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Thermal transient finite element computation of a mixing Tee by utilizing CFD results

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Summary. Thermal distribution and fluctuation in any piping component due to turbulent mixing of flows with different temperatures vary greatly. Usually, computational fluid dynamics (CFD) tools are used for estimation of flows in piping components. Fatigue that results from fluctuating thermal mass flow across the components can be computed by coupling the CFD results with structural mechanics based finite element (FE) results. However, this procedure is laborious and computationally very expensive. A fluid temperature function has been developed in this paper as a function of internal wall coordinates and time by interpolating experimental or CFD results. Bicubic interpolation function has been used for accurate interpolation. Finally, a thermal transient FE analysis for an actual Tee from a nuclear power plant (NPP) was performed by using the developed fluid temperature function and interpolated CFD results.

Key words: finite elements, thermal cycling

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Introduction

Turbulent flow is a common phenomenon in piping components, such as straight pipes, pipe bends, reducers and Tees of light water reactor (LWR) plants. Computational fluid dynamic (CFD) tools are used extensively to estimate temperature distributions and fluctuations of the fluids inside the components. When two water flows with high- and low-temperature meet, which occurs e.g. in mixing Tees, complex thermal fluctuations ensue. Temperature fluctuation through pipe wall and consequent stress fluctuations occur due to mixing of high- and low-temperature fluids. Thus, as discussed in [7], detailed thermal fatigue analysis is required for: ensuring fatigue limit is not exceeded, or in case it is exceeded then preforming fatigue crack growth analysis for initiated crack to estimate the remaining life of the component before leak or break.

Transient thermal analysis of the components needs to be performed for computation of temperature distribution through the solid wall. Finite element (FE) analysis codes are

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commonly used for such computations, while fluid temperature distributions and heat transfer coefficient at the internal surface of the components are provided.

The temperature distributions at the inner surface of the components can be solved with CFD analysis, as mentioned above. Usually, the coupling of the thermal transient CFD and FE analyses is computationally very expensive. Similar coupling has been performed in [5], where in the fluid-solid interface the nodes of the structural model and fluid model coincide. Therefore, no approximation of the heat transfer between the fluid and the structure was needed. Similar approach has been tried on an actual Tee from a NPP with very complex geometry and loads [1]. However, due to complexity of the model the analysis had to be stopped as the computational time had increased substantially. Thus, a method has been developed in this study to obtain the fluid temperature at the wall as a function of inner wall coordinate and time from the CFD results and then perform thermal transient FE simulation through solid wall. This method greatly reduces the computational time, as full CFD-FE coupling is not needed and at the inner surface the fluid model and the structural model meshes do not need to be compatible. A sinusoidal interpolation function has been developed from CFD results to obtain the fluid temperature as a function of inner wall surface coordinates and time. In order to enhance the accuracy, bicubic interpolation function has been used for processing the CFD results. More simplified approach has been applied for computation of fluid temperature and temperature through solid wall in mixing Tees e.g. in [6]. However, it is not applicable for very complex turbulence in three dimensions.

Furthermore, CFD temperature results for an actual mixing Tee are provided by [1], where thermal mixing occurred due to meeting of hot and cooler water flows. Thermal transient FE simulation of the mixing Tee is preformed through wall, where the heat transfer problem is governed by convection in the fluid-solid interface and by conduction through the solid wall. Thus, the developed sinusoidal interpolation function was used in the FE simulation to determine the fluid temperature at the fluid-solid interface by utilizing the CFD results.

Modelling methods

Flow temperature in an LWR piping component can fluctuate with respect to time. Fluctuating fluid temperature as a function of time can be described with a sine function. The simplest form of a fluid temperature equation in LWR piping components as a function of time is given as:

$$T(t) = T_m + A \times \sin(2\pi f t) \tag{1}$$

where T is temperature, t is time, T_m is mean temperature, A is amplitude and f is frequency of temperature fluctuation. Equation (1) is presented graphically in Figure 1 below.

