THERMAL LOADING TEST OF NUCLEAR REACTOR NOZZLE MODEL USING SODIUM LOOP

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SUMMARY

It is generally well-known that thermal shock occurs at the inner surface of the inlet and outlet nozzles of a fast breeder reactor by sodium when the reactor is started and stopped in usual operation or by any accidents. It is, however, very difficult that the exact transient stress or strain by thermal shock can be obtained quantitatively at the area, experimentally and also theoretically.

We recently tried several tests using a sodium testing loop to obtain experimentally the values of thermal strain and to compare the results with the theoretical values. Many chromel-alumel thermo-couples were attached to stainless steel nozzle model, in which the shell and pipe thickness was 15 and 3 mm, respectively, to measure the temperature distributions on the inner and outer surface and radial direction and some high temperature strain gages (Microdot type) were welded on the outer surface to measure the thermal strain before the model was set in the sodium loop.

Thermal loading was given by flowing very rapidly a hot sodium into the testing part, nozzle model, in which a cold sodium had been flown. As an example, the expansion tank and nozzle model sodium temperature was 600 and 203 °C respectively before the thermal shock test was performed. In this test, the hot sodium was flown into the nozzle model with 94 l/min flow rate and the following temperature change was obtained at each place of the radial direction of the nozzle corner (nozzle corner thickness = 18 mm):

<table>
<thead>
<tr>
<th>Depth from outer surface (mm)</th>
<th>Time after sodium temperature change (sec)</th>
<th>Temperature change (°C/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9.5</td>
<td>2.8</td>
</tr>
<tr>
<td>5</td>
<td>7.0</td>
<td>4.8</td>
</tr>
<tr>
<td>10</td>
<td>5.0</td>
<td>7.5</td>
</tr>
<tr>
<td>15</td>
<td>1.8</td>
<td>8.8</td>
</tr>
</tbody>
</table>

The maximum temperature difference was nearly 100 °C at 22.5 sec after the hot sodium was flown into the testing part. In this case the maximum thermal strain change, 46.5 × 10⁻⁶/sec occurred at the outer surface in the axial direction of the pipe near the nozzle corner after 4.3 sec and the maximum thermal strain became 784 × 10⁻⁶ at the same place after 98 sec. In this experiment, the thermal strain of each high temperature strain gage was obtained by correcting individually the apparent strain.

It was shown in this test that the maximum thermal strain was nearly equal to the yield point of stainless steel, although it seems to us that these testing conditions were severe. We are preparing for comparing these experimental results with the theoretical values.
1. Introduction

In nuclear reactors the start and stop are given some times for periodic inspections, any accidents or other reasons during their lifetime. In this case, since any transient temperature changes are caused in the pressure vessel and other components with the coolant temperature change and any thermal stresses or deformations occur at any positions of them, it should be considered from the viewpoints of the design and integrity where they occur and how much values they have. It is especially important in fast breeder reactors for us to know the places where the thermal stresses or deformations are caused and their values, since the sodium used as the coolant has some excellent thermal properties. There are, however, not so many examples [1] in which they are obtained exactly on three-dimensional complex structures, constrained by the pipes, supports, flanges etc. with any transient temperature difference, theoretically and also experimentally. It is probably due to the difficulty that they can not be separated according to every load of the pipe or support reaction, circumferential constraint and temperature difference.

The aim of this paper is to obtain the maximum stresses which are caused at the nozzle model, installed in a sodium loop, by thermal shock. In this experiment it is very difficult that every stress could be separated according to the transient pipe reaction, flange constraint and temperature difference, respectively. Therefore, the stresses caused by the pipe reaction and flange constraint were obtained in a steady state when the test section temperature was gradually increased and the stresses caused by the pipe reaction were calculated based on the load, which was obtained in the same state by the strain value measured in the outer surface of the pipe. The stresses caused by the temperature difference in the direction of plate thickness were obtained by subtracting the pipe reaction and flange constraint stresses from the measured total strains, based on the assumption that the temperature distribution of each time in a transient state is the same one as in a steady state.

