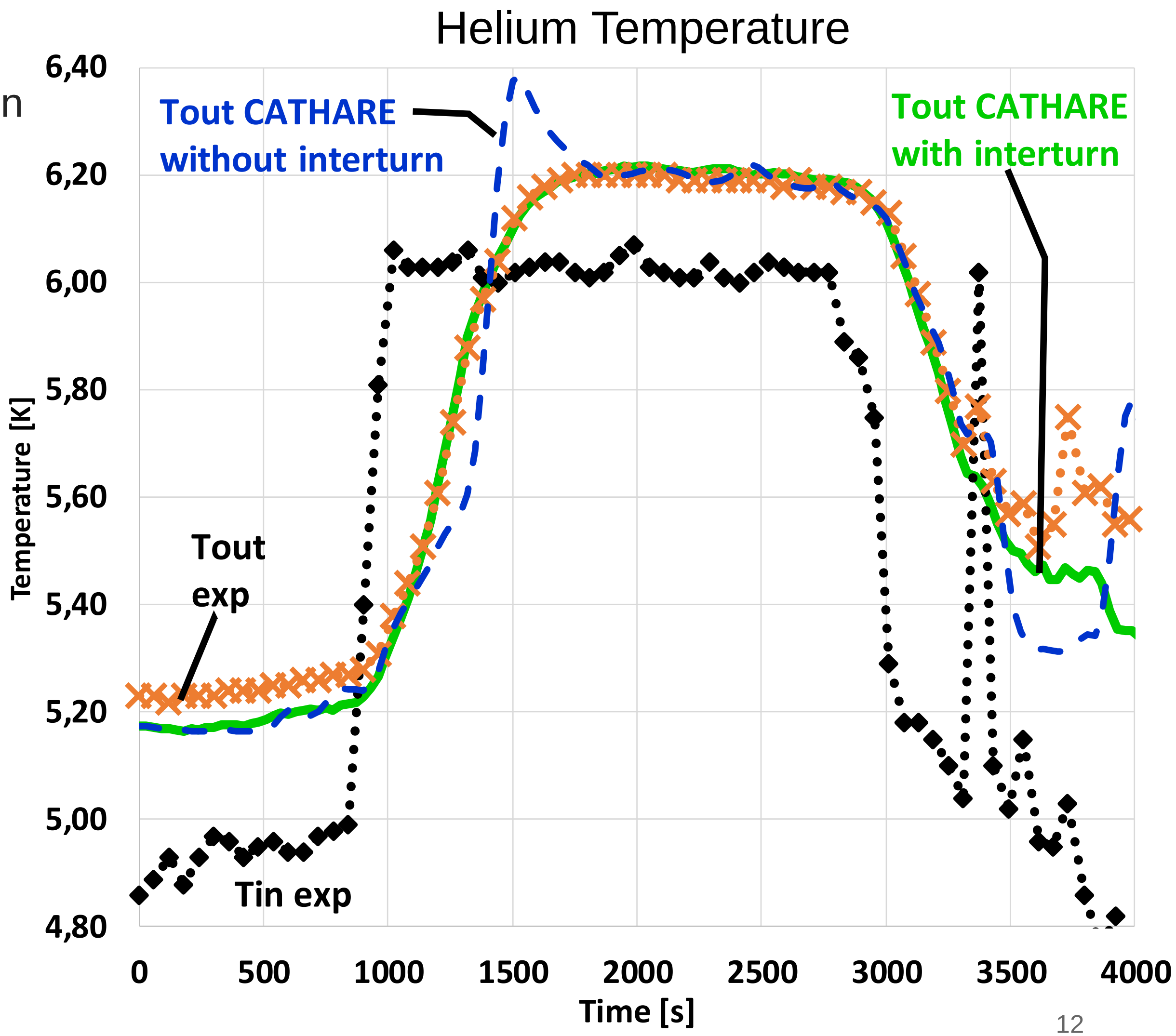
$$N_u = \frac{f}{2} Re Pr^{\frac{1}{3}}$$

Heat Conduction : Heat conduction equation

$$\rho C_p \frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) + Q$$

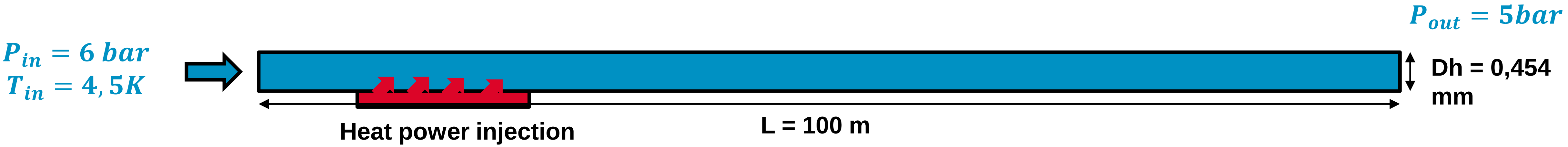
MODELLING OF AN EXPERIMENTAL THERMAL-HYDRAULIC TEST (3/3)

- Without inter-turn heat conduction :
  - Propagation of the warm helium front only by advection
  - Computed Tout has a different shape compared to the experiment
- With inter-turn coupling :
  - The outlet temperature is closed to the experiment
  - Some differences appear after t = 3500 s



NUMERICAL COMPARISON BETWEEN THEA AND CATHARE : THERMAL – HYDRAULIC MODELLING OF AN IMPORTANT HEAT LOAD ON A CICC (1/4)

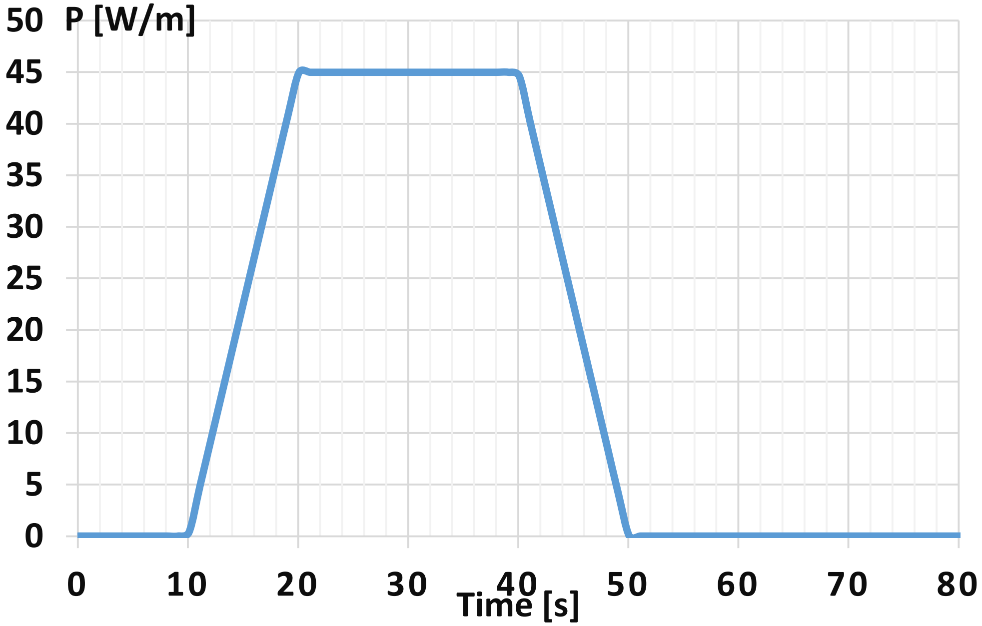
- Thermal-hydraulic model of a 100m long TF JT60-SA CICC in THEA* and CATHARE :
  - No current
  - Adiabatic jacket and strand
  - Heat power directly injected in the fluid between x =15m et x =25m
  - **Friction factor calculated with Darcy Forchheimer $\varphi = 0,28$.**