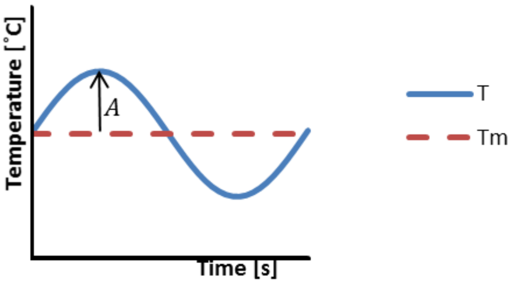

Figure 1. Sinusoidal fluid temperature function.

Equation (1) assumes in hoop direction the same temperature distributions and fluctuations for a piping component with given values for T_m, A and f. Temperature distributions and fluctuations of the fluid inside the components in actual conditions are very seldom evenly distributed. Usually, when two water flows with different temperatures mix turbulently, temperature distributions and fluctuations vary greatly locally. Consequently, it is essential to define T_m and A as a function of locations across the inner surface of the components. Throughout this paper the word "space" will be used to replace the phrase "locations across the inner surface of the components". Equation (1) needs to be defined as a function of both space and time. Space dependent T_m and A for given thermal mass flow conditions can be specified from measurements or CFD analysis results. Interpolation functions for T_m and A are developed from the measured or CFD analysis results.

Before developing these functions, the geometry of the inner surface of the components needs to be simplified. The components mentioned in section 1 have mostly cylindrical shapes, thus they are described in three-dimensional (3D) space. Due to simplifications contained by the interpolation functions, 3D cylindrical surface must be transformed to a two dimensional (2D) flat sheet. Transformation of 3D coordinates of a cylindrical surface to 2D Cartesian coordinates is shown in Figure 2. The length of the cylinder along z-axis remains the same as shown in Figure 2, the circular length converts to straight line as follows:

$$r = \sqrt{x^2 + y^2} \tag{2}$$

$$\theta = \sin^{-1}\frac{y}{r} \tag{3}$$

$$s = r \times \theta = \sqrt{x^2 + y^2} \times \theta \tag{4}$$

where r, x, y, s and θ are shown in Figure 2. Now, any information in x, y and z coordinates of a cylindrical surface can be fully transformed to the corresponding 2D coordinates z and s. Average temperature and root mean square (RMS) distributions for a given flow across a cylindrical surface can be determined from measurements or CFD analysis results. The following relation between RMS value, rms, and amplitude, A, exists:

$$A = \sqrt{2}rms \tag{5}$$

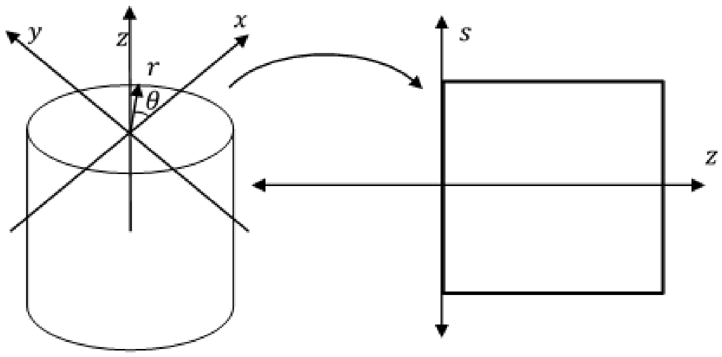

Figure 2. Transformation of 3D coordinates of a cylindrical surface to 2D coordinates.

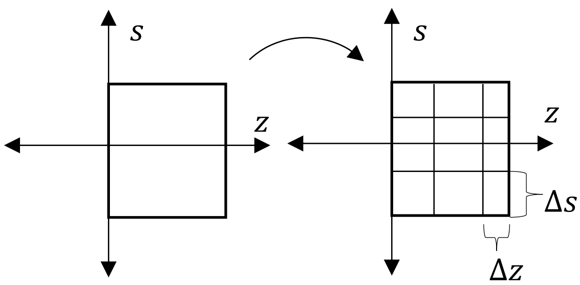

Figure 3. Discretization of a 2D surface into number of rectangles with unequal size.

