Study of online measurements techniques of metallic phase spatial distribution into a corium pool

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Abstract— **In the context of in-vessel retention (IVR) strategy in order to better assess the risk of reactor vessel failure, the knowledge related to the kinetics of immiscible liquid phases stratification phenomenon needs to be further improved. So far, only one medium-scale experiment (MASCA-RCW, in the frame of the OECD MASCA program) gives direct information regarding the transient relocation of metal below the oxide phase through post-mortem measurements. No experimental characterization of the stratification inversion kinetics when heavy metal becomes lighter and relocates at the top exists. Further investigation of these hydrodynamic and thermochemical processes could be made possible thanks to on line instrumentation enabling to follow displacement of oxidic and metallic phases into the corium pool. At CEA Cadarache, studies are under progress to set up innovative technologies for corium stratification monitoring which would be integrated to a cold crucible induction melting furnace. Based on space and time resolution specifications, three on-line measurements techniques were selected and studied. The first one is an ultrasonic technique using a refractory material waveguide and based on a time-of-flight measurement. We present the feasibility approach with the preliminary results obtained during experiments at high temperature on VITI facility. The second method consists in electromagnetic characterization of the corium pool thanks to an excitation by a magnetic field induced by surroundings coils and measurement of magnetic response by sensors placed around the crucible. A modelling study has enabled to define an appropriate experimental configuration. An experimental set up has also been tested to verify the calculation results. The third technique is 2D X-rays imaging. A feasibility study for a real-time X-ray imaging with a framerate of 1 image/s has been performed using home-made simulation software MODHERATO, accounting for scattering, based on corium behavior previsions. Results on the detection of interfaces between different type of corium phases (oxide, light metal, heavy metal) are shown.**

Index Terms— **PLINIUS-2, Severe Accidents, Corium, Ultrasonic testing, Electromagnetic testing, X-ray imaging**

I. Introduction

IN case of a nuclear severe accident, when core meltdown occurs, the main objective is to limit the consequences on environment and populations, in terms of contamination and radiation. One of the strategies of severe accident management is the in vessel retention (IVR) strategy which aims at minimizing the risk of vessel failure by reflooding the reactor pit and whose likelihood of success is determined by the assessment of the heat flux from the corium pool to the vessel. This is why there is an interest in the knowledge related to the kinetics of immiscible liquid phases stratification phenomenon.

Today, the understanding and modelling of this kinetic only lies on the conclusions and timescales deduced from post-test examination of MASCA-RCW test [Asmolov, 2003], a medium-scale experiment giving limited information regarding the transient relocation of metal below the oxide phase. There is no experiment regarding the stratification “inversion” kinetics, when addition of metal leads to a light metallic layer on top of the oxide pool.

In the framework of PLINIUS 2 CEA project dealing with the building of a large corium facility [Journeau, 2017], the development of an experimental device in order to measure the kinetic of stratification of the different liquids layers is under consideration. The set-up is based on the induction melting technique in a cold crucible in order to perform medium-scale experiments with a ~50 kg corium pool as in MASCA-RCW. The key feature of the experiments is the online measurement of the metallic phase spatial distribution with the following criteria: (1) measuring continuous phases axial thicknesses with spatial resolution of about 1 mm and time resolution of about 1 min; (2) quantifying a dispersed phase (i.e. droplets) distribution of about 1cm and time resolution of about 1s. Three techniques have been selected for this measurement:

- an ultrasonic technique using a refractory material waveguide and based on a time-of-flight measurement;
- an electromagnetic characterization of the corium pool thanks to an excitation by a magnetic field induced by surroundings coils and measurement of magnetic response by sensors placed around the crucible;
- 2D X-rays imaging of the corium pool.

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We present the feasibility study of each method, their specifications and their limitation regarding the objective of the experiments in

section II, III and IV. Section V will finally present the conclusion and perspectives of this work.

II. Ultrasonic testing

A. Principle

In order to monitor online the evolution of a stratified corium, measurements of ultrasonic pulse time-of-flight are investigated for the localization of the upper light metal / oxide interface. An ultrasonic pulse is emitted by a transducer. By crossing an interface, part of the energy of this pulse is reflected (see **Fig. 1**). It is then possible to deduce the position *D* of the interface thanks to the time-of-flight (*tof*) of this reflected pulse and the acoustic velocity *v* in the propagation medium thanks to the relation : $tof = \frac{2D}{v}$.

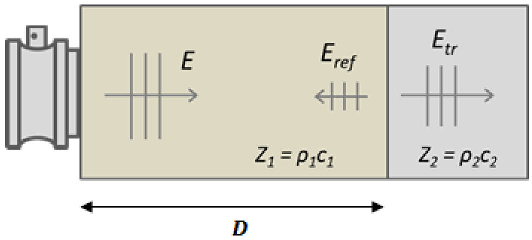

Fig. 1. Reflection of an acoustic wave at the interface between two materials.

