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Qualification of the MEXIICO loop dedicated to nuclear power transients: An experimental and modelling approach

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ABSTRACT

The MEXIICO project carried out by the CEA and supported by EDF and AREVA has the objective to characterize the behaviour of irradiated fuel pellet issued from nuclear water reactor during power transients. The MEXIICO experimental loop has been recently implemented in the LECA-STAR facility of the CEA Cadarache. It will allow studying the fuel fragmentation of nuclear fuels submitted to various temperature and pressure histories (up to1600 °C and 1600 bar) using the monitoring of released ^{85}Kr activity during the experiment.

Since the fission gas release is measured thanks to a gamma detector located in the rear cell, while the nuclear fuel sample is located inside the MEXIICO furnace in the hot cell, it is necessary to take into account the residence time of the gas in the loop to accurately correlate fission gas release to the local temperature and pressure conditions of the sample, which are also time dependent.

In this paper, we will compare a thermal hydraulic approach mixing both an analytical method and a numerical CFD simulation to experimental test results. This modelling of the MEXIICO loop will support the interpretation of future tests, and will allow, more precisely, to determine the fuel fragmentation thresholds for various stress conditions.

1. Introduction

The MEXIICO experimental loop, recently implemented in the LECA-STAR facility in the CEA Cadarache has been designed to study the fuel behaviour during power transients by a nuclear irradiated fuel sample submitted to temperature and pressure transients (MEXIICO, 2016). It will thus allow performing analytical separate effect tests, which will be of great value in order to better understand the fuel behaviour under different kind of nuclear reactor transients (Kashibe and Une, 2000); (Pontillon et al., 2005).

Indeed, depending on the choice of the temperature and pressure histories (up to 1600 °C and 1600 bar), It will provide useful data regarding the impact of hydrostatic stress conditions on the fuel fragmentation for different kind of fuels, UO_2 or MOX fuel at intermediate or high burn-up rates, i.e. for different kind of fuel microstructure with or without High Burn-Up structures (NRC LOCA, 2012).

The slow depressurization tests carried out in the MEXIICO loop enable to characterize the fuel fragmentation state by the measure of the fission gas released by a pellet sample during the experiment (Une et al., 2001). In the MEXIICO facility, the emission of fission gas is made possible by progressively decreasing pressure in the furnace that contains the fuel pellet.

Since fission gas release is measured thanks to gamma detector placed in the rear zone of the hot cell, requiring thus a long piping between fuel sample and fission gas detection, it is of primary importance to accurately evaluate the residence time of the fission gas inside the piping.

The objective of this paper is to present the dual approach mixing experimental evaluation and theoretical calculation of this residence time. In the first section, we will describe the MEXIICO experimental loop, focusing on the different parts of the facility. In the second section, we will describe the experimental setup used to characterize the gas residence time. In the third section, we will present an analytical and a numerical simulation based on Computational Fluid Dynamics (CFD) with the STAR-CCM + software to evaluate the residence time. In the last section, the comparison between experimental results and modelling will be dealt with.

2. The MEXIICO experimental loop

2.1. General view of the loop

The MEXIICO furnace, as viewed in Fig. 1, is the essential component of the loop in which the fuel pellet is present in order to be heated

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Nomenclature

CFD	Computational Fluid Dynamics
MEXIICO	Experimental tool for insertion of important Stresses
RANS	Reynolds-Averaged Navier-Stokes
VDW	Van Der Waals gas

Abbreviation

T	Argon temperature, K
T_A	Upward argon temperature, K
T_B	Downward argon temperature, K
T^*	Critical temperature, K
T_{ext}	Room temperature, K
T_{init}	Initial temperature, K
$T(z)$	Temperature at position z on the z axis, K
P	Argon pressure, Pa
P_A	Upward argon pressure, Pa
P_B	Downward Argon pressure, Pa
P^*	Pressure at the nozzle, Pa
P_{ext}	Atmospheric pressure, Pa
ΔP	Loss of pressure, Pa
ρ_A	Upward Argon density, kg/m^3
ρ_B	Downward Argon density, kg/m^3
ρ	Argon density, kg/m^3
ρ_1	Argon density in high pressure and high temperature region, kg/m^3
ρ_2	Argon density in high pressure and room temperature region, kg/m^3
ρ_{ext}	Argon density in low pressure and room temperature region, kg/m^3
c_P	Heat capacity at constant pressure, J/kg-K
v	Argon velocity, m/s
v_1	Argon velocity in high pressure and high temperature region, m/s
v_2	Argon velocity in high pressure and room temperature region, m/s
v_{ext}	Argon velocity in low pressure and room temperature region, m/s
v^*	Argon velocity at the nozzle, m/s
c	Sonic velocity ($c = \sqrt{\gamma \cdot r \cdot T}$), m/s
D	Mass flowrate, kg/s
D^*	Mass flowrate at the nozzle, kg/s
Q	Volume flowrate, m^3/s
S^*	Critical section, m^2
S_1	Argon section in high pressure and high temperature region, m^2
S_2	Argon section in high pressure and room temperature region, m^2
S_{ext}	Argon section in low pressure and room temperature region, m^2
R	Constant of perfect gas, J/K-mol
M	Argon molar mass ($39.948.10^{-3}$), kg/mol
a	Van der Waals constant (for argon a = 0,135), J.M^3.mol^{-2}
b	Van der Waals constant (for argon b = 0,0000322), m^3.mol^{-1}
T_c	Critical temperature for Van der Waals gas, K
P_c	Critical pressure for Van der Waals gas, Pa
m	Gas mass, kg
n	Number of moles, mol
V	Volume of the MEXIICO furnace, m^3
h	Heat transfer coefficient between Argon loop and air, W/m^2-K

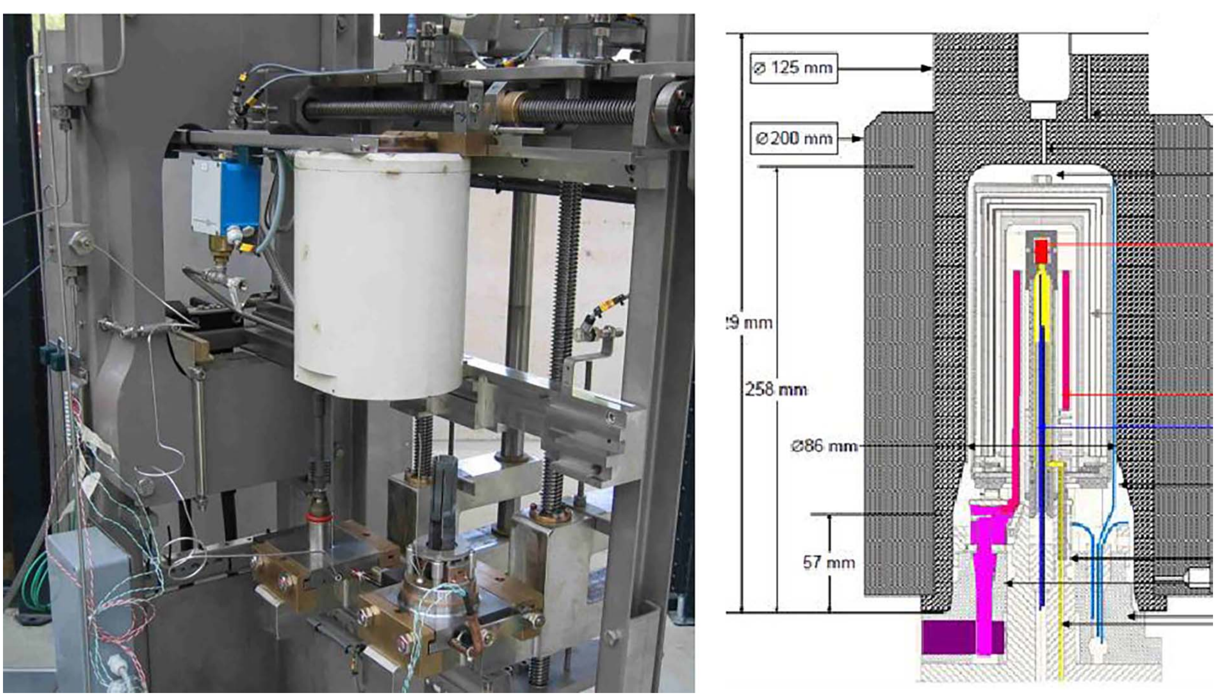

Fig. 1. The photo (left) and schematic view of the furnace (right).

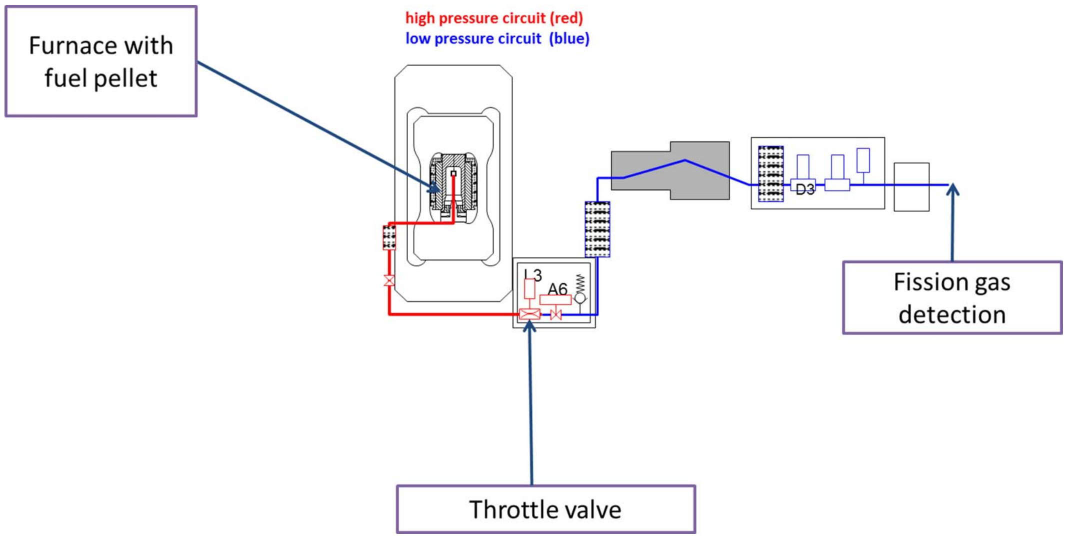

Fig. 2. Description of furnace and downward MEXIICO loop.

and pressurized to specified experimental conditions.