- Value of the heat power was chosen in order to obtain :
  - Hot spot temperature ~150 K
  - Observe back-flow in the CICC

- **The final objective :**
  - Compare CATHARE and THEA on hydraulic response of a CICC which receives intense heat power injection
  - Check CATHARE abilities to compute backflow with helium and to predict hot spot temperature

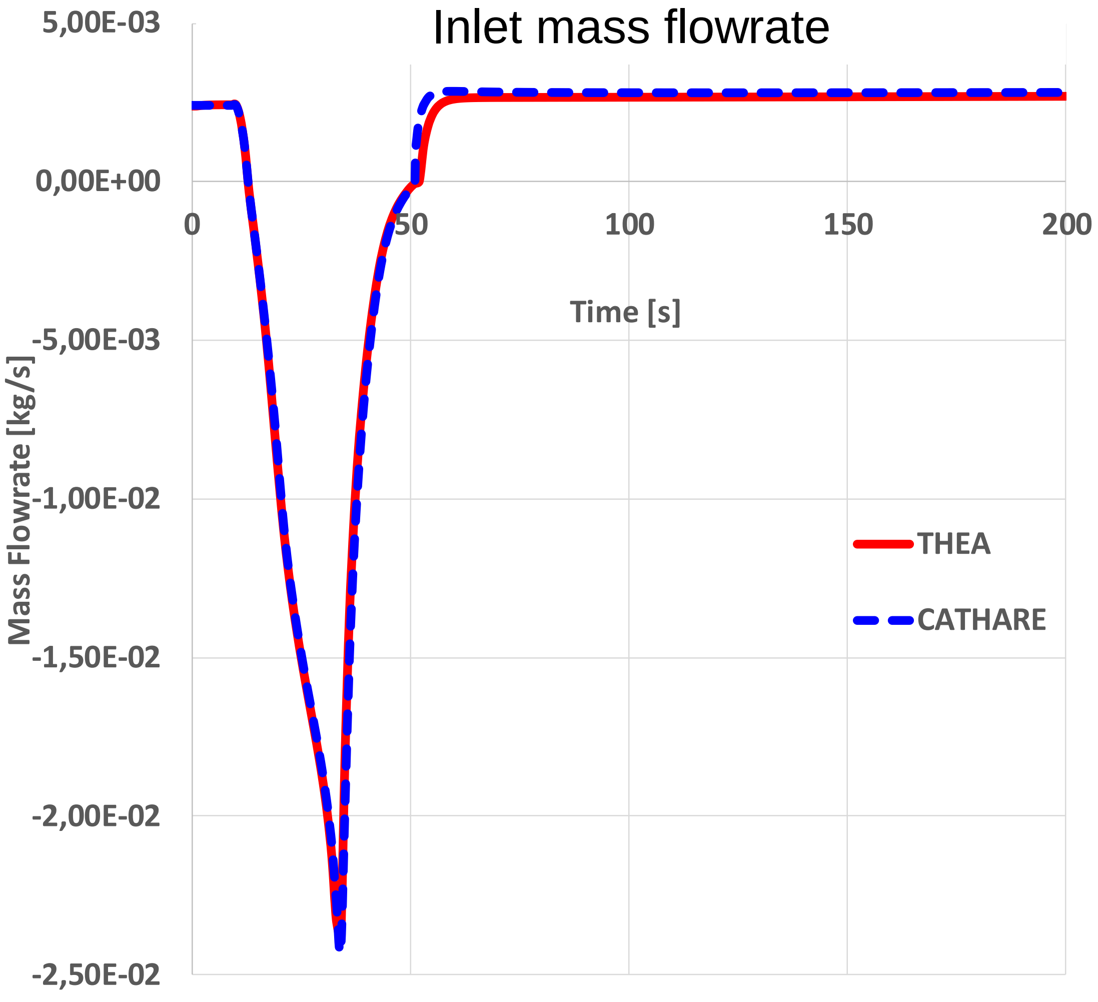
Thermal power injected in the helium flow

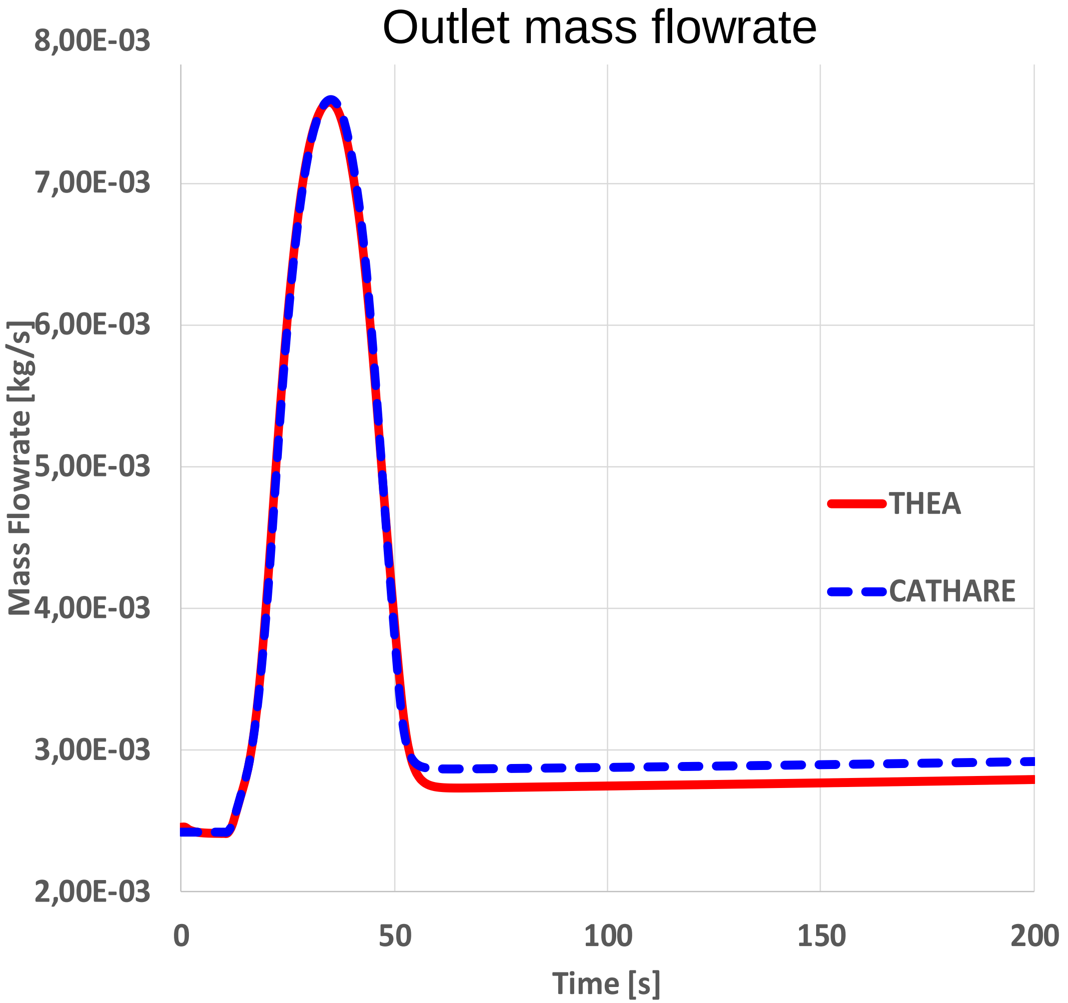


* L. Bottura, C. Rosso, M. Breschi,*''A general model for thermal, hydraulic and electric analysis of superconducting cables''* , Cryogenics 40 (2000) 617 - 626

