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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 to 1600 °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, $\text{J/kg}\cdot\text{K}$

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, $\text{J/K}\cdot\text{mol}$
 M Argon molar mass ($39.948 \cdot 10^{-3}$), kg/mol
 a Van der Waals constant (for argon $a = 0,135$), $\text{J}\cdot\text{M}^3\cdot\text{mol}^{-2}$
 b Van der Waals constant (for argon $b = 0,0000322$), $\text{m}^3\cdot\text{mol}^{-1}$
 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, $\text{W}/\text{m}^2\cdot\text{K}$

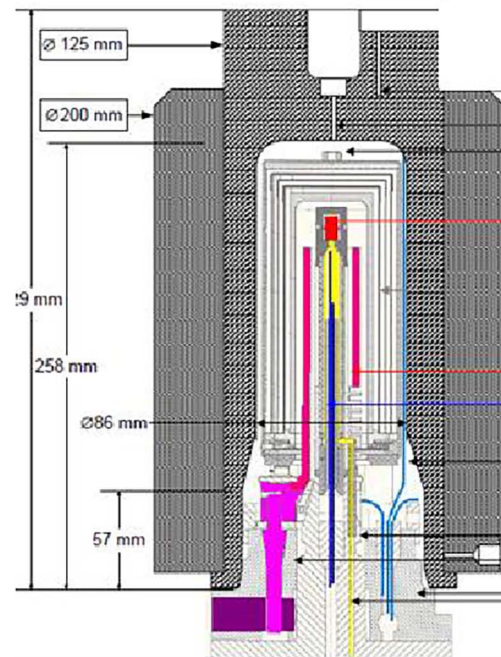


Fig. 1. The photo (left) and schematic view of the furnace (right).

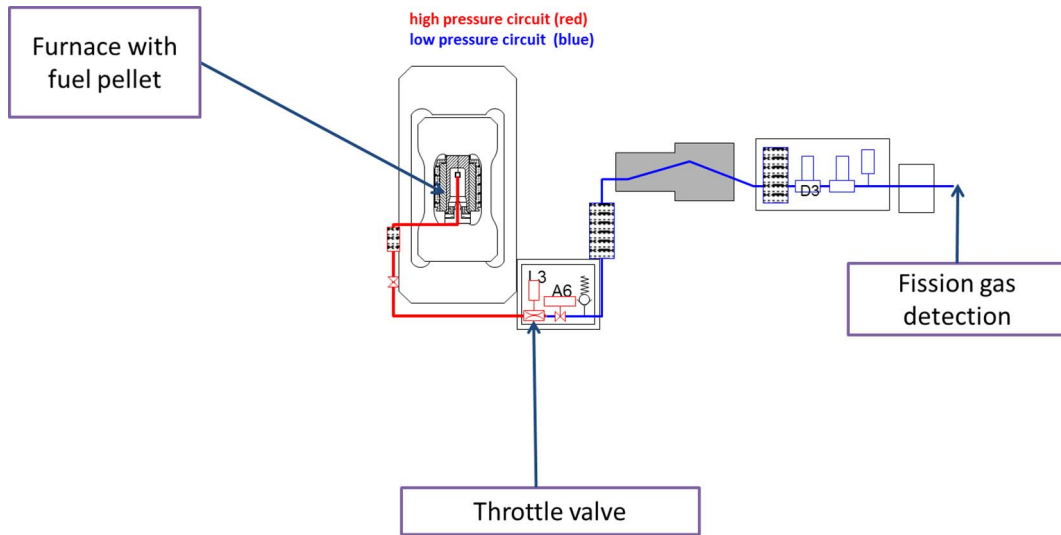


Fig. 2. Description of furnace and downward MEXIICO loop.

