The 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH-14
Toronto, Ontario, Canada, September 25-30, 2011

NURETH14-432

ANALYSIS OF THERMAL STRATIFICATION IN THE UPPER PLENUM OF THE "MONJU" REACTOR VESSEL – EFFECT OF CHAMFER OF FLOW-HOLE ON THERMAL STRATIFICATION -

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Abstract

The analysis of thermal stratification in the upper plenum of the "Monju" reactor vessel is an IAEA Coordinated Research Program (CRP). In spite of many attempts to predict the height of the thermal stratification interface, all calculated results indicated a higher height at approximately 10 minutes after the transient than what was measured at "Monju". Hence, the present paper discusses the effect of chamfer of the flow-holes and heat capacity of the upper instrumental structure (UIS) on the height of the thermal stratification interface, using the 3D CFD code. The chamfer hypothesis stems from the engineer's intuition that the edges of the flow-holes should have a rounded edge or chamfer. A flow-hole with chamfer exhibits a much lower local friction loss coefficient of the sodium than a straight-edge flow-hole, resulting in a flow increase from the flow-holes. The presence of chamfer is assumed although there is no direct information about them. Three cases were calculated, one case without chamfer and one case with chamfer on the flow-hole edge, to investigate the effect on the interface behavior. Third one is a calculation taking into account the chamfer on the edge and heat capacity of UIS. In the case of calculation taking into account flow-holes with chamfer and the heat capacity of UIS, the height of the thermal stratification interface is closer to the experimental result.

Introduction

The analysis of thermal stratification phenomenon in the upper plenum of the "Monju" reactor is one of coordinated research programs (CRP) organized by IAEA. Temperature distributions during this phenomenon in the upper plenum of the reactor vessel were measured at the "Monju" when the plant was scrammed from 40% power in electric (45% in thermal) as the turbine trip test. The primary heat transport system (HTS) and the secondary HTS were cooled by the forced circulation with small capacity motors during the transient. The flowrates in the HTSs were decreased to approximately 1/10 of the rated conditions. This result is summarized in the report by Yoshikawa and Minami [1] as a document of IAEA CRP. Organizations such as CEA in France, ANL in USA, IPPE in Russia, IGCAR in India, KAERI in Korea and CIAE in China are participating in the benchmark analysis. Although each organization calculated the phenomenon using 2D or 3D model of CFD codes, the calculated thermal stratification interface rose higher than the measured result at around 10 minutes after the transient. The participating organizations discussed the causes which effect on the interface rising velocity in the meeting held on 16 November 2010 at ANL in USA. The following possible causes are proposed.

(1) Asymmetric configuration in the upper plenum
(2) Heat transfer between outer sodium and inner sodium via the inner shroud with flow holes
(3) Upper instrumental structure (UIS) modelling
(4) Calculation models of turbulent or laminar flows
(5) Configuration of flow-holes

In spite of our precise calculation models of the upper plenum including items (1), (2), and (3), all calculated results were almost the same and calculated results predicted the thermal stratification interface higher than that of the test result according to the calculation in advance. The effect of the item (4) was confirmed as negligible small after several minutes from the start of the transient by the several organizations participating in the IAEA CRP. Therefore, the remaining cause is discussed in the present paper. The effect of the heat capacity relating the item (3) is also confirmed in the present study. ANL proposed to check the effect of the flow hole with a rounded edge rather than a straight-edge. When an engineer designs the hole, it is the engineer's intuition that the edges of the flow-holes should have a rounded edge or a chamfer. It is well known that the loss coefficient of the pipe inlet with the rounded edge becomes drastically smaller than that with the straight-edge as shown in **Fig. 1**[2]. The smaller local loss coefficient will help to suppress the interface rising velocity by discharging a larger amount of sodium from the flow holes. As a matter of fact, pressure loss of the flow-hole was already discussed by Doi & Muramatsu [3] to have the better calculated result to fit to the test result. Since they modelled 120-degree sector of the plenum with the cylindrical coordinate, they could not calculate directly the effect of the configuration of the flow-hole. They assumed the local loss coefficient of 1.6 at the flow-holes on second stage and 0 at the flow-holes on the first stage. When one thinks about the flow of a pipe with the straight edge, the loss coefficients at the inlet from the bulk and outlet to a bulk are approximately 0.5 and 1.0 respectively. They obviously took into account the loss coefficient reduction due to rounded edge on the flow-hole. However, the difference of the loss coefficients between the stages is somewhat intentional. In the present analysis, the predictability is discussed whether the 3D-CFD code can calculate the difference between the straight edge and the edge with the chamfer.

