Analysis, by TRACE code, of Natural Circulation Phenomena in the MASLWR-OSU-002 Test

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ABSTRACT

Oregon State University has constructed a system-level test facility to examine natural circulation phenomena of importance to integral reactors. The test facility is based on the Multi-Application Small Light Water Reactor (MASLWR) integral reactor concept design developed by Idaho National Engineering and Environmental Laboratory, OSU and NEXANT–Bechtel. The MASLWR is a small modular pressurized light water reactor relying on natural circulation during both steady-state and transient operation.

Most of the tests previously conducted on the OSU MASLWR test facility were in support of the MASLWR concept design verification. It has been the goal of OSU that future work be of value not only to specifically investigate the MASLWR concept design further but advance the broad understanding of integral natural circulation reactor plants and accompanying passive safety features as well. Furthermore an IAEA international collaborative standard problem on the OSU MASLWR test facility is envisaged.

In the framework of this activity, this paper illustrates a preliminary analysis, performed by TRACE code, aiming at the evaluation of the code capability in predicting natural circulation phenomena and heat exchange from primary to secondary side by helical SG in superheated condition. The preliminary results, obtained by simulating the OSU-MASLWR-002 test (natural circulation operation with core power up to 210 kW, where 6 different core powers as well as 7 different feed water mass flow rates were used) are here reported and show a qualitative agreement with regard to the main thermal-hydraulic experimental parameters.

In addition the results of some sensitivity analyses, carried out in order to evaluate the importance of some key phenomena such as heat losses, are reported as well in order to evaluate the real capability of the code in predicting heat exchange from primary to secondary side by helical SG in superheated condition.
INTRODUCTION

Oregon State University (OSU) has constructed a system-level test facility to examine Natural Circulation (NC) phenomena of importance to integral reactors. The test facility is based on the Multi-Application Small Light Water Reactor (MASLWR) [1] integral reactor concept design, figure 1, developed by Idaho National Engineering and Environmental Laboratory, OSU and NEXANT–Bechtel. The MASLWR is a small modular pressurized light water reactor relying on NC during both steady-state and transient operation. Each module of the prototypical MASLWR has a net output of 35MWe. Its small size makes the prototypical MASLWR relatively portable and thus well suited for employment in smaller electricity grids. These smaller electricity grids may be found in developing or remote regions. It is postulated that these developing and remote regions may be the focus of grid infrastructure investment in the future. The MASLWR module is also scalable and a number of modules could be used in a “field” concept to generate electricity for larger electricity grids. This project includes also a testing program that has been conducted at OSU MASLWR test facility.

Figure 1: MASLWR conceptual design layout.

The purpose of the OSU MASLWR test facility [2] is to assess the operation of the prototypical MASLWR under normal full pressure and full temperature conditions and to assess the passive safety systems under transient conditions. To this end four tests were conducted and they included one design basis accident and one beyond design basis accident [3].

It has been the goal of OSU that future work be of value not only to specifically investigate the MASLWR concept design further but advance the broad understanding of integral NC reactor plants and accompanying passive safety features as well. Furthermore an IAEA International Collaborative Standard Problem (ICSP) on the OSU MASLWR test facility is envisaged [4].

In the framework of this activity, this paper illustrates a preliminary analysis, performed by TRACE code (V4225), aiming at the evaluation of the code capability in predicting NC phenomena and heat exchange from primary to secondary side by helical SG in superheated condition.

DESCRIPTION OF THE FACILITY AND OF THE EXPERIMENT

2.1 OSU MASLWR facility

The OSU MASLWR test facility [2] shown in figure 2, is scaled at 1:3 length scale, 1:254 volume scale and 1:1 time scale, is constructed entirely of stainless steel, and is
designed for full pressure (11.4 MPa) and full temperature (590 K) prototype operation. The test facility includes three major component packages. The first is the primary circuit which includes the RPV with its internal components (core, Hot Leg (HL) riser, Steam Generators (SG), pressurizer (PRZ)) and Automatic Depressurization System (ADS) blowdown lines, vent lines and sump recirculation lines. The second is the secondary circuit which includes the SG (internal to vessel), feed water pump, and associated feed water and steam valves. The third is the containment structure. The test facility models the containment structure in which the RPV sits as well as the cavity within which the containment structure is located. This modelling is accomplished by using two vessels, a high pressure containment vessel and a cooling pool vessel, with an heat transfer surface between them to establish the proper heat transfer area. In addition to the physical structures that comprise the test facility, there is an instrumentation and control system.

