Numerical Evaluation of Wall Temperature Measurement Methods Developed to Investigate Thermal Fatigue at T-Junction Pipe

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Keywords: Thermal fatigue, T-junction pipe, temperature fluctuation, numerical simulation, thermocouple, braze

ABSTRACT
Thermal fatigue cracking may initiate at a T-junction pipe where high and low temperature fluids flow in from different directions and mix. Thermal stress is caused by a temperature gradient in a structure and its variation. The accurate simulation of the temperature distribution in structures is, therefore, important for estimating thermal fatigue. In this study, an experimental method using a T-junction pipe with thermocouples was developed. Wall temperatures in the experiment have to be obtained at the inner surface of the pipe to validate numerical simulation results. The difference of position between the inner surface and the measurement point where using thermocouples may, however, have an effect on temperature data. The numerical simulation results showed that the amplitude of temperature fluctuations was reduced to 54% and the difference of phase was 0.91 radians when the sinusoidal temperature fluctuation of 5Hz was applied from the inner surface to the thermocouple measurement points. These results showed that wall temperatures at the inner surface should be estimated from measured data obtained by the thermocouples. A transfer function was, therefore, obtained to calculate wall temperatures at the inner surface from measured data. In addition, the numerical simulation results showed that the amplitude and the phase of temperature fluctuations differed depending on existence of voids around thermocouples. Respective differences of it in the amplitude and the phase were about 5% and 3% when the sinusoidal temperature fluctuation of 5Hz was applied at the inner surface. These results showed that thermocouples should be installed in pipes without voids to measure accurate temperature fluctuations. A mock-up test showed that voids stayed behind the thermocouples when the thermocouples were brazed into the pipe wall at atmospheric pressure, but the voids disappeared when thermocouples were brazed in a vacuum atmosphere into the inner surface of the pipe.

1. INTRODUCTION
Thermal fatigue cracking may initiate at a T-junction pipe where high and low temperature fluids flow in from different directions and mix. This phenomenon is called thermal striping. In Japan in 1999, a damage due to thermal striping occurred in a pipe from the regenerative heat exchanger in the Tsuruga Nuclear Power Plant [1]. After that a design rule for thermal striping was determined to be necessary for the design and the review of nuclear power plants. In 2003, the Japan Society of Mechanical Engineers published the “Guideline for Evaluation of High-Cycle Thermal Fatigue of a Pipe” [2] to establish and prescribe the design process methodology to prevent thermal fatigue. In particular, it aims at assessing thermal striping at mixing tees and thermal stratification at closed-end branch pipes. It prescribes an evaluation flow chart which consists of four separate steps, with an option for detailed evaluation in a final step, when the cumulative usage factor exceeds one after applying all the previous four steps. In the final optional step, numerical simulation is needed for example to estimate thermal load at a specific geometry and flow condition. In this guideline, the basic processes of thermal striping are as follows:
(1) Production of temperature fluctuations in the main flow  
(2) Attenuation of temperature fluctuations in the boundary layer  
(3) Attenuation of temperature fluctuations due to unsteady heat transfer effects  
(4) Attenuation of temperature fluctuations due to heat conduction in structures
According to process (4), thermal stress is caused by a temperature gradient in a structure and its time variation. In addition to simulating the temperature distribution accurately in the mixing fluid, it is important, therefore, to simulate temperature distribution accurately in the structure to estimate thermal fatigue. Some experiments have been performed to estimate thermal fatigue. Researchers at the Japan Atomic Energy Agency (JAEA) experimentally investigated the temperature fluctuation in a T-junction pipe [3]. In their experiment, temperatures in the fluid and structure were measured at 20 positions to obtain spatial distributions of the heat transfer coefficient. A thermocouple tree was used to measure the fluid temperature inside the pipe. The thermal contact point of the thermocouple on the structure was set at 0.125mm from the structure surface. In France, an experimental program sponsored by AREVA NP, CEA and EDF was initiated to study the thermal fatigue phenomenon in mixing tees that occurred in the Civaux Nuclear Power Plant. In the experiment, temperatures in the fluid and the structure were measured at 52 positions to obtain the unsteady heat transfer coefficient [4]. A specific sensor called the “coefh” was used in the experiments. This sensor simultaneously recorded local temperature fluctuations in the fluid and in the structure due to its design which incorporated thermocouples in the body of the sensor. JAEA, EDF and others have focused on the heat transfer coefficient.