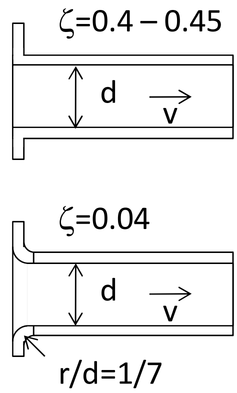

Figure 1 Local loss coefficient at the pipe inlet

1. General description about benchmark test

1.1 Description about upper plenum of "Monju"

The upper plenum of the "Monju" reactor is illustrated in **Fig. 2**. It consists of a reactor vessel of 7060 mm in inner diameter and 50 mm in thickness, an upper core structure (UCS) with flow guide tubes, a fuel handling machine, a plug for thermocouples, and an inner barrel of 6600 mm in outer diameter and 40 mm in thickness with two-stage flow-holes. Outer diameter of the plug is 200 mm. Since there are three loops for the primary HTS, three outlet nozzles are welded on the reactor vessel at the level of EL27050 mm. The driver region of the core is located beneath the UCS. Outer diameter of upper instrumental structure (UIS) is 1997 mm.

Levels of the upper support plate, the core top surface and the liquid sodium are EL26120 mm, EL27050 mm and EL33050 mm, respectively. The sodium flow from the core is rectified by the flow guide tubes and collided on the honey comb structure which holds flow guide tubes and control rod guide tubes. A part of sodium is flow out of flow-holes to the space between the reactor vessel and the inner barrel. Sodium going upward the upper plenum is overflowed from the inner barrel to the above mentioned space.

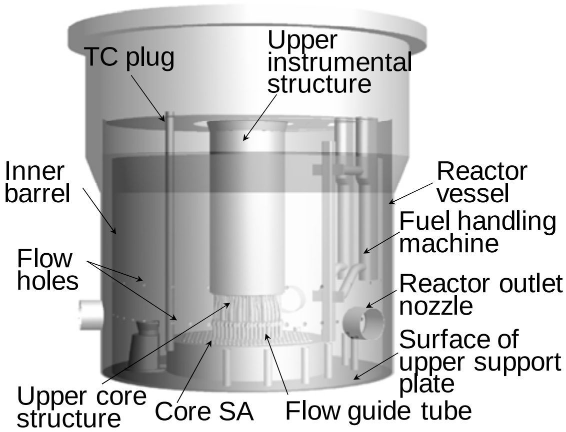

Figure 2 Components inside the upper plenum of "Monju"

Number of flow holes provided at the first stage is 48, and the diameter is 92 mm. These are provided at the level of EL27750 mm. Number of flow holes at the second stage is 24 with the same diameter as the first one. These are provided at the level of EL28670 mm. Existence of chamfer or the roundness on the edge is not clear. The vertical positions of thermocouples on the TC-plug are reported in the reference [1], and the peripheral location is mentioned by Doi et al. [4]. Three thermocouples are provided on the same height. One is facing to the direction of the core, i.e., 0 degree, and the other two are installed at rotated locations by 60 degrees in clockwise and counter-clockwise.

1.2 General description of turbine trip test

Table 1 Initial major parameters at turbine trip test at "Monju"

Items	Measured
Thermal power (MW/loop)	106
Primary coolant flow rate (kg/s/loop)	702.8
Primary hot leg temperature (^{o}C)	485
Primary cold leg temperature (^{o}C)	362
Secondary coolant flow rate for B (kg/s/loop)	394.4
Secondary hot leg temperature for A&B (^{o}C)	485
Secondary cold leg temperature for A&B (^{o}C)	285
Temperatures at exit of subassemblies for channel 1 to 8	512-513, 509-511, 510-515, 500-513, 499-511, 483-509, 483-509, 427

A turbine trip test at 45% thermal power of "Monju" was conducted in 1995 to investigate the overall functions of the plant and the capability of the air cooling system (ACS) in an actual situation. **Table 1** shows important parameters of the plant before the transient. In this test, an abnormal situation of the turbine was assumed. The reactor was scrammed by the signal of turbine trip, and then pumps in primary and secondary loops were tripped. Pony motors took over operation when flow rates in primary and secondary loops were approximately 10% and 8%, respectively. This means that flow rates in the HTSs are kept at 10 % and 8 % of the rated ones respectively during the transient except the very beginning of the transient.

