EXPERIMENTAL AND NUMERICAL STUDY OF THE MYRRHA CONTROL ROD SYSTEM DYNAMICS

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This paper presents an experimental and numerical investigation of the buoyancy driven MYRRHA control rod (CR) insertion during an emergency SCRAM. The study aimed to support the MYRRHA reactor design and characterise the hydrodynamic behaviour of the CR system while demonstrating the proof-of-principle. A full-scale mock-up test section of the MYRRHA CR was constructed to test the hydrodynamics in Lead Bismuth Eutectic over a wide range of operating conditions, to provide experimental data for the qualification of the CR system.

A numerical CFD model of the CR test section was also setup in STAR-CCM+. The simulations make use of the recently developed overset mesh method to simulate the dynamic two-way coupling between the moving CR bundle and the fluid domain. The numerical methodology and post-test simulation results are validated against the experimental results.

The steady state hydraulic results and the transient insertion results from both the experimental and numerical efforts are presented. The influence of the global process conditions on the CR insertion time are presented as well. This investigation successfully demonstrates the CR insertion proof-of-principle during a SCRAM.

I. INTRODUCTION

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is a flexible fast-spectrum research reactor under design at SCK•CEN, the Belgian Nuclear Research Center. MYRRHA is a pool-type reactor with Lead Bismuth Eutectic (LBE) as the primary coolant. Conceived as an accelerator driven system prototype, it is able to operate in sub-critical mode. Operating in critical mode, MYRRHA is identified as the European Technology Pilot Plant for the Lead Cooled Fast Reactor which is one of the Generation IV reactor concepts [1].

The MYRRHA Control Rod (CR) system consists of an absorber bundle within a guide tube filled with LBE. During normal operation the control rods are inserted in the LBE, in the lower part of or below the active core. The high density of the liquid metal coolant allows buoyancy to be the passive driving force for the emergency insertion of the control rods during SCRAM. In this particular case the control rods will also have a safety function. The MYRRHA design requires that in the event of SCRAM, the insertion of the control rods should take less than 1 second. While numerous experience and operational feedback has been gathered on CR development and operation in liquid sodium, as documented in [2], the operation of a buoyant CR system within liquid metal is rather different from standard systems. According to the authors' knowledge there is no published literature on buoyant CR operation in LBE.

Therefore, to support the MYRRHA reactor design and the CR design specifically, an experimental and numerical research campaign was established with the aim of characterising the hydrodynamic behaviour of the CR system and demonstrating the proof-of-principle. A full-scale mock-up of the MYRRHA CR was constructed and installed in the COMPLOT (COMPonent LOop Testing) LBE experimental test facility at SCK•CEN, to test the hydrodynamics over a wide range of operating conditions, taking into account the actual transient acceleration and inertial effects of the rod bundle and liquid metal coolant, and thereby provide valuable experimental data for the qualification of the CR system.

A numerical CFD model of the CR test section was also setup in STAR-CCM+ in the framework of the MAXSIMA FP7 project. The simulations make use of the recently developed overset mesh method in a very constrained flow with free surfaces and two-way coupling. The numerical methodology and post-test simulation results will be validated against the COMPLOT experimental results.

This paper presents the experimental test section and numerical model setup and reports the steady state hydraulic results and the transient insertion results from both the experimental and numerical efforts. The influence of the global process conditions on the CR insertion time are presented.

II. OVERVIEW OF THE CONTROL ROD SYSTEM

The MYRRHA CR consists of an open absorber tube bundle assembly located within a guide tube filled with LBE. This CR guide tube is installed in the core and so the CR is a parallel flow channel with the fuel assemblies in the core. The tube bundle is coupled by means of a long shaft to a control mechanism (actuator and electromagnet assembly) above the reactor cover. The control mechanism pushes the bundle down using the actuator for accurate positioning.

During normal operation the CR tube bundle is inserted in the LBE, below the active core, with the primary flow upwards. During emergency operation the control rods perform a safety function and emergency shutdown (SCRAM) is initiated by the deliberate (or accidental) de-energising of the electromagnet which allows the absorber bundle and rod to rise due to buoyancy. Buoyancy is the passive driving force during the emergency insertion and also keeps the CR assembly inserted into the active core region. When the primary LBE pumps are running, CR insertion is assisted by the fluid drag on the bundle assembly.

