

INTERACTION OF A HELIUM/AIR STRATIFIED LAYER WITH AN AIR JET COMING FROM BELOW: LARGE AND SMALL SCALE EXPERIMENTS AND SCALING ANALYSIS

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Abstract

In the frame of the OECD-NEA/SETH-2 project, an experimental programme has been carried out in the PANDA facility at PSI and in the MISTRA facility at CEA until December 2010. Part of the program focuses on gas stratification break-up induced by mass sources and similar tests have been performed in both facilities. The present paper gives an overview of the CEA experimental results dedicated to the study the phenomena of erosion by a low momentum air jet on the helium/air stratified layer located at the top of the confined volume. The tests were conducted in the MISTRA, a large facility. Different mass flow rates of air were used, inducing different regimes including pure diffusive mixing, global dilution and slow erosion processes, characterized by the interaction Froude number. A discussion ended this paper with some comparison of the results with CAST3M CFD simulations.

1. Introduction

The OECD SETH-2 project is a follow-up to the previous OECD/SETH¹ project ended in December 2006 and should complement the data obtained in the previous project. The SETH-2 experimental programme involves the Paul Scherrer Institute (PSI) PANDA and Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA) MISTRA facilities and has ended in 2010. The main objective of the proposed experimental programme is to perform phenomena-oriented experiments in the large-scale, multi-compartment PANDA and MISTRA facilities, to investigate steam/gas distribution and hydrogen transport inside LWR containment compartments. In both facilities, helium is used to simulate hydrogen. The main phenomena to be studied are mixing/stratification, natural and forced convection, direct-contact condensation and wall condensation. The description of the complex flow fields suitable for CFD code validation will be the main outcome of the tests. Comparative tests in the PANDA and MISTRA facilities are also proposed in particular to study different mechanisms for stratification break-up, such as condensation, natural convection, jet impingement, and spray. Thus, this test series complements the data produced in PANDA SETH, where conditions leading to build-up of stratification were studied. The test proposed are listed according to increasing complexity, where the first series of experiments especially addresses current CFD capabilities and the following address mostly new challenges for CFD model development and validation [1].

The MISTRA facility is involved in the first test series dedicated to the separate effect/coupled effect tests and experiments will be devoted to the erosion of previously established gas stratification by 4 different ways:

- Low momentum vertical injection of air or steam
- Impinging vertical jet of steam on the annular ring
- Heat-up or cool-down of the condenser
- Spray system

The present paper gives an overview of one of the MISTRA test series called

¹ SETH : SESAR Thermal-Hydraulics (OECD project) and SESAR is the Senior Group of Experts on Nuclear Safety Research

INITIALA-LOWMA. The objective here was to study the phenomena of erosion by a low momentum air jet on the helium/air stratified layer located at the top of the facility. Different mass flow rates of air were used, inducing different regimes including pure diffusive mixing, global dilution and slow erosion processes, characterised by the interaction Froude number.

2. Description of MISTRA facility and instrumentation

The MISTRA (Mitigation and STRATification), experimental programme, started in 1998, is part of CEA's programme on severe accidents occurring in Pressurized Water Reactors (PWR) or naval nuclear reactors and is focused on the containment thermal hydraulics and hydrogen risk [2] [3]. The MISTRA facility, Figure 1, is a scaled-down model of French PWR containment with a linear length scale ratio of 0.1. Until 2004, the test series were conducted using the vessel without internal partitioning. The MISTRA vessel was then modified to accommodate compartments consisting of an inner cylinder with an annular floor called 'ring plate' as shown Figure 2.

The MISTRA coupled and separate effect test facility was designed to facilitate simulation of depressurisation of a containment, injection of hydrogen (simulated by helium) in time and at different locations, creation and breaking-up of stratified helium layer, three-dimensional flows of air, steam and helium created by the natural convection, condensation heat transfer occurring on internal structures and containment walls, enrichment of local helium concentration due to wall condensation or condensation on droplets (when using spray systems to control the pressurization due to steam release), effect of mitigation devices such as hydrogen recombiners (thermal effect only), and inerting of small-scale containments. The data generated has been extensively used for code validation [4-8]. The main characteristics of MISTRA facility are described below.



Fig. 1 : Side view of MISTRA facility

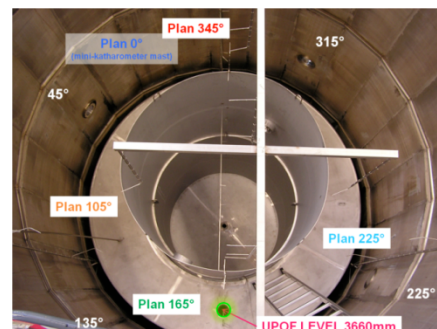


Fig. 2 : Internal view from the top, of MISTRA with its compartment

MISTRA facility is thermally insulated stainless steel containment with a free volume of 97.6m³, an internal diameter of 4.25m and a height of 7.38m. MISTRA comprises 2 cells, a flat cap and a bottom that are fixed together with twin flanges. Three cylindrical thermally regulated walls, inserted inside the containment along the stainless steel containment wall on top of each other, are called condensers. Figure 3 shows the different elements of MISTRA facility and the main geometrical characteristics.

