ANALYSIS OF NATURAL CIRCULATION PERFORMANCE OF THE DESIGNED THERMOHYDRAULIC TEST LOOP

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ABSTRACT

This paper discusses the results of the simulation of a natural circulation (NC) loop performance with the aid of Relap5 thermohydraulic system code. This loop has been constructed for the analysis of relevant thermohydraulic parameters of a nuclear reactor. In this study, the NC behavior of the designed loop is analyzed with the use of NC flow maps (NCFMs) that were obtained from relevant experimental data gathered from PWR simulators. The obtained results are put in referenced NCFMs. The comparison shows that the NC behavior of the designed loop is in good agreement with the NC behavior of addressed test facilities in the NCFMs.

1 INTRODUCTION

The complex set of physical phenomena that occur in a gravity environment when geometrically distinct heat sink and heat source are connected by a fluid flow path can be identified as Natural Circulation (NC). No external sources of mechanical energy for the fluid motion are involved when NC is established.

NC is an important mechanism in several industrial systems and the knowledge of its behavior is of interest to nuclear reactor design, operation and safety \([1], [2]\). In nuclear technology, this is especially true for new concepts that largely exploit the gravity forces for the heat removal capability \([3]\). Natural circulation in a PWR occurs due to the presence of the heat source (core) and the heat sink constituted by the steam generators. In a gravity environment, with core located at a lower elevation than steam generators, driving forces occur that generate flow rate suitable for removing nuclear fission power. Following accidents originated by recirculation pumps trip or even small break Loss of Coolant Accidents, NC may constitute the main mechanism to transfer energy from the core to the steam generators, therefore keeping the NPP in a safe condition. At present, the NC core power removal capability is only exploited for accident situations, basically to demonstrate the inherent safety features of the plants \([4]\).
The evaluation of the NC Performance (NCP) of experimental facilities simulating the integral system behavior of PWR has been the object of previous activities, [5], [6] and [7]. Data have been gathered and analyzed coming from the PWR simulators Semiscale, Spes, Lobi, Bethsy, Pkl and Lstf.

In order to evaluate the NCP of the mentioned facilities, significant information comes from the analysis of the trend of the core inlet mass flow rate and the primary loop mass inventory. The flow rate and the residual masses have been normalized taking into account of the volume of each facility and of the power level (typically n times 1% of the nominal core power, where n ranges between 1 and 5) utilized in the selected experiment. Natural Circulation Flow Maps (NCFMs) have been obtained from the experimental data. With making reference the obtained NCFMs [8], one can evaluae the NCP of the other NC loops.

The TTL-1 loop has been designed and operated at Atomic Energy Organization of Iran (AEOI) with cooperation of Department of Physics and Nuclear Science (DPNS) of University of Amir Kabir, in the context of a wider research program especially in NC field [9].

The Relap5 system code has been developed to predict the behavior of Nuclear Power Plants during transient and accident conditions and has been used extensively at Department of Mechanical, Nuclear and Production Engineering (DIMNP), University of Pisa for several activities [10].

In this activity the Relap5 system code is used to evaluate the NCP of above-mentioned loop. The specific goals of this paper can be summarized as follows:

- To give an overview of the NCFMs based upon experimental data;
- To show the use of the NCFMs for assessing the NC behavior of TTL-1 loop.

2 LOOP DESCRIPTION AND NODALIZATION

The TTL-1 apparatus is an integral test facility (ITF) that has been designed and operated at AEOI, in the context of wider research program for the analysis of relevant thermohydraulic parameters of a nuclear reactor. Changes in the electric power and on the elevation of the heat sink relatively to the heat source and orientation of heat sink are allowed. The sketch of the loop is shown in Figure 1. It includes main pump, preheater, test section (TS), cooler, pressurizer, power supply, instrumentation apparatus, and piping. Further detail can be found in Ref [9]. The adopted nodalization sketch, suitable for Relap5/m3.3 code is shown in Figure 2.

3 CALCULATIONS AND RESULTS

The study performed about design optimization [9], suitable for achievement to high NCP, gives the Figure 1 sketch as selected configuration in this study. The working parameters of performed study and main dimensions of the loop can be found in Table 1.

In the present work the heater power is kept constant at assigned value in the simulation time and after reaching to a maximum NC flow rate, the mass inventory of the loop is decreased with a draining scenario in the TS inlet. Concerned results of the calculations are summarized in Figures 3-8.

4 ANALYSIS OF NC BEHAVIOR OF THE LOOP

In order to evaluate of NCP of the designed loop, the two NC flow maps; NC Flow Regime Map (NCFRM) and NC System Performance Map (NCSPM) that have been obtained from NC experimental data gathered from PWR simulators [8], are used hear after.
Figure 1: TTL-1 Test Loop Sketch