In our case, the implementation of this technique requires:

- the knowledge – or an *in situ* measurement – of the speed of sound in the upper layer,
- an appropriate waveguide able to ensure the transmission of ultrasound in the molten metal (T ~ 2000°C),
- an appropriate ultrasonic transducer. Even if not directly immerged in molten metal, this should be a high temperature one (see **Fig. 2**).

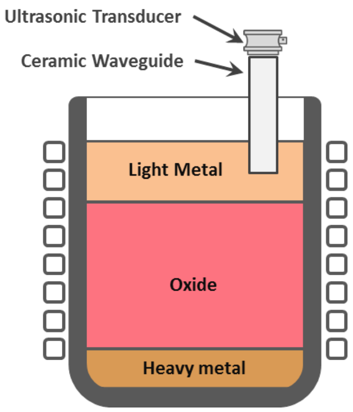

Fig. 2. Principle diagram of acoustic measurement with a ceramic waveguide.

B. Preliminary experimentations

In order to rule on the feasibility of the method and to confirm the simulation results, experiments were conducted on the VITI facility (see **Fig. 3**). Based on induction heating, VITI allows the melt of samples up to 3000 ° C. We performed tests in liquid steel with zirconia and hafnia waveguides. We used a Framatome® TUCSS high temperature transducer (able to operate at 200 °C).

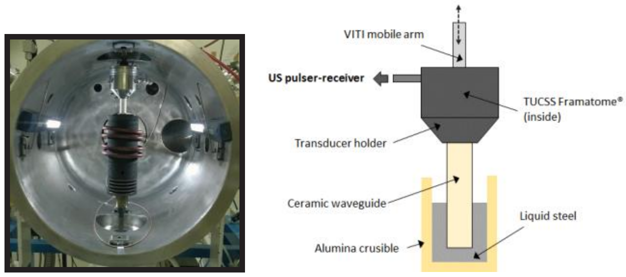

Fig. 3. The VITI facility.

These experiments allowed the demonstration of zirconia and hafnia acoustical ability in liquid steel. We also managed to perform speed of sound measurements in liquid steel between 1500 and 1850°C. The sensor-waveguide assembly is mounted on a motorized micrometer plate. We have shown that the tested acoustic technique allows a very precise positioning by tracking the echo returned by the liquid steel interface - alumina crucible (see **Fig. 4**).

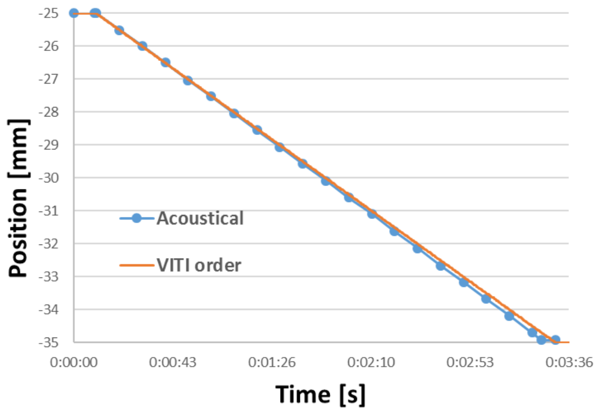

Fig. 4. Positioning by acoustic monitoring versus VITI order.

C. Prospects

The preliminary experiments carried out allowed the demonstration of the feasibility of the ultrasonic pulse time of flight measurement for the localization of an interface through a molten metal. Further tests will be necessary to understand phenomena that we have observed on the surface of ceramic waveguides. An application of the technique on real stratified corium is now under study. Solutions will be studied to be able to work in metal mixtures of unknown acoustic celerity.

III. Electromagnetic testing

Even if materials in corium are at a temperature above their Curie point, they can be discriminated by the way of an electromagnetically mean. They differ by their electrical conductivity that can be exploited for monitoring their nature and position in the bath. By the way of time varying electromagnetic induction, currents can be induced in the melted corium. Induced currents modify surrounding magnetic field that can be used to determine nature of materials and their geometrical distribution in space.

Finite element analysis is used to numerically test various configurations of excitation coils arrangements around the furnace before doing some experiments on relevant mock-up. The melted corium was sliced in relevant areas (light and heavy metal, oxide) (see **Fig. 5**).