INSS researchers have developed a method to estimate thermal stress distributions from temperature distributions in a pipe, which was called “IMAT-F” (Integrated Methodology of Assessment for Thermal Fatigue) [5,6]. Fig.1 shows the evaluation flow chart of IMAT-F. This software can automatically interpolate spatial - time data of the fluid and structure temperatures which were obtained by experiments or numerical simulations. It automatically also calculates the maximum stress amplitude and cumulative usage factor. On the other hand, Fig.1 shows that it is possible to estimate stress distributions by the structure temperature measured experimentally. This approach can estimate thermal stress distributions without the heat transfer coefficient.

In this paper, a water experiment for a T-junction was planned to measure wall temperature fluctuations in a pipe. Important points to measure temperature in the experiment are as follows.

1. To measure the spatial temperature distribution that can be used to calculate the maximum stress amplitude
2. To measure temperature fluctuations near the inner surface of the pipe to reduce the attenuation

The development of the experimental method using thermocouples installed in a T-junction pipe wall were reported in this paper. The main object of the experiment is the validation of the future numerical simulations.

2. Measuring points for thermocouples

2.1 Decision using numerical simulations

It is important to calculate the maximum stress amplitude using temperature data obtained at the inner surface of pipe to evaluate thermal fatigue phenomenon in the mixing tees. It is expensive to install many thermocouples in a pipe wall. Then numerical simulations were performed to decide measuring points for thermocouples. The numerical simulation steps are as follows.

1. Obtain temperature distributions in a structure by fluid-structure coupled numerical simulations
2. Simulate stress distributions at elements of the FEM using the time history of temperature which was obtained in step (1).
3. Extract temperature data at the temporarily decided thermocouple positions.
4. Obtain temperature data at the inner surface by interpolating temperature data from step (3) using IMAT-F [5,6].
5. Simulate stress distributions using the results of heat conduction analysis by temperature data from step (4).
6. Compare results of stress distribution in steps (2) and (5), so as to optimize thermocouple measuring points.

Numerical simulations were performed for a T-junction pipe geometry which was almost the same as the test section used in JAEA [7].

2.2 Fluid-structure coupled numerical simulations

2.2.1 Analysis conditions

In the JAEA study [7], flow patterns were categorized as impinging jet, deflecting jet and wall jet. In addition, it was cleared that a flow pattern of the wall jet, where the jet from the branch pipe was bent by the main pipe flow and flowed along the pipe wall, makes higher fluctuation intensity of the fluid temperature near the pipe wall than in other cases. From these results the wall jet flow case was, therefore, chosen as the case for this study. The JAEA test section made of acrylic resin is shown in Fig.2. But the pipe wall was modeled with austenitic stainless steel for the numerical simulations to measure wall temperature fluctuations in this study. Flow velocity was set at $V_m = 1.46 m/s$ and $V_b = 1.0 m/s$ for the main and branch pipes, respectively, and temperature was set at $T_m = 48^\circ C$ and $T_b = 33^\circ C$ for the main and branch pipes, respectively, same as experiment conditions. Inlet velocity and temperature were set with uniform distributions. The outer boundary of the pipe was adiabatic. The boundary condition between the fluid and structure was non-slip and wall function. The commercial CFD code CFX developed by ANSYS Inc. was employed for the numerical simulations. The detached eddy simulation (DES) was used for the
turbulence model. Physical properties for the fluid and the structure were set as constant values [8] at 40°C, since they would not affect the results under inlet conditions with a small temperature difference. Initial temperatures of the fluid and the structure were set as constant values at 40°C. The initial velocity was set at 1.5m/s uniformly in the direction of the main flow. The heat transfer coefficient was decided using a wall function in the numerical simulations. The object of this analysis was to decide thermocouple measuring points, so the accuracy of the heat transfer coefficient was not considered. In a previous study [9], it was reported that the temperature of fluid simulated by the above analysis conditions agreed well with the JAEA experimental data.

2.2.2 Analysis region
The numerically simulated region of the test section is shown in Fig.2. Inlet lengths of the main and branch pipes were shorter than the test section to minimize the number of computational meshes. The computational meshes are shown in Fig.3. The mesh width near the wall is controlled by $y^+$, where $y^+$ is equal to $y \times u^*/\nu$, $y$ is the distance from the pipe wall, $u^*$ is friction velocity ($\sqrt{\tau_w/\rho}$), $\nu$ is dynamic viscosity of fluid, $\tau_w$ is shear stress on the wall, and $\rho$ is fluid density. The minimum mesh width was decided as about 10. The mesh width near the wall was as follows.