Measured or CFD temperature and RMS results of a cylindrical component are used to formulate interpolation functions as a function of coordinates z and s. In this study, bicubic interpolation function is proposed, which requires discretization of a 2D surface to a finite number of rectangles. The sizes of the rectangles need not to be equal, as shown in Figure 3.

Bicubic interpolation function

Bicubic interpolation function for a 2D discretized surface of Figure 3 is given as follows:

$$f(s,z) = \sum_{i=0}^{3}\sum_{j=0}^{3} a_{ij} s^i z^j \tag{6}$$

where f is average temperature or RMS function, s and z are coordinates shown in Figure 3, whereas a_{ij} is coefficient for a given $s^i z^j$. There are 16 a_{ij} coefficients in equation (6). If function values, f, are known at the corners of the rectangles of Figure 3, a_{ij} coefficients for each rectangle can be determined separately. For a discrete rectangle, 16 equations are needed to determine the a_{ij} coefficient values. Therefore, the following derivatives are also needed to be known at each corner of the discrete rectangle to form the 16 equations:

$$\frac{\partial f}{\partial s} = \sum_{i=1}^{3}\sum_{j=0}^{3} a_{ij} i s^{i-1} z^j \tag{7}$$

$$\frac{\partial f}{\partial z} = \sum_{i=0}^{3}\sum_{j=1}^{3} a_{ij} s^i j z^{j-1} \tag{8}$$

$$\frac{\partial^2 f}{\partial s \partial z} = \sum_{i=1}^{3}\sum_{j=1}^{3} a_{ij} i s^{i-1} j z^{j-1} \tag{9}$$

The derivatives of equations (7) to (9) can be determined numerically with finite difference method (FDM) as follows:

$$\frac{\partial f}{\partial s} \approx \frac{f(s+\Delta s, z) - f(s-\Delta s, z)}{2\Delta s}$$

$$\frac{\partial f}{\partial z} \approx \frac{f(s, z+\Delta z) - f(s, z-\Delta z)}{2\Delta z} \tag{10}$$

$$\frac{\partial^2 f}{\partial s \partial z} \approx \frac{f(s+\Delta s, z+\Delta z) - f(s+\Delta s, z-\Delta z) - f(s-\Delta s, z+\Delta z) + f(s-\Delta s, z-\Delta z)}{4\Delta s \Delta z}$$

where Δz and Δs are horizontal and vertical lengths of a discretized rectangle, respectively, as shown in Figure 3. Bicubic interpolation function for each discretized rectangle of Figure 3 can be defined separately, by numerically solving a_{ij} coefficient values with equations (6) and (10).

Average temperature and RMS functions

The interpolation function introduced in section 2.1 will be used to develop space dependent $T_m(x, y, z)$ and $rms(x, y, z)$ functions for a thermal mass flow in a cylindrical piping component. The following average temperature and RMS functions are developed:

$$T_m(x, y, z) = \delta \sum_{i=0}^{3} \sum_{j=0}^{3} b_{ij} s^i z^j \tag{11}$$

$$rms(x, y, z) = \delta \sum_{i=0}^{3} \sum_{j=0}^{3} c_{ij} s^i z^j \tag{12}$$

where δ is equal to 1 or 0, s is given as a function of x and y in equations (2) to (4), whereas b_{ij} and c_{ij} are coefficients of the bicubic interpolation functions. The coefficients b_{ij} and c_{ij} can be found with the same procedure as explained in section 2.1. Independent of the number of discretized rectangles in a surface, for a given point with x, y, z coordinates, δ is 1 only for one rectangle, where x, y, z coordinates fall in the interval of that rectangle. The values of δ for the rest of the rectangles are 0. Equation (1) can be defined as a function of space and time by inserting equations (5), (11) and (12) into it, as follows:

$$T(x, y, z, t) = T_m(x, y, z) + \sqrt{2} rms(x, y, z) \times \sin(2\pi f t) \tag{13}$$

Equation (13) presents the fluid temperature as a function of time and coordinates of a 3D cylindrical surface. A critical frequency, f, should be chosen for equation (13) as based on experimental or CFD results. Precisely, the same approach can be used to develop a fluid temperature function for other components by transforming their surface from 3D to 2D and then discretizing the surface, as mentioned earlier.