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 MEXIICO 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):

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

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

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

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/m³)

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

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

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

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

2.2.2.1. Determination of the section. The critical flow at the nozzle is written:

$$D^* = \rho^* \cdot S^* \cdot v^* \quad (7)$$

with: D^* : Critical flow (kg/s) ρ^* : Critical density (kg/m³) S^* : Section at the nozzle (m²)

For a perfect gas, the density is equal to:



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

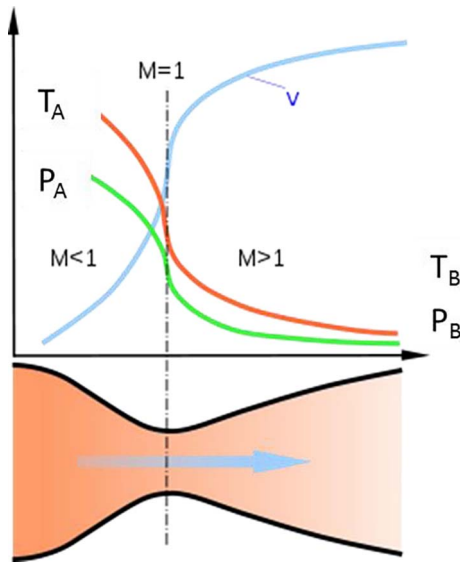


Fig. 4. Principle of the throttle valve.

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

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:

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

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

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

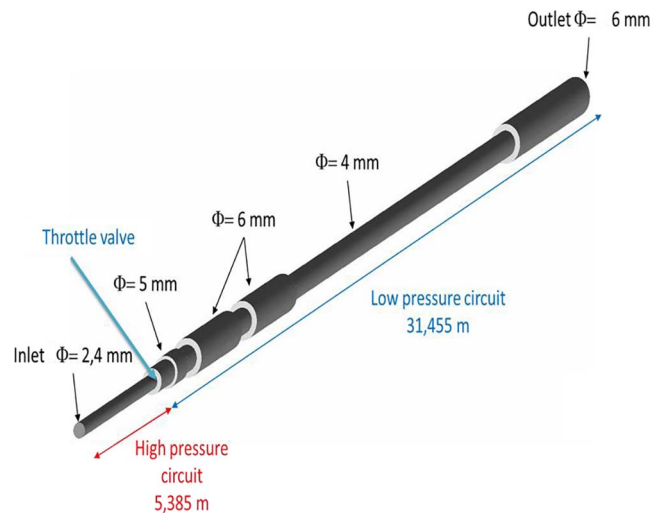


Fig. 5. The different regions of the MEXIICO loop.

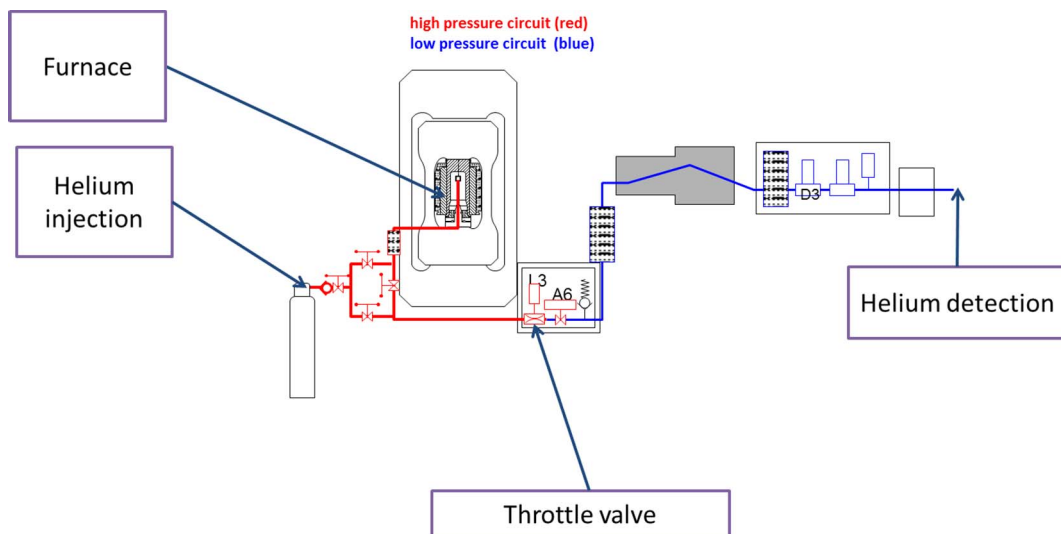


Fig. 6. The helium injection loop.