NUMERICAL COMPARISON BETWEEN THEA AND CATHARE : THERMAL – HYDRAULIC MODELLING OF AN IMPORTANT HEAT LOAD ON A CICC (2/4)

- The measurement of hydraulic signals is an additional safety detection of quench ignition
- Mass flowrates during the backflow are very closed ⇨ **Predict same hydraulic signal response at the quench ignition**





NUMERICAL COMPARISON BETWEEN THEA AND CATHARE : THERMAL – HYDRAULIC MODELLING OF AN IMPORTANT HEAT LOAD ON A CICC (3/4)

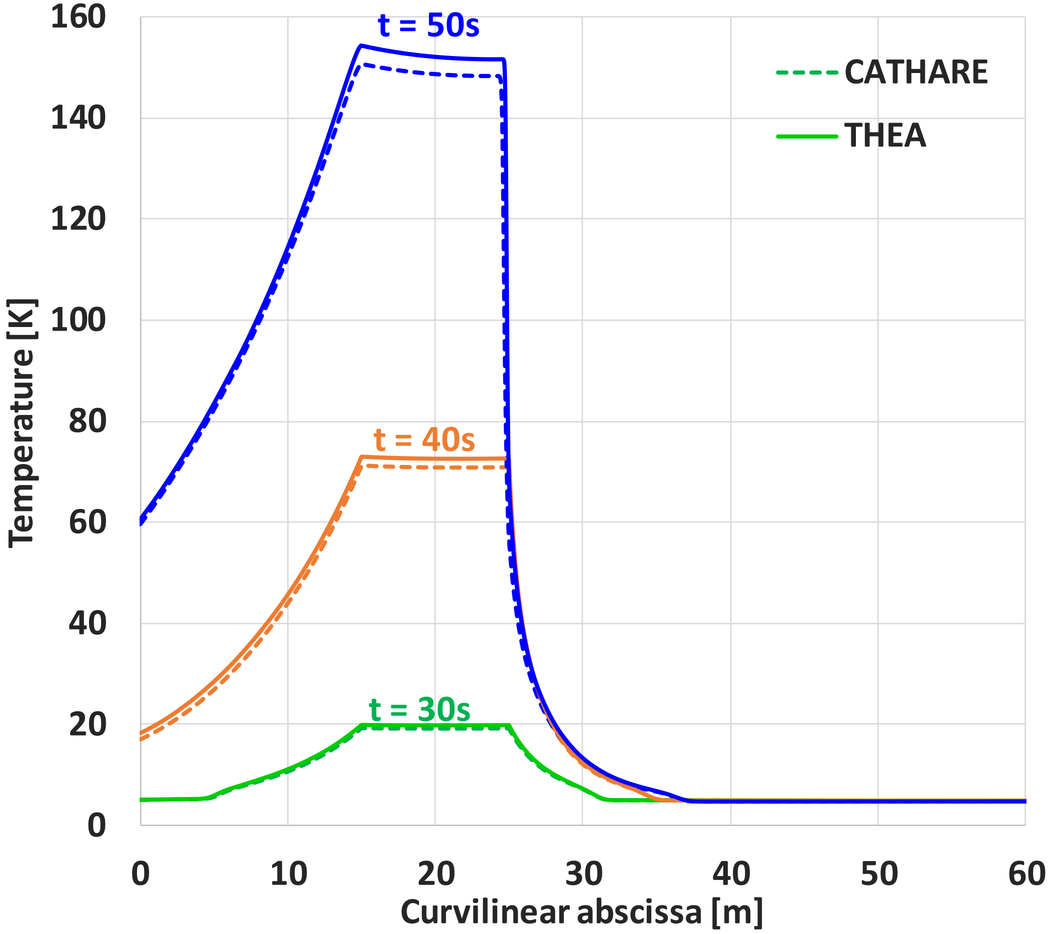
- **During power injection** , results computed by both codes are similar :
  - Same shape of the temperature profile
  - Propagation of the warm helium at the same velocity

- $T_{hot\ spot}\ CATHARE$ is 3,6 K lower than $T_{hot\ spot}\ THEA$

- Internal energy balance has been checked in CATHARE

- Some differences are found between helium databases used by each code ➪ Sufficient to explain the difference?

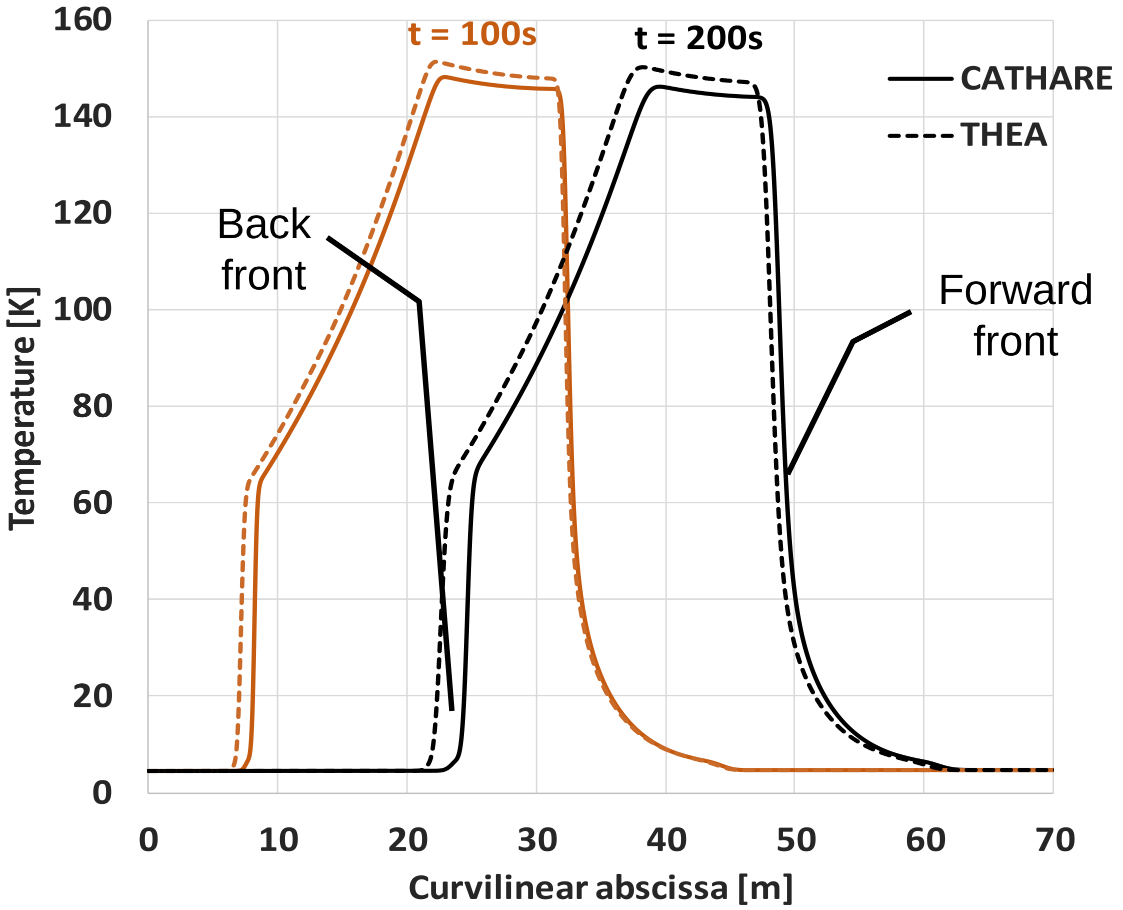
Temperature profile in the CICC during power injection