Application of fluid temperature function

The fluid temperature function expressed by equation (13) will be utilized in the following in a thermal transient FE analysis of a Tee, using available CFD results. Outer diameter and wall thickness of the Tee are 406.4 mm and 21.41 mm, respectively. The material of the Tee is austenitic stainless steel AISI 304L.

Processing CFD results

CFD results from ref. [1] for a thermally stratified flow of 10 kg/s in a Tee are used. Ansys Fluent code [4] was used for the CFD analyses. Figure 5 shows the distributions and transformations of the CFD results in 3D and 2D, where the hollow cylinder consists of

50665 nodes. Therein, the temperature and the mass flow of the cold water are 20 ˚C and 10 kg/s and, respectively, those of the hot water are 273 ˚C and 55 kg/s, see Figure 4.

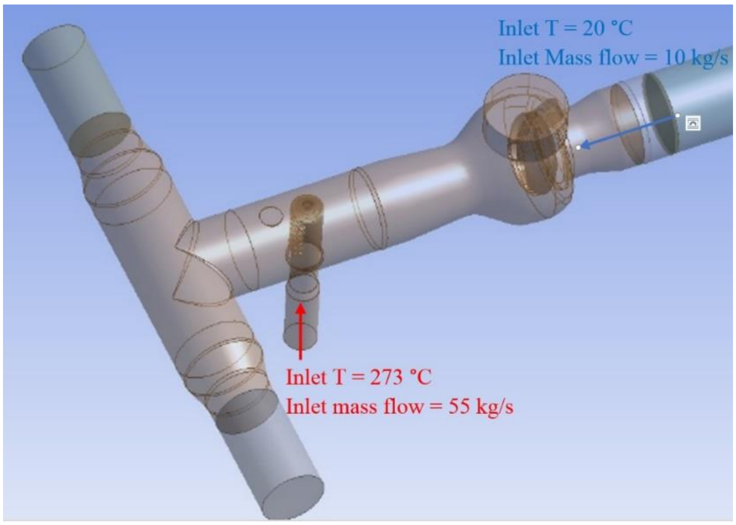

Figure 4. Inlet flow velocities and temperatures for CFD simulation.