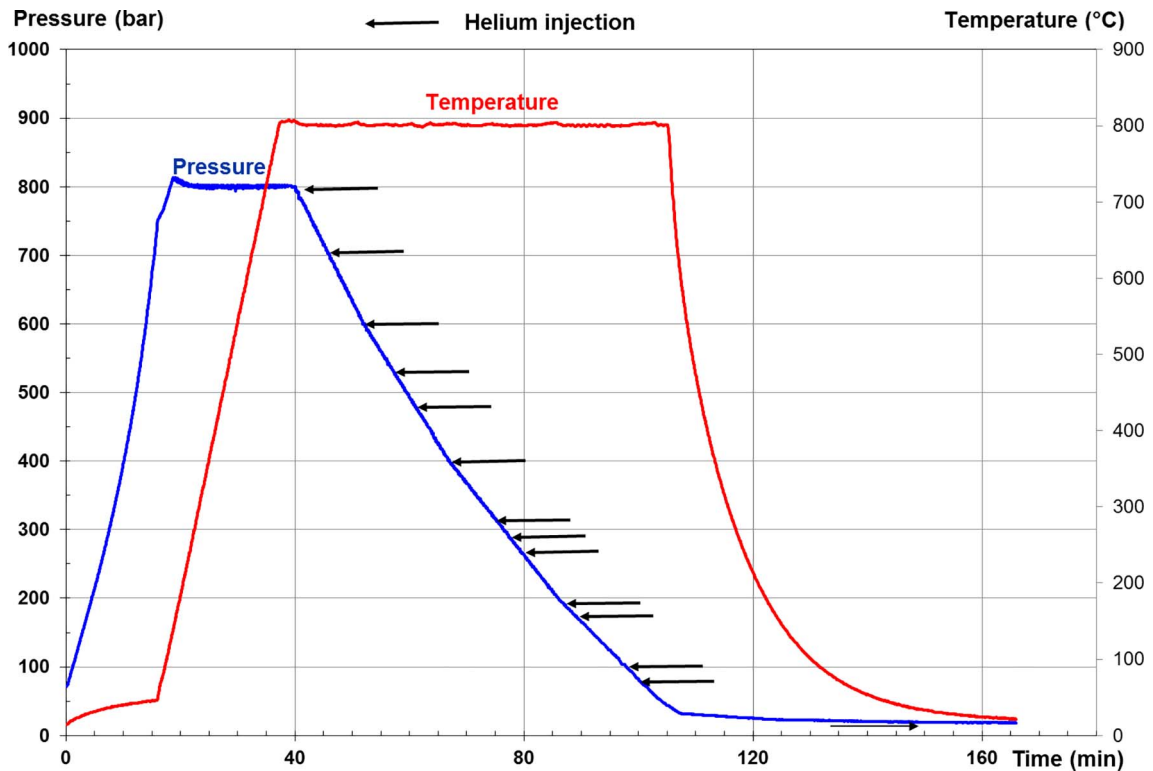


Fig. 7. Pressure and temperature protocol for the cycle 800 °C and 800 bar.

response time of the throttle valve to adjust the imposed outlet flow-rate.

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.

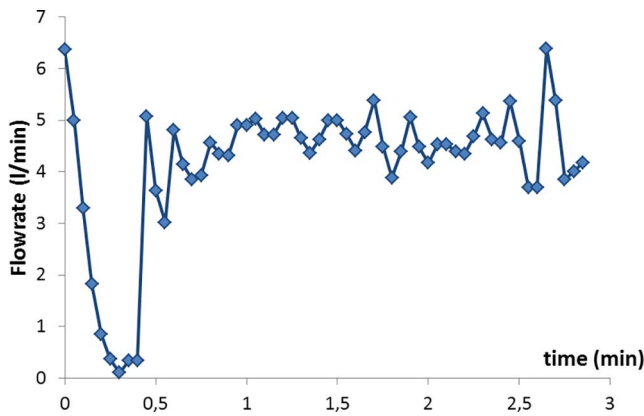


Fig. 8. Evolution of the instantaneous flowrate versus time at the outlet of the circuit.