NUMERICAL COMPARISON BETWEEN THEA AND CATHARE : THERMAL – HYDRAULIC MODELLING OF AN IMPORTANT HEAT LOAD ON A CICC (4/4)

- **During the advection phase :**
  - Velocity of the warm helium forward front are closed
  - Velocity of the warm helium back front computed by CATHARE is slighly higher than the THEA one

Temperature profile in the CICC during advection phase



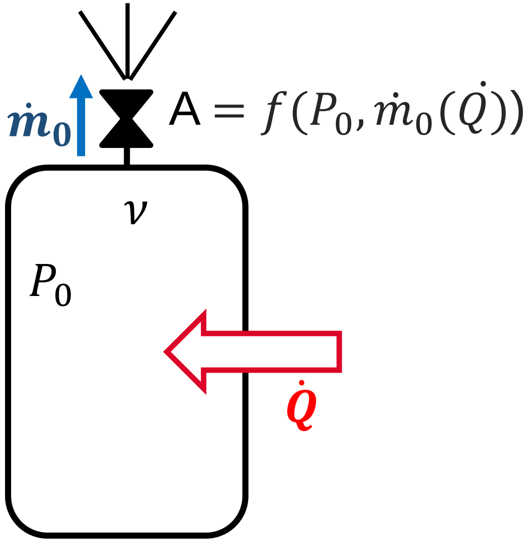
CONCLUSION ON CICC MODELLING

- CATHARE gives satisfactory results for the comparison data on JT-60SA TFC measurements
- CATHARE reproduces the same thermal hydraulic behaviours as THEA for a configuration closed to a Quench ignition

SAFETY VALVE FOR CRYOGENIC DEVICES

SAFETY VALVE SIZING ISSUE

- Cryogenics facilities have to be protected against accidental pressure increase
  - All devices must be equipped of a safety valve
  - The safety valve must be sized correctly to ensure a sufficient mass flowrate and the pressure decrease
- Valve sizing criterion : section $A = f(P_0, \dot{m}_0(\dot{Q}))$
- $\dot{m}_0$ evacuated mass flowrate to maintain constant pressure P_0
- $\dot{Q}$ heat power received by the fluid
- First law of thermodynamics for open system : $\dot{m}_0 = \dfrac{\dot{Q}}{v\left(\frac{\partial h}{\partial v}\right)_{P_0}}$



SAFETY VALVE SIZING ISSUE

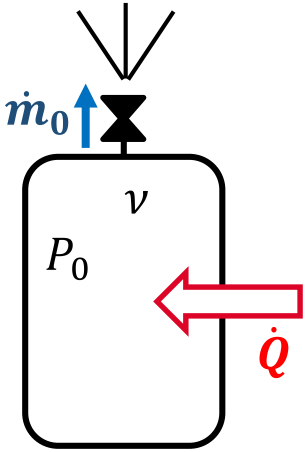
- Valve sizing criterion : $A = f(P_0, \dot{m}_0(\dot{Q}))$

Depend on maximal admissive pressure of the device

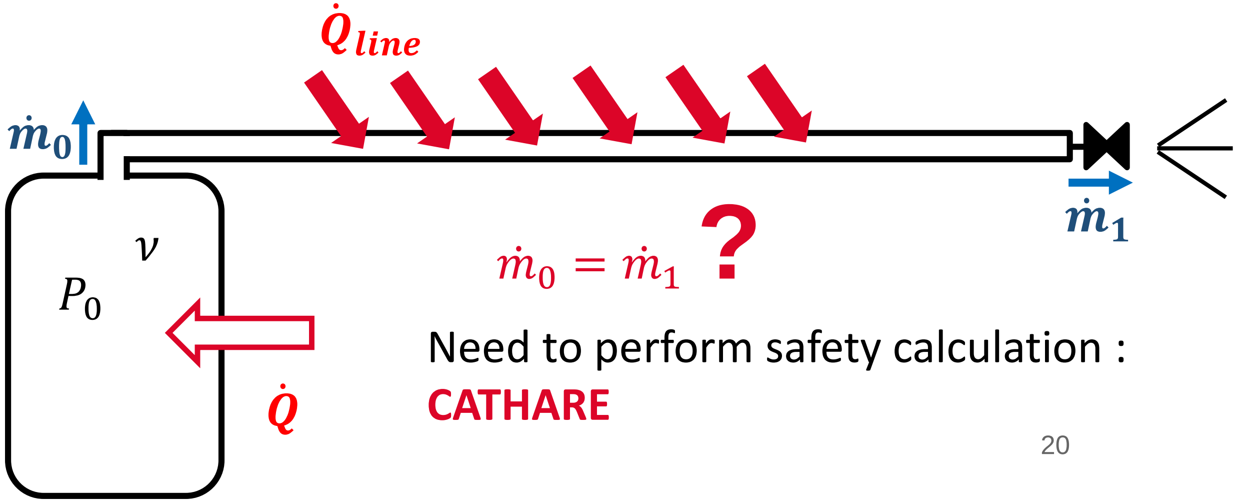
Have to be measured for each fluid :
Experimental device *“Cryostat Soupape”* for supercritical helium

All values are known to size the safety valve?

Yes



No



$\dot{m}_0 = \dot{m}_1$ **?**

Need to perform safety calculation :
CATHARE

CATHARE & SAFETY VALVE FOR CRYOGENIC DEVICES

- Final aim ➩ Perform calculation for sizing deported safety valve in “industrial devices”
- ***<u>First steps :</u>***
  - Evaluation of CATHARE abilities to model the pressure and temperature increase in helium tank after loss of insulating vacuum.
  - First evaluation of the mass flowrate calculated by CATHARE

➩ Modelling of the experiment facility “*Cryostat soupape*”

THE EXPERIMENTAL FACILITY « *CRYOSTAT SOUPAPE* » (1/4)

- Quantification of heat flux in supercritical helium $\dot{Q}$:
  - In case of failure of the insulating vacuum