The MISTRA's compartment consists of 2 cylindrical shells with a diameter of 1906 mm and a height of 4219 mm, equipped with a 'ring plate' as shown in figure 2 and figure 3. The material chosen is stainless steel 304L with a mean thickness of 3 mm. The lower central injector device is suspended at the bottom and the nozzle is integrated into the cylindrical opening. No recirculation is allowed from the bottom of MISTRA facility into compartment. This compartmented configuration allows several possibilities of injection, two vertical in the lower area, centred and off-centred, one vertical at the level of the ring plate with a chimney and several radial injection at different locations (four per level).

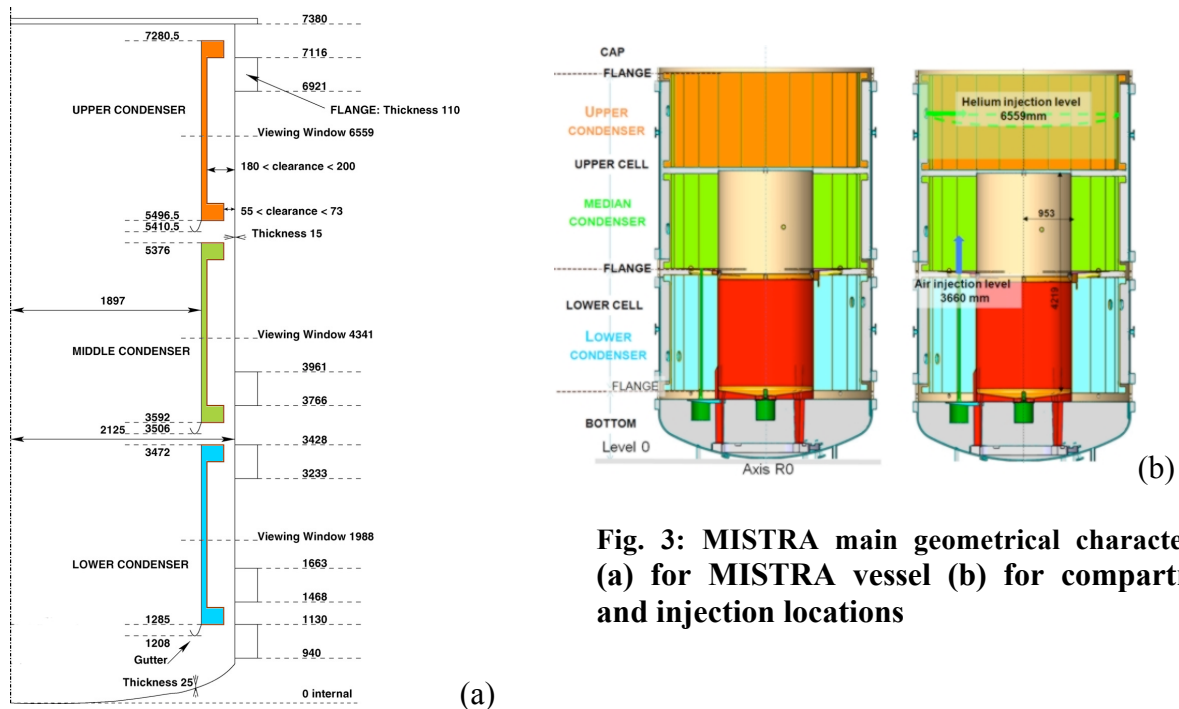


Fig. 3: MISTRA main geometrical characteristics (a) for MISTRA vessel (b) for compartments and injection locations

Here, for the INITIALA-LOWMA presented test series, helium is injected by means of a four-point radial injection, located at 6559 mm height and 45°; 135°; 225°; 315° of angles, allowing the establishment of an axisymmetric helium cloud as shown in figure 2 and figure 3. Air is injected through an off-centred upper line located at the level of the ring plate 3660 mm height and 165° of angle as shown in figure 2 and figure 3. A vent is located in the lower part of MISTRA, in order to keep pressure constant during the test (no pressurisation). This vent is an opened window, located at angle 315°. The vent diameter is 200 mm.

Specifically for the INITIALA-LOWMA test series, MISTRA instrumentation is concerning measurements of temperature, gas concentration, gas mass flow rate and pressure. The temperature measurement is performed with thermocouples chromel-alumel type K (313 sensors), used for measuring fluid temperature in the main gaseous volume, at the injection device location (gas, steam...) and also for solid temperature on the condensers and the vessel and the compartment structures. The main gas concentration measurement technique (helium, air, nitrogen, steam) is based on Quadrupole Mass Spectrometer (QMS) associated with 72 sampling lines connected through a sampling system [9]. To study the phenomena of erosion by a low momentum air jet on the helium/air stratified layer and to allow fine spatial and temporal resolution, katharometry technique (10 thermal conductivity gauges) has been introduced. The katharometry technique was applied with success in our laboratory for other facilities in order to measure helium/air mixtures [10-11]. The gas flow rates is controlled and measured with sonic nozzles designed according to the norm NF EN ISO 9300 (July 1995). This ensures a constant flow rate independently of the downward operating conditions. The regulation of this sonic nozzle is only dependent of the upstream sonic nozzle pressure and temperature, sonic nozzle diameter, an isentropic coefficient, the molar characteristics of the gas and the downstream sonic nozzle pressure. For the pressure measurement one pressure gauge is used to monitor the total pressure of the containment.