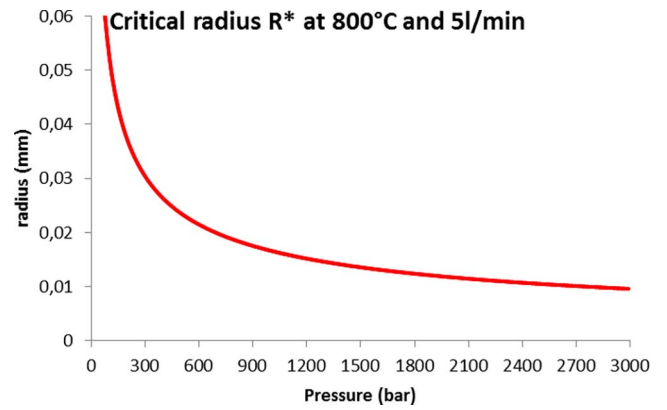


Fig. 11. Radius of the throttle valve versus upstream pressure.

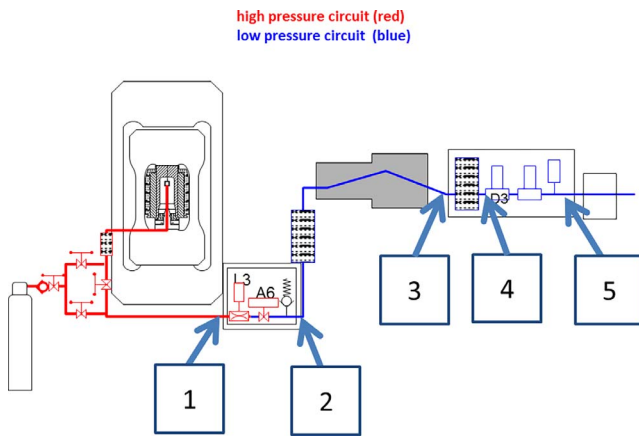


Fig. 9. The MEXIICO loop.

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 $k-\epsilon$ 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.

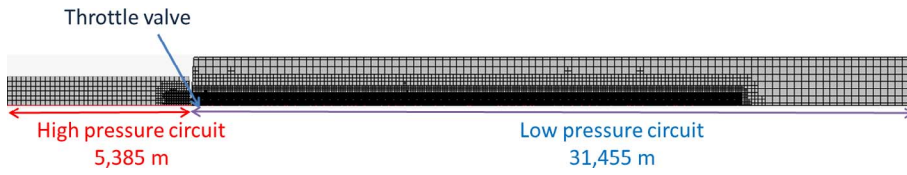


Fig. 12. Meshing of the fluid domain.

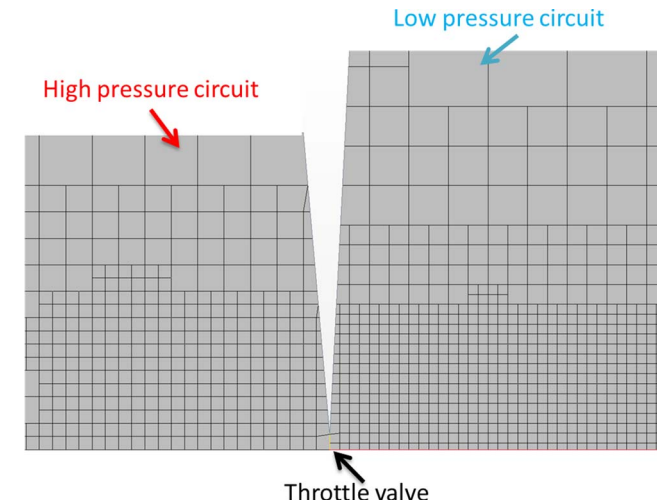


Fig. 13. Zoom on the throttle valve region.

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).