The RPV houses the core, which is modelled with 57 cylindrical rods (56 heater rods and 1 thermocoupled rod) distributed in a 1.86 cm pitch square array with a 1.33 pitch to diameter ratio. The nominal power of each heater rod is 7.1 kW resulting in a maximum core power of 398 kW. The core is shrouded to separate the downcomer region from the core region and ensure all flow enters the core via the bottom and travels the entire heated length (i.e., there is no core bypass flow). The flow exits the un-rodded Lower Plenum (LP) region below the downcomer radially inward into the rodded (but unheated) LP region, then upward into bottom of the core via the 20.3 cm diameter lower core flow plate.

After leaving the core, the flow enters the chimney of the HL riser. The HL riser, extending above the core shroud from the chimney to the Upper Plenum (UP), creates a riser/downcomer configuration to enable NC.

After leaving the top of the HL riser, the flow enters the UP. The UP directs the flow radially outward and then down into the SG coil bundle of the SG section. The UP is separated from the heated upper PRZ section by a 0.95 cm thick baffle plate. The baffle plate has eight 2.54 cm diameter holes, radially located at 12.7 cm and spaced uniformly around the baffle plate periphery which allow free communication of the PRZ pressure to the remainder
of the RPV during normal operation and for volume surges into and/or out of the PRZ due to transients. In the PRZ there are three heater elements, each 4 kW, that are modulated by the test facility control system to maintain nominal primary system static pressure at the desired pressure level (nominally 11.4 MPa).

In the MASLWR concept design, the primary coolant is circulated around the outside of the SG tubes. The test facility tube bundle is a helical coil consisting of fourteen 1.59 cm OD tubes with a total heated length of 86.0 m. This SG is a once through heat exchanger and is located within the pressure vessel in the annular space between the HL riser and the inside surface of the RPV. There are three separate parallel sections (coils) of stainless steel tubes. The outer coil and middle coils consist of five tubes each while the inner coil consists of four tubes. Each coil is separated from the others but joined at a common inlet header to ensure pressure equilibrium within the coil. Cold Main Feed Water (MFW) enters at the bottom of the SG and boils off after traveling a certain length in the SG. This boil off length is a function of both core power and MFW flow rate. Nominally, this boil off length is approximately 40% shorter than the actual length of the SG tubes so the steam will leave the SG superheated. Each SG coil exhausts the superheated steam into a common steam drum from where it is subsequently exhausted to atmosphere via the main steam system.

After leaving the UP, the flow continues downward through the SG section and into the Cold Leg (CL) downcomer region. The CL downcomer region is an annular region bounded by the RPV wall ID on the outside and the HL riser OD on the inside, and the flow area reduces at the HL riser cone. The flow exits the CL downcomer region into the LP to complete the primary flow circuit.

2.2 OSU-MASLWR-002 and 003A tests

The manner of control for the MASLWR facility is to vary the degree of the steam superheat. The main steam superheat is a function of the core power and the feed water flow rate and can be adjusted by varying core power, feedwater flow rate or both. An increase in core power increased the slope in the main steam superheat curve. An increase in the feed water flow rate tended to decrease the slope of the main steam superheat curve. The main steam superheat was calculated using the difference between the main steam saturation temperature and the measured main steam temperature.