3. Test scenario and parameters

3.1. Test scenario

The first step, called INITIALA phase consists of the helium stratification build-up, performed in the upper gaseous volume of the facility, at room temperature and pressure (lower

vent). The objective is the creation of a high helium concentration cloud above the compartment (the volume of this part is approximately 25 m³), the average target concentration of the cloud is about 20% molar helium, the stratification gradient has to be the sharpest as possible and the cloud has to be symmetrical. A total of 7 tests have been carried out during the INITIALA phase study (for the determination of the test sequence, and 5 tests dedicated to the reference test, called INITIALA_3, including tests of reproducibility and characterization of the symmetry). The initial conditions, called INITIAL0, are the atmospheric pressure room temperature and the vessel filled with 100% of air. The INITIALA phase is the creation of the stratified layer with helium lateral injection (Figure 3(b)). A complementary phase, called post-INITIALA, is for few tests the follow-up of the evolution of the stratified layer behaviour without air injection. The objective is to check if we are in a pure diffusion regime or if some small temperature differences can lead to a convective behaviour that can mix the atmosphere faster. The INITIALA test sequences are summarised in Figure 4 (a). The time references for test sequences are summarised in table 1.

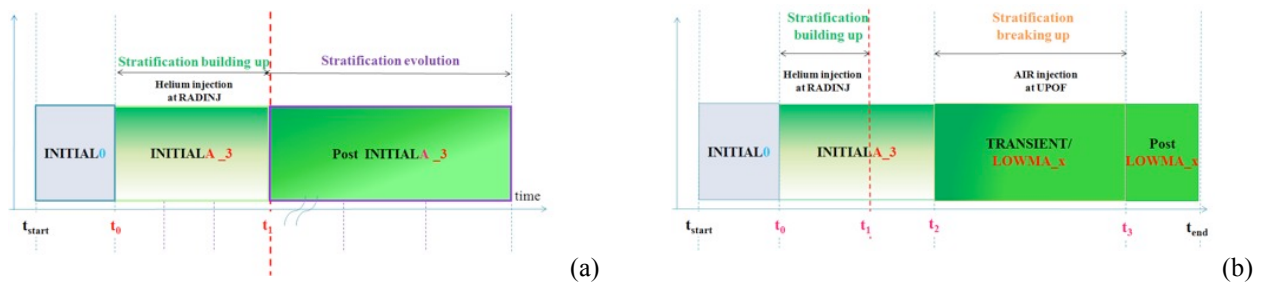


Fig. 4: INITIALA test (a) and INITIALA/LOWMA test (b) sequences

The second step, called LOWMA phase consists of the helium stratification break-up thanks to different low momentum vertical air injections coming from below. A total of 9 tests have been carried out during the LOWMA phase which study the effects of the air flow rate on the stratification, and special focus on one particular test, called LOWMA_3 (6 tests). The main objective during the phase is the stratification behaviour with upward air jet interaction for different air flow rates. The effects of the off-centred injection on the symmetry of the stratification are also evaluated. The LOWMA transient phase follows the INITIALA phase with a delay of about 6 minutes necessary to prepare the air injection after the end of the helium injection. The LOWMA test sequences are summarised in Figure 4b. The air injection is located at upper off-centred nozzle. The air mass flow rates are chosen thanks to its interaction Froude number value, at the level of the stratification, that will determine the theoretical behaviour expected on the helium stratification.

Table 1: references time for test sequences

t_{start}	start of the test		t_{end}	end of the test
INITIALA step			LOWMA step	
t_0	start of helium injection		t_2	start of air injection
t_1	end of helium injection		t_3	end of air injection

The Froude number is a dimensionless number that enables to evaluate the relative resistance of the inertial and gravitational forces. In our case, we define an interaction Froude number [12] located at the interface between the air and the helium cloud:

$$Fr = \frac{U}{NL} \quad (1)$$

where U is the local velocity of the jet at the interface, L the jet characteristic length scale at the impact and N a sort of strength of the stratified layer. The impact velocity of the air flow at the

helium cloud interface can be obtained by the use of well-defined correlation for free air jets [13]:

$$U = 6.2U_{inj} \frac{d_{inj}}{(z - H_{inj})} \quad (2)$$

with U_{inj} is the injection velocity, d_{inj} is the diameter of the injection nozzle, H_{inj} , injection location of air jet and z is the elevation.

L is the full width of the air flow at the helium cloud and the expansion rate of air jets can be used [13]:

$$L/2 = 0.086(z - H_{inj}) \quad (3)$$

with z is the elevation and $H_{inj}=3.66\text{m}$ the elevation of the air injection.

N is the characteristic pulsation of the stratification [14] usually defined as:

$$N = \sqrt{\frac{g}{\bar{\rho}}} \frac{\Delta\rho}{\Delta z} = \sqrt{\frac{2g(\rho_{air} - \rho_s)}{(\rho_{air} + \rho_s)H_s}} \quad (4)$$

with $\bar{\rho}$ is the average density inside the stratification zone, $\Delta\rho/\Delta z$ is the density variation inside the stratification zone with ρ_s stratification density ρ_{air} air density, g is the acceleration due to gravity

- If Froude number is lower than 1, buoyancy of the stratified layer dominates, and the air flow erodes the stratification without penetration.
- If Froude number is greater than 1, momentum of the air flow dominates, and the air flow penetrates inside the stratification.

3.2. Experimental conditions

For the first INITIALA step, three different types of tests have been carried out (with three different helium mass flow rates, but the same quantity of helium injected). The criterion to determine the reference test is very simple: the sharpest stratification will be selected as reference test. In the next paragraph we will present here only the results of INITIALA_3 test that has been selected as the reference pre-conditioning test. The main experimental conditions are summarised in table 2.