Table 2 shows a time table of operation conditions according to the interlocks. During this test, thermal stratification appeared in the upper plenum as reported in reference [1].

Table 2 Major plant responses after turbine trip

Time (sec)	Event
0	A signal input to cause turbine trip
0.2	Reactor scram
	Trip of pumps in the primary and secondary HTSs and trip of feed water pumps
1.0	Start-up of air coolers in the secondary HTS
1.5	Start-up of pony motors in the primary and secondary HTSs and trip of generator
26	Transfer to low flow rate forced circulation by pony motors in the primary HTS
27	Rated air flow rate of the air cooler
55	Closure of the inlet stop valve of the steam generators
75	Transfer to low flow rate forced circulation by pony motors in the secondary HTS
800	Zero flow rate of feed water
6300	Operation mode change of the air coolers from high to low forced circulation

2. Analysis

2.1 Analytical model

The upper plenum with the internals mentioned in the previous chapter was modelled with the CAD at first, then, a calculation model with 25 million tetrahedral meshes is created by the meshing software. **Figure 3** shows the overall meshing configuration of the upper plenum when the plenum is cut by the line connecting between the center of the core and the center of the TC-plug. Inside of the upper plenum is meshed by the meshing software ANSYS "Meshing" on the basis of the 3D CAD data made by the ANSYS "DesignModeler". Honey comb structures for flow guide, inner barrel, the fuel handling machine, and other internals are modelled using the tetrahedral meshes. However, hexahedral meshes are used for the layers of the outer shroud. The UIS located at the center of the figure is treated as a body with heat capacity consisting of steel and sodium. In the heat transfer calculation, no sodium flow is assumed inside the UIS, and heat is conducted from the center to the surface, then is transferred to the sodium in the upper plenum by convection. The fuel handling machine which is not illustrated in the figure is treated as a body without heat capacity. A column illustrated at the center illustrates meshes for the control rod guide tube. Since the flow guide tube above the core are seemed to be important to rectify the flow, configurations are considered in the present analysis. However, the meshes for flow guide tubes are not clear in the figure. The TC-plug is situated on the left hand side of the figure. Since three temperatures were measured on the same level, these locations are modelled properly in order to calculate the different temperature. The inner barrel is modelled so as to calculate the heat transfer between sodium inside and outside the inner barrel.

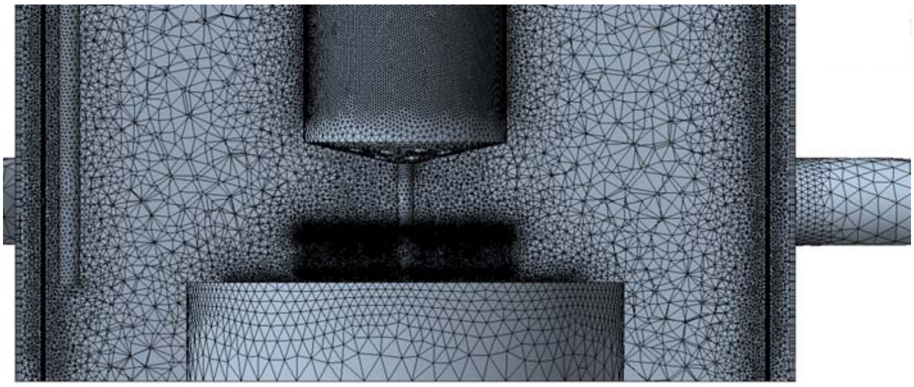

Figure 3   Tetrahedral mesh configuration in the plenum

Figure 4 shows the assumed configuration of the flow hole with chamfer.   The original model is illustrated on the left hand side.   Although there is no information on the configuration, 5 mm chamfer is assumed on the both sides of the flow-hole in the present analysis.   According to the discussion by Doi and Muramatsu [3], the shape of the edge should be rounded one.   However, the edge with chamfer is selected because of easiness of meshing and also no-information about the radius of curvature.   Even if the configuration is not correct, the effect of the chamfer on the rising velocity of the thermal stratification can be confirmed by the present calculation.