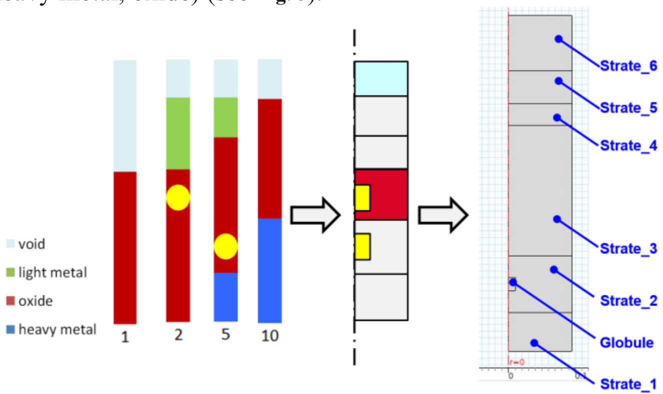

Fig. 5..Relevant volumes inside the melted corium

One of the challenges of this measurement is that the magnetic field must go into the corium through the surrounding cold crucible induction-melting furnace. Therefore, modelling has to take into account the furnace structure (see **Fig. 6**).

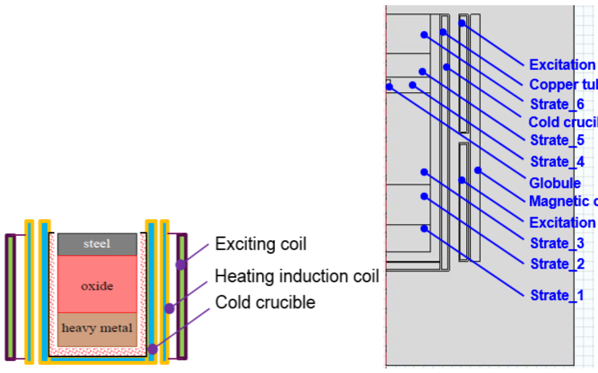

Fig. 6..Modeling of cold crucible induction furnace

Some of the several configurations that were tested, are promising (see **Fig. 7**). Major goal is to obtain a sufficient magnetic induction flux penetrating everywhere inside the melted corium.

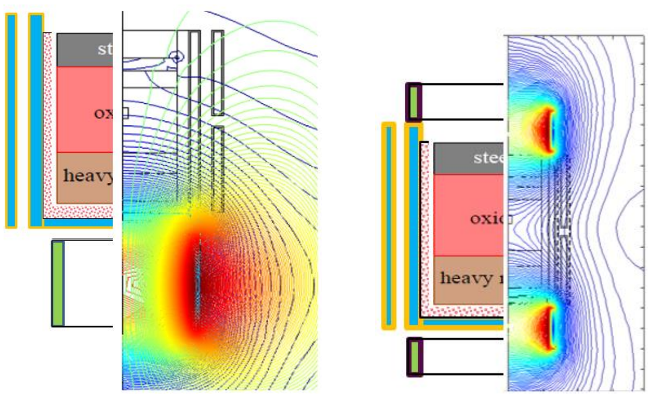

Fig. 7. Example of tested configurations of exciting coils arrangement (located only at the bottom and both at bottom and top)

Results of simulations let appear some perspectives in the possibility to locate materials of significantly to slightly different electromagnetic properties (electrical conductivity and magnetic permeability). For example, when stratum 5 is chosen with a magnetic permeability different from that of the others, results show local inflexion of magnetic induction measurement around the furnace (see **Fig. 8**).

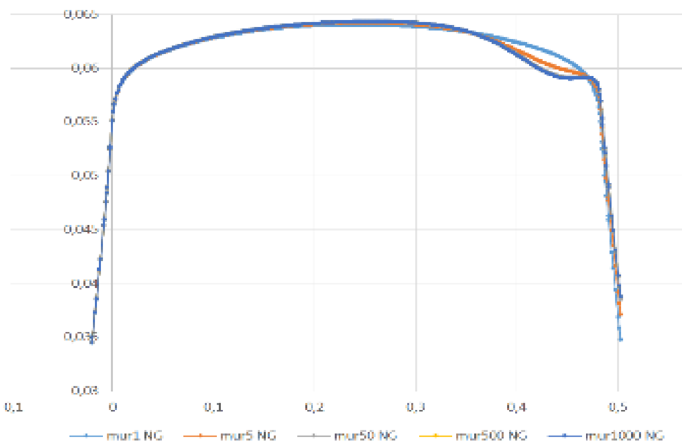

Fig. 8. Numerical measurments on a ficitve line of sensors disposed on the side of the furnace (along a vertical axis)

The simulations indicate the possibility to do the measurements but also confirm that the furnace structure acts as a very powerful shield against propagation of magnetic induction. The challenge is to obtain a sufficient induction everywhere in the melted corium in order to receive an exploitable distortion of inducting field. Next step will be to go on simulation and to experiment the measurement system on a relevant mock-up.