The CR assembly is expected to accelerate sharply after lift-off. To stop the bundle after full insertion a damper is used to impose a smooth deceleration.

III. EXPERIMENTAL SETUP

III.A. COMPLOT LBE facility

The COMPLOT LBE facility is a closed-loop experimental facility, designed to characterise the hydraulic and hydrodynamic behaviour of numerous MYRRHA reactor components at full-scale, in a flowing LBE environment representative of the MYRRHA conditions. The vertical test section is designed to represent a single core channel, with the LBE flow entering from below and flowing upwards. The loop is isothermal, meaning it operates at a constant LBE temperature for a given test, although the temperature can be varied up to a maximum of 400°C to investigate temperature effects. At nominal reactor power, the core inlet and outlet temperatures are 220°C and 275°C respectively, so the facility is capable of testing over the required temperature range. A pump variable speed drive and the combination of a throttle valve and bypass valve means that a wide range of flow rates can be achieved in a test section: 6 – 104 kg/s. This flow rate range is sufficient to experiment with low flow rates associated with natural convection during a Loss Of Flow (LOF) accident, while higher flow rates up to and exceeding nominal operation flow rates can also be achieved. Fig. 1 illustrates a schematic of the COMPLOT loop with the constituent components.

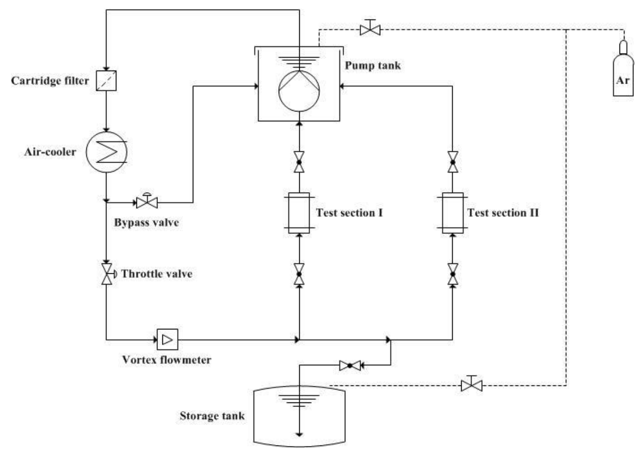

Fig. 1. Schematic of the COMPLOT loop

III.B. Control rod test section

The control rod test section is a 1:1 scale mock-up of the MYRRHA CR design. The long thin-walled guide tube construction, which includes the damper and the LBE outlet labyrinth components internally, houses and guides the CR bundle. The CR bundle tubes are filled with modified stainless steel rods such that the weight of each tube is equivalent to that of the MYRRHA design. The tubes are located between an upper and lower grid which are guided by spring-loaded rollers that push against the inside of the guide tube. Intermediate spacer grids are included along the length of the tubes which prevent the relative rotation of the two grids.

The complete CR component assembly is mounted into the COMPLOT test section, as shown in Fig. 2. The COMPLOT test section serves as the pressure retaining shell while the lower core region has a hexagonal internal geometry representative of a core channel. The upper region of the test section has an enlarged diameter to represent the reactor upper plenum. The CR displacement is measured by means of a laser-optical displacement sensor which tracks the position of a metal plate that is directly mounted to the external CR shaft.