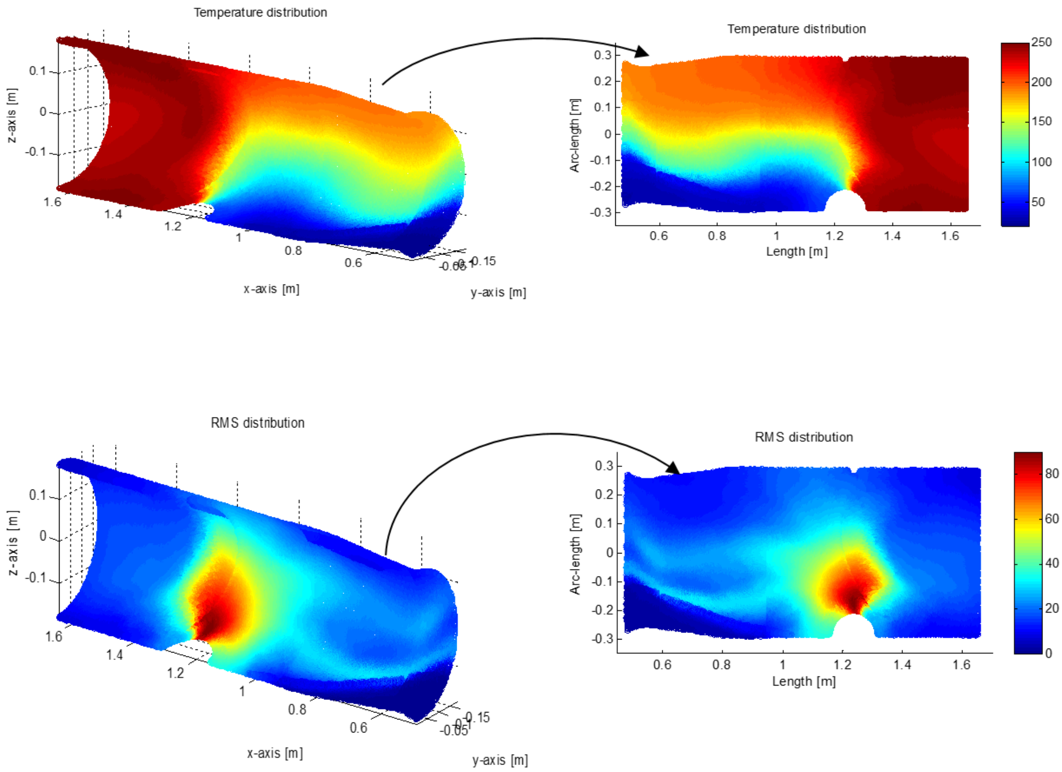

Figure 5. CFD results of average temperature and RMS distributions in unit of °C in a pipe component and transformation of 3D cylindrical surface to 2D surface in meters.

Figure 5 shows temperature and RMS distributions on the inner surface of the cylindrical pipe component, and transformation from 3D to 2D surface with maintaining temperature and RMS distributions. According to section 2, the 2D surface must be discretized to a number of rectangles for generating the interpolation functions. Exactly the same surface discretization must be used in generating interpolation functions for both the average temperature and RMS, which is because these interpolation functions will be inserted in equation (13) that presents only a rectangle for a given point in x, y and z coordinates. This procedure not only prevents the overlapping of the interpolation functions, but it also reduces substantially the computational time in a thermal transient FE analysis. The discretization of the 2D surface is shown in Figure 5, with both average temperature and RMS distributions.

The surface has been discretized to equal size rectangles for simplicity. For those regions which are not covered by discretized rectangles, a temperature function has been extrapolated. The interpolation functions used in this paper are limited to regular rectangles with straight lines, see section 4. Thus, regions resulting with irregular shape rectangles are not covered for interpolation. It should be noted in Figures 4 and 5 that only half of the cylindrical pipe component across the length has been plotted, which is due to symmetry. The symmetry condition is also applied to the thermal transient FE analysis.

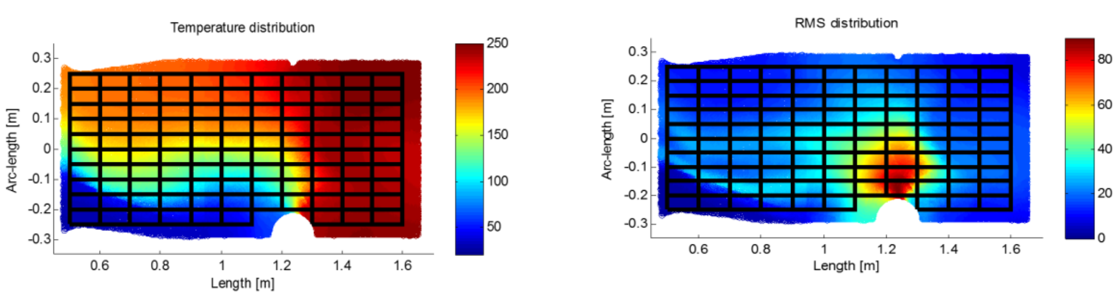

Figure 6. Discretization of the 2D surface in unit of m into equal number of rectangles for generating average temperature and RMS in unit of °C interpolation functions.