(1) Fluid region near the wall
Region of main flow: 0.1mm
Region of branch flow: 0.1mm

(2) Structure region near the wall
Region of main flow: 0.1mm

![Fig.2 Simulated region of test](image1)

![Fig.3 Computational meshes](image2)

![Fig.4 Instantaneous temperature distributions near the wall in the main pipe](image3)
Region of branch flow: 0.06mm
The total number of mesh nodes was 1,734,158 (1,310,234 for the fluid and 423,924 for the structure).

2.2.3 Time step
The time step was determined with reference to Courant number calculated by the following formula.
\[ C = \frac{U \Delta t}{\Delta x} \] (1)
Here, \( \Delta x \) is the mesh width in the flow direction, \( \Delta t \) is the time step, and \( U \) is the average velocity in the test section. In this case, \( U \) and \( \Delta x \) was 1.57 m/s and 0.5 mm, respectively. So the time step \( \Delta t \) was 0.00079 s when the Courant number \( C \) was 1. However, the time step \( \Delta t \) was 0.01s from 0 to 30s and \( \Delta t \) was 0.001s from 30 to 40s to reduce the calculation time since it took a large time to simulate a quasi-steady temperature distribution in the structure.

2.2.4 Results of analysis
Fig.4 shows the instantaneous temperature distribution near the wall in the main pipe at \( t=40s \). Fluid temperature was obtained 1mm from the surface of the pipe. Structure temperature was obtained at 1mm depth from the surface of the pipe. The wall jet with low temperature winded from side to side. The temperature variation in the structure was smaller than in the fluid.

2.3 Stress analysis using results of fluid-structure coupled simulations
2.3.1 Analysis conditions
The stress distribution in the pipe was calculated by the commercial code ABAQUS. The temperature distribution in the structure was given using the results of Sec.2.2. The computational meshes in the structure were the same meshes as the simulation of Sec.2.2. The analysis region included only the lower half of the main pipe, because the jet exiting from the branch pipe flowed along the pipe wall in the analysis conditions. The pipe was assumed to be made of austenitic stainless steel for this simulation. The material properties are listed in Table 1. As boundary conditions, the displacement of the inlet sections in each pipe was zero. The displacement of the outlet section in the main pipe was free, but rotation was arrested. Every 0.01s data from 30s to 40s were adopted for the temperature distribution in the structure, because it seemed to be a quasi-steady state condition and the order of fluctuation frequency was several Hz in the JAEA experiment [3].

<table>
<thead>
<tr>
<th>Table 1 Physical properties for the stress analysis</th>
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<tbody>
<tr>
<td>Density [kg/m^3]</td>
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<tr>
<td>Thermal conductivity [W/(mK)]</td>
</tr>
<tr>
<td>Specific heat [J/(kgK)]</td>
</tr>
<tr>
<td>Young's modulus [MPa]</td>
</tr>
<tr>
<td>Poisson's ratio [-]</td>
</tr>
<tr>
<td>Thermal expansion coefficient [1/K]</td>
</tr>
</tbody>
</table>

2.3.2 Results of analysis
The position of the maximum stress amplitude is important to evaluate thermal fatigue phenomenon in the mixing tees. The stress amplitude was simulated by conditions of Sec. 2.3.1. This process corresponded to the final step in Fig.1. The amplitude \( \Delta \sigma \) of axial stress \( \sigma \) was calculated with the time history of stress during 0.2s, and is shown in Fig.5. The maximum of \( \Delta \sigma \) was 7.13MPa at Z=153mm and at \( \theta=21^\circ \) (=azimuthal angle in the main pipe).

2.4 Stress analysis using results of fluid-structure coupled simulations with extracted data at the thermocouple positions
2.4.1 Analysis procedure
The stress distribution was simulated with the temperature data which were interpolated with the extracted data at these thermocouple positions in Table2. The every 0.01s data during 30 to 40s from the results of analysis in Sec.2.2 were adopted for the extracted temperature data. The temperature at the inner surface was set to the interpolating data using IMAT-F. In next step, the temperature distribution in the structure was simulated. The time step \( \Delta t \) of the heat conduction analysis was 0.01s, and initial temperature in the structure was set to the temperature distribution at 1st time step previous to the results of Sec.2.2 at 30s. The outer surface of the pipe was an adiabatic condition. In next step, the stress distribution was simulated with the same procedure in Sec.2.3.