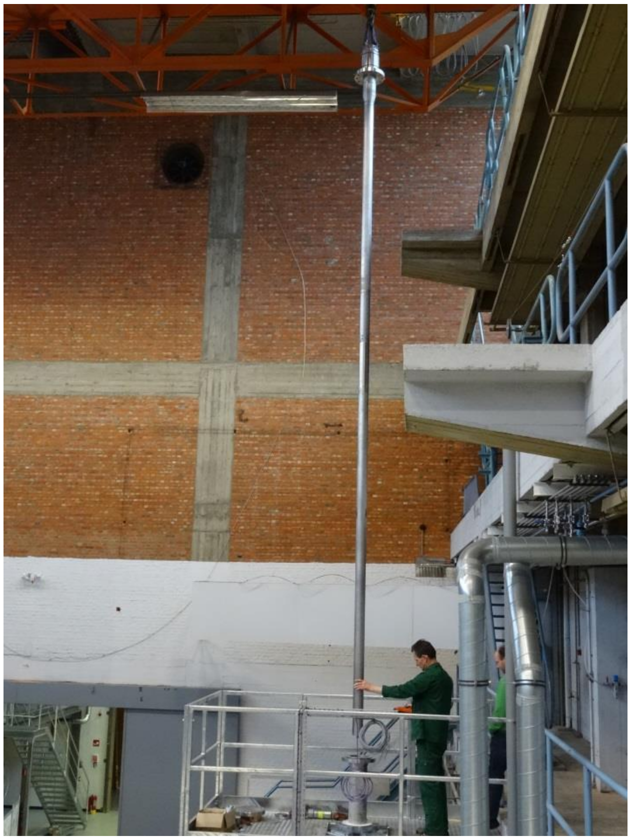

Fig. 2. CR assembly being mounted into the COMPLOT facility

III.B.1. Test section inlet buffer tank

The hydrodynamic CR tests in COMPLOT need to be representative of the MYRRHA conditions. Therefore, in COMPLOT, a pressurised buffer tank (expansion tank) of sufficient size is installed immediately upstream of the control rod test section inlet to suppress any local CR inlet pressure decrease, associated with the transient piston-like motion of the CR during insertion. In MYRRHA, the core inlet originates from a large stable LBE pool at constant pressure (the lower plenum), which provides rapid pressure recovery at the CR inlet. The COMPLOT buffer tank is installed to serve a similar purpose, and suppresses the pressure decrease and provides a fast pressure recovery which the LBE pump cannot respond to. The buffer tank volume (diameter and height) has been optimised for maximum pressure suppression and contains a relatively large volume of argon at constant pressure.

IV. NUMERICAL CFD MODEL

The buoyancy driven control rod system emergency insertion was simulated by CFD means, in an LBE environment specific to the COMPLOT experimental loop and to the MYRRHA configuration.

IV.A. Geometry and mesh

The CR geometry was modeled with high accuracy, preserving a reasonable balance with the affordable computational power. The fluid domain was modeled in full detail, while some simplification was made for the moving component. A symmetrical CR design allowed for the CR geometry and mesh to be modelled with half the domain.

The overset mesh methodology implemented in STAR-CCM+ allowed for the entire CR displacement to be simulated. The background domain and a volume enclosing the moving component are represented by separated overlapping regions, each one with its own mesh. A volume interface of a few cell layers is created in order to couple the solutions on the two overlapping grids. The Zero Gap Overset Interface feature allowed us to approach the narrow/zero gaps present in the flow path of the CR assembly, and more specifically in the damper. The sealing ring at the top of the damper shaft feedthrough, is treated as a fluid region with an LBE dynamic viscosity that is locally and artificially increased by up to four orders of magnitude. With this order of magnitude, the flow through the sealing ring is lower than through one of the dampers uppermost slots. In hindsight, looking at the displacement curves, it is observed that the numerical seal is tighter than the experimental one. In this context, the choice not to model any friction is justified.

Different geometries of the pin bundle were implemented and tested in order to get the best representation of the experimental bundle, whilst still maintaining a geometry that is suitable for the overset mesh method. A pre-test numerical CR bundle (so-called *Bundle I*) was constructed with the 3D-CAD modeler embedded in STAR-CCM+. This pre-test geometry of the pin bundle implemented a slightly smaller absorber pin diameter than in reality, due to the limited space available for the overset mesh method. The volume of bundle I is therefore moderately smaller than the real one, leading to a smaller contribution of buoyancy. After an improvement in the STAR-CCM+ overset mesh methodology, we could build a new bundle (so-called *Bundle II*) for post-test simulations, with a larger volume than Bundle I, closer to the real geometry, while preserving the coupled mesh. The numerical results from the simulations with these different bundles are presented later in §VI.