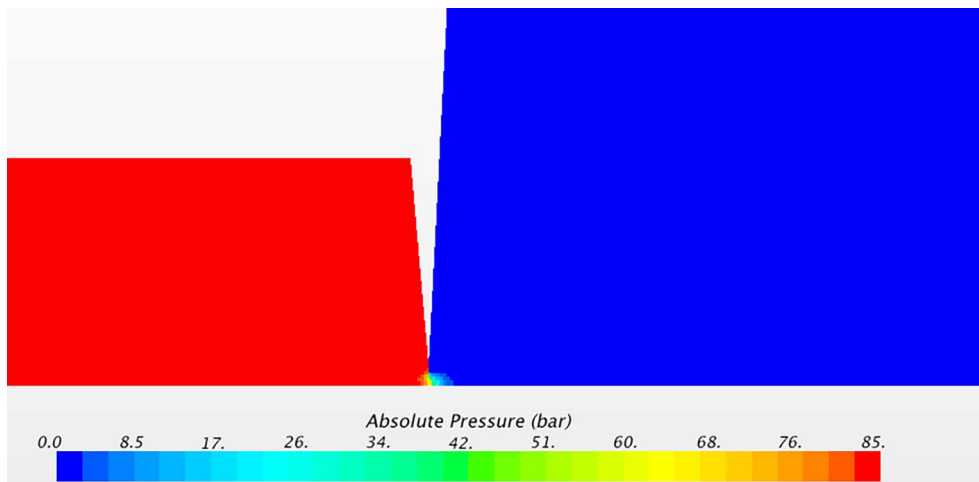


Fig. 14. Pressure drop at the transit of the throttle valve.

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 $-173\text{ }^{\circ}\text{C}$, close to the liquefaction temperature of argon ($-186\text{ }^{\circ}\text{C}$) and even of its solidification temperature ($-189\text{ }^{\circ}\text{C}$) 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 51/min by dimensioning the section of the throttle valve is guaranteed Fig. 21). The oscillations on this figure

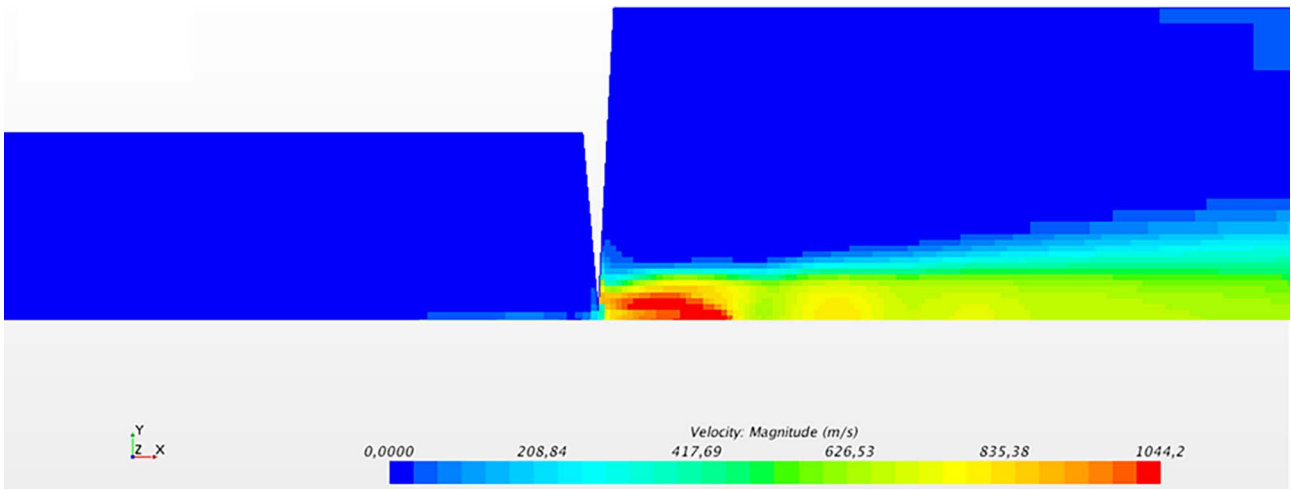


Fig. 17. Zoom on the velocity for the transit of the throttle valve.