For the second INITIALA/LOWMA step, the driven parameter is the Froude number to select the air mass flow rate. The interaction Froude numbers (Fr) for the different LOWMA tests is also given in table 2 with the experimental conditions. In the small interaction Froude number regime, a factor of 10 has been achieved to be in the buoyancy dominant regime ($Fr=0.1$). Conversely, in the high interaction Froude number regime, the design of MISTRA air injection line allows only a factor 3. Then to characterise the effects of the air flow on the vertical helium distribution, five test series were considered INITIALA_3 with a Froude number of zero, LOWMA_1 with a Froude number of 0.10, LOWMA_2 with a Froude number of 0.31, LOWMA_3 with a Froude number of 1.01 and LOWMA_4 with a Froude number of 3.38.

4. Results and discussions

4.1. INITIALA test results

The sharpest stratification is obtained with the higher helium mass flow rate 4.25g.s^{-1} for INITIALA_3. In this case the helium injection was short enough so that reduced diffusion effect occurs during this period of time, and also due to an efficient concentration homogenisation in the helium cloud according to higher levels of turbulence. The figure 5 shows the helium stratification characteristics at the end of helium injection time t_1 . The stratification depth is

around 10% of the total MISTRA height.

This INITIALA_3 reference test has been repeated 5 times in order to ensure proper capture of the phenomenon. The symmetry of the stratification was checked thanks to the displacement of the katharometer instrumentation rod at three different angle locations (7.5°, 141° and 277.5°). This symmetry was characterised during post-INITIALA phase at different time t_1 , t_2 between t_2 and t_{end} .

Table 2: Experimental parameters

TEST ref.		Vessel configuration	Katharometers		Initial conditions		Helium injection		Air injection		Fr	Final conditions	
			Radius (mm)	Angle (°)	Pressure (bar)	Temperature (°C)	Mass Flow Rate (g/s)	Duration	Mass Flow Rate (g/s)	Duration		Pressure (bar)	Temperature (°C)
INITIALA_3	Test 1	Open	1540	7.5	1.005	18.6	4.25	t ₁ -t ₀	-	-	0	1.005	18.6
INITIALA_3	Test 2	Open	1540	7.5	1.005	18.2	4.25	t ₁ -t ₀	-	-	0	1.005	18.2
INITIALA_3	Test 3	Open	1540	7.5	1.004	18.4	4.26	t ₁ -t ₀	-	-	0	1.005	18.5
INITIALA_3	Test 4	Open	1480	141	1.005	18.1	4.26	t ₁ -t ₀	-	-	0	1.005	18.1
INITIALA_3	Test 5	Open	1060	277.5	1.005	19.3	4.26	t ₁ -t ₀	-	-	0	1.005	19.3
LOWMA_1	Test 6	Open	1540	7.5	1.005	18.3	4.25	t ₁ -t ₀	1.51	t ₃ -t ₂	0.10	1.005	18.4
LOWMA_2	Test 7	Open	1540	7.5	1.005	18.4	4.25	t ₁ -t ₀	4.53	t ₃ -t ₂	0.31	1.005	18.4
LOWMA_3	Test 8	Open	1540	7.5	1.005	18.6	4.26	t ₁ -t ₀	15.16	t ₃ -t ₂	1.01	1.005	18.5
LOWMA_3	Test 9	Open	1480	141	1.005	18.3	4.26	t ₁ -t ₀	15.17	t ₃ -t ₂	1.01	1.005	18.4
LOWMA_3	Test 10	Open	1480	141	1.005	18.3	4.26	t ₁ -t ₀	15.17	t ₃ -t ₂	1.01	1.005	18.6
LOWMA_3	Test 10	Open	1060	277.5	1.004	19.4	4.26	t ₁ -t ₀	15.17	t ₃ -t ₂	1.00	1.005	19.1
LOWMA_3	Test 12	Open	1060	277.5	1.004	19.2	4.25	t ₁ -t ₀	15.16	t ₃ -t ₂	1.01	1.004	19.3
LOWMA_3	Test 13	Open	1060	277.5	1.004	22.9	4.24	t ₁ -t ₀	15.12	t ₃ -t ₂	1.00	1.004	22.9
LOWMA_4	Test 14	Open	1540	7.5	1.005	19.8	4.24	t ₁ -t ₀	50.58	t ₃ -t ₂	3.38	1.004	17.4

The figure 6 shows the symmetry of the stratified layer at the end of helium injection time t_1 . The repeatability of the test was also checked at 3 times with the same measurement configuration here the katharometer rod located at same angle. The figure 7 shows the repeatability for the reference test INITIALA_3 at the end of helium injection time t_1 . For each of these 5 INITIALA_3 tests, the mass balance has been checked; the results are given in table 3. The mass balance check gives good results, with less than 6% difference between the two ways of determination of the volume of helium. The first way is the measurement of the helium injected, the other one is the integration of the concentration profile at the end of the injection (t_1)

Table 3: Results of mass balance check

	Volume of helium calculated from helium injection (m ³)	Volume of helium calculated from concentration measurements (m ³)	Error (%)
Test 1	5.53	5.39	2.5%
Test 2	5.58	5.29	5.3%
Test 3	5.44	5.49	1.0%
Test 4	5.55	5.63	1.5%
Test 5	5.52	5.44	1.3%