<table>
<thead>
<tr>
<th>Table 2 Position of thermocouples</th>
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<tr>
<td>Axial direction</td>
</tr>
<tr>
<td>Range[mm]</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>
2.4.2 Results of analysis

The maximum of stress amplitude was investigated by IMAT-F using the time history of stress distribution, which was simulated by the procedure in Sec. 2.4.1. Distribution of axial stress amplitude is shown in Fig. 6. The position and maximum value are also shown there. Fig. 6(b) shows that the stress amplitude was large upstream because the thermocouples were not set upstream in this case. The calculated data caused the temperature gradient, since the procedure of IMAT-F interpolated the data between the inlet boundary and the branch pipe if the thermocouple were not set around the branch pipe. The distribution and the maximum position in Figs. 6(a)(b) were similar to those of Fig. 5. Figure 7 shows the distribution of the axial stress amplitude at axial position 150 mm. The sampling interval of 10 mm (case 1) and 25 mm (case 2) did not affect the stress distribution. The stress distribution in Fig. 6 also showed axial symmetry. Consequently, the thermocouple positions were as follows:

(1) Axial direction
   Range: -50 mm to 225 mm  Interval: 25 mm
(2) Circumferential direction
   Range: 0° to 60°    Interval: 5°

3. Methods to predict temperature at the inner surface of the pipe

3.1 Effect of depth of thermal contact point from the pipe inner surface

When thermocouples are brazed in the inner wall surface, the distance between the thermal contact point and the inner surface is more than the radius of the thermocouple sheath. When the sheath diameter is 0.5 mm, it is impossible that temperatures at the surface of the structure are measured exactly. The numerical simulations were conducted to investigate how to predict the inner surface temperature from the measured temperature.

3.1.1 Analysis conditions

The commercial code ABAQUS was employed for the heat conduction analysis. The two-dimensional meshes are shown in Fig. 8. The analysis region was 3.3 mm in the width, which was equal to the circumferential length of pitch 2.5°. The wall thickness was 7.6 mm, the depth and the width of the groove were 0.7 mm and 0.6 mm. The colors red, green, and gray indicate stainless steel, magnesium oxide (MgO), and nickel.
MgO is used as the insulator in the thermocouple sheath. Ni is used as the solder to fix the thermocouples at the surface. The material properties are listed in Table 3.

The packing fraction of MgO was set to 95%, considering results of the experiment in Sec.3.1.3. The analysis region is the cross section at the thermal contact point in the sheath, so two wires in the sheath are not modeled. Temperatures at the boundary of the inner surface were set to sinusoidal fluctuations. The reference temperature was 40°C and the amplitude was 20 K. The ambient temperature was set to 20 °C. The heat transfer coefficient was set to 4.38W/(m²K) [10], which was used in the case of natural convection conditions in air. The side boundary was adiabatic. Initial temperatures of the structure were set as the constant value at 40°C.

### Table 3 Physical properties for heat conduction analysis

<table>
<thead>
<tr>
<th>Material</th>
<th>SUS304</th>
<th>MgO(*)</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m³]</td>
<td>7916</td>
<td>3332.7</td>
<td>8894</td>
</tr>
<tr>
<td>Thermal conductivity [W/(mK)]</td>
<td>16.1</td>
<td>1.55</td>
<td>89.4</td>
</tr>
<tr>
<td>Specific heat [J/(kgK)]</td>
<td>501</td>
<td>937</td>
<td>453</td>
</tr>
</tbody>
</table>

* Packing fraction 95% (Air 5%, MgO 95%)

#### 3.1.2 Results of analysis

Figure 9 shows temperature fluctuations at the measuring point, at the center of the sheath, when the frequency of the sinusoid fluctuations at the inner surface was set to 5Hz. The time step $\Delta t$ was 0.001s and the calculation time was 3s. The amplitude of temperature fluctuations was reduced to 54% and phase difference was 0.91 radians. This difference could not be ignored, because the JAEE experiment results [3] showed that the prominent frequency of temperature fluctuations was several Hz. These results showed that wall temperatures at the inner surface should be estimated from measured data, which was obtained by the brazed thermocouples. On the other hand, the time-averaged temperature at the measuring point during 3s was 0.06 K higher than that at the inner surface. This difference might be caused by the variation of thermal conductivity around the thermocouples, but it could be ignored.