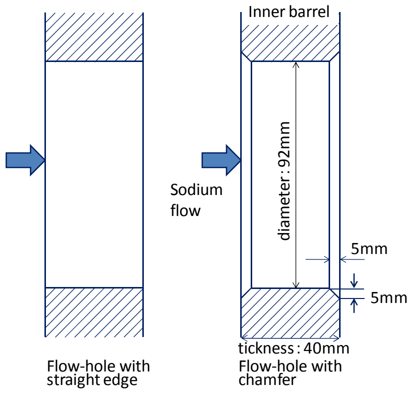

Figure 4   Assumed chamfer on flow hole edge

Figure 5a and **5b** illustrate the meshes around the flow hole for both cases.   The inner barrel is illustrated at the center of the figure and the reactor vessel is situated on the end of right hand side.   Since the mesh size is not very small due to a lot of holes, the shape is somewhat rough.   However, difference of meshes between the two cases can be recognized from the figures.

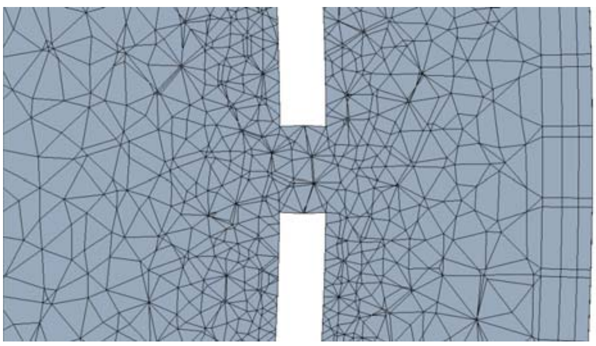

Figure 5a   Meshes around the flow-hole with straight edge (Basic case)

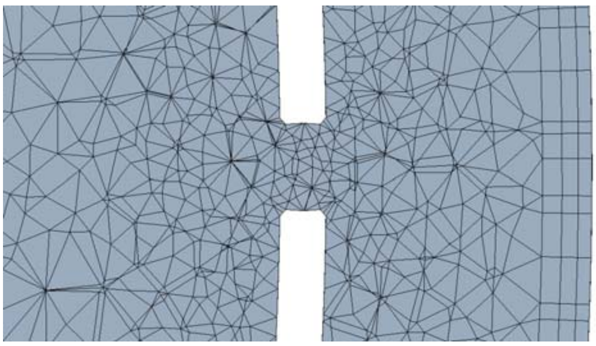

Figure 5b   Meshes around the flow-hole with chamfer

2.2 Analytical conditions

The core configuration in the test is illustrated in **Figure 6**. Temperatures from the subassemblies near the center of the core are higher that from the peripheral subassemblies, and flowrates are larger too. Appropriate result cannot be obtained if the proper boundary conditions are not given to the code. Outlet mass flowrates and temperatures for each array of subassemblies are given in the reference [1] as time tables. **Figure 7** illustrates the example of trends of boundary conditions for the representative channels of the inner driver core, outer driver core and the blanket subassemblies. Therefore, mass flowrates are converted to velocities from the subassemblies with circular outlet of 80 mm. These initial flowrates are approximately 98 % of the flowrates reported by Doi et al.[4] Hence, the flowrates in the IAEA benchmark calculated by 1D code are lower than the measured result at “Monju”. Outlet temperatures from each sub-assembly groups are basically measured one. Another boundary condition in terms of pressure is provided at the outlet of the hot legs. The length of hot leg with 790.6 mm in inner diameter is approximately 4 m.