IV.B. Numerical representation of the MYRRHA configuration

The numerical CFD model representing the CR test section needs to include the dynamics of the free surfaces for the representation of the hot and cold plena. From the numerical point of view, it means that the model must consider the Volume of Fluid (VOF) framework and the geometrical representation of the hot and cold plena. Therefore, the annular outlet channel and the guide tube were extended and connected (Fig. 3). The total height of the system is enough to completely host the control rod in its initial position and up to the complete insertion.

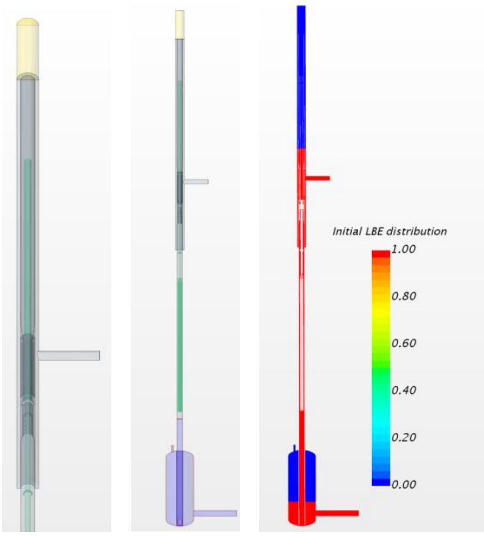

Fig. 3 Upper connected geometrical parts (left); overview of the complete computational geometry (center) and the initial distribution of the VOF phases (right)

In this enlarged geometrical setting, only four boundaries remain to be set:

i. bottom lateral inlet: mass flow inlet (constant or time varying)
ii. buffer tank numerical inlet: no flow during the initialization procedure, then stagnation pressure inlet (explained in subsequent paragraphs)
iii. top lateral LBE outlet: fixed pressure outlet determining the top free surface level
iv. top gas pressure: pressure outlet fixed as zero reference pressure.

To fix the top free surface level, the pressure at the lateral outlet is fixed at the required static pressure to account for the difference of height. In the VOF model a second phase to represent the cover gas was defined, numerically treated as incompressible.

The initialisation procedure is performed in two steps:
(i) achieve the operational steady state condition by imposing the prescribed mass flow rate (MFR) at the bottom inlet and no flow at the buffer tank argon inlet, (ii) the buffer tank Argon inlet is then changed to a stagnation pressure inlet, fixing the reference pressure to the value measured at the end of step (i).

During the initial transient to reach the desired mass flow rate, before the CR insertion transient, the argon inlet is deactivated to preserve the initial free surface level. When a steady flow rate is achieved, the gas inlet is reactivated setting the pressure to the measured current value. In this way, the inventory of LBE in the buffer tank is no longer rigidly constrained and can vary to account for the pressure variations induced by the CR displacement. The establishment of this initialisation is illustrated in Fig. 4.

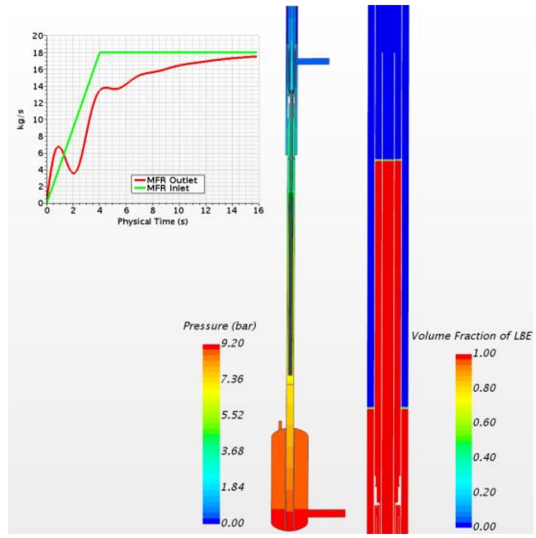

Fig. 4 Top left: history of the channels LBE filling with prescribed MFR= 36 kg/s (18 kg/s is shown due to the half domain); bottom left: free surface level in the buffer tank; center: partial filling of the guide tube; right: final LBE equilibrium level in the guide tube