The experimental loop, see Fig. 2, is designed for measuring the gas release kinetics out of the fuel pellet versus temperature and pressure during a pre-determined scenario of slow depressurization. For that purpose, the MEXICO loop is composed of a high and a low pressure section filled by argon which plays the role of the carrier gas. The high pressure section represented in red is separated from the low pressure one in blue by a throttle valve with a variable opening. By this way, the argon flowrate, which transports fission gas, is controlled in order to expand it to atmospheric pressure (Experiments to Study the Gaseous, 1997).

2.2. The throttle valve

2.2.1. Presentation of the component

The throttle valve has the function to drop the argon pressure from the furnace pressure to the atmospheric pressure while dynamically controlling the outlet argon flowrate thanks to a variable opening, in order to analyze the fission gas dragged along by argon (see Fig. 3).

2.2.2. The operation principle

The throttle valve consists in a convergent pipe followed by a divergent one (see Fig. 4) (Candel and Dunod, 2001).

With a compressible gas, the flowrate at the nozzle, called critical flowrate, is sonic, regardless of the downward pressure. The initially subsonic flow (upward of the nozzle) becomes supersonic after the nozzle. For a Mach number *M,* modifications in temperature, pressure and density for a perfect gas on both sides of the nozzle are given by (*A:* upward, *B: downward*):

$$\frac{T_A}{T_B} = 1 + \frac{\gamma - 1}{2} \cdot M^2 \tag{1}$$

$$\frac{P_A}{P_B} = \left(1 + \frac{\gamma - 1}{2} \cdot M^2\right)^{\frac{\gamma}{\gamma - 1}} \tag{2}$$

$$\frac{\rho_A}{\rho_B} = \left(1 + \frac{\gamma - 1}{2} \cdot M^2\right)^{\frac{1}{\gamma - 1}} \tag{3}$$

with: $\gamma = \frac{c_p}{c_v} = 1667$ gamma (ratio of the argon heat capacity at constant pressure and constant volume) $(-)M = \frac{v}{c}$: Mach number $(-)v$: Flow velocity (m/s)c: Sound velocity (m/s)T_A and T_B: Upward and downward temperature (K)P_A *and* P_B: Upward and downward pressure (Pa)ρ_A *and* ρ_B: Upward and downward density (kg/m^3)

The section at the nozzle is deduced from the imposed outlet flowrate. As the flow is sonic, i.e. $M = 1$(noted$*$), we get:

$$\frac{T_A}{T^*} = \frac{\gamma + 1}{2} = 1{,}33 \tag{4}$$

$$\frac{P_A}{P^*} = \left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma}{\gamma - 1}} = 2{,}05 \tag{5}$$

$$\frac{\rho_A}{\rho^*} = \left(\frac{\gamma + 1}{2}\right)^{\frac{1}{\gamma - 1}} = 1{,}66 \tag{6}$$

2.2.2.1. Determination of the section.

The critical flow at the nozzle is written:

$$D^* = \rho^* \cdot S^* \cdot v^* \tag{7}$$

with: D^*: Critical flow (kg/s)ρ^*: Critical density (kg/m^3)S^*: Section at the nozzle (m^2)

For a perfect gas, the density is equal to:

Fig. 3. View of the throttle valve in the MEXIICO installation.

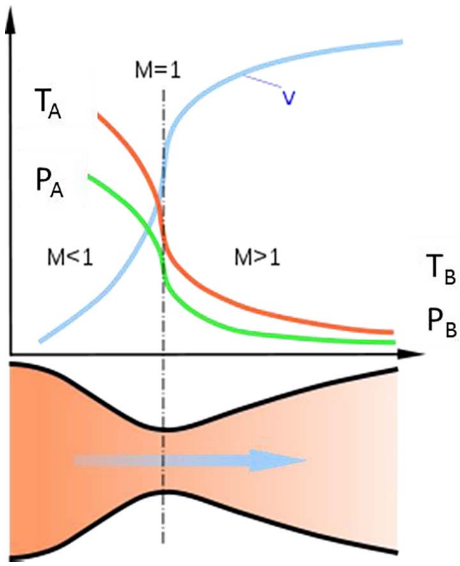

Fig. 4. Principle of the throttle valve.

$$\rho^* = \frac{P^*}{r \cdot T^*} \tag{8}$$

The speed of the sound is:

$$v^* = c^* = \sqrt{\gamma \cdot r \cdot T^*} \tag{9}$$

with:R: Gas constant (J/kg/mol)$M = 39{,}948 \cdot 10^{-3}$: Argon molar mass (kg/mol)$r = \frac{R}{M}$: Reduced constant of argon (J/kg-K)

The critical flowrate is expressed as a function of the upward pressure, sonic speed and critical section:

$$D^* = \rho^* \cdot S^* \cdot v^* = \frac{P^*}{r \cdot T^*} \cdot S^* \cdot \sqrt{\gamma \cdot r \cdot T^*} = \frac{P_A \cdot \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}}{r \cdot \sqrt{\frac{2}{\gamma+1}} \cdot \sqrt{T_A}} \cdot S^* \cdot \sqrt{\gamma \cdot r} = \frac{\Gamma \cdot S^* \cdot P_A}{c_A} \tag{10}$$

with $\Gamma = \gamma \cdot \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2\cdot(\gamma-1)}} = 0{,}9375$

Knowing the mass flowrate imposed at the loop outlet, the flow area at the throttle valve is:

$$S^* = \frac{D^*}{\rho^* \cdot v^*} = \frac{D^* \cdot c_A}{\Gamma \cdot P_A} \tag{11}$$

2.3. The gas flow in the high and low pressure pipes

The fission gas is emitted from the fuel pellet in the high pressure region consisting of an internal diameter pipe of 2.4 mm over a length of 5,385 m, before being expanded through the throttle valve. The gas then continues in the low pressure region (diameters successively of 5, 6, 4 and 6 mm) up to the outlet.

The characteristics (length and diameter) of the different pipes of the MEXIICO loop are presented Fig. 5. The residence time corresponds to the time necessary for fission gas to cross the whole loop before being detected 36,84 m downstream.

3. Experimental determination of the fission gas residence time

In order to characterize the gas flow in the MEXIICO loop, preliminary tests have been carried without fuel pellet in which helium is injected instead of fission gas for different pressures. Helium is carried by argon and detected at the outlet after having crossed the whole loop.

On Fig. 6, the high pressure region with the helium injection system is represented in red, the low pressure region including the helium detection in blue.

3.1. Experimental results

These tests consist in carrying out a series of depressurization steps at high temperature and pressure (maximum 1600 °C, maximum 1600 bar). The outlet flow is controlled by the regulated throttle valve. For each of these steps, a one-time injection of helium is made.

The initial conditions for these three tests are respectively 800 bar and 800 °C for the first one, 1600 bar and 1400 °C for the second one and 1600 bar and 1600 °C for the latter one. Temperatures are kept constant for all these three tests and the outlet flow is adjusted to around 5 l/min for the first two tests and variable for the latter one. In the end, 42 injections were carried out during these three tests, of which 35 proved exploitable, the 7 other were rejected due to insufficient output flowrate (< 1 l/min). For illustration, the cycle at 800 bar and 800 °C is given in Fig. 7. Helium injections are indicated by arrows.

3.2. Uncertainty on the residence time

In order to better characterize the residence time, it is essential to evaluate its sensitivity to the experimental conditions, in particular to the argon flowrate. This is done in the sensitivity studies at the end of this paper by considering the consequences on the residence time of the maximum flowrate. Furthermore, the time spent by argon in the different components of the loop will be also evaluated.

3.2.1. Instantaneous flowrate of argon

The volume flowrate measured at the output is not strictly constant in spite of the regulation imposed by the throttle valve. For example, the instantaneous actual flowrate obtained for an injection of the expansion cycle at 1600 bar and 1600 °C is reproduced in Fig. 8, for an average objective flowrate of 4,2 l/min. The sensitivity to these flowrate variations will be addressed later by studying the effect on the assessment of the residence time by taking the maximum and minimum flowrate values.

The non-uniform flowrate is due to the technical limitations on the

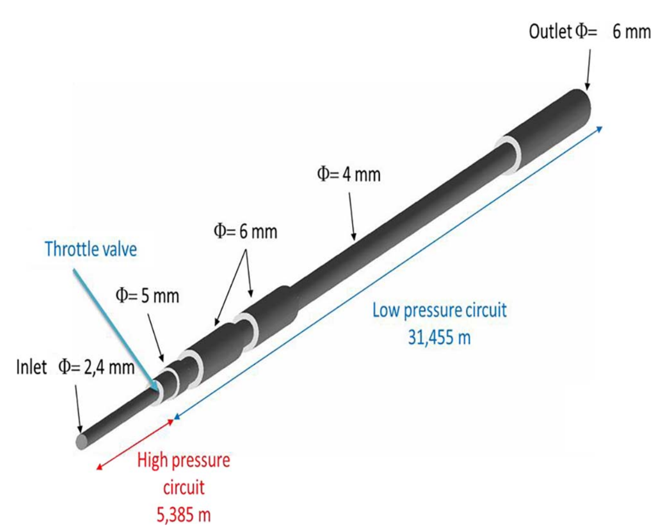

Fig. 5. The different regions of the MEXIICO loop.