The ANSYS Fluent-12.0 is used to solve the 3D thermal-hydraulics. In the analysis, the standard k-ε model, standard wall function and SIMPLE method are applied to solve the momentum equation coupled with the equation of continuity. The accuracy of the turbulence in energy equation is 2nd order upwind.

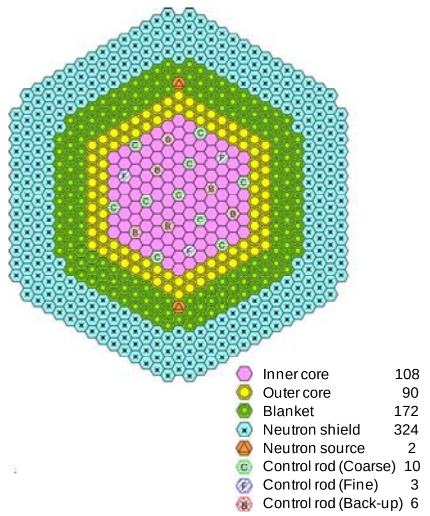

Figure 6 Scheme of the reactor core at the test

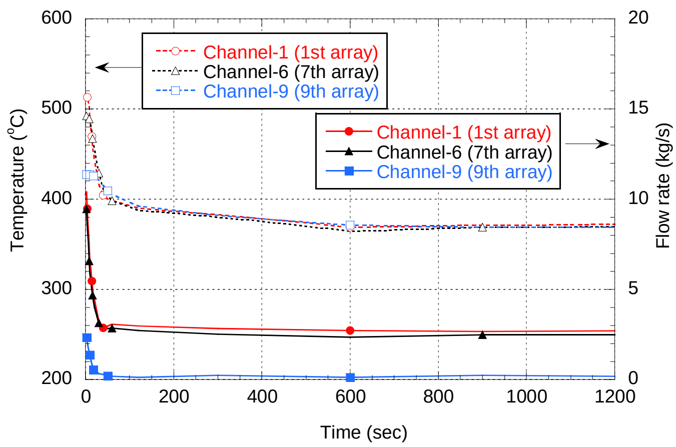

Figure 7 Example of boundary conditions for the calculation

2.3 Analytical results

After the initial steady state calculation, the transient calculation is conducted with the time step of 1 second. Based on common sense, although this is a very large time step, the sensitivity of the time mesh was checked beforehand. The time step is lather large for this sort of calculation. However, since the major objective of the present calculation is to confirm the effect of chamfer on the flow-hole edge, it obliged to keep eyes closed to degradation of the accuracy because of the calculation time.

Figure 8 shows the comparison between two calculations under the different flow-hole configurations. The height 0 stands for the liquid sodium surface. The parameter in the legend shows time after the transient. The character "S" stands for flow-hole with straight edge, and "C" stands for flow-hole with chamfer. Since three calculated results at the same height where three thermocouples are installed are plotted in the same figure, the calculated results have widths. It is obvious from the comparison that the analysis with chamfer results in a lower thermal stratification interface. The interface is lowered by approximately 300 mm at 600 seconds after the start of the test. If the edge has curvature, height of the thermal stratification interface will be much lower. Therefore, much precise meshing around the flow-hole is required to trace the height of the thermal stratification if the flow-hole has the round edge.