2. Experimental Procedures

2.1 Sodium Loop and Testing Model

For this experiment, the sodium loop installed at Oarai Engineering Center was used, the flow sheet of which is shown in Fig. 1. After the sodium was charged, this loop is always operated at nearly 250°C and 40ℓ/ℓ/min. The test section of the nozzle model was welded to the pipe and hung by a couple of springs as shown in Fig. 1 and its detail is depicted in Fig. 2. The pipe of 60.5mm outer diameter and 3.5 mm thickness is welded to the dish plate of 15 mm thickness, the end of which is welded to a large flange. The flange was at first prepared to do this experiment using some sorts of nozzle models, but since it was very difficult for this sodium loop to change them, a kind of nozzle model was welded directly to the test section.
The bugle-like guide for hot sodium, shown in Fig. 2, was made in order to flow directly and violently the hot sodium to the nozzle corner. The sodium flow direction is designated by arrows. This test section is all made by SUS 304 stainless steel. The sodium temperature was measured by sheathed chromel-alumel thermocouples through guide tubes.

2.2 Fixing of Thermocouples and High Temperature Strain Gages

As shown in Fig. 3, 54 chromel-alumel thermocouples were soldered or spot-welded at each position to measure the outside and inside temperature. The each depth temperatures at the nozzle corner and inner surface were measured by drilling accurately the hole of 2Φmm diameter to a predetermined depth, which is shown with a parenthesis respectively, and soldering the thermocouples at the bottom of each hole. If all holes are drilled at one position to measure the temperature distribution in the depth direction, there are some important problems, for example, the crack initiation when hot sodium is run violently and the difficulty to solder some thermocouples at the same position. Therefore, as shown in Fig. 3, each hole is drilled at intervals of 22.5°, based on the assumption that the temperature distribution in the circumferential direction is axi-symmetric and then the temperature is equal on a circle. In Fig. 3 the numbers of circles and brackets mean the thermocouples fixed to measure the temperature at each depth of the inside and outer surface, respectively.

Five high temperature strain gages were spot-welded at each position, as shown in Fig. 3, to measure the thermal strains at the outer surface of the nozzle corner when thermal shocks are given. These high temperature strain gages were spot welded to the test section, which were made by Microdot Co., i.e., SG-425 Type. The apparent strains of these gages were obtained by spot welding them at a small specimen (350mmL × 25mmW × 6mmT) made from the same stainless steel as in the nozzle model and measuring the strains when it expands and contracts freely between room temperature and 580°C. After three temperature cycles were given to this specimen, the average value of them was used as the correct curve, by which the real thermal strains were obtained from the strains measured in the nozzle model test. After these tests were carried out to obtain the correct curves, all strain gages were carefully removed from this small specimen and were spot welded at each position shown in Fig. 3. The temperature of each strain gage was obtained by spot welding one thermocouple near the strain gage base, fixing another on the base and averaging these two measured values.

After these preparations were finished, the test section was covered by asbestos as in Fig. 4.

2.3 Thermal Shock Tests

To give thermal shock to the test section, two procedures were used in the loop shown in Fig. 1; one is that hot sodium is suddenly run by opening the valve, VI-3, from the main outer pipe in which sodium is held at high temperature before this test and another is that hot sodium is directly run
from the expansion tank through the pipe, shown by a big line in Fig. 1, to
the storage tank. The thermal shock in the latter is more severe than that
in the former. These thermal shock tests were tried several times using both
procedures.

2.4 Temperature and Thermal Strain Measurements

In the experiments of steady states, performed before thermal shock, the
test section temperature was measured by a volt meter and the strain by static
strain meters. In the thermal shock tests both temperature and strain were
recorded by a photocorder. One example recorded in the thermal shock test is
shown in Fig. 5. In this test, the expansion tank temperature was 590°C, the
test section one 170°C and the sodium flow rate 59 l/min, respectively.

3. Experimental Results

3.1 Static Test

Before thermal shock tests, static tests were carried out to know the
strains caused by the pipe reaction and flange constraint. As shown in Fig. 6,
as an example, the nozzle corner and dish plate temperature was gradually
increased so that the temperature difference between inner and outer surface
is nearly equal to zero and the average temperature is 235, 310, 360, 415 and
455°C, respectively. The outer surface temperature near the flange is,
however, lower than that in the other positions, since the flange may have
large heat capacity. Therefore, it is presumed from these experimental
results that the dish and nozzle corner are contained by the flange when the
test section temperature is gradually increased.