Figure 2: TTL-1 Relap5/M3 Nodalization

Table 1: List of working parameters

<table>
<thead>
<tr>
<th>Working Conditions</th>
<th>Water</th>
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<tbody>
<tr>
<td>Working Fluid</td>
<td>Water</td>
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<tr>
<td>Loop height (m)</td>
<td>8.5</td>
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<tr>
<td>Loop Pressure (Pa)</td>
<td>10e5</td>
</tr>
<tr>
<td>Simulation Time(s)</td>
<td>30e3</td>
</tr>
<tr>
<td>Heater Power (W)</td>
<td>30e6</td>
</tr>
<tr>
<td>Average Heat Flux (W/m²)</td>
<td>6.82e5</td>
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<tr>
<td>Loop Mass Inventory (kg)</td>
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<tr>
<td>Loop Volume (m³)</td>
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<tr>
<td>Test Section Dimension</td>
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<td>Heater O.D. (mm)</td>
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<tr>
<td>Heated Length (m)</td>
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<tr>
<td>External Tube I.D. (mm)</td>
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<tr>
<td>Length (m)</td>
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</tr>
<tr>
<td>Net Elevation</td>
<td></td>
</tr>
<tr>
<td>Cooler-Center of Heater Elevation (m)</td>
<td>8</td>
</tr>
</tbody>
</table>
Figure 3: Mass flow rate versus Time

Figure 4: Heater surface temperature along the heater length

Figure 5: Void fraction along the TS

Figure 6: DNBR along the heater length

Figure 7: Void fraction versus Time

Figure 8: Heater surface temperature versus Time
4.1 Use of the NCFRM

Four main flow patterns were characterized depending upon the value of the mass inventory of the primary loop [11].

- Single phase (SP) NC with no void in the primary system excluding the pressuriser and the upper head;
- Stable co-current two-phase (STP) NC with mass flow rate increasing when decreasing primary system fluid inventory;
- Unstable two-phase (UTP) NC and occurrence of siphon condensation [12];
- Stable reflux condensation (RC) with liquid flowing countercurrent to steam in the hot legs: flow rate is sufficient to remove core power till loop mass inventory achieves values as low as 30-40% of the nominal values.

Based on the results of computer codes calculations and of experiments performed in the PWR simulators, the NC regimes are characterized in figure 9, taken from Ref. [13]. The mass flow rate at core inlet is given as a function of the primary system mass inventory. Other than the flow regimes, the transition zones and the occurrence of dryout situation at mass inventory roughly below the 40% of the nominal value can be noted. The dryout occurs owing to the sharp decrease in the heat transfer coefficient in the core when void fraction and mass velocities reach a lower boundary. The wideness of the transition zones comes from uncertainties of the database, generally originated by lack of quality assurance, as well as from differences in some boundary and initial conditions.

The original NCFRM has been obtained for maximum 7% of nominal power of ITFs. In the present study the calculation is performed in 100% heater power; then for better judgment the obtained results are put in the upper part of “extrapolated” map (figure 9). Comparison shows the following observations:

- NC behavior of the TTL-1 NC loop is similar to that of the ‘reference’ PWR simulator loops.
- At high power working conditions the STP flow regime is predominant flow regime;
- Occurrence of dryout conditions is shifted to higher mass inventories;

And finally, due to the higher heat transfer coefficient of two phase flow regimes and its wider range at nominal power working conditions, removing of high percentage of reactor power is possible by NC and it is important in future NC nuclear reactor design.

4.2 Use of the NCSPM

The similitude in the geometry and in the operational characteristics of the PWR simulators mentioned in the chapters above allowed a direct comparison between results of NC experiments. The database gathered from ten experiments performed in the six ITF has been used in refs. [6] and [7] to establish a NCSPM.

Measured values of core inlet flow rate (G, Kg/s), core power (P, MW), primary system fluid mass inventory (RM, Kg) and net volume of the primary system (V=const., m3) have been used for setting up the NCSPM. The diagram G/P versus RM/V has been preferred for the NCSPM over other possible choices including non-dimensional quantities.

The experimental database from ITF (six ITF, ten experiments) and the envelope of curves are given in figures 10 and 11, respectively. The envelope in figure 11 is assumed to constitute the NCSPM of PWR at decay core power.
Figure 9: Obtained Results in NCFRM

Figure 10: NC. System behavior measured in ten experiments performed in six PWR simulators

Figure 11: Natural Circulation Flow Map achieved from the envelope of curves in PWR simulator
As shown in Fig. 11 the NC behavior of designed loop is more or less the same as other ITFs and its performance is inside the envelope, even though in comparison with others, it has small performance; the effective parameters such as system pressure, linear power, pipe diameter, system volume, heat sink size, heat losses to the environment and loop height should be considered.

5 CONCLUSIONS

The performed activity allowed the analysis of the natural circulation behavior of the designed NC loop installed at the atomic energy organization of Iran by the use of the referenced natural circulation flow maps. The referenced NCFMs that allowed the judgment of performance of natural circulation of pressurized water reactors are applicable for other NC loops and they are not restricted to the same types as those used for deriving the maps. Conclusions can be summarized as follows:

• Comparison of obtained results in NCFRM show that the NC behavior of the designed loop is same as referenced loops.
• In nominal powers the SP zone is limited and instead of it the STP zone takes a wider range and the UTP and RC zones are combined and constitute one zone and finally the dryout will occurred at lower mass inventories.
• Due to the higher heat transfer coefficient of two phase flow regimes and its wider range at nominal power working conditions, removing of high percentage of reactor power is possible by NC and it is important in future NC nuclear reactor design.
• Analysis of the obtained results in NCSPM show that the NC behavior of designed loop is more or less the same as other ITFs.
• NCP of the designed loop is inside the envelope, even though in comparison with others, it has small performance; the effective parameters such as system pressure, linear power, pipe diameter, system volume, heat sink size, heat losses to the environment and loop height should be considered.

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