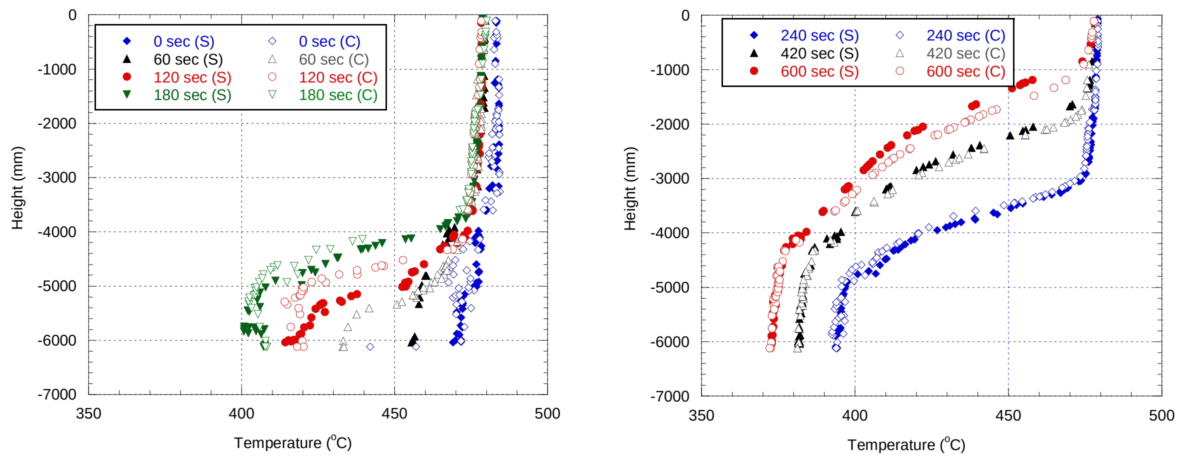

Figure 8 Comparison between calculated results for flow-hole with straight edge (basic case) and for flow-hole with chamfer

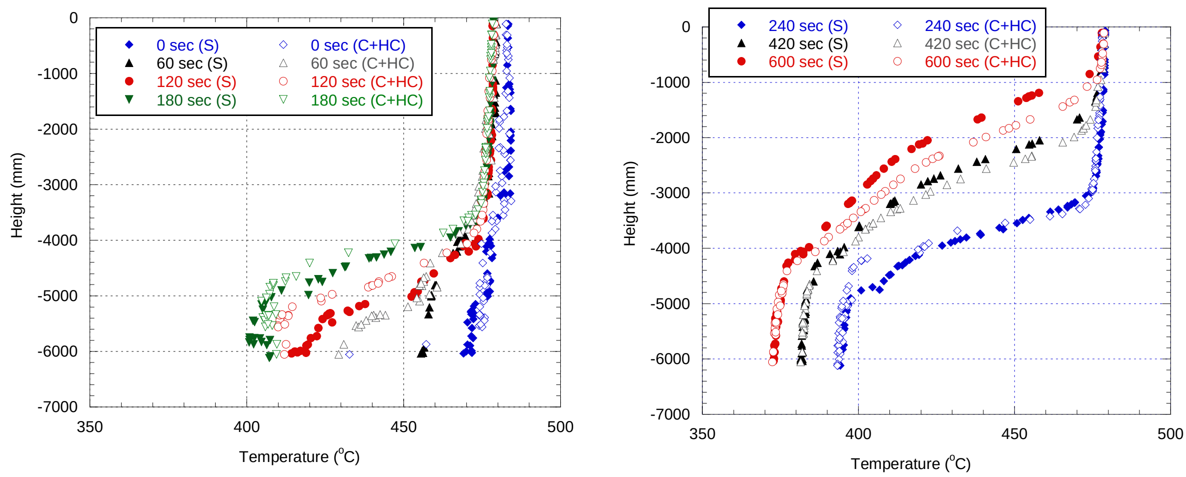

Figure 9 Comparison between calculated results for flow-hole with straight edge and for flow-hole with chamfer

Figure 9 shows the comparison of calculations between the basic case and the result taking into account chamfer and heat capacity of the UIS. The character "C+HC" stands for flow-hole with chamfer and heat capacity of the UIS. It is assumed that the UIS consists of steel and sodium with no flow. As shown in the figure, the interface at 600 seconds is lowered by 500 mm compared with the basic case. Therefore, the effect of the heat capacity of the UIS on the interface cannot be neglected.

A comparison between the test result and the simulation is illustrated in **Fig. 10** when the above mentioned effects are reflected in the analysis. The calculated results trace the rising of the thermal stratification interface in general. However, the height of the thermal stratification interface is calculated lower before 240 seconds, and the thermal stratification interface is calculated higher than the test result after 420 seconds. Especially, the thermal stratification interface is higher than the experimental result by approximately 1.0 m at 600 seconds.