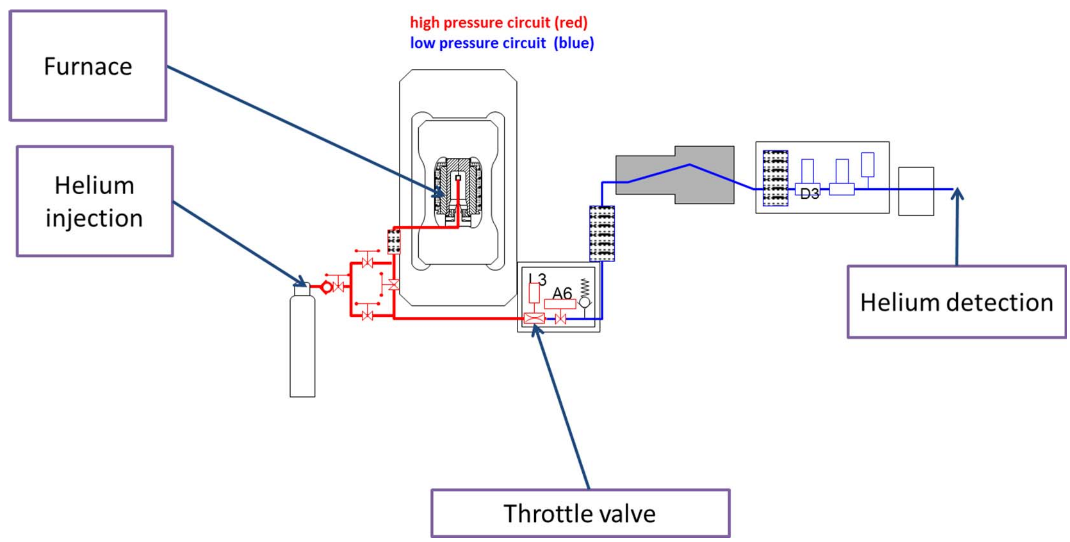

Fig. 6. The helium injection loop.

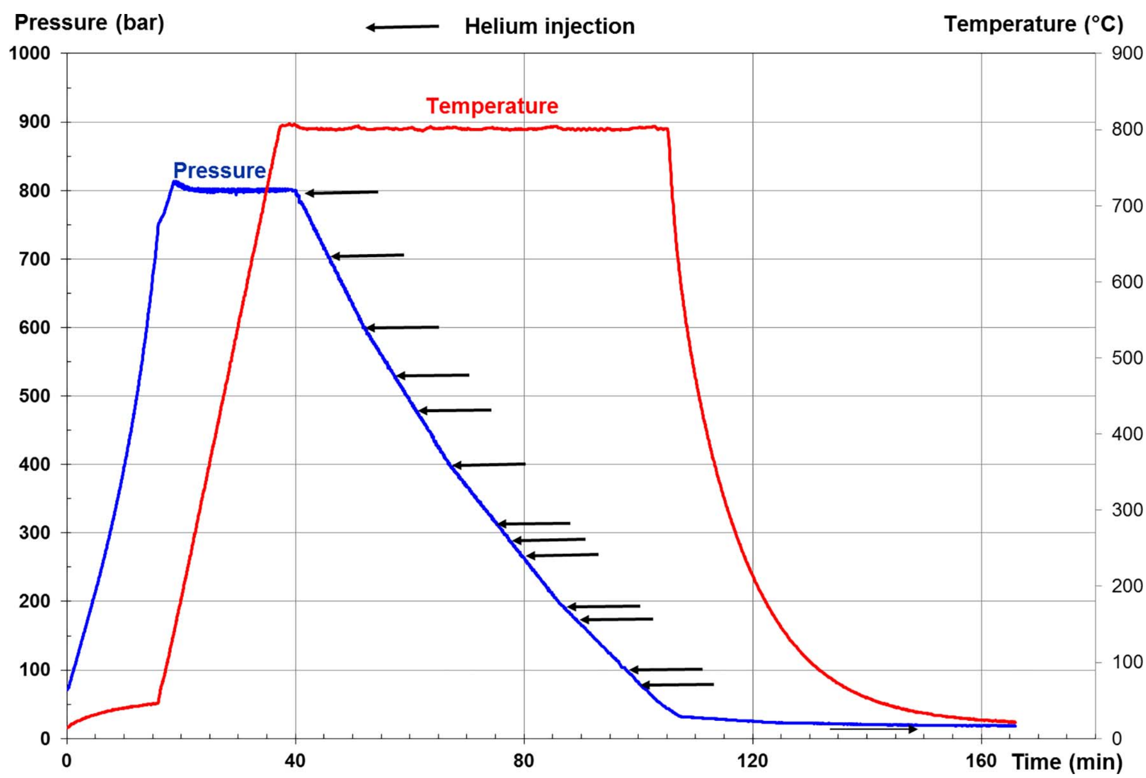

Fig. 7. Pressure and temperature protocol for the cycle 800 °C and 800 bar.

response time of the throttle valve to adjust the imposed outlet flowrate.

3.2.2. Impact of components on the helium residence time

The pressure drop for the different components of the loop is experimentally characterized (see Fig. 9).

From experimental measurement, the pressure losses are expressed by:

- Between point 1 and 2 (throttle valve): $\Delta P \sim P_{upward}$
- Between point 2 and 3 (filter): $\Delta P = 0{,}0091 \cdot Q^{1{,}1606} \sim 950 \cdot v$
- Between point 3 and 4 (filter): $\Delta P = 0{,}0022 \cdot Q^{1{,}0967} \sim 200 \cdot v$
- Between point 4 and 5 (flowmeter): $\Delta P = 0{,}0168 \cdot Q^{0{,}9298} \sim 1100 \cdot v$

with:

ΔP: Pressure loss (bar)
Q: Volume flowrate (l/min)
v: Helium velocity (m/s)

With a flowrate of 1 l/min (8 l/min), the velocity would be 1,3 m/s (respectively 10,6 m/s) in a pipe with a diameter of 2 mm, which gives a pressure drop of about 0,02 bar (0,15 bar respectively) (Fig. 10).

For a component 10 cm long, the residence time of helium to cross it would be at most 0,1 s, which is negligible compared to the total residence time spent in the loop. It is therefore justified not taking into account the different components in the evaluation of residence time.

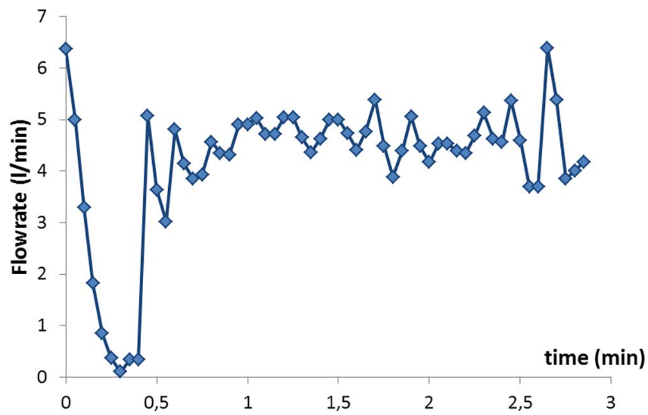

Fig. 8. Evolution of the instantaneous flowrate versus time at the outlet of the circuit.

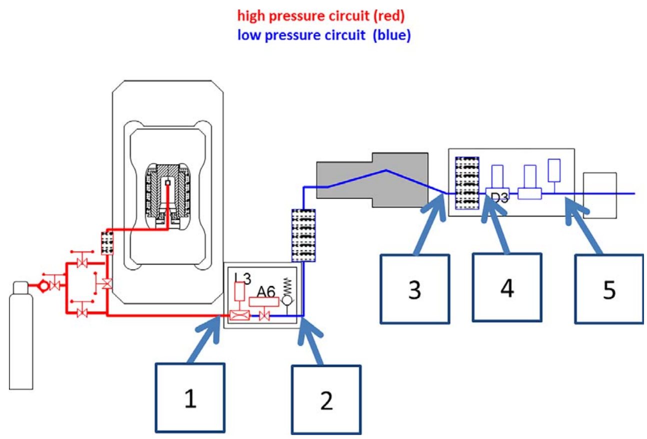

Fig. 9. The MEXIICO loop.

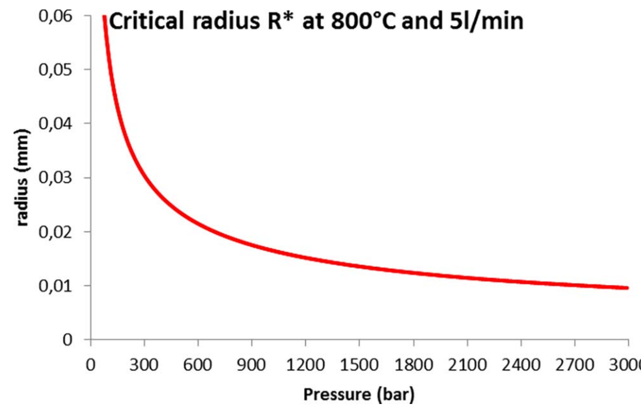

Fig. 11. Radius of the throttle valve versus upstream pressure.

4. Modelling aspects

The throttle valve is the component of the MEXIICO loop in which the gas flow is greatly modified. For that purpose, a detailed thermal-hydraulic analysis of the flow on both sides of the throttle valve is proposed.