#### 3.1.3 Experiment to investigate the packing rate of magnesium oxide

A schematic drawing of the thermocouple with a sheath is shown in Fig.10. The red and orange lines are the thermocouple wires and the blue is the magnesium oxide (MgO). It was planned to install the non-grounded type in the test section to avoid noise. MgO is used as the insulator in the thermocouple sheath. The insulator is made of compressed MgO powder. So the packing fraction of MgO should be measured to decide the physical properties in Table 3. A numerical simulation and experiment were conducted to obtain the packing fraction of MgO. In the experiment, the thermocouple was inserted into a pool where the temperature was 40, 50, 60, 70, and 80°C. The time history of the measured temperature was recorded at 10 times for each pool temperature. The measured data were compared with the results of the numerical simulations, changing the packing fraction of MgO. The heat transfer coefficient, however,
should be obtained in advance. The experimental data were, therefore, obtained using the grounded thermocouple which can simulate the temperature without MgO. The difference in the fall velocity of thermocouples might cause the difference of heat transfer coefficient. The grounded thermocouples and non-grounded thermocouples were inserted into the pool at the same time, so the heat transfer coefficient was assumed to be equal.

At first, the heat transfer coefficient was decided by the experiment and analysis using the grounded thermocouple. The commercial code ABAQUS was employed for the heat conduction analysis. The computational meshes for the grounded thermocouple are shown in Fig. 11. The analysis model had axial symmetry. The heat transfer coefficient was given at the surface of the sheath and the other boundary was adiabatic. The experimental data at 50°C and the analysis results are shown in Fig. 12. The temperature was normalized by Eq. (2):

\[ T_n = \frac{T - T_{in}}{(T_{end} - T_{in})} \]  

where \( T \) is the measured temperature, \( T_{in} \) is the initial temperature and \( T_{end} \) is the steady state temperature. The heat transfer coefficients obtained by fitting the measured data was 7500 W/m²K for 40°C and was 10000 W/m²K for 50, 60, 70, and 80°C.

In the next step, the packing fraction of MgO was decided by the experiment and analysis using the non-grounded thermocouple. The computational meshes for the non-grounded thermocouple are shown in Fig. 13 to obtain the packing fraction of MgO. The packing fraction is the volumetric ratio of air to MgO when they are mixed uniformly. The analysis model had axial symmetry. The heat transfer coefficient for each pool temperature was given at the
surface of the sheath and the other boundary was adiabatic. The experimental data at 50°C and the analysis results are shown in Fig.14. The temperature was normalized by Eq.(2). The packing fraction obtained by fitting the measured data was 95%.

3.1.4 Effect of the thermocouple diameter
In Sec. 3.1.1 to 3.1.3, the thermocouple diameter was assumed to be 0.5mm. Its diameter should be small to measure in the pipe inner surface, because the distance between the thermal contact point and the inner surface influences the measurement errors shown in Fig.9. The thermocouple diameter, however, should be more than 0.5mm to avoid breaking the wire. A numerical simulation was conducted to estimate the error when the diameter was increased. The attenuation and phase delay of the temperature fluctuations were simulated for a 1.0mm diameter sheath in the same way as in Sec.3.1.1. The computational meshes are shown in Fig.15. Figure16 shows temperature fluctuations at the measuring point when the frequency of the sinusoid fluctuations at the inner surface was set to 5Hz. Figure16 also shows the results for the 0.5mm diameter sheath. For the 1.0mm diameter sheath, the amplitude of temperature fluctuations was reduced to 22.3% and difference of phase was 2.07 radians. The results showed that the increase of sheath diameter had a large effect on the increase of the measuring errors. The thermocouple of 0.5mm diameter was therefore adopted.

3.2 Transfer function to estimate the temperature at the pipe surface
The results in Sec. 3.1 showed that the wall temperatures at the inner surface should be estimated from the measured data obtained by the thermocouples. The procedure is shown as follows.
(1) Measure the temperature fluctuations with thermocouples.
(2) Convert the above data to the frequency response by FFT analysis.
(3) Prepare the transfer function which estimates the data at the surface from the measured data, by heat conduction analysis.
(4) Calculate the amplitude and phase at the inner surface from the frequency response with the transfer function.
(5) Convert the above data to the time response by inverse-FFT analysis.