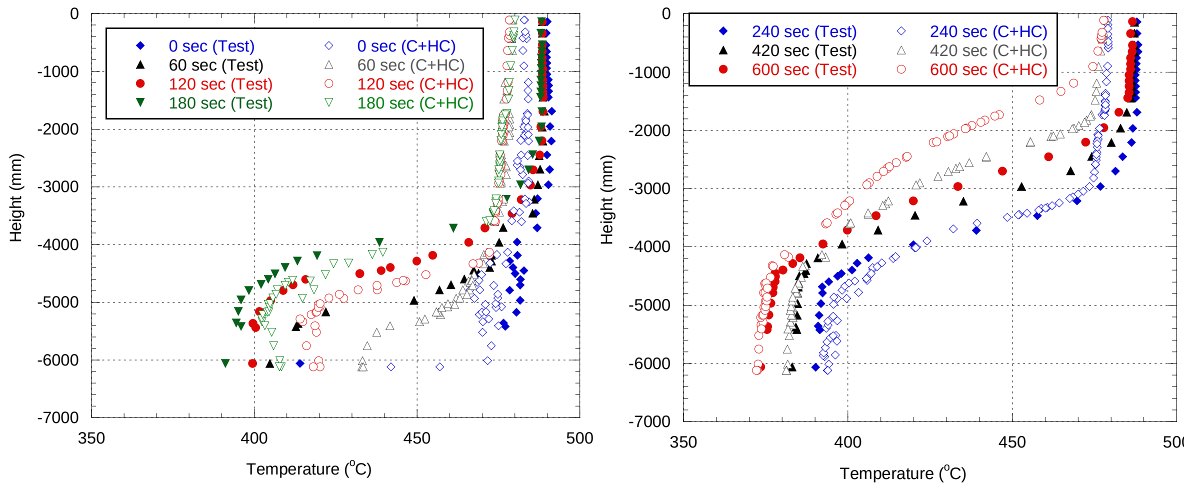

Figure 10 Comparison between measured results and calculation taking into account the flow-hole with chamfer and heat capacity of UIS

3. Discussion

It is clarified that the calculated total flowrate from each subassembly groups in the IAEA benchmark calculation are approximately 98 % of the measured flowrate at the "Monju" plant, when the reference [4] is investigated. Outlet temperatures from each subassembly groups are measured results except that for shielding. Therefore, the boundary conditions for the IAEA benchmark are somewhat hybrid. In this case, amount of energy input into the upper plenum has an error when the flowrate is not accurately calculated. When one checks the temperature distribution near the surface of liquid sodium, calculated result underestimates the measured temperature by approximately 8 °C in Fig. 10. There is a possibility that this may be caused by the boundary conditions of flowrate and temperature, which is different from the actual test. Another factor that may effect on the temperature distribution is the bypass flow. This flow of "Monju" is supposed to be less than 1% of the total flow. It may have a little effect on the temperature distribution close to the core outlet at time 0. However, the bypass flow has almost no effect on the temperature distribution after the main primary pumps are tripped because the driving force to circulate the bypass channel is very small. In some case, the direction of the driving force may be reversed for the bypass channel.

In order to keep the consistency of the boundary conditions from the stand point of energy put in the upper plenum, 1D analysis has been conducted using the NETFLOW++ code [5] that is validated using the plant data measured at "Monju". The calculated flowrates and temperatures at the outlet of the subassemblies shown in **Fig. 11** are given to the CFD code as the boundary conditions. The Comparison between the calculated results and the measured results are shown in **Fig. 12**. Almost perfect agreement is obtained for the temperature distribution before 3 minutes. The thermal stratification interfaces beyond three minutes are also predicted with better accuracy than before. However, further discussion is necessary in order to get the perfect coincidence. This may be possible if precise configuration of the flow-hole is informed.