In this paper we report the successful attempt to reproduce the CR insertion in a configuration that is most representative of the MYRRHA conditions. In MYRRHA, the incoming and outgoing LBE flows are related to large plena with an open access to a cover gas by means of free surfaces. For this reason, the two-way coupling has been implemented in the context of the two-phase flow set-up specific of the MYRRHA configuration. In practice, recognizing that in COMPLOT the buffer tank and the guide tube top are already a good representation of MYRRHA, the numerical model was upgraded with the inclusion of the free surfaces in the buffer tank, representative of the cold lower plenum, and in the guide tube, representative of the hot upper plenum.

V. EXPERIMENTAL RESULTS

The CR experimental tests aimed to characterise the CR hydraulic performance and demonstrate the CR insertion proof of principle during a SCRAM. One of the MYRRHA CR design criterion requires that the CR is inserted within 1 second after a SCRAM initiation during any reactor operating mode or state. The CR insertion therefore needed to be tested across a range of operating conditions, extending from Nominal Operating Conditions (NOC), i.e. full flow, to “no-flow” conditions. The effect of LBE temperature was also tested to determine the influence of changing LBE properties with temperature, particularly the LBE density which determines the driving buoyancy force.

Fig. 5 presents the experimental CR insertion time response for different steady state LBE flow rates, at two different temperatures of 200°C and 350°C. The 8.4 kg/s case is considered a representative flow rate for natural convection during a typical LOF accident. As expected, insertion times are reduced with higher flow rates due to the additional insertion force due to the fluid drag and dynamic pressure. The displacement time curves in Fig. 5 indicate that the effect of LBE temperature does not influence the CR insertion significantly. The CR insertion at 350°C is slightly slower (3% slower) than at 200°C, for a given flow rate.

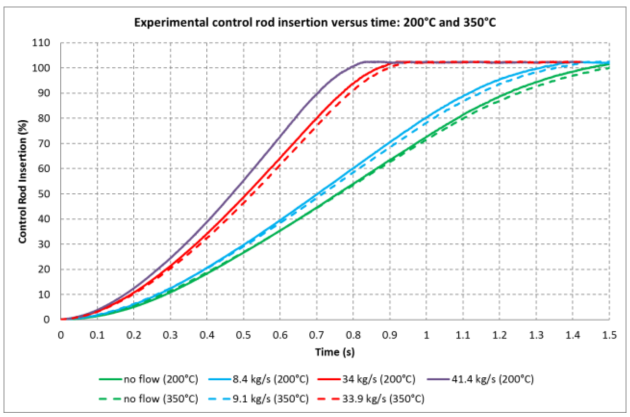

Fig. 5. Experimental CR insertion depth versus time – at LBE temperatures of 200°C and 350°C

In order to compare the CR insertion times for different cases, and also for comparison with the CFD results, an “effective insertion time” is defined as the time until 90% of the nominal insertion stroke is completed. After 90% insertion, the additional reactivity worth of the MYRRHA CR is effectively zero and therefore this definition of effective insertion time is relevant for comparisons. The CR 90% insertion times are plotted in Fig. 6 for comparison. Note that the insertion times are measured from the moment that the CR movement is detected, i.e. t=0 at the start of motion, identified by post-processing of the displacement signal. The insertion times therefore do not account for any possible time delay between the SCRAM signal and the CR release.

As shown in Fig. 6, the CR insertion times are all less than 0.8 seconds for the “nominal” higher LBE flow rates. At 200°C, for the no flow and low flow case of 8.4 kg/s, the insertion times are 1.22 seconds and 1.12 seconds respectively. As was shown in Fig. 5, the results at 350°C indicate that the CR insertion is very slightly slower than what was measured at 200°C. The insertion times are inversely proportional with LBE flow rate.