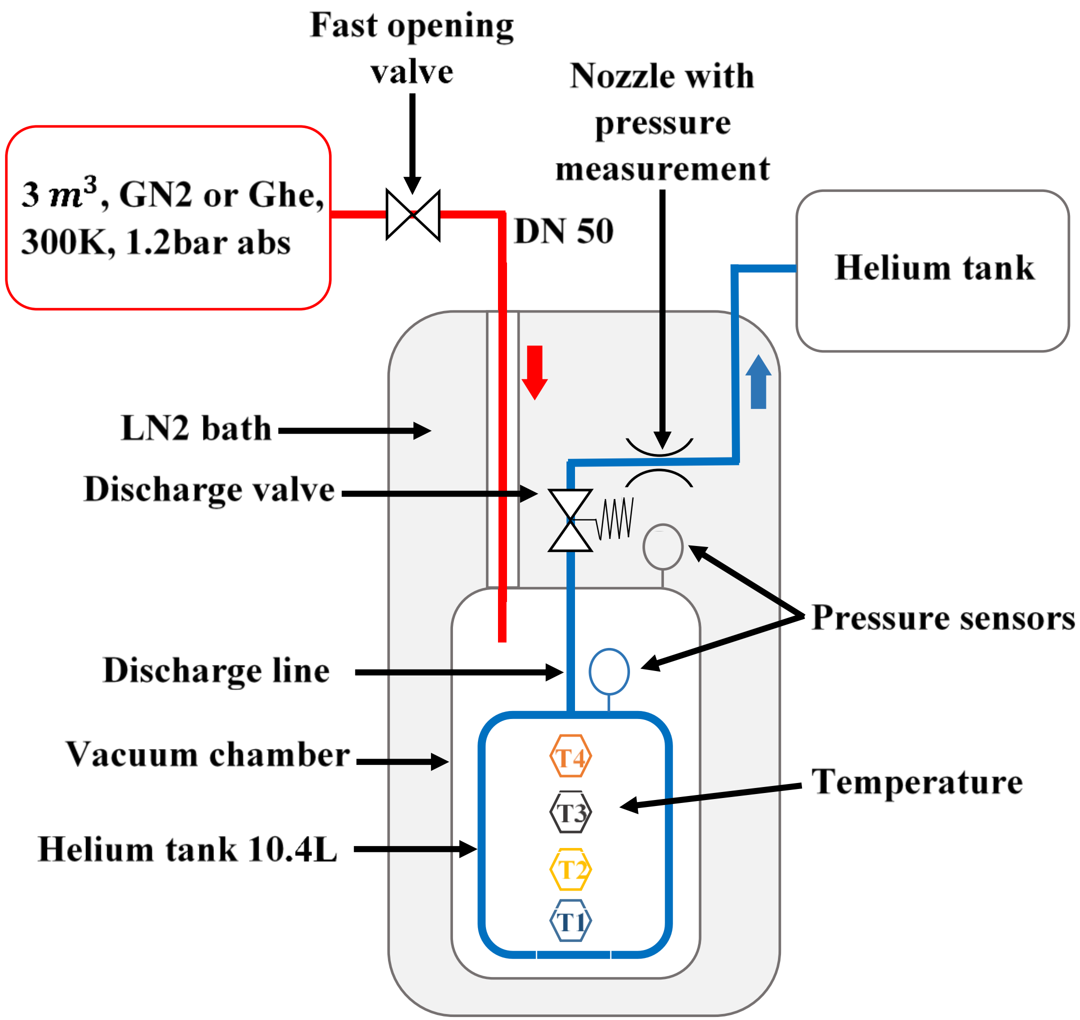
  ⇨ **What is the heat flux received by helium ?**
  - Discharge in supercritical helium

- Lehmann with liquid helium at 1bar: $\varphi = 3{,}8\ W/cm^2$

- Development of an experiment for the supercritical helium case
  Set pressure of the discharge valve : 17 bars

- Heat flux calculated by internal energy balance with supercritical helium ⇨ 1,85W/cm² ($\pm 10\%$)

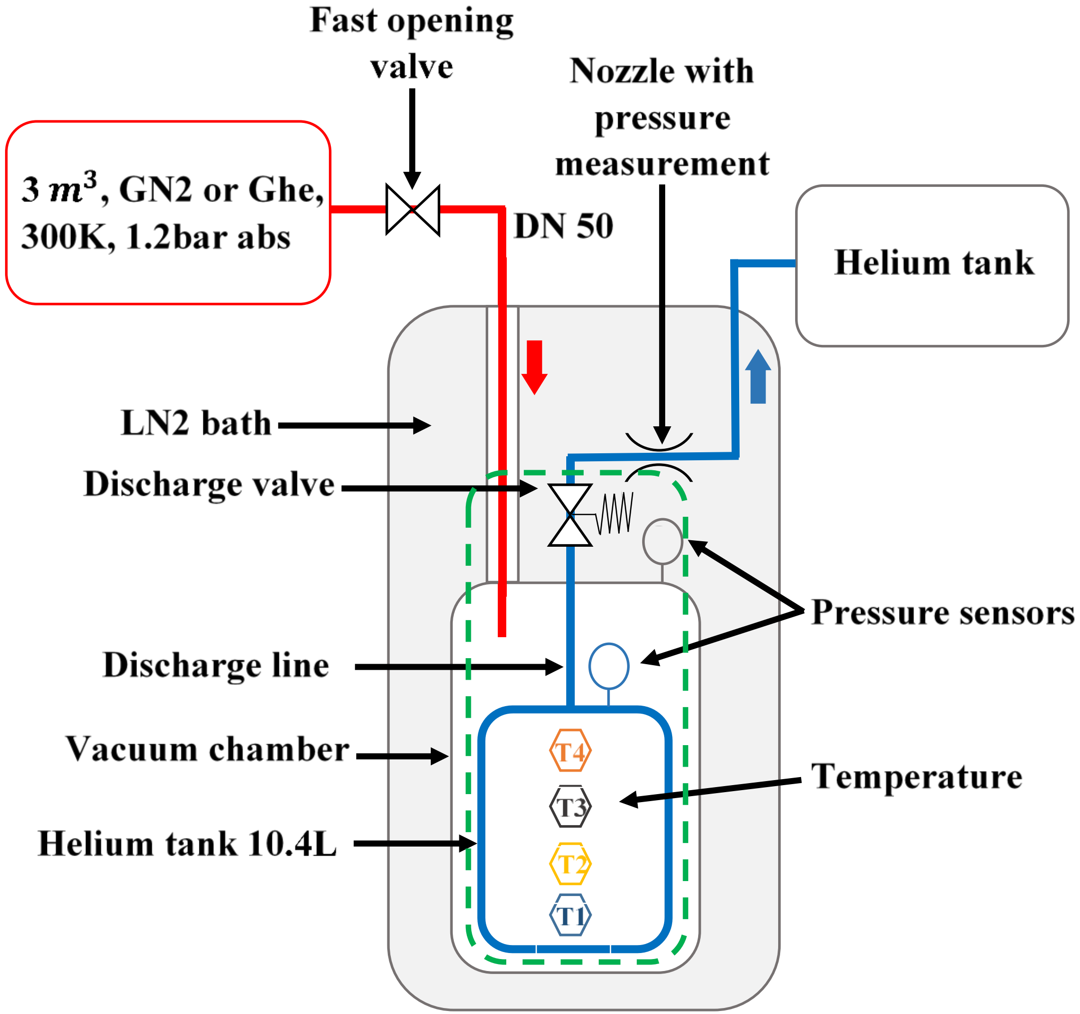
- ***<u>Advantage for CATHARE modelling :</u>***
  - Experimental measures of temperature and pressure
  - Small discharge line (1,36m between tank and discharge valve, 4% of the volume tank)
  - Limited heat flux on the discharge line