The OSU-MASLWR-002 test [3] (NC operation with core power up to 210 kW) and the OSU-MASLWR-003A (NC operation at 210 kW) investigated the primary system flow rates and secondary side steam superheat for a variety of core power levels and feedwater flow rate. OSU-MASLWR-002 stepped power level incrementally to 210 kW, varying feed water flow rate at each power level, and OSU-MASLWR-003A was an extended 210 kW steady test establishing initial conditions for the following test (OSU-MASLWR-003B inadvertent high containment ADS vent line actuation). During these two tests seven different core powers were used as well as nine different feed water flow rates.

3 CODE APPLICATION

3.1 OSU MSLWR TRACE model

The present OSU MSLWR TRACE model [5], shown in figure 3, is developed in order to evaluate the TRACE code capability in predicting NC phenomena and heat exchange from primary to secondary side by helical SG in superheated condition. This model will be used in the envisaged ICSP to simulate the pre test calculation of the selected postulated transients tests.
The “slice nodalization” technique is adopted in the current analysis in order to improve the capability of the code to reproduce NC phenomena. This technique consists in realizing the same dimension in nodes of different zones of the nodalization simulating zones of the plant at the same elevation.

This nodalization models the primary and the secondary circuit. The third circuit is under development.

The primary circuit comprises the core, the HL riser, the SG and the PRZ. The core is modelled with one thermal hydraulic region thermal-coupled with one equivalent active heat structure simulating the 56 electric heaters. The core shroud and the core flange are modelled. After leaving the top of the HL riser, the flow enters the UP divided in two thermal hydraulic regions connected to the PRZ. The PRZ is modelled with two pipes in order to allow NC/convection phenomena. The three different PRZ heater elements are modelled with one equivalent active heat structure. The thick baffle plate is also modelled. After living the UP the flow continues downward through the SG section and into the CL downcomer region.

The internal shells between the primary circuit hot and cold regions are modelled with heat structures thermal-coupled with these two different hydraulic regions in order to simulate the direct heat exchange between them. The RPV shell and the connected insulation, are modelled.

The secondary circuit comprises the common inlet header, the SG coil and the steam drum. The SG coils are simulated with three different equivalent group of pipes in order to simulate the three separate parallel sections (coils) of tubes. The secondary side volumes simulating the helical tubes are, in general, thermal-coupled with more than one volume of the primary side.

Figure 3: MASLWR TRACE model.

3.2 TRACE model qualification process

A nodalization, representing an actual system (integral test facility or nuclear power plant), can be considered qualified when:

- it has a geometrical fidelity with the involved system,
- it reproduces the measured nominal steady-state conditions of the system, and
- it shows a satisfactory behaviour in time dependent conditions.
Taking into account these statements, the standard procedure reported in [6] has been considered.

The facility experimental characterization will be conducted in the framework of the envisaged ICSP in order to evaluate several important facility operational characteristics including operational system/component heat losses, pressure drops (forward/reverse and single/two phase) and other characteristics determined to be of importance during the selected experiments. Therefore the OSU MASLWR nodalization qualification process is still in progress. In particular the pressure drop and heat losses calibration will be performed after the release of the experimental data.

The analysis performed in this preliminary phase of the activity are:
- OSU-MASLWR-002 reference calculation results analysis,
- OSU-MASLWR-002 sensitivities calculation results analysis.

The target of these sensitivity analyses, table 1, is to improve the main thermal hydraulic primary parameters by tuning the heat losses and the secondary side heat transfer coefficient. Another target of these analyses is to analyse the code sensibility to the direct exchange between the primary circuit hot and cold regions and its relevance on the primary side parameters.