After the end of the helium injection (post-INITIALA phase), the measurements are maintained to evaluate the time evolution of the helium molar concentration during this diffusion phase and to compare it with the theoretical evolution of the diffusion of an initial Heaviside function. Recall the definition of the solution of the equation of the diffusion of a Heaviside function is given by [15]:

$$X(z,t) = X_0 \frac{l}{L} \sum_{k=1}^{\infty} \frac{2X_0}{k\pi} \sin\left(\frac{k\pi l}{L}\right) e^{-\left(\frac{k\pi}{L}\right)^2 Dt} \cos\left(\frac{k\pi z}{L}\right) \quad (5)$$

where X_0 is the initial molar helium concentration of the gap mean value of the measurements at the top of the katharometers rod, L is the total height of MISTRA equal to 7.38m, D is the molar diffusion coefficient of helium in air equal to $7.35 \cdot 10^{-5} \text{ m}^2 \cdot \text{s}^{-1}$ and l is defined as the height of the zone at $X_0\%$ helium and equal to 1.004m, l is calculated as follows:

$$l = \frac{Q_{mHe} t}{X_0 \rho_{He} 2 \pi R_{Mistra}} \quad (6)$$

where Q_{mHe} is the average helium mass flow rate, t is the injection duration, ρ_{He} is the average helium density during the injection and R_{Mistra} is the radius of MISTRA.

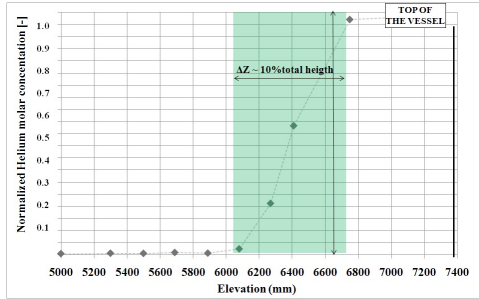


Fig. 5 : Helium stratification characteristics at the end of helium injection time t_1

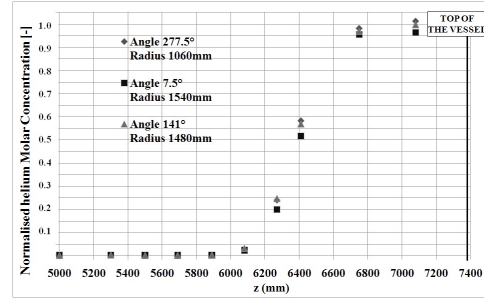


Fig. 6: Symmetry of the helium stratified layer at the end of helium injection time t_1

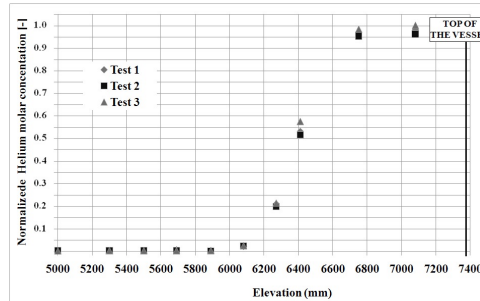
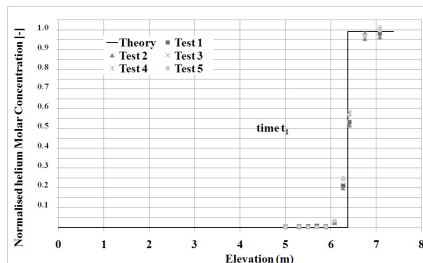
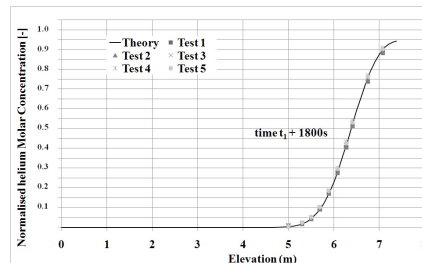


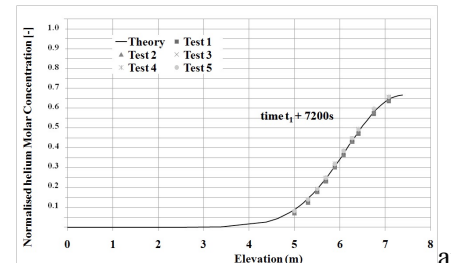
Fig. 7: Repeatability checking, comparison of the vertical evolution of helium stratification at the end of helium injection for 3 different tests (time t_1 , angle 7.5°, radius 1540 mm) time t_1



at the end of the helium injection t_1



at $t_1 + 1800s$



at $t_1 + 7200s$

Fig. 8: Diffusion effect, comparison experiment versus theory of the vertical evolution of helium stratification at different time after the end of helium injection t_1

The comparison of the experimental concentration curve and the theoretical diffusion is given at the end of the helium injection t_1 , at $t_1 + 30min$ and at $t_1 + 120min$. At the end of helium injection t_1 we assume that the initial stratification is a Heaviside function. The figure 8 shows the evolution of the experimental helium molar concentration compared to theoretical curves. This comparison confirmed that we have a pure diffusion effect after the end of helium injection without any convection driven effect.