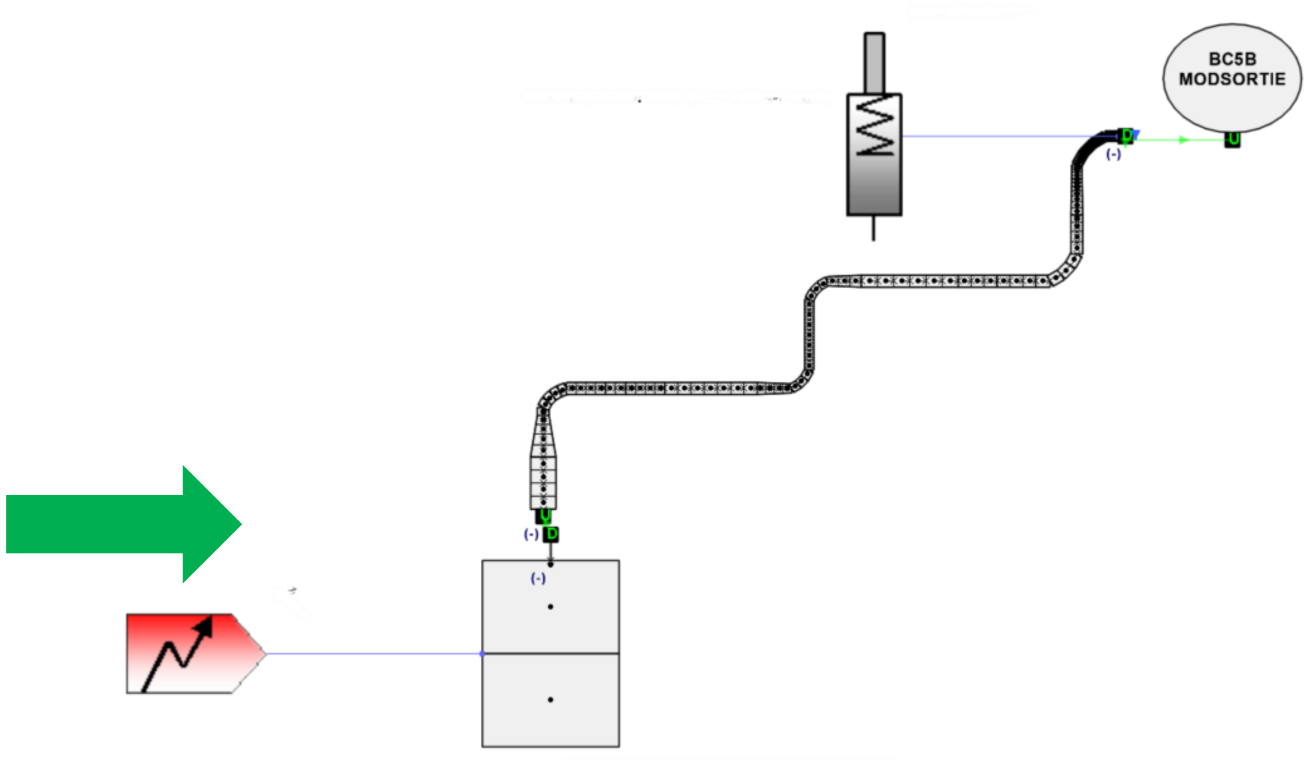


THE EXPERIMENTAL FACILITY « *CRYOSTAT SOUPAPE* » (2/4)

- CATHARE model : 0-D Tank, 1-D **adiabatic** discharge line, **5000W heat power received by the fluid** $(1{,}85\frac{W}{cm^2} * S_{tank})$

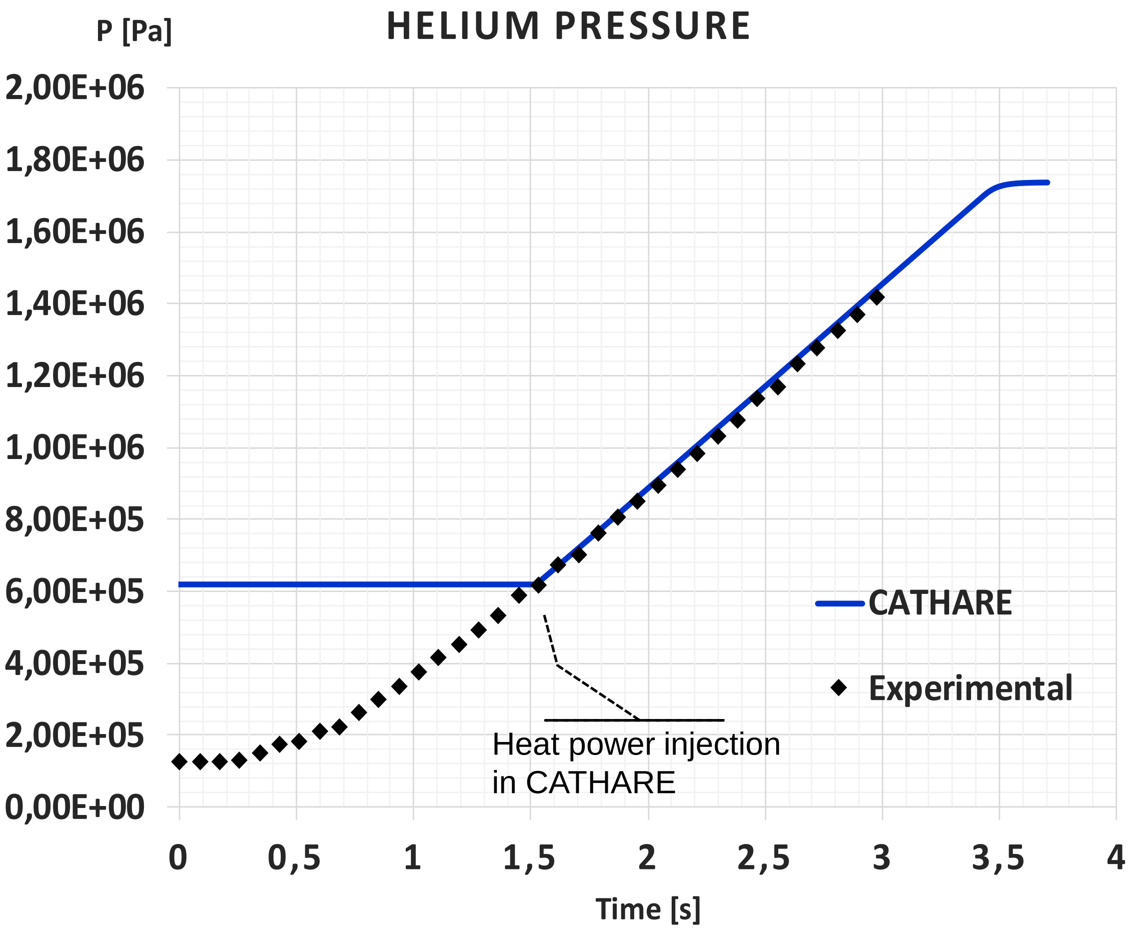
- Transient start from a steady state, defined by experimental data measured when helium is supercritical everywhere in the circuit (Pinit = 6,19 bar, Tinit = 6K)