IV. High energy X-ray imaging

High energy X-ray imaging is investigated for the study of corium stratification. The experiment consists in observing the evolution of different corium phases inside a cold crucible. The feasibility study for a real-time X-ray imaging with a framerate of 1 image/s consists in determining the maximum thickness of the self crucible of the cold crucible, allowing the detection of the oxide/heavy metal interface. MODHERATO simulation code, developed by CEA/LMN for high-energy imaging applications in radiography and tomography, has been used with the last developments including scattering contribution on the radiography image simulation [Berge, 2018]. Test section is composed of a vessel, an inductor, a cold crucible, a self crucible and the corium bed. Fig. 9 and **Fig. 10** give a geometric description of the test section.

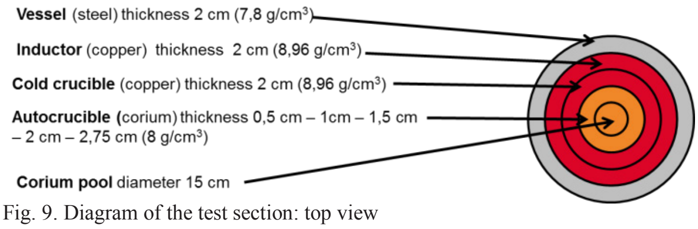

Fig. 9. Diagram of the test section: top view

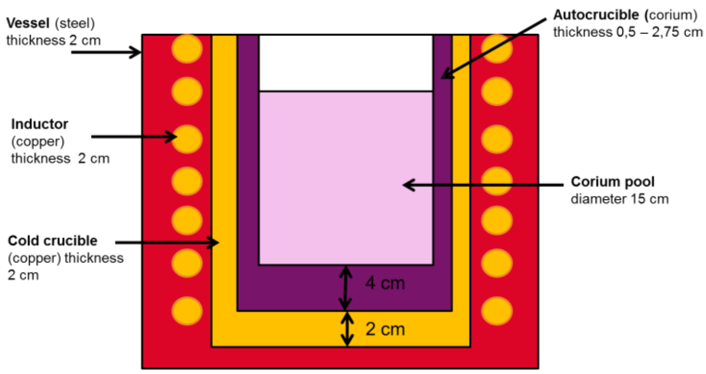

Fig. 10. Diagram of the test section: side view

The corium bed cylinder is decomposed into 33 slices of different chemical composition and density. The time evolution of these 33 slices is discretized into 17 configurations describing a temporal stratification process. Each slice has its own volumic mass and chemical composition. Fig. 11 shows image simulated with MODHERATO of using a 15 MeV LINAC (with a 4 µs pulse duration@250 Hz with an intensity of 100 mA), and the same detector as on KROTOS [Estre, 2016] (Gd_2O_2S scintillator coupled to a camera, pixel size 0.86 mm). Distance from high energy X-ray source to the detector is 1.3 m, distance from source to the center of the test section is 0.86 m.
The interfaces between different corium phases (oxide, light metal, heavy metal) are detectable, as shown on Fig. 11.

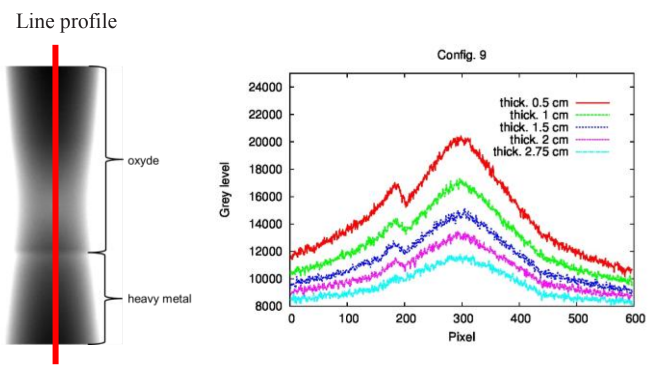

Fig. 11. On the left, simulated radiography of the corium bed with an oxide/heavy metal interface (configuration 9). On the right, comparison of vertical profiles of corium cylinder for different tickness of the autocrucible. The small peak corresponds to the interface visible on simulated radiography.

Simulations show that the contrast between the different layers (oxide, heavy metal and light metal) is sufficient to identify them if the thickness of the autocrucible does not exceed 1 cm (considering a cylinder of liquid corium diameter 15 cm thick, a 2 cm thick copper crucible, a 2 cm thick copper inductor and a 2 cm thick steel vessel).

V. CONCLUSION

The preliminary experiments carried out with ultrasonic testing allowed the demonstration of the feasibility of the ultrasonic pulse time of flight measurement for the localization of an interface through a molten metal. Simulations with electromagnetism testing indicate the possibility to do the stratification measurements. Work is under progress to go further on a relevant mockup. High energy X-ray imaging simulations show that stratification layers can be identify with a 15 MeV linear accelerator. Radiography imaging on a real mockup will allow confirming simulations results.

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