FE analysis

The inner surfaces of the hollow cylinder shown in Figures 4 and 5 are actually a portion of a symmetric Tee. The thermal transient FE analysis of the Tee has been performed with a general-purpose FE code Abaqus [4]. Element type DC3D8 has been used, which is a 3D solid element used for thermal analyses. Fluid temperature function has been applied to the inner surface of the Tee in Abaqus model with a developed FORTRAN subroutine. Temperature data provided in Figures 4 and 5 are extrapolated to the full Tee model. A frequency of $f = 1Hz$ is assumed for fluid temperature fluctuation in equation (13), while average temperature and amplitude are determined by interpolating data of Figure 5, as explained earlier. Heat transfer coefficient values are provided. Thermal loading is determined at the inner wall surface with Abaqus, as boundary convection vector, by given fluid temperature and heat transfer coefficient value. Since the Tee is symmetric, only half of it has been simulated, and for cut surfaces symmetry boundary conditions have been utilized.

Temperature dependent material properties have also been used in the analysis. Material properties that were needed in the FE analysis for solving the heat transfer problem due to conduction through solid wall are, thermal conductivity, heat capacity and density of the solid pipe.

According to equation (13), temperature fluctuates around the average temperature with an amplitude of $\sqrt{2}rms$ for a given point across the internal surface. Thus, for $f = 1Hz$, temperature distribution across the Tee is equal to the average temperature distribution at $t = 0s, 0.5, 1s, 1.5s$, and so on. Temperature distribution across the Tee is at maximum at $t = 0.25s, 1.25s, 2.25s$, and so on. The minimum temperature distribution across the Tee occurs at $t = 0.75s, 1.75s, 2.75s$, and so on.

Figures 7 and 8 present the thermal transient FE analysis temperature results for the Tee at a time when the temperature distribution in the inner surface is equal to the average temperature distribution. The fluid temperature at extra inner parts of the Tee, which are not shown in Figures 4 and 5, are extrapolated.

Figure 9 presents the FE temperature fluctuation results at a node located at the inner surface of the Tee in the vicinity of high RMS distribution, see Figures 4 and 5 for the RMS distribution. At this location after 70s the maximum temperature was 159.4°C, the minimum temperature was 101°C and the average temperature was 130.2°C.

Discussion and conclusion

A simplified sinusoidal fluid temperature function has been developed to describe the complex fluid temperature distribution for a cylindrical piping component as a function of space and time. CFD or experimental thermal results can be utilized to obtain the fluid temperature function for a given flow. Discretization of a surface under a thermal mass flow is produced with regular rectangular shapes. Discretization of the surface can be achieved with other four cornered shapes too. This requires generalized curvilinear coordinate transformation of grids to uniform rectangles, see ref. [2]. The analysis presented in this paper uses discretized flow surface with equally sized grids. However, there is no restriction on the refinement of the discretization at critical areas.

The fluid temperature function developed in this paper is a sufficiently accurate approach for analyses governed by thermal fatigue, fatigue crack growth and other fatigue cases due to fluid temperature fluctuations in piping mixing points. Average temperature and RMS distributions are well formulated with bicubic interpolation function. Critical frequencies should be determined for a turbulent flow and inserted into the fluid temperature function for estimation of crack growth due to fatigue. This method provides a realistic spectrum of fluid temperatures across the component walls.

The computational time taken by this analysis is substantially less than the CFD-FE coupling would have taken. The number of nodes in the CFD results shown in Figures 5 and 6 is 50665, while the number of nodes in the discretized surface, see Figure 6, is only 131, which is less than 0.3 % of the number of nodes used in the CFD analysis.