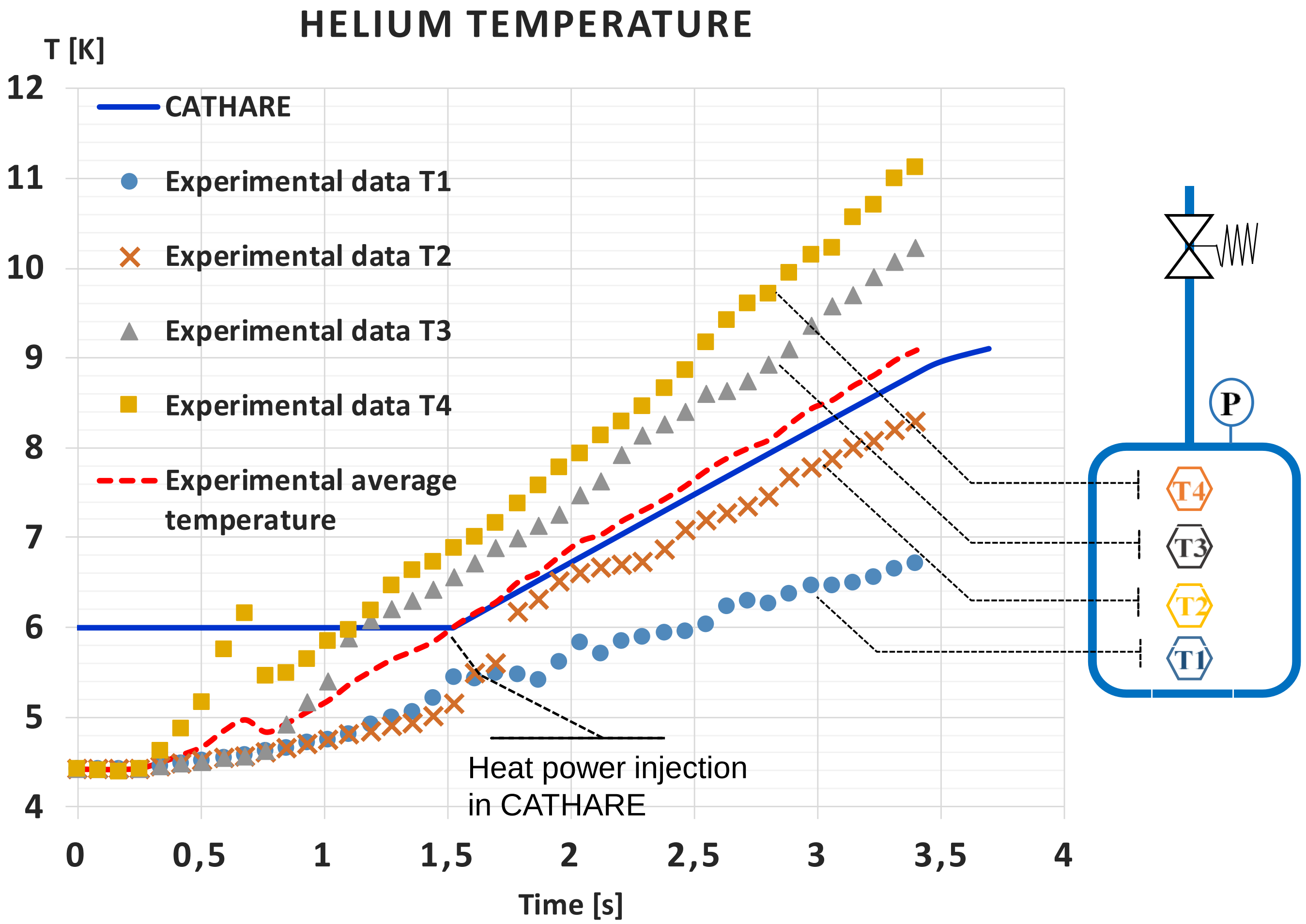




THE EXPERIMENTAL FACILITY « *CRYOSTAT SOUPAPE* » (3/4)

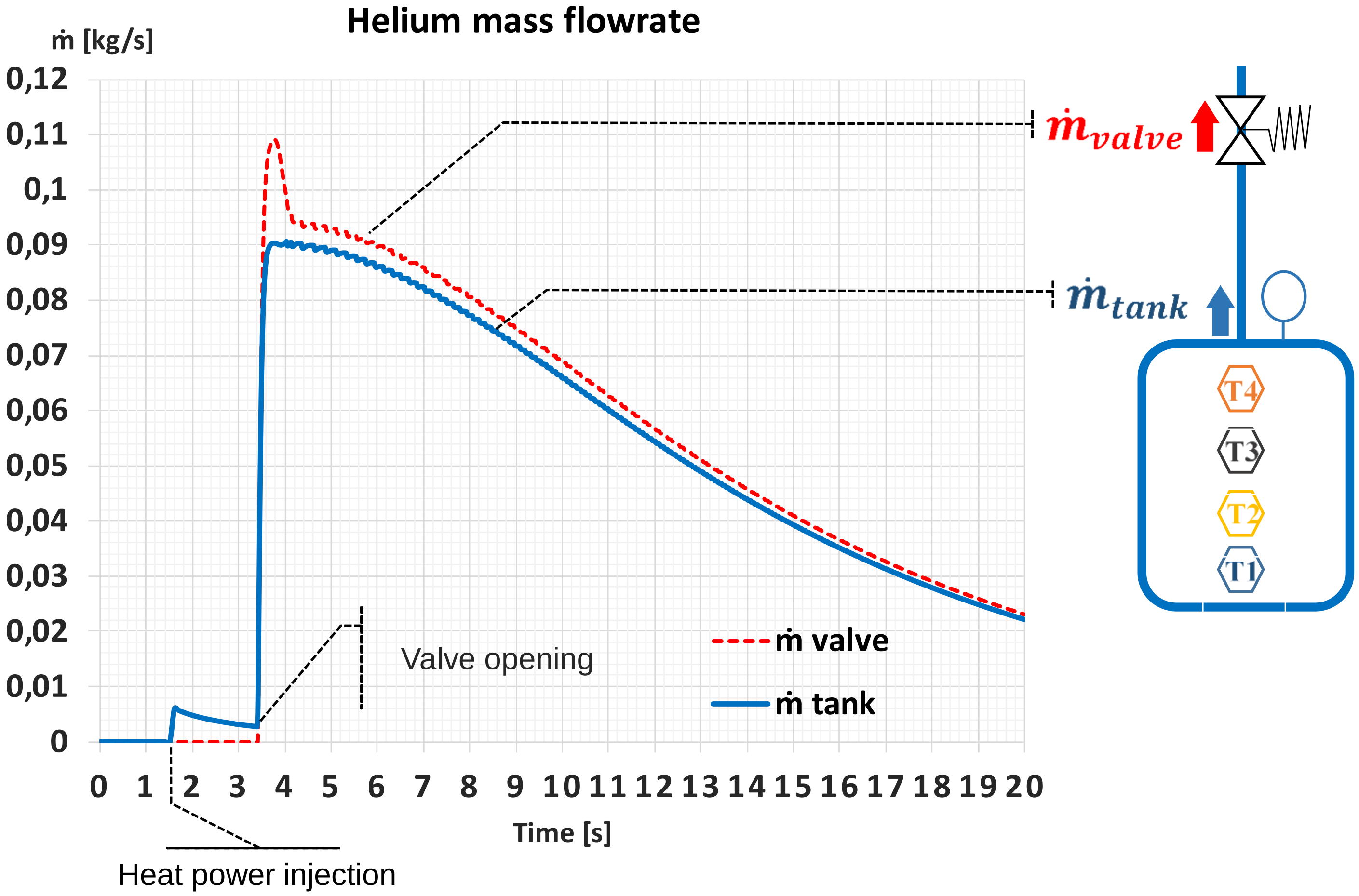
- Temperature and pressure increase in the helium tank before the discharge valve opening