To conclude on the first INITIALA step, INITIALA_3 results show that the helium stratification is established with the quality requested for the next step and the operating conditions applied ensure to have a symmetrical helium cloud and the repeatability between each test, the mass balance is well verified and the accordance with the theory during the molecular diffusion phase after the end of helium injection. The INITIALA_3 test will be the reference test for pure

molecular diffusion effect and will be compared with LOWMA tests series at different interaction Froude of interest.

4.2. INITIALA+LOWMA test results

The results focus here on the comparison between the helium concentration measurements performed during INITIALA_3 and the four LOWMA tests in order to evaluate the effects of the low momentum vertical air injection on the helium cloud, regarding the interaction Froude number value with increasing values between 0 to 3.38 [16]. The air injection duration is $t_3 - t_2$.

The figure 9 shows the evolution of the stratification during the air injection phase at selected times. We observe three different behaviours on these four graphs.

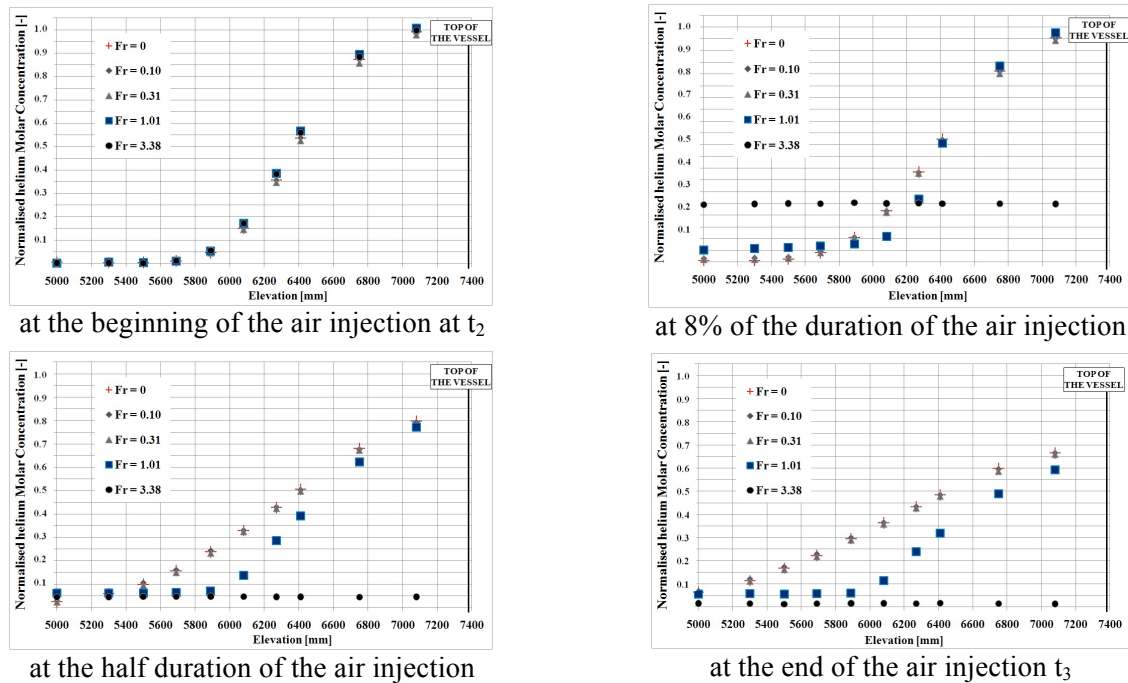


Fig. 9: Vertical evolution of the helium stratification during the air injection phase at different times

At Froude equal to 0 to 0.31, the buoyancy of the stratified layer dominates. The air flow does not penetrate inside the stratification. This stratification is very stable, and the air flow has no effects on it. At Froude equal 1.01, this is an intermediate case, buoyancy and momentum has the same order of magnitude. We can observe that the air flow penetrates the lower layers of the stratification, up to 5.9m height (2.2m above the air injection). The result of the air flow penetration is a complete homogenisation of the penetrated layers. Above this homogeneous zone, the stratification still exist, but with lower helium concentration. Finally for the higher Froude number equal to 3.38, the momentum of the air flow dominates. The air flow completely penetrates the helium cloud. The stratification is completely broken, and the helium concentration has a constant value around 1.5% of C_{max} .

Penetration of the air flow within the stratified layer can be also illustrated by the evolution of the helium concentration at the elevation 5.9m identified previously as transition level in case of $Fr=1$. We also observe three different behaviours on Figure 10. At Froude equal to 0 to 0.31, the air flow has no effects (or only a small effect) on the concentration evolution during time. At Froude equal 1.01, the air flow penetrates inside the stratification up to this altitude. The helium concentration remains constant during the air injection. This concentration is an equilibrium

value between the helium feed from the upper layers, and the dilution made by the air injection. After the end of the air injection, the helium concentration grows up, because of the helium feed from the upper layers (helium diffusion). Finally at Froude equal 3.38, momentum of the air flow dominates and as the air flow completely penetrates the helium cloud. We observe first a rapid growth of the helium concentration during the first seconds of air injection. This rapid growth is due to the mixing with the upper layers of the stratification. Then, once the whole helium cloud is mixed and homogeneous, helium concentration decrease due to the dilution of the air flow.