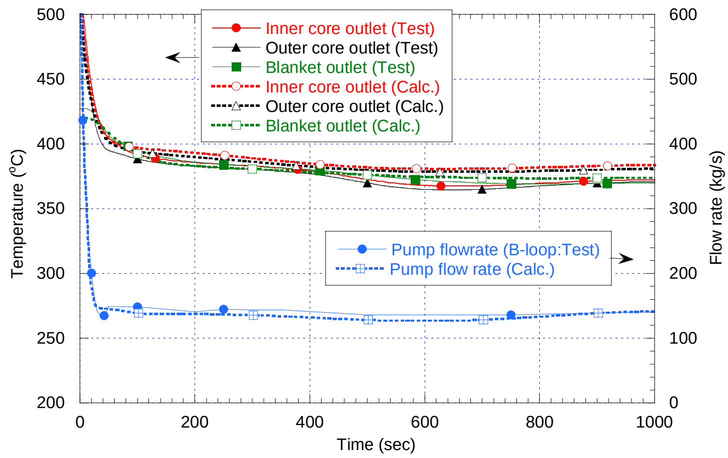

Figure 11 Comparison between test results and calculated results using the NETFLOW++ code for temperatures at the outlet of classified subassemblies and pump flow rate

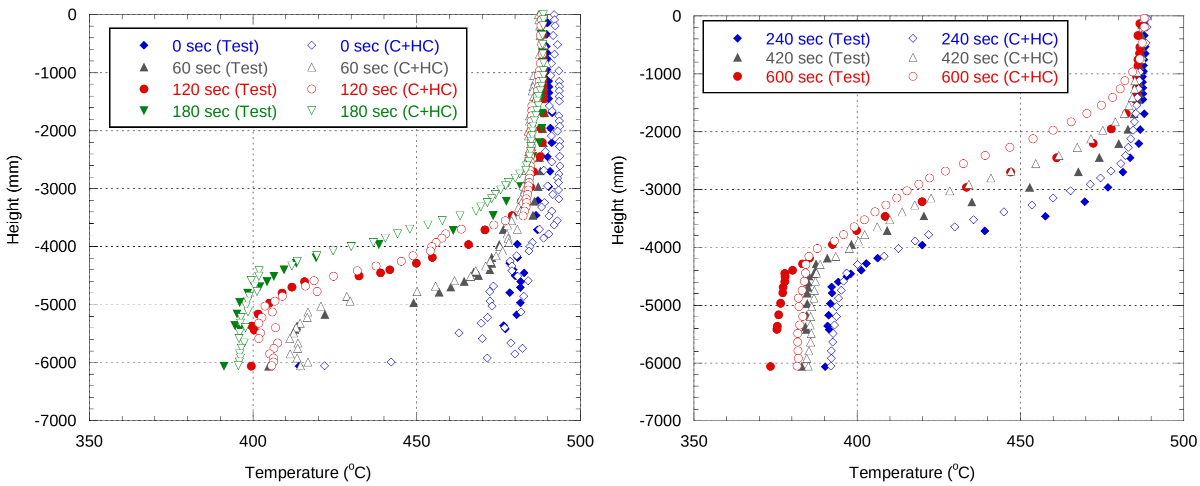

Figure 12 Comparison between measured results and calculation taking into account the flow-hole with chamfer, heat capacity of UIS and boundary conditions at the outlet of the subassemblies

As far as the thermal stratification in the upper plenum is concerned, the accurate modelling of the internals in the upper plenum has only a small effect on the thermal stratification problem. However, modelling of the configuration of the flow-hole and heat capacity of the UIS has a possibility to predict the temperature distributions in the upper plenum during the transient as indicated in the present analysis. A real configuration should be obtained in order to investigate precisely the thermal stratification phenomenon.

4. Conclusion

The thermal stratification in the reactor vessel of "Monju" is calculated using the 3D CFD code. In the present analysis, the full sector of the upper plenum of "Monju" reactor is modeled. Two kinds of meshes have been generated to compare the effect of the chamfer on the flow-hole edge. One is the flow hole with the straight edge, the other one is the flow-hole with chamfer. The configuration of the chamfer on the both edges is assumed in the analysis. Other calculation conditions for the two models are quite same.

(1) The difference of flow-hole configurations can be calculated with the CFD code.
(2) The analysis with chamfer results in a slow rising velocity of the thermal stratification interface, which is closer to the experimental result. However, the calculated rising velocity is still faster than the experimental result.
(3) The comparison shows that the real configuration of the flow-hole should be reflected to the meshing.
(4) Heat capacity of the upper instrumental structure also has an effect on decreasing the rising velocity of the thermal stratification interface.
(5) Good agreement is obtained when the boundary conditions are calculated by the validated 1D code.

5. References

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