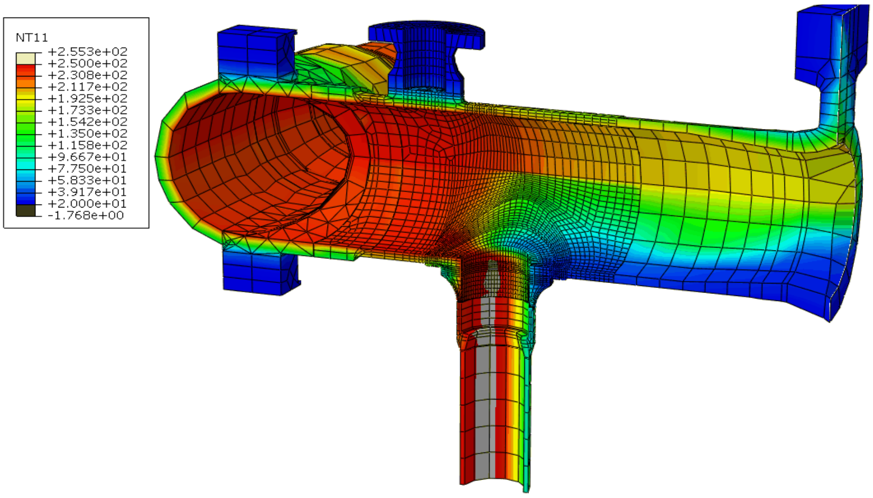

Figure 7. FE results for temperature distribution in unit of °C at inner surface at time $t = 100\ s$.

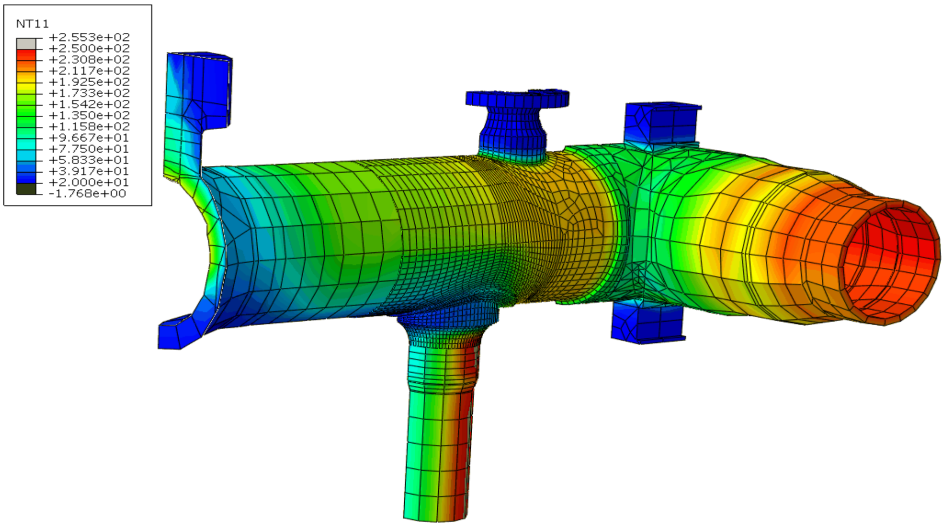

Figure 8. FE results for external temperature distribution in unit of °C at time $t = 100\ s$.

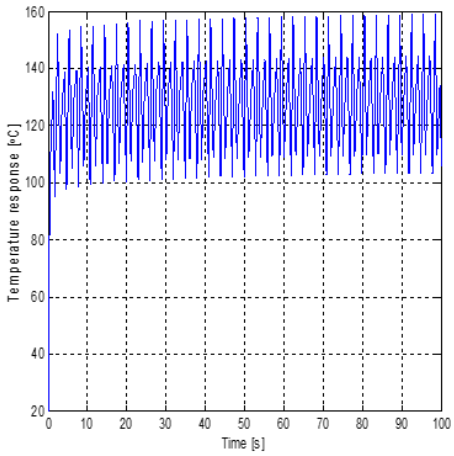

Figure 9. Temperature response in °C as a function of time for a selected node from FE results.

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