4.1. The CFD approach

A numerical simulation based on a CFD approach with the STAR-CCM + software (www.cd-adapco.com) is selected, since it allows any fluid flow in a complex geometry to be described.

A CFD calculation is divided into three parts:

- Geometrical modelling of the fluid physical domain (boundary conditions, physical properties of argon), domain mesh.
- Solving Navier-Stokes equations using the CFD solver.
- Post-processing and analysis of results of temperature, pressure and velocity.

The description is based on a 2D axi-symmetric modelling. The RANS approach is solved by the Navier-Stokes equations. Turbulence is modelled by the usual k-ε model that consists in representing the effects of turbulence and eddy diffusivity by a turbulent viscosity. This eddy viscosity is calculated according to the turbulent energy k per mass unit, and energy dissipation ε per mass unit. Each of these two terms is the solution of a transport equation. Wall laws "All y^+ wall treatment" for approximating boundary layers. The numerical unsteady scheme with implicit solver is used.

4.1.1. Domain of study

In the CFD approach, the fluid domain is modeled each side of the throttle valve by a 2 dimensional axisymmetric representation

The size of the section restriction results from the imposed outlet flowrate. Depending on the upstream pressure, the radius of the throttle valve section to obtain a volume flowrate of 5 l/min, given Fig. 11, is determined from the sonic flow at the nozzle (Eq. (11)).

Argon pressure and temperature are imposed in the high pressure region. As output, atmospheric pressure and atmospheric temperature are set up.

4.1.2. The throttle valve meshing

The fluid domain is meshed with a total of 8800 cells upward of the valve and 39,000 cells downwards Fig. 12). In the vicinity of the throttle valve, the number of cells is of 1000.

The base size features the average size of the mesh. A value of 15 mm has been chosen for modelling. In order to capture at best the flow near the throttle valve, the mesh has been refined very strongly in this area with a base size of 0,02 mm, as shown in Fig. 13.

A mesh convergence was conducted by using 4 different meshes with base size of the cells ranging from 10 to 20 mm with a volumetric control at the throttle valve comprised between 0,01 and 0,03 mm. No significant change was observed on the pressure evolution. The

Fig. 10. zoom on the domain of study at the cross of the throttle valve.

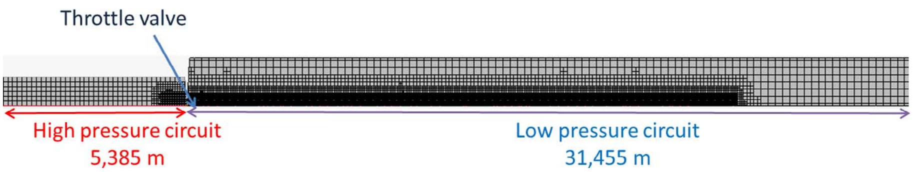

Fig. 12. Meshing of the fluid domain.

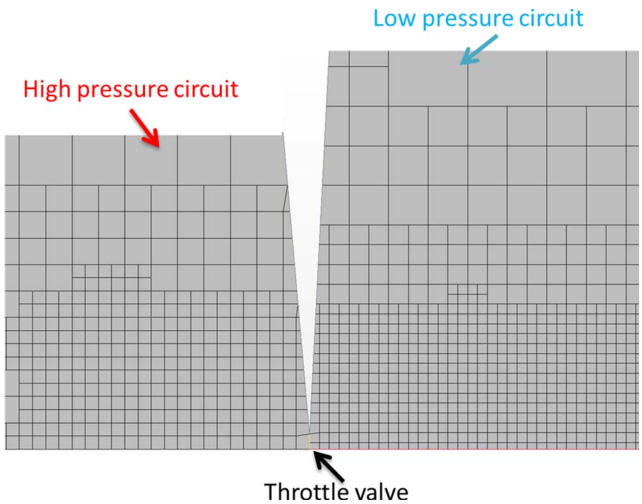

Fig. 13. Zoom on the throttle valve region.

uniformity of the flow except near the throttle valve was also evidenced independently of the mesh size (Fig. 14).

4.2. The CFD study of one of the MEXIICO injections

The CFD study is proposed previously to the analytical approach in order to validate the hypothesis made on the characteristics of the flow.

4.2.1. Characteristics of the test

The argon flow simulation at the crossing of the throttle valve has been conducted for the injection characterized by an upward pressure of 85 bar and a temperature of 800 °C (Table 1).

4.2.2. The CFD results at the cross of the throttle valve

The initial pressure of 85 bar sharply decreases to the atmospheric pressure at the crossing of the throttle valve (see Fig. 15).

Table 1
Characteristics of the analysed injection.

Pressure (bar)	Temperature (°C)	Average flowrate (l/min)	Residence time (s)
85	800	5,05	34

The temperature distribution obtained by crossing the throttle valve is reproduced hereafter. The depressurization causes a local lowering of temperature to −173 °C, close to the liquefaction temperature of argon (−186 °C) and even of its solidification temperature (−189 °C) at atmospheric pressure (http://encyclopedia.airliquide.com) Fig. 16).

Similarly, the argon velocity significantly evolves downward of the throttle valve (see Fig. 17).

The disturbed area by the throttle valve is confined to a small region, as shown by the flow streamlines in Fig. 18. The residence time of the valve is of the order of 0,6 s.

The analysis of the velocity profile upward of the throttle valve shows two distinct flow regions (see Fig. 19):

- a uniform velocity zone (0,006 m/s) in the high pressure region, except in the vicinity of the valve,
- an area of high acceleration of argon flow 10 cm before the valve.

Similarly, the downward zone shows two different flow regimes (Fig. 20):

- a supersonic zone in the region extended to 2 cm around the valve,
- an area in which the velocity of argon is uniform, of the order of 6 m/s.

The evaluation of the outlet flowrate makes it possible firstly to ensure the convergence of computing calculations and secondly to ensure that flowrate imposed to 5 l/min by dimensioning the section of the throttle valve is guaranteed Fig. 21). The oscillations on this figure

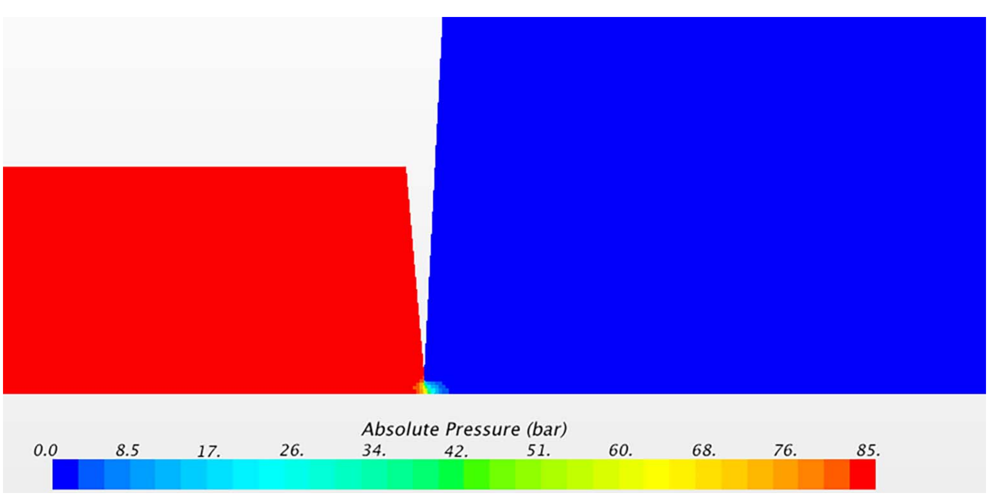

Fig. 14. Pressure drop at the transit of the throttle valve.

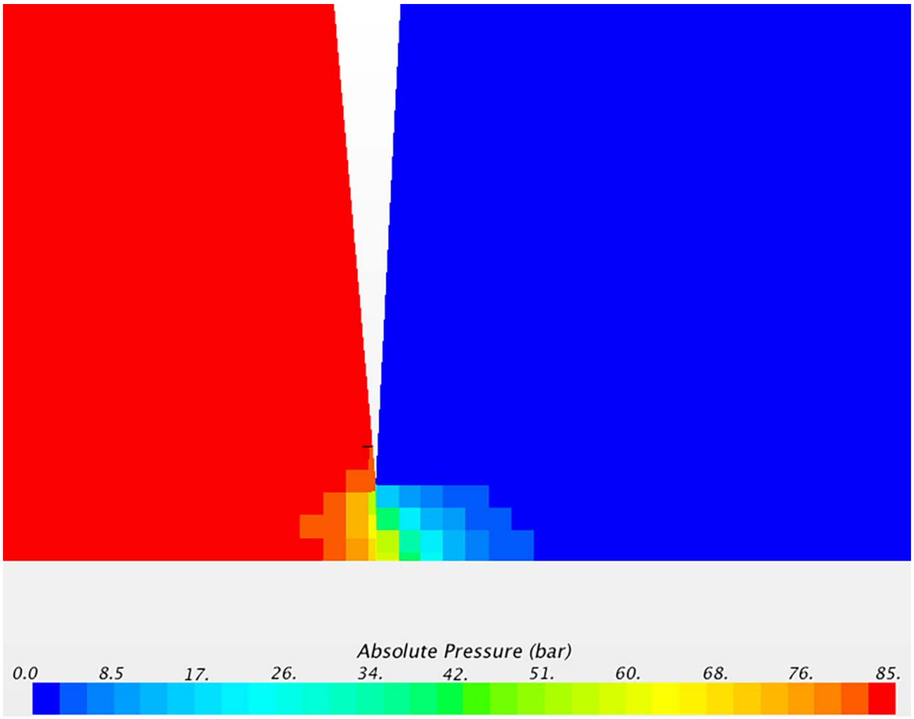

Fig. 15. Zoom on the pressure near the throttle valve.

correspond to the number of iterations necessary before convergence.