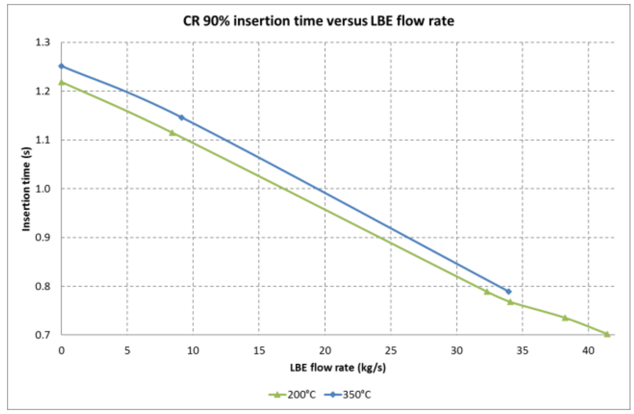

Fig. 6. Experimental CR insertion time for varying LBE flow rates, at LBE temperatures of 200°C and 350°C

VI. CFD RESULTS AND COMPARISONS

For the realistic simulation of the control rod insertion, a fully explicit two-way coupling is implemented in STAR-CCM+. The acceleration is obtained from the resultant of the forces acting on the control rod; the acceleration is integrated in time and the obtained velocity is given to the control rod.

VI.A. CFD results: Bundle I

Fig. 7 illustrates the numerical results from the fully explicit two-way coupled simulations of the smaller pre-test *Bundle I*, at 200°C. The results in Fig. 7 show that the dynamic behaviour of the control rod displacement versus time is very comparable and the operating principle of the damper is well simulated. Only the high flow case simulation exhibits a moderately faster insertion (9%) than the experiment.

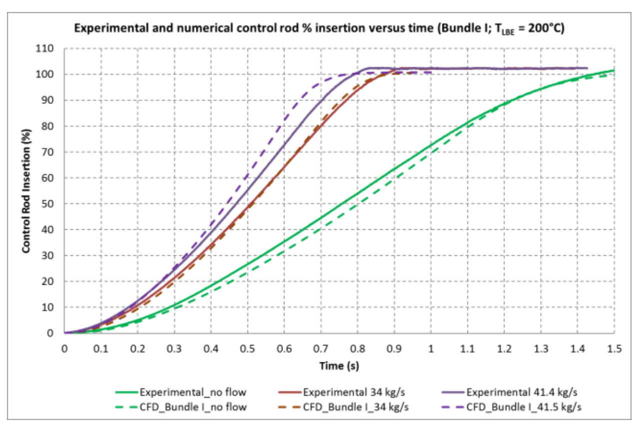

Fig. 7 Control Rod insertion results: experimental versus numerical (Bundle I) at 200°C

However, with *Bundle I*, the dominant buoyancy force is considerably smaller than in reality due to the smaller bundle volume and so the balance of forces acting on the control rod is not entirely representative.

In the experimental setup there is an important negative contribution to the driving force, originating from the dry friction on the CR shaft feedthrough to the outside of the test section. This friction component is absent in the numerical model. As a consequence, the combined lack of positive buoyancy force from Bundle I and the absence of the negative friction contribution, presumably results in a CR resultant force that is rather similar to the experimental scenario. It is therefore suggested that the CR dynamic displacement with Bundle I is coincidentally rather similar to the experimental results. Future experimental friction measurements will need to confirm this hypothesis. The effect of the larger, more realistic Bundle II is presented in the next section.

VI.B. CFD results: Bundle II

The larger, more buoyant *Bundle II* was implemented in the post test simulations for comparison and evaluation of the CR force differences. Slightly higher fluid drag and dynamic pressure was also registered with the larger bundle. As expected, Fig. 8 shows that the larger numerical bundle exhibits faster insertion times for all flow cases. At 200°C and an LBE flow rate of 34 kg/s, the insertion time of bundle II is 13% faster than that of bundle I, and 15% faster than the experimental results. At an LBE flow rate of 8 kg/s, the insertion time of bundle II is 14% faster than the experimental results.