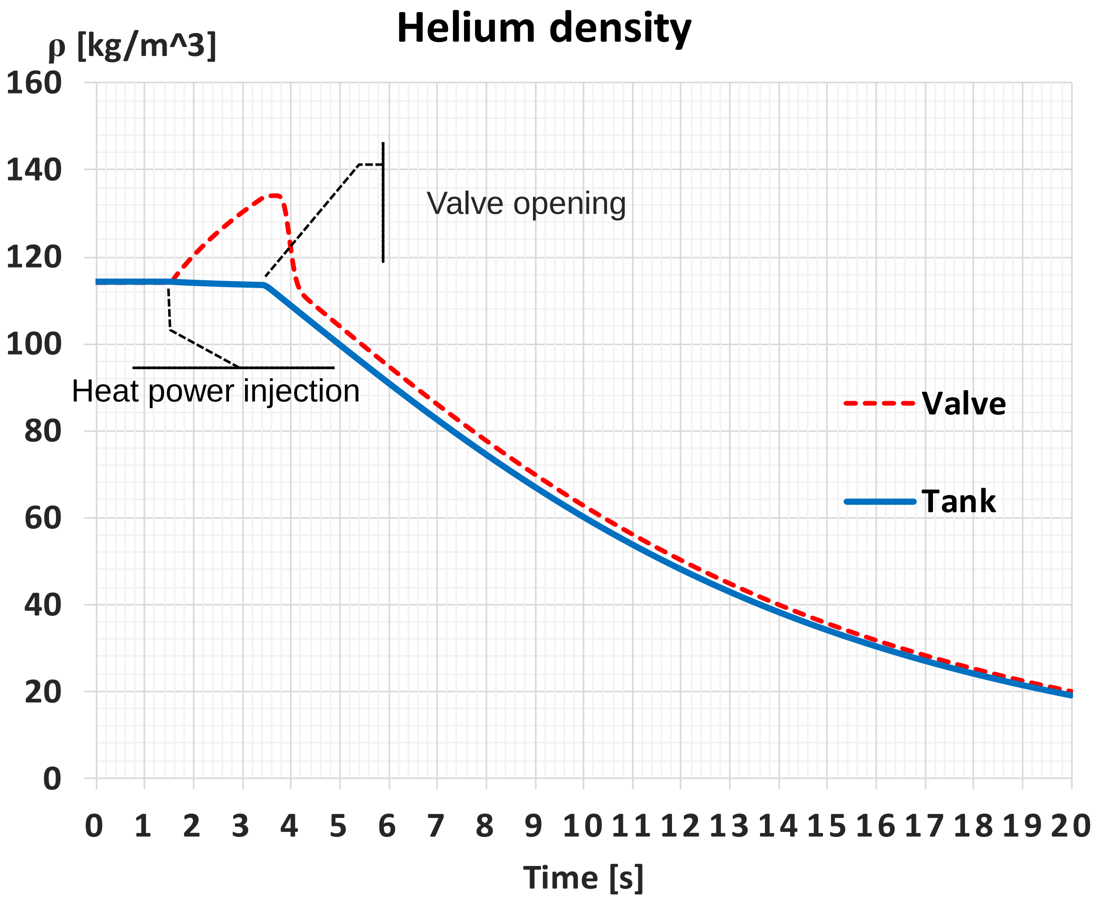




THE EXPERIMENTAL FACILITY « *CRYOSTAT SOUPAPE* » (4/4)

- Mass flowrate computed by CATHARE at 2 different locations : $\dot{m}_{valve} > \dot{m}_{tank}$
- Small volume of discharge line (0,4L) but sufficient to have mass accumulation between start of heat power injection and discharge valve opening





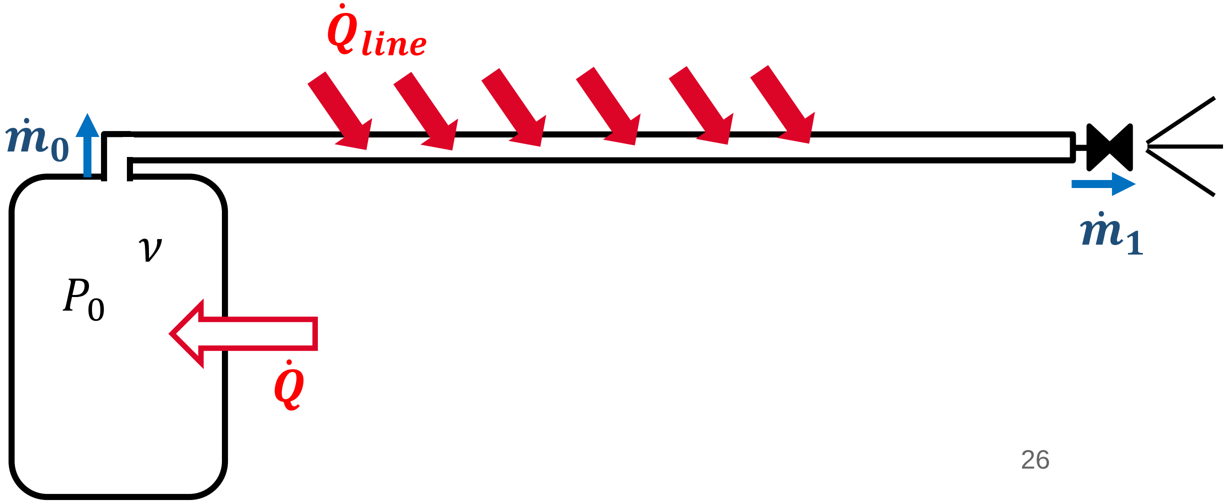
FUTURE WORK ON SAFETY VALVE MODELLING

- The pressure and temperature increases computed by CATHARE is in good agreement with experimental data

- CATHARE shows that even with a small adiabatic discharge line, difference can be observed on inlet and outlet discharge line mass flowrates

Next step : Industrial case

- 100 L tank and 10 m long DN100 discharge line ➪ Ratio Volume line / Volume tank ~ 0,78 (X20), heat power : 24000 W (X5)
- Case with adiabatic and none adiabatic line
- Influence of the discharge line geometry (L vs D)
- Influence of the value of $\dot{Q}_{line}$
- Impact on the mass flowrates : Increase, back flow?



CONCLUSION

CONCLUSION & PERSPECTIVE

Conclusion

- CATHARE is able to perform calculations with supercritical helium
- Comparison have been performed with experimental data and the THEA code on pure thermal-hydraulic tests in CICC :
  ➪ CATHARE gives satisfactory results
- Modelling of the experiment facility *Cryostat Soupape* shows the relevance of using CATHARE for safety calculation on circuit with deported safety valve

Future work

- Further investigation of Quench scenarios in TFC JT-60SA (no electrical law implemented)
- Modeling of the Quench line
- Study of “industrial case” with long discharge line