### Table 1: Sensitivity Analyses

<table>
<thead>
<tr>
<th>ID</th>
<th>Calculation</th>
<th>Variation form reference calculation</th>
<th>Target of the sensitivity analysis</th>
<th>Results of the sensitivity analysis</th>
<th>Future actions</th>
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</thead>
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<td>REF</td>
<td>Reference calculation</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>1</td>
<td>SEN1</td>
<td>Increase primary side heat losses</td>
<td>Improve the main thermal-hydraulic parameters by tuning the facility energy balance</td>
<td>Improving the main thermal-hydraulic parameters</td>
<td>Calibration of the heat losses in steady state condition at different T level</td>
</tr>
<tr>
<td>2</td>
<td>SEN2</td>
<td>Increase secondary side heat transfer diameter</td>
<td>Improve the main thermal-hydraulic parameters by increasing the secondary side heat transfer coefficient</td>
<td>Improving the main thermal-hydraulic parameters</td>
<td>Evaluation of the capability of the code in predicting the heat exchange primary to secondary side after the complete qualification of the TRACE model</td>
</tr>
<tr>
<td>3</td>
<td>SEN3</td>
<td>Increase heat losses and heat transfer diameter</td>
<td>Improve the main thermal-hydraulic parameters by combining the effect of the previous sensitivity</td>
<td>Improving the main thermal-hydraulic parameters</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>SEN4</td>
<td>Insulation of the internal shell</td>
<td>Show the effect of this direct exchange on the primary side parameters</td>
<td>The primary side parameters are affected by this direct exchange</td>
<td>-</td>
</tr>
</tbody>
</table>

#### 3.3 OSU-MASLWR-002 reference and sensitivity calculation results

These preliminary reference calculated results [5] show a qualitative agreement with regard to the main thermal-hydraulic experimental parameters during the first 2500 s and a qualitative difference in the last 500 s, as shown in figure 4 a for the core outlet/inlet temperature. This difference is due to the different energy balance of the calculated results during the last part of the transient.

The core flow is well predicted in the interval between about 280 s - 2500 s. It shows an underestimation compared to the experimental data in the last 500 s of the test, pressure drop calibration is required, and an overestimation at the start of the simulation, due to the preliminary phase used to reach the initial conditions of the test.
The core delta T is well predicted during the first 2500 s and it shows an overestimation in the last 500 s of the transients, figure 4 b.

The PRZ level is qualitatively predicted during the first 2500 s. Anyway the PRZ pressure behaviour needs to be further investigated because of discrepancies with experimental data.

The secondary side temperature at the outlet of the helical tubes shows a good agreement compared with experimental data in the first 750 s, but shows a continuous oscillation between saturated and superheated conditions for the rest of the transient. That shows the difficult of reaching stable superheated conditions in the secondary circuit during the transient simulation. In the last 500 s the fluid at the outlet of the helical tubes is in superheated conditions only for a short time, figure 5 a.

The main steam pressure shows discrepancies compared with the experimental data. A detailed model of the main steam line is necessary to further investigate this parameter.

The results of the sensitivity analyses show a general improvement of the main thermal hydraulic parameters by tuning the heat losses and the secondary side heat transfer coefficient, figure 5 b.

Figure 4: Experimental and reference calculated data for a) T at the core outlet/inlet, and b) core delta T.

Figure 5: a) Experimental and reference calculated data for T at the SG coil outlet, and b) experimental and sensitivities calculated data for T at the core outlet/inlet.
These analyses show also that the primary side parameters are affected by the direct heat exchange between the primary circuit hot and cold region. An overestimation of this heat exchange produces an overestimation of the core inlet temperature.

4 CONCLUSIONS

This paper illustrates a preliminary analysis, performed by TRACE code, aiming at the evaluation of the code capability in predicting NC phenomena and heat exchange from primary to secondary side by helical SG in superheated condition.

The preliminary results, obtained by simulating the OSU-MASLWR-002, show a qualitative agreement with regard to the main thermal-hydraulic experimental parameters. These results also show that primary circuit stores more energy compared with the experimental data and show that the secondary circuit has difficulties in reaching stable superheated conditions during the transient simulation.

The results of the sensitivity analyses show a general improvement of the main thermal hydraulic parameters by tuning the heat losses and the secondary side heat transfer coefficient and show that the primary side parameters are affected by the direct heat exchange between the primary circuit hot and cold region.

However to evaluate the real capability of the code in predicting heat exchange from primary to secondary side by helical SG in superheated condition, is necessary, after the release of the experimental data, the complete qualification of several important operational characteristics of the facility including operational system/component heat losses and pressure drops (forward/reverse and single/two phase).

REFERENCES