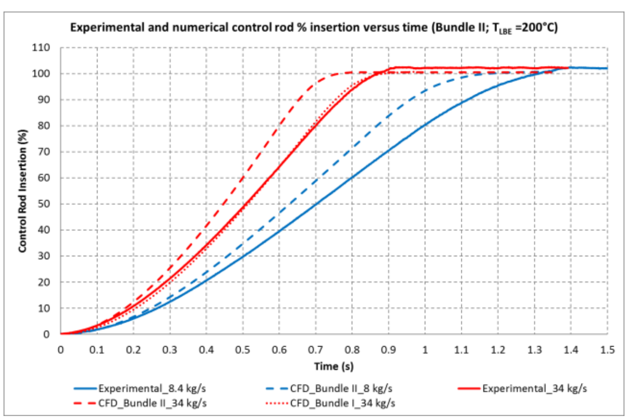

Fig. 8 Control rod insertion results at 200°C: experimental versus numerical (Bundle II: 8 kg/s and 34 kg/s)

The effect of a more realistic numerical volume and buoyancy force (although still underestimated), and the absence of the negative friction contribution, results in a significantly faster numerical CR bundle insertion. In MYRRHA, the shaft feedthrough friction contribution will be much lower (possibly zero by design) and so the COMPLOT experimental scenario can be considered conservative with respect to the CR SCRAM insertion time, for all LBE flow rates considered.

The CFD bundle II was also used to simulate the CR insertion at 350°C. Fig. 9 shows the experimental versus numerical comparison of the CR insertion at a nominal flow rate of 34 kg/s, for both LBE temperatures of 200°C and 350°C. The numerical results at 350°C are almost the same as the numerical results at 200°C, with the insertion at 350°C being only 0.01 seconds faster. Since the experimental CR insertion is slightly slower at 350°C, the numerical insertion time of bundle II at 350°C is 23% faster than the experimental results.

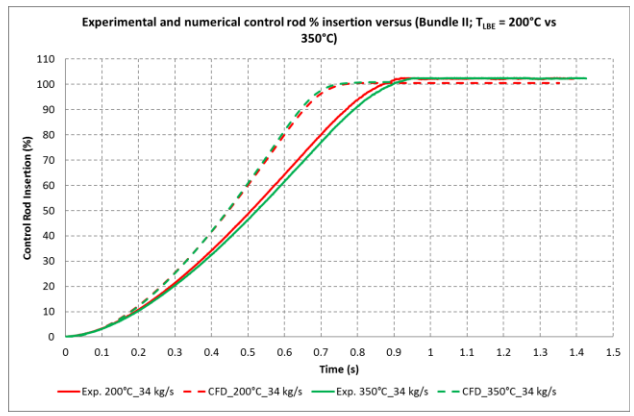

Fig. 9 Control rod insertion results at 200°C and 350°C: experimental versus numerical (Bundle II: 34 kg/s)

VI.C. COMPLOT – MYRRHA comparison

By analyzing the simulations, it became clear that the current use of the buffer tank in COMPLOT to mimic the behavior of the MYRRHA cold plenum was rather good, but could be improved in ideal circumstances. In the COMPLOT experiment, all the LBE in the rising tube between the buffer tank and the CR bottom contributes to an added mass effect to the CR movement. In MYRRHA, there should not be such added mass effect, or only marginally, because the bottom of the control rod is closely connected to the large lower plenum.

Cutting the computational domain just below the CR bottom and inserting a pressure inlet, mimics an access to an infinite plenum. This is much closer to the MYRRHA configuration than the full COMPLOT one, even if it is slightly less “resistive”. Therefore, the buffer tank was removed and the inlet of the guide tube became the mass flow inlet and successively the pressure inlet of the system.

For both cases of no flow and an LBE mass flow rate of 37 kg/s, the results of the two-way coupling simulation at

200°C indicate a reduction of insertion time by about 10% (Fig. 10) in the case of the MYRRHA configuration. This reduction of the insertion time is consistent with the set-up change and is justified by the absence of the vertical pipe used for the connection of the buffer tank with the guide tube.

This comparison of the MYRRHA configuration with the COMPLOT configuration, furthermore confirms the validity of the COMPLOT facility, showing that it is conservative with respect to CR insertion time and representative of the MYRRHA conditions.