Using the 2D axi-symmetric modelling, the azimuthal representation of the calculated domain is arbitrary fixed to 1 rad, so that the real flowrate must be divided by 2π. The final value of $2 \cdot 10^{-5}$ kg/s obtained after 500 iterations on this 2D modelling corresponds therefore to the imposed volume flowrate of 5 l/min.

The objective of the CFD approach was mainly to show that two stabilized flows exist each size of the throttle valve, except in its vicinity. On this manner, the analytic method, presented just below, is justified.

4.3. The analytical approach

4.3.1. Introduction

The CFD approach showed that the argon flow is unaffected away from the valve region. Specifically, the perturbed area is limited to 10 cm on both sides of the valve. In addition, there is in this zone, a sudden drop in temperature that could reach the actual liquefaction temperature of argon.

The flow study can thus be dissociated into two parts, on either side of the throttle valve characterized by a uniform pressure and temperature. An analytical approach study is therefore proposed in this section to evaluate the residence time.

Argon pressure and temperature conditions each side of the throttle valve are firstly considered. This approach is then applied to the three experimental tests. A sensitivity study on the output flowrate and the choice of equation of state for argon concludes this part.

4.3.2. Evolution of argon temperature, pressure and velocity

Apart from pressure, argon temperature evolves in the MEXIICO loop, due to the exchange with the environment. On a length dz, energy conservation leads to:

$$D \cdot c_p \cdot (T(z + dz) - T(z)) = -h \cdot 2 \cdot \pi \cdot r \cdot dz \cdot (T(z) - T_{ext}) \quad (12)$$

with:

D: Mass flowrate (kg/s)
c_p: Heat capacity of argon (J/kg-K)
$T(z)$: Temperature on the z axis (K)
h: Heat transfer coefficient (W/m^2-K)
r: Pipe radius (m)
T_{ext}: Room temperature (K)

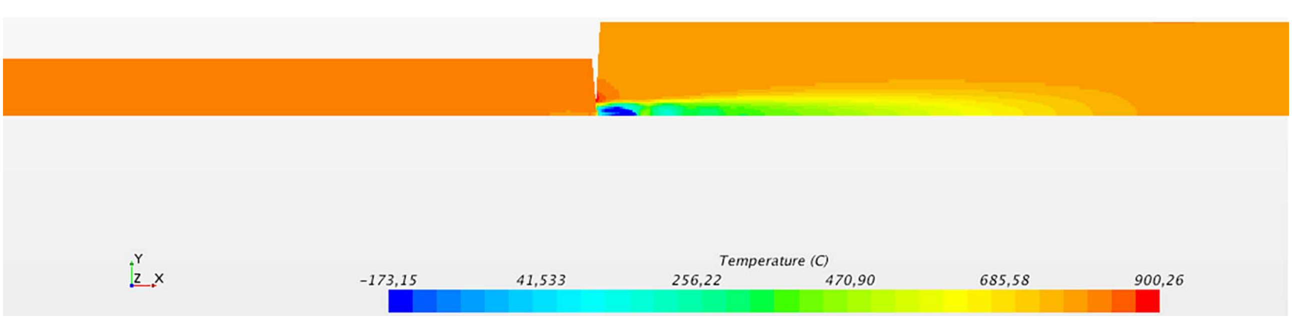

Fig. 16. Evolution of the temperature of the portion of the throttle valve.

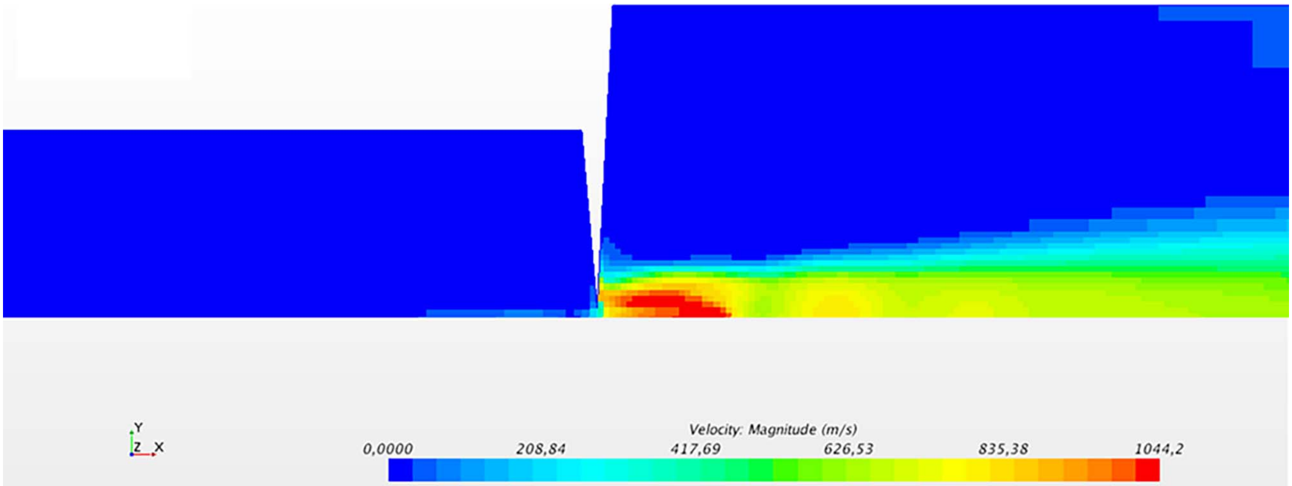

Fig. 17. Zoom on the velocity for the transit of the throttle valve.

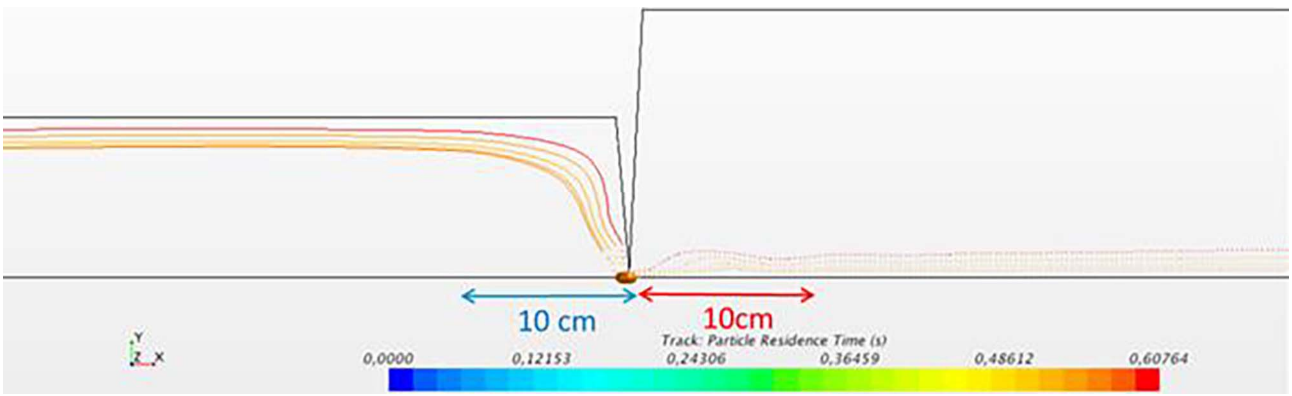

Fig. 18. Streamline at the throttle valve.

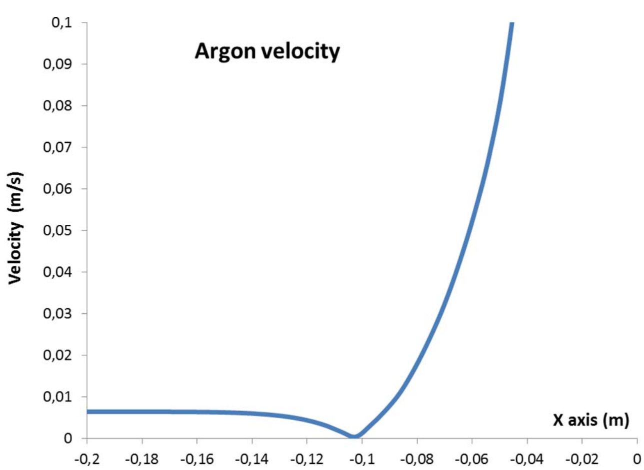

Fig. 19. Velocity profile upstream of the throttle valve.

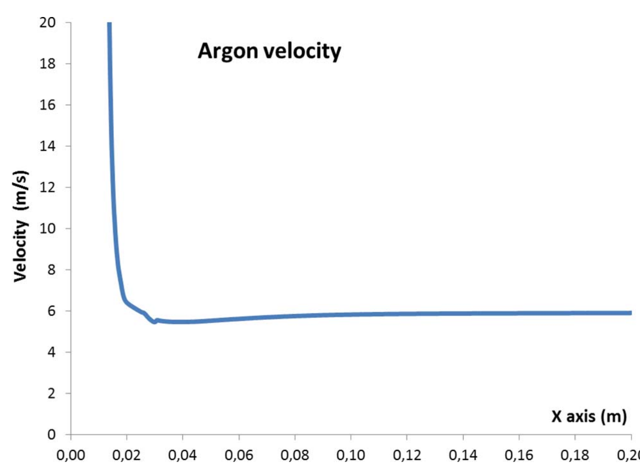

Fig. 20. Velocity profile downstream of the throttle valve.