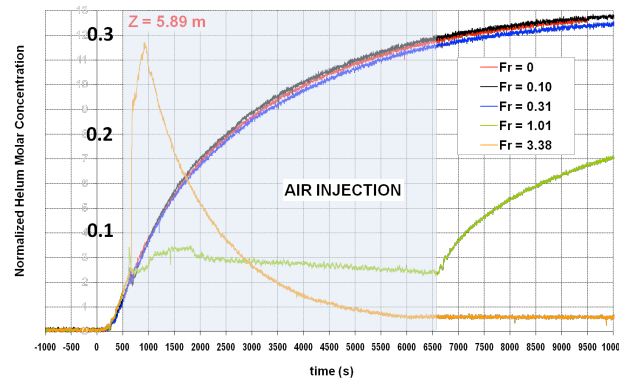


Fig. 10: Time evolution of helium concentration at the level 5.9m height

As for INITIALA phase, a special focus was given to the symmetry and the repeatability of the test. The LOWMA_3 ($Fr = 1.01$) was chosen as it is an intermediate case with buoyancy and momentum competition. The main conclusions are firstly for symmetry whereas the air injection is off-centred, the gas concentration field in the upper part of MISTRA is still symmetric (inside the penetrated zone ($z = 5.5m$) and also inside the stratification zone ($z > 6m$)). Secondly, the repeatability tests highlight the sensitivity of the phenomena to the thermal conditions even if all the different LOWMA_3 tests were carried-out assuming same boundary conditions (helium and air mass flow rates, times of injections, etc.). For these reproducibility tests, the behaviour observed in the helium cloud are different from one test to another. We attribute these differences to 2 factors. The first one is the value of the Froude number closed to 1 which is an intermediate value between two effects and secondly to the small temperature differences between gas and air injection from days to days. The interaction Froude number is very sensitive to these temperature differences that have an impact on its value. The difference between the air injection temperature and the gas temperature causes a change in the momentum of the air flow (addition of buoyancy effects): the higher the temperature difference is (here close to 4°), the lower is the momentum, lower is the interaction Froude number and the lower is the penetration length [16]. According the reproducibility point of view, two tests were carried out with same difference of temperature between the air injection temperature and the gas temperature, the observed behavior was strictly the same, and then we confirm here the reproducibility of this test.

4.3. Discussion

These different tests previously presented show the different possible mechanisms leading to the stratification break-up in time. Interaction of a fountain like flow with the stratified layer was observed as a complex phenomenon.

The first mechanism observed in INITIALA_3 test, with a Froude number equal to zero (without air injection) concerns erosion of the helium layer with a diffusive process (figure 8). Similarly, for tests with Froude numbers lower than 1, namely LOWMA_1 ($Fr=0.1$) and LOWMA_2 ($Fr=0.31$) with the air flow small enough, the erosion of the stratified layer is still governed by diffusion process as shown in figure 11 for LOWMA_2 test conditions. The experimental data are compared with calculation with CAST3M CFD code and confirm the behaviour driven by

molecular diffusion process.

At the other end, the larger interaction Froude number equal to 3.38 leads to a rapid break-up of the stratified layer (figure 12). Just after the beginning of air injection the layers up to 6.75m are impacted by the dilution process. During a short delay is observed for the upper layers at 7.1 where first diffusion is the driving process and followed after this delay by dilution process involves in whole layer.

In the critical range of Froude close to 1, the injected air starts to dilute the lower layers of the air/helium cloud and then, the diffusion process is enhanced by convective contribution as showed in figure 13 compared to the diffusion profile.

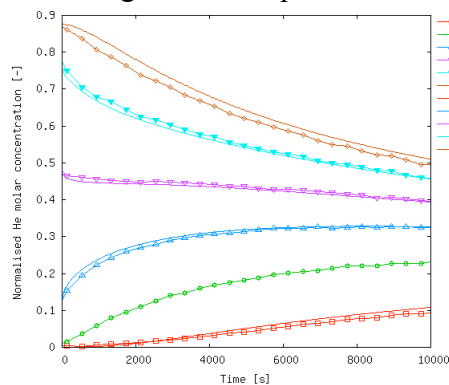


Fig. 11: Time evolution of helium concentration at different elevations for MISTRA LOWMA_2 test and comparison with CAST3M calculation

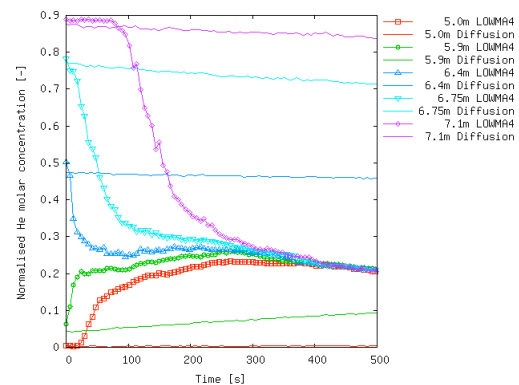


Fig. 12: Time evolution of helium concentration at different elevations and at the beginning of air injection, comparison between LOWMA_4 and INITIALA_3 tests

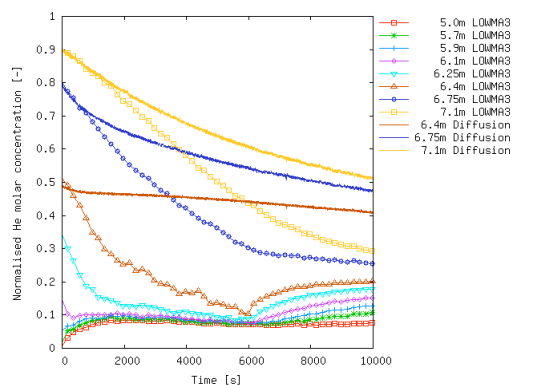


Fig. 13: Time evolution of helium concentration at different elevations for LOWMA_3 tests

Following this experimental campaign on the MISTRA facility, we carried out a complementary campaign on the stratification break-up with vertical fountains at reduce scale. These investigations were performed on GAMELAN facility, volume close to 1m³ [17].