The numerical simulation was conducted to obtain the transfer function using the computational meshes shown in Fig.8. The amplitude ratio and the phase difference were obtained when temperatures at the boundary of the inner surface were set to sinusoid fluctuations. That reference temperature was 40°C and the amplitude was 20K. The frequency of the sinusoid fluctuations at the inner surface was changed from 0.01Hz to 50Hz. Figure 17 shows the obtained transfer function, that shows the attenuation of amplitude and the delay of phase became larger as the frequency increased. These interpolated equations are given by Eq.(3),(4).

\[ a = \exp(-0.236f^{0.628}) \]  \hspace{1cm} (3)

\[ \theta = 0.359f^{0.599} \]  \hspace{1cm} (4)
\[ a \text{ and } \theta \text{ is the ratio of amplitude and the delay of phase.} \]

4. Methods to install thermocouples at the inner surface of the pipe

4.1 Effect of voids around thermocouples

In order to measure the structure temperature at the inner surface, the thermocouples have to be fixed in the right place. It was decided to caulk them or braze them on the pipe surface. Metal brazing was selected to reduce the gap between the pipe and the thermocouple because the purpose of this study was to measure the temperature fluctuations accurately in the structure. Figure 18 shows a photo around the thermocouple in a cross section that was brazed by Ag at atmospheric pressure. It is observed that there are voids at the corner of the groove, because a sufficient amount of braze metal might not flow into the corner. The numerical simulation was conducted for the same analysis conditions as in Sec. 3.1 to investigate the effect of the voids on the temperature fluctuations. The computational meshes around thermocouple are shown in Fig. 19. The boundary condition around the voids was adiabatic. Temperatures at the boundary of the inner surface were set to sinusoid fluctuations, that the reference temperature was 40°C and the amplitude was 20K. As the result, the amplitude ratio increased from 54% to 56% and the phase difference decreased from 0.91 radians to 0.88 radians for the case of 5Hz. The voids seemed to reduce the heat conduction. Since the volume of the voids cannot be known in advance when the thermocouples are installed, the method to reduce the voids has to be decided.
4.2 Method to braze thermocouples in the pipe

A mock-up test was conducted to verify whether the brazing thermocouples in a high vacuum could reduce voids. In order to braze the thermocouple in the high vacuum, the test section with the braze metal was put in a chamber vacuum furnace. It becomes difficult to control the amount of solder metal under such conditions. Ni brazing was adopted, because its flowability is smaller than that of Ag. A groove was made in the austenitic stainless steel pipe surface with 0.7mm depth and 0.6mm width. The vacuum was $10^{-2}$ to $10^{-6}$Pa. Figure 20 shows a photo around the thermocouple in a cross section that was brazed by Ni in the high vacuum. The voids behind the thermocouple in Fig.18 disappeared in this case shown in Fig.20, for example, thirteen thermocouples were installed by this method, and in all cases no voids was observed.

5. Conclusion and future work

In this study, an experimental method using thermocouples installed in a T-junction pipe wall was developed to obtain the inner surface temperature time-history. The following conclusions were obtained.

(1) Numerical simulations were performed to decide the optimum measuring points for the thermocouples for the diameter ratio of two pipes =3, and wall jet condition. The axial direction was from -50mm to 225mm and the interval was 25mm. The circumferential direction range was from $0^\circ$ to $60^\circ$ and the interval was $5^\circ$.

(2) Numerical simulation results showed that amplitude of temperature fluctuations was reduced to 54% and the phase difference was 0.91 radians between the inner surface and the measuring point of thermocouples when the sinusoidal temperature fluctuation of 5Hz was applied. The transfer function to estimate temperature fluctuations at the surface from the measured data was calculated by the measured heat conduction properties.

(3) The voids around thermocouples influenced the amplitude ratio and the phase difference of temperature fluctuations and the errors could not be ignored, when the thermocouples were brazed inside the pipe surface.

(4) High vacuum brazing of the thermocouples by Ni at the pipe surface was effective to remove voids around the thermocouples.

It is planned to make a test section with thermocouples and measure the temperature fluctuations, taking the above findings into account. The distribution of thermal stress in the T-junction pipe will be estimated according to the flow chart in Fig.1 using the measured temperature time-history.

REFERENCES