The argon temperature is finally solution of the following differential equation:

$$D\cdot c_p\cdot\frac{dT(z)}{dz} + h\cdot 2\cdot\pi\cdot r\cdot T(z) = h\cdot 2\cdot\pi\cdot r\cdot T_{ext} \tag{13}$$

Either:

$$T(z) = T_{ext} + (T_{init}-T_{ext})\cdot e^{-\frac{z}{L}}\text{with } L = \frac{D\cdot c_p}{h\cdot 2\cdot\pi\cdot r} \tag{14}$$

Assuming a heat transfer coefficient (10 W/m^2-K) (Taine and Dunod, 2011), for the respective flowrates of 1.3 l/min, 5 l/min and 7.5 l/min, the initial temperature of the argon of 800 °C rapidly decreases (Fig. 22) to the room temperature after less than 2 m of circulation. This result would deserve to be confirmed by an experimental approach. Indeed, the value used here for the heat transfer coefficient is a standard value, which just gives an order of magnitude of heat exchange.Evolution of argon temperature and pressure is finally

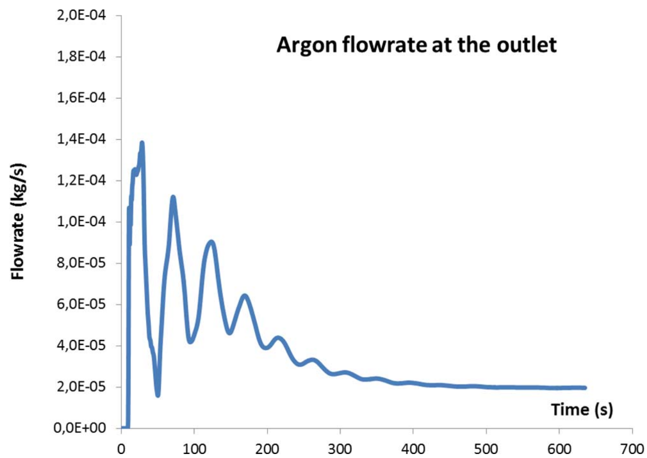

Fig. 21. Mass flowrate downstream of the valve.

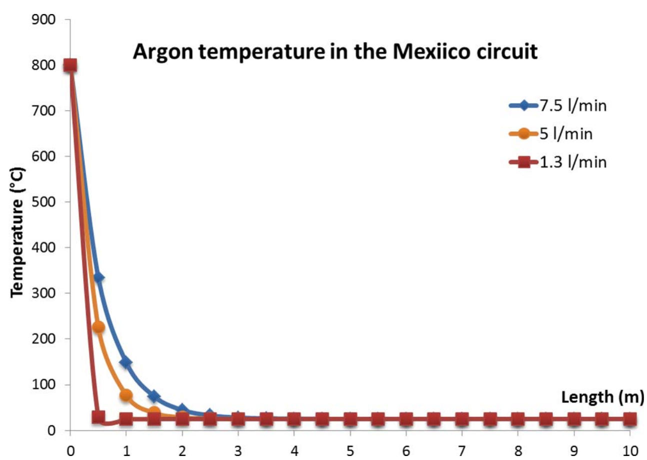

Fig. 22. Evolution of the temperature along the loop according to the flow.

summarized on the below Fig. 23.

Based on the knowledge of pressure and temperature, the analytical approach can now be implemented for determination of residence time in three identified zones (see Fig. 24):

- the high pressure and high temperature zone (P_1, T_1),
- the high pressure and room temperature zone (P_1, T_{ext}),
- the atmospheric pressure and room temperature zone (P_{ext}, T_{ext}).

In addition, the assumptions made for the evaluation of the residence time are as follows:

- The various elements (flow meters, filters and detector) do not affect the total residence time of argon.
- The residence time for crossing the throttle valve is also negligible.
- The heated gas initially drops to room temperature after 1.5 m in the loop.

The conservation of mass flow is:

$$D = \rho_1 \cdot v_1 \cdot S_1 = \rho_2 \cdot v_2 \cdot S_2 = \rho_{ext} \cdot v_{ext} \cdot S_{ext} \tag{12}$$

Hence:

$$v_1 = \frac{D}{\rho_1 \cdot S_1} \tag{13}$$

$$v_2 = \frac{D}{\rho_2 \cdot S_2} \tag{14}$$

$$v_{ext} = \frac{D}{\rho_{ext} \cdot S_{ext}} \tag{15}$$

It simply remains to evaluate the argon density in these three areas. As the argon density is written:

$$\rho = \frac{m}{V} = \frac{n \cdot M}{V} \tag{16}$$

Using the Van der Waals equation of state for argon (see Appendix A) (www.bcs.whfreeman.com/pchem9e), the volume occupied for a given pressure and temperature provides its density as follows:

$$\rho = \frac{n \cdot M}{f(P,T)} \tag{17}$$

Once the argon density is known for the three regions, argon velocity is deduced from the flowrate imposed on the output. Knowing the length of the three zones (respectively 1,5 m, 3,885 m and 31,455 m), the residence time of the helium is finally obtained.

5. Comparison between simulations and experimental tests

This method for velocity determination, applied to the three tests, conducted to the results presented Figs. 25–27. The agreement with the experimental results obtained is acceptable, with a maximum difference lower than 20% for test 1 (except 25% for the first injection) and test 2 and 8% for test 3.

5.1. The residence time in the MEXIICO loop

Once the argon flow has been characterized by the analytical approach, additional results are derived on the respective residence time in the high and low pressure regions.

For the three tests discussed, the results are summarized in Fig. 28. As expected, most of the residence time is spent in the high pressure region (about 90% of total time).

The analysis of argon cooling led to choose 1,5 m as the length required for cooling the gas. However, this choice has little impact on the total residence time of helium. Indeed, as shown in Fig. 29, approximately 90% of time is spent with argon already cooled. Accordingly, in the event that the argon would already be cooled at the time of injecting helium, the error in the residence time is less than 10% of the total residence time in the high pressure part. To remove any ambiguity about the argon temperature, one might perform an instrumented test in an equivalent loop to the MEXIICO one that would provide the evolution of argon temperature versus time. These tests would be carried out outside the MEXIICO device, which would improve the accuracy of slow depressurization modelling.

5.2. Sensitivity studies

5.2.1. The equation of state of argon

In order to check the impact of the equation of state on results, the equation of state of ideal gas has been substituted to the Van der Waals gas law. As shown in Fig. 30, this substitution degrades the results by a factor more than two for the slower depressurization tests.The

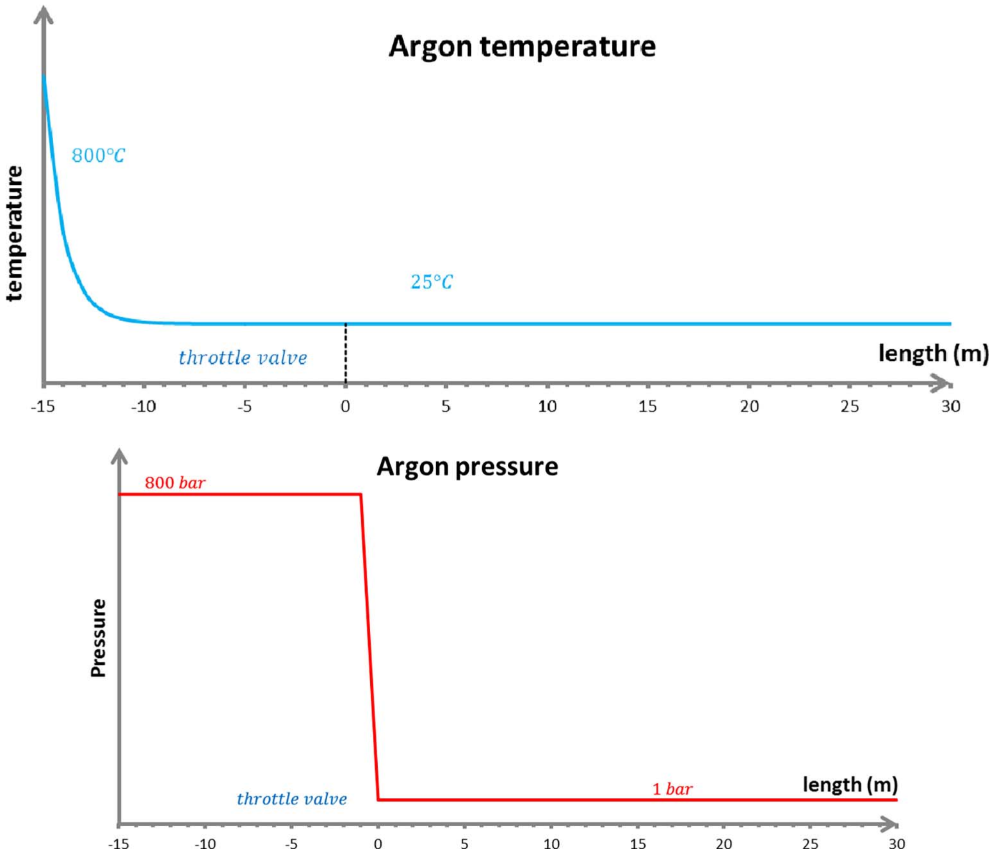

Fig. 23. Evolution of the argon temperature and pressure versus the z axis.

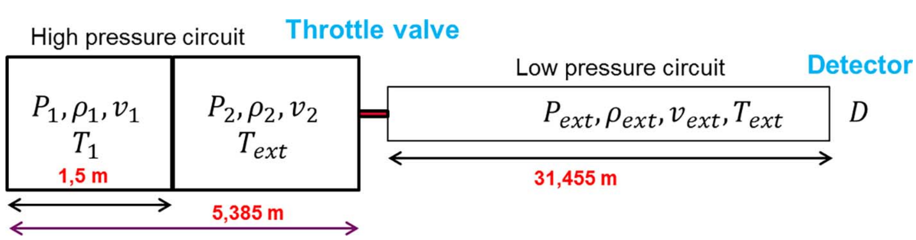

Fig. 24. Decomposition of the argon flow field into three flow regions.

