Creep-Fatigue Design Studies for Process Reactor Components Subjected to Elevated Temperature Service as per ASME-NH

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Abstract

A number of process reactors in refinery and petrochemical industry are constructed using low chrome alloys which are operating in the creep range and are in cyclic service. ASME B&PV Section VIII Code provides allowable stresses at elevated temperatures for design of reactor components, which are controlled by creep properties. However, fatigue design rules and fatigue exemption rules are not applicable, precluding construction of reactors using low chrome alloys at temperatures above 371°C (700°F). ASME B&PV Section III Division 1 - Subsection NH (ASME-NH) Code considers cyclic failure modes at elevated temperatures and provides creep-fatigue interaction rules and damage limits. In this paper, creep-fatigue damage under elevated temperatures is investigated for process reactor components using elastic analysis method of ASME-NH Code for a defined representative load cycle. Also the complexities in application procedures of ASME-NH rules with thermal and structural analysis results are described in detail.

1. Introduction

The operating conditions of process reactors used in refinery and petrochemical industry are not always in steady state. During their service life, reactors experience cyclic loads such as variable operating conditions as a part of process, startup-shutdown operating cycles or significant excursions from the normal operating conditions. Fatigue damage due to cyclic operating conditions may need to be considered for reactor design and operation. At elevated temperatures, creep damage adversely affects the fatigue damage and can no longer be ignored or treated separately. ASME B&PV Section VIII Code provides allowable stresses at elevated temperatures for design of reactor components, which are controlled by creep properties. The ASME Boiler & Pressure Vessel Code Section
VIII, Division 2 [1] (hereafter referred as ASME VIII-2) provides the data and the methods for fatigue exemption rules and analysis procedures for various materials and operating conditions at lower temperatures or in the non-creep range. ASME VIII-2 requires either meeting the requirements for exemption from fatigue analysis, or, if that requirement is not satisfied, meeting the requirements for fatigue analysis. However, above the 371/427°C (700/800°F) limit, the only available option is to satisfy the exemption from fatigue analysis requirements because the fatigue curves required for a full fatigue analysis are limited to 371°C and 427°C (700°F and 800°F) for ferritic and austenitic materials, respectively.

Fatigue analysis is straightforward at temperatures below the creep range but it becomes more difficult to evaluate at elevated temperatures. Stress relaxation, level of tri-axiality and stress concentration factors affects the cyclic life of a component. In addition, fatigue strength tends to decrease with an increase in temperature due to surface oxidation or chemical attack. These and other factors contribute to the tediousness and complexity of creep-fatigue evaluation. Also, the data needed to evaluate the cyclic stress in a given material is extensive and large amounts of time and cost are involved in obtaining such data. As a consequence, data for creep-fatigue analysis has been provided for only one material (2.25Cr-1Mo-0.25V) in recent ASME B&PV Code Case 2605-1 [2] (hereafter referred as CC 2605-1) and for five materials (2.25 Cr-1Mo and 9Cr steels, 304 and 316 stainless steels, and 800H nickel alloy) in ASME-NH [3]. CC 2605-1 and