The results observed at this smaller scale confirm the MISTRA INITIALA-LOWMA test campaign results. The figure 14 shows the time evolution of helium concentration at the lower interface of the stratified layer. This also allowed providing complementary elements for a detailed interpretation with data on the velocity measurements concern the upward and downward flow of the air jet and the propagation of gravity waves through the stable lighter layer. Figure 15 shows a picture of the lower helium stratified layer with the air jet impingement at $Fr=1.09$ measured by Particle Image Velocimetry technique (PIV), the velocity field (red arrows of the picture) and the associated iso-velocity graph show the fountain behavior of negatively buoyant air jet.

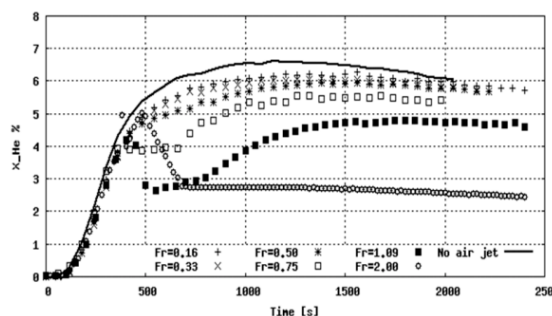


Fig. 14: Time evolution of helium concentration at the lower interface of the stratified layer

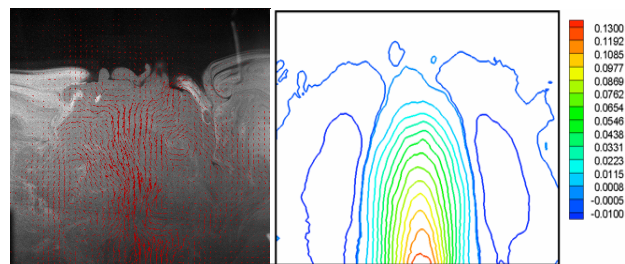


Fig. 15: Example of the air fountain impinging the helium layer with the velocity field and iso-velocity curves here for $Fr=1.09$

5. Conclusions

The main results of the first MISTRA test series, called INITIALA-LOWMA, were presented on the basis of 16 tests carried out during this test campaign with 7 tests for the INITIALA phase study and 9 tests for LOWMA phase study. This great number of tests was necessary in order to fully understand the phenomenon occurring during the different phases of the tests, to assess the reproducibility and to ensure confidence in the produced results as the final goal will be the possible LP and CFD codes validation. A particular instrumentation was implemented specially for these tests, namely a vertical rod, instrumented with katharometer sensors. The test campaign was carried out in two steps. The first one, called INITIALA phase has consisted of the helium stratification build-up, performed in the upper gaseous volume of the facility, at room temperature and pressure. The second one called LOWMA phase has consisted of the helium stratification break-up thanks to different low momentum vertical air injections coming from below. The INITIALA_3 test results were detailed because it has been selected for the quality of its sharp stratification being good initial conditions for LOWMA tests. INITIALA_3 tests conditions were very good to ensure the symmetry of the helium layer, the repeatability, the mass balance and finally the accordance with theory during the molecular diffusion phase

The LOWMA test series gives also some very interesting results and puts into evidence the effect of the low momentum air flow strongly linked with the interaction Froude number as defined in equation (1). The helium stratification is very stable for the Froude numbers lower than 1. For the Froude number of 0 (no air injection), the dominant mechanism is pure molecular diffusion mixing as observed for INITIALA_3. Same observation for the two tests LOWMA_1 ($Fr=0.1$) and LOWMA_2 ($Fr=0.31$) where, the air flow rate is small enough to not interact with the stratified layer; the mixing process remains driven by diffusion. At the other end, the larger interaction Froude number equal to 3.38 leads to a rapid break-up of the stratified layer with fast global mixing. For Froude number equal to 1, LOWMA_3 test, the air flow penetrates the lower part of the helium cloud and the stratification becomes instable. The fountain flow rate, buoyancy dominated mixing is experienced: the stratification is pushed upward, stiffened and eroded by the fountain's entrainment. The last case, LOWMA_4 ($Fr=3.38$), the air flow is strong enough to lead to a dilution overall. This definition of Froude number allows the identification of the ability of the air jet to erode or to dilute the stratified layer.

This experimental work was continued in the frame of the OECD/NEA SETH-2 project. These test conditions have also been proposed and similar tests were performed in PANDA facility at PSI. This common test series was analysed and detailed in [18].

These test results with high-quality measurements can be regarded as a good basis for CFD models verification.

In this paper we don't give details on the numerical part of these test results analysis (only few examples of comparison with CAST3M CFD simulation). The analytical activities carried out by the OECD/NEA SETH-2 project participants allowed the assessment of the capabilities of various computational tools, including GOTHIC, FLUENT, TONUS, CFX, ASTEC and others for predicting the SETH-2 tests. An OECD/SETH-2 analytical seminar, planned for September 2011, will provide additional insight on the strengths and drawbacks of the various codes [19].

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