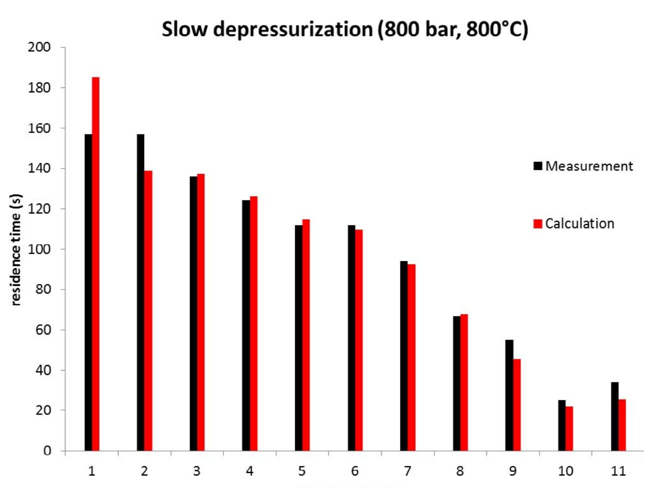

Fig. 25. Analytical results for test 1.

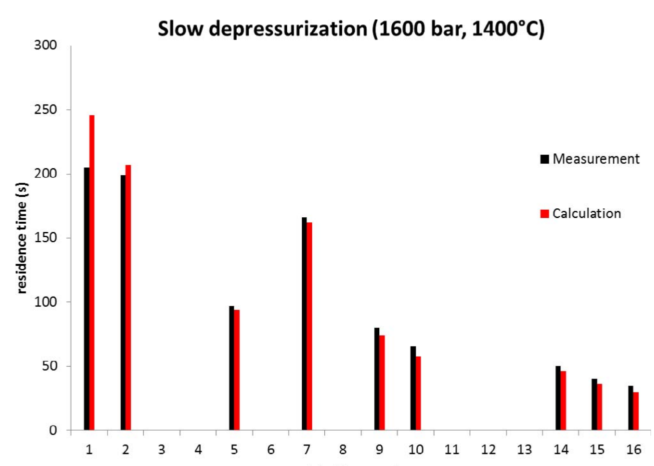

Fig. 26. Analytical results for test 2.

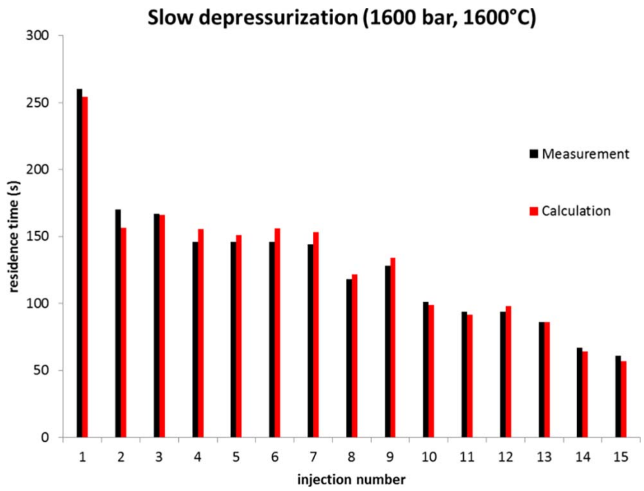

Fig. 27. Analytical results for test 3.

difference on the residence time using the ideal or VDW equation of state is mainly present for the first injections at higher pressure and temperature. This is explained by the difference in argon density at high pressure and room temperature Fig. 31).

5.2.2. The uncertainty on the flowrate

Due to the low flowrate required and the experimental control system of the throttle valve, the volume flowrate at the outlet cannot be exactly maintained at a fixed value. As shown on Fig. 32, the impact of experimental uncertainty on the residence time is however rather limited.Indeed, the difference with measurement between the calculated residence time using the average flowrate or the maximum flowrate reaches 18% instead of 8% for the second injection but is otherwise lower than 10%.

5.2.3. Margin to argon liquefaction near the nozzle valve

Blockage of the flow at the throttle valve was noticed for some tests. In light of the CFD approach, this experimental observation shows that argon could be locally liquefied at −186 °C and even solidified at −189 °C.

In order to avoid any risk of liquefaction of argon at the throttle valve after depressurization, a maximum pressure versus temperature must be imposed in the MEXIICO furnace. If one considers the depressurization as adiabatic, the maximum upstream pressure to respect is given versus temperature in Table 2.

Thanks to this evaluation, the experiment conditions to comply for the non-liquefaction of argon could be proposed for the future tests.

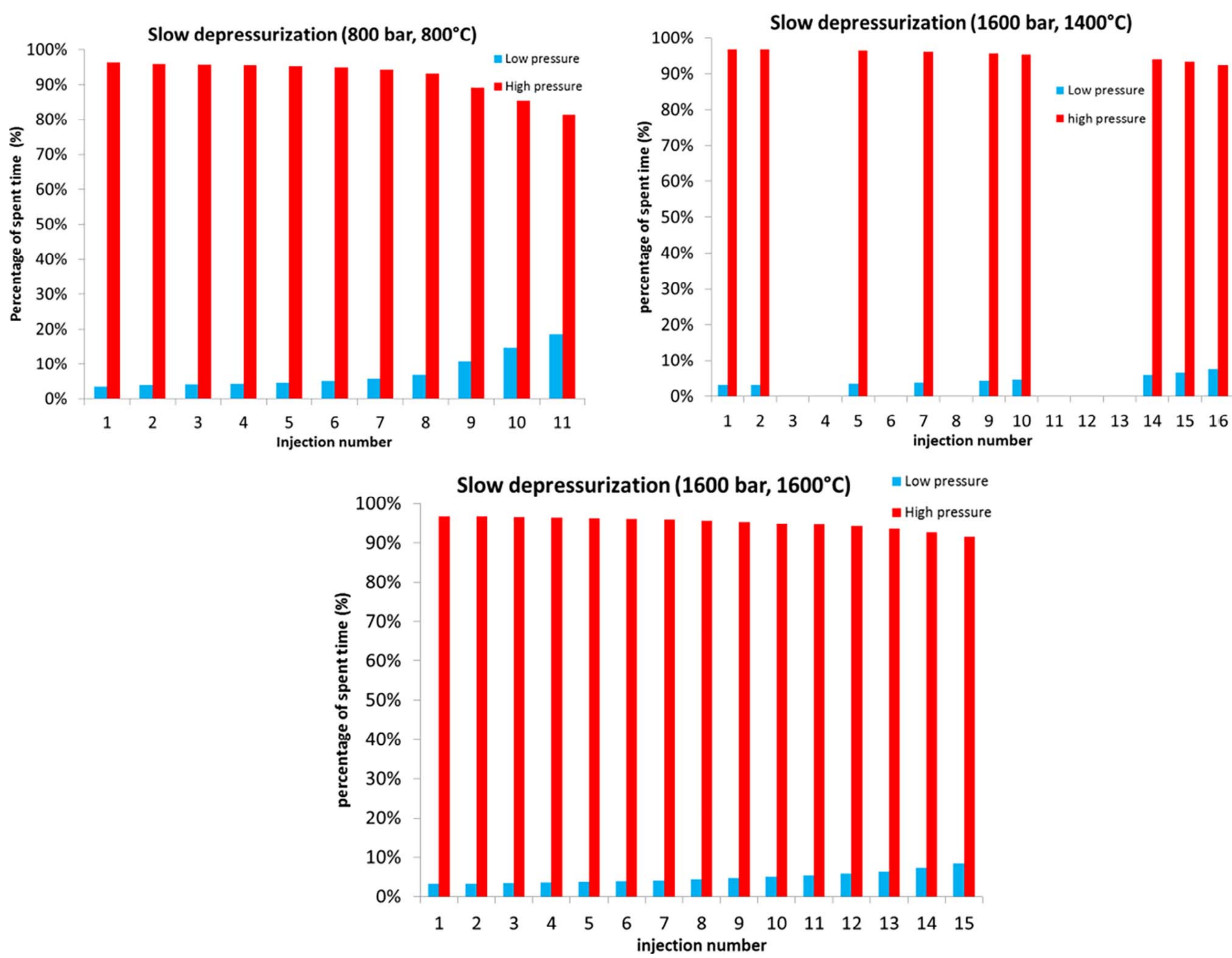

Fig. 28. Residence time in the high and low pressure regions.