It is shown in Fig. 7 that all the strains in five points near the nozzle
corner are linearly and positively increasing with temperature increase. From
the experimental result that the strain gage, No. 4855-2, fixed at the pipe
shows a positive strain, it can be estimated that the pipe reaction is working
as a positive load. We can consequently calculate the stresses due to the
pipe reaction from this load. The largest strain is the one, No. 4671-2, in
the radial direction near the nozzle corner. It is very difficult to evaluate
the stresses due to the flange constraint, but they could be estimated roughly
by subtracting the calculated pipe reaction from the experimental pipe
reaction plus flange constraint.

3.2 Thermal Shock Tests

As an example of thermal shock, let us illustrate here the case that
600°C hot sodium was directly run at 92 l/min from the expansion tank to the
test section which was kept at 203°C. The temperature variation of the
thermocouples placed at the five high temperature strain gages is shown in
Fig. 8. The temperature change of the thermocouple, No. 39, placed at the
pipe is more remarkably than that of other four thermocouples placed at the
outer surface of the dish plate. A further interesting point is that these
four thermocouples have the same temperature variation, i.e., they change
isothermally with time. In Fig. 9 the strain variation of the five gages is
plotted with time. Very much remarkable change is initially indicated on the No. 4671-2 and No. 4855-2 strain gages, which are welded in the radial direction at the nozzle corner and in the axial direction at the pipe, respectively. The largest strain occurs on the No. 4671-2 gage after 160 sec.

The temperature variation at the nozzle corner is shown on the 0, 5, 10 and 15 mm depth from the outer surface in Fig. 10. The largest temperature change occurs initially near the inner surface and the change decreases with decreasing the depth. In Fig. 11 the temperature gradient at three sections is indicated with time. Very high temperature differences occur at the nozzle corner between 13 and 40 sec. and those values reach about 90°C. After the time passes above 100 sec., the temperature difference decrease with time and the steady state is caused.

As described in the introduction, the stresses caused by the pipe reaction, flange constraint and temperature difference occur at the same time on thermal shock. It is, however, very difficult that the stresses can not be individually separated according to each load. In these experimental results, some assumptions are given in order to try to separate individually these stresses; 1) the stress at each time in a transient state is equal to that in a steady state, 2) the temperature difference occurs only in the direction of plate thickness and 3) all the measured strains are only dependent on the outer surface temperature. In Fig. 12, the largest strain in the radial direction at the nozzle corner is indicated with the surface temperature when a thermal shock test was carried out. When 600°C hot sodium is violently run at 92 L/min to the test section kept at 203°C, the strain is increasing with the surface temperature (with time). Initially the strain due to the temperature difference is nearly equal to that due to the pipe reaction plus flange constraint, but the former is decreasing with time comparing with the latter. When the outer surface temperature of the test section approaches to hot sodium, the strain due to temperature difference is equal to zero. This means that a steady state is caused in this test section. The large stresses due to temperature difference occurs between 30 and 70 sec. The stresses are calculated using Young's Modulus of SUS 304 stainless steel at each temperature.

4. Conclusions

The following conclusions are obtained from an example of the thermal shock, which is presumed to be one of the severe temperature variations in consideration of the design conditions in the nozzle corner of Fast Breeder Reactor Vessels; 1) the stresses due to the pipe reaction and flange constraint are large than those due to the temperature difference in the direction of plate thickness, 2) the maximum stress in the radial direction near the outer nozzle corner is about 6.5 kg/mm², but if the stress concentration factor due to the temperature difference in the nozzle corner is assumed to be nearly 1.5(2), the maximum stress is about 10 kg/mm² and 3) as the future work, it
is necessary for these experimental results to be compared with the theoretical values.

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References


**Fig. 1** Sodium loop used for thermal shock

**Fig. 2** Detail of test section and thermocouple positions
Fig. 2  Detail of thermocouple and high temperature strain gage positions

Fig. 4  View of test section installed in sodium loop
Fig. 5  Temperatures and strains recorded by a photocorder in thermal shock

Fig. 6  Temperature distribution in steady state

Fig. 7  Temperature variation in steady state
Fig. 8 Temperature change of strain gages in thermal shock

Fig. 9 Strain change in thermal shock

Fig. 10 Temperature change at nozzle corner in thermal shock
Fig. 11 Temperature distribution at three sections in thermal shock

Fig. 12 Radial maximum strain in the outside of nozzle corner