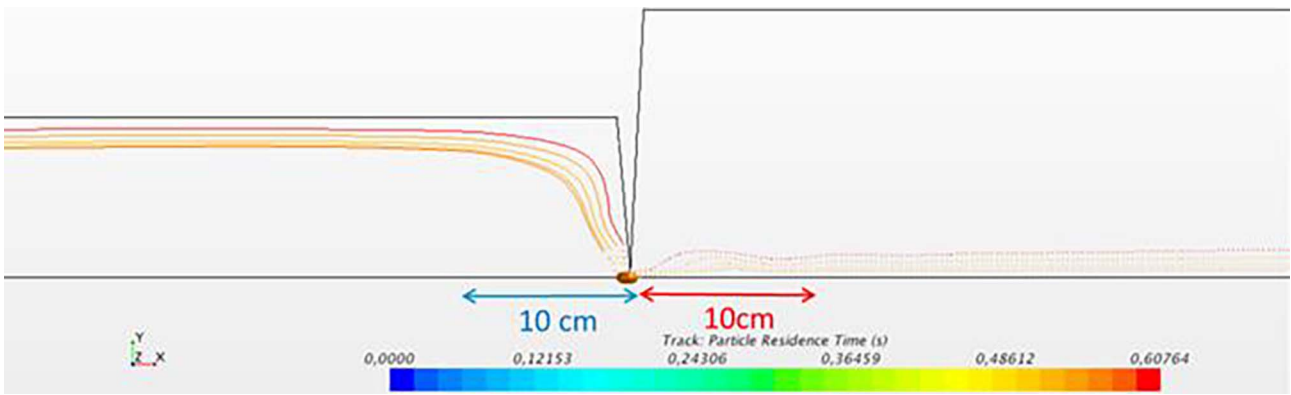


Fig. 18. Streamline at the throttle valve.

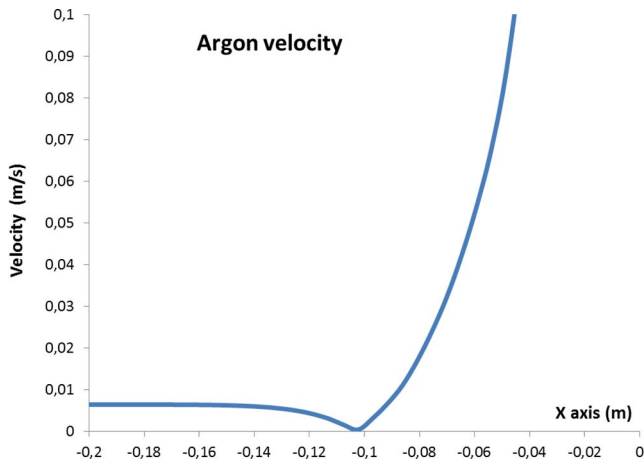


Fig. 19. Velocity profile upstream of the throttle valve.

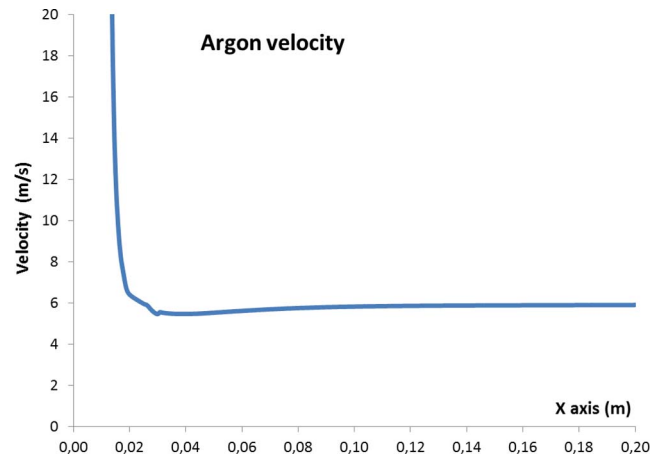


Fig. 20. Velocity profile downstream of the throttle valve.

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

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

Either:

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

Assuming a heat transfer coefficient (10 W/m²·K) (Taine and Dunod, 2011), for the respective flowrates of 1.3l/min, 5l/min and 7.5l/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