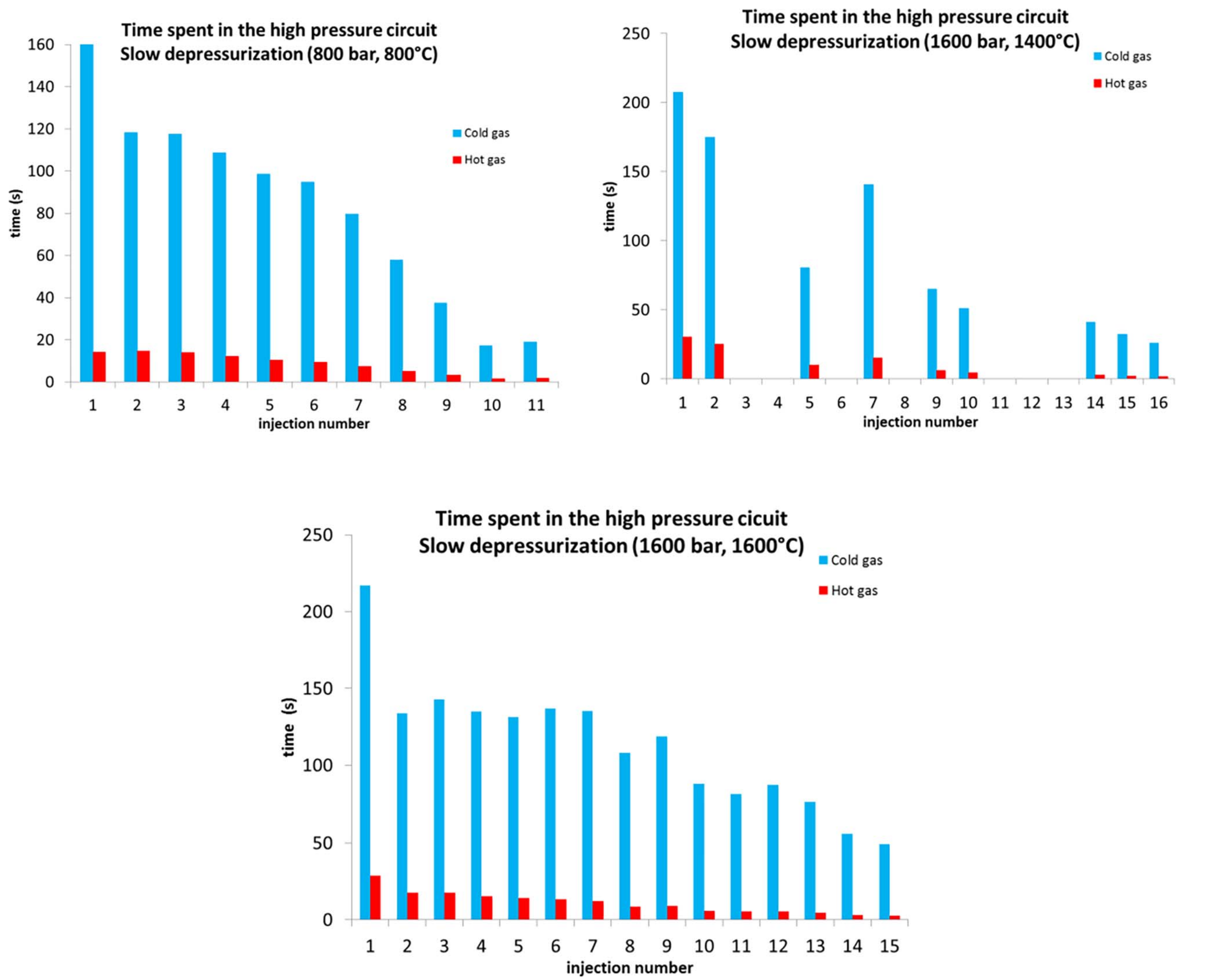

Fig. 29. Time spent the high pressure region.

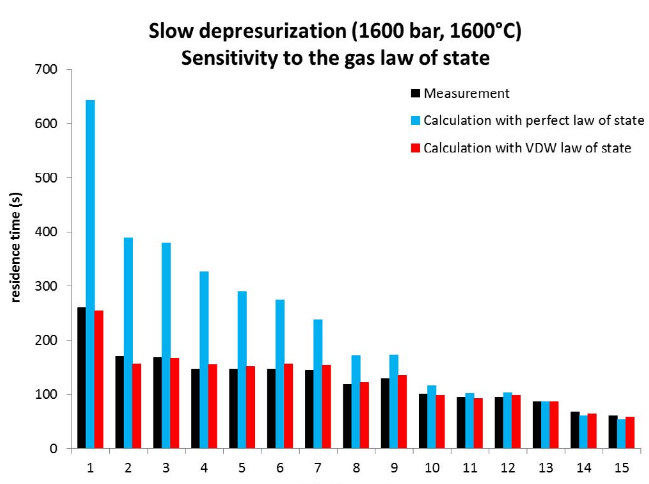

Fig. 30. Impact of the equation of state on the residence time.

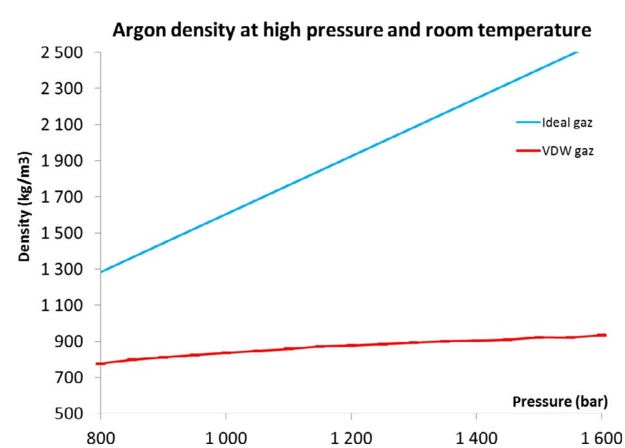

Fig. 31. argon density at high pressure and room temperature.

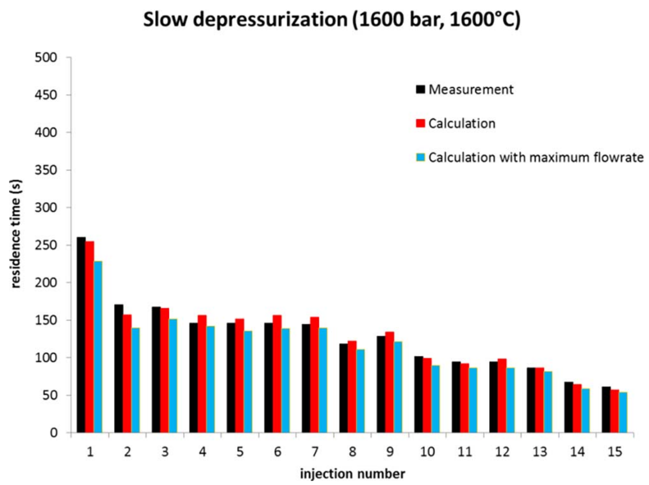

Fig. 32. Residence time: sensitivity to uncertainty in the flowrate.

Table 2
Maximum pressure to respect in order to avoid argon liquefaction.

T (°C)	P (bar)
27	22
800	530
1400	1608
1600	2132

6. Conclusion

The thermal-hydraulic modelling of the MEXIICO loop in slow depressurization condition contributes to date the main events occurred in the fuel sample during an experiment and thus to better understand behaviour of one the fuel pellet submitted to high pressure and temperature in the furnace in order to simulate hydrostatic stress conditions.

The proposed approach aiming at estimating the residence time between the fission gas emission and its detection in the rear cell by gamma detector is based on a two-step approach:

- characterize the flow on either side of the throttle valve.
- highlight the uniformity of velocity, apart from at the crossing of the throttle valve for which a refined CFD study was implemented.

Taking into account the results provided by the CFD approach, it is finally concluded that the analytical model is sufficient to assess the residence time with an acceptable precision. The contributions of the study are that:

- argon temperature drops very quickly in the loop (in less than 1,5 m in the high pressure circuit),
- the residence time is mainly spent in the high-pressure region (~90% of total time),
- liquefaction and even solidification of argon while crossing the throttle valve could occur and can be avoided by respecting criteria on upstream pressure and temperature.

The test campaigns with various fuel pellets of different burn-up and different experimental conditions will be pursued in the future.

Appendix-characteristics

The main characteristics of argon are recalled below [18]

Critical point	Critical temperature	−122,46 °C = 150,69 K
	Critical pressure	48,63 bar
	Critical density	535,6 kg/m^3
Triple Point	Temperature at the triple point	−189,34 °C = 83,66 K
	Triple point pressure	0,687 bar
Liquefaction temperature at 1 bar		−185,85 °C = 87,30 K
Solidification temperature at 1 bar		−189,4 °C = 83,75 K

Argon behaviour is similar to that of a Van der Waals gas:

$$(P + \frac{a \cdot n^2}{V^2}) \cdot (V - n \cdot b) = n \cdot R \cdot T$$

for which the a and b constants are:

a = 0,135 J.m^3.mol^{-2}
b = 0,0000322 m^3.mol^{-1}

From the a and b values, temperature and critical pressure are calculated:

$$T_c = \frac{8 \cdot a}{27 \cdot b \cdot R} = 150{,}69K$$

$$P_c = \frac{a}{27 \cdot b^2} = 48{,}98bar$$

The plot of the isotherms (see Fig. 33) shows that for high temperatures, argon behaves as an ideal gas. By cons, at low temperature (liquid-vapor saturation curve) it can no longer be considered as an ideal gas.

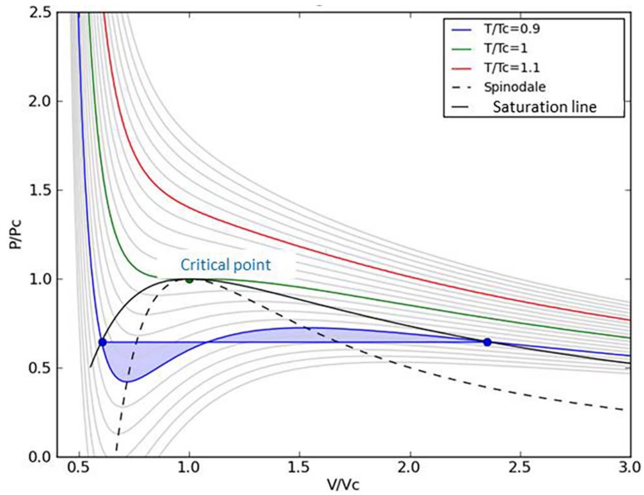

Fig. 33. Van der Waals gas.

Characterisation of the behaviour of fuel pellet during the pressure and temperature ramps
Study of fission gas release by the fuel pellet
Analytical and CFD study of fission gas entrained by the Argon flow

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