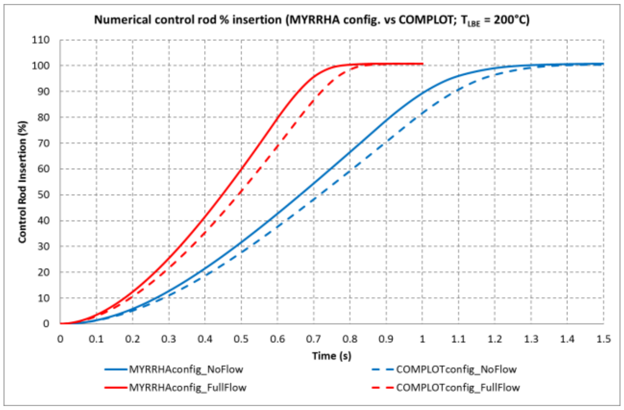

Fig. 10 Numerical MYRRHA configuration vs. numerical COMPLOT set-up. Rod displacement curves in two-way coupling motion (no flow and 37 kg/s)

VII. CONCLUSIONS

A full-scale mock-up of a MYRRHA CR was constructed and installed in the COMPLOT LBE experimental facility to test the CR hydrodynamic response during an emergency SCRAM insertion. Separate isothermal experimental campaigns were completed with LBE temperatures of 200°C and 350°C, for a range of LBE flow rates ranging from no flow conditions to nominal full flow conditions.

The COMPLOT experimental results at 200°C indicate that the experimental CR insertion takes place within the required 1 second for nominal flow cases, but insertion is slower for the no flow case (1.22 s) and low flow (natural convection) case of 8.4 kg/s (1.12 s). When compared to the experimental results at 200°C, the experimental results at 350°C showed very similar dynamic responses with slightly slower insertion times (3% slower). Although the insertion times are greater than the required 1 second, for the low flow cases, these insertion times are regarded acceptable for MYRRHA. The experimental results successfully demonstrate the CR insertion proof-of-principle during a SCRAM.

Comparison of the numerical CFD results with the experimental results reveals that the numerical bundle underestimates the realistic bundle volume (and therefore buoyancy force) considerably, due to the geometric limitation in generating a reliable mesh overset in such a confined geometry. Therefore, the most representative and affordable pin bundle geometry was used, whilst still maintaining a geometry that is suitable for the dynamic overset mesh method. This so-called *Bundle II* exhibited a slightly reduced absorber pin diameter. Whilst the numerical model underestimates the buoyancy force with this bundle, the model doesn't consider the dry friction which exists at the CR shaft feedthrough on the experimental test section. The global result is that the numerical model predicts an insertion time which is faster than the experimental insertion time; 15% faster at 200°C and 23% faster at 350°C. In MYRRHA, the shaft feedthrough friction contribution will be much lower (possibly zero by design) and so the COMPLOT experimental scenario can be considered conservative with respect to the CR SCRAM insertion time. Having no friction on the MYRRHA CR shaft will likely mean that insertion times will also be acceptable in no/low flow conditions.

The transient two-way coupling simulation of the CR insertion predicts the CR motion rather well. Although high frequency pressure oscillations exist (not presented here), the resultant CR displacement curves are very smooth and representative of the experimental results. With the current experimental and numerical results comparison, and future quantification of the experimental CR shaft friction contribution, simulation accuracy could be improved further and confirm the validation of the CR numerical CFD model.

The transient CFD results demonstrate further that for a given mass flow rate, a MYRRHA CR insertion is 10% faster than the COMPLOT CR insertion, due to the added mass effect from the LBE in the riser between the buffer tank and CR inlet. The COMPLOT CR insertion times are therefore conservative and can be regarded as sufficiently representative of the MYRRHA conditions, suitable for demonstrating the CR proof-of-principle and contributing to the eventual qualification of the MYRRHA CR design.

While these proof-of-principle experiments confirm the design foreseen for MYRRHA, future experiments will be performed to test long term reliability by means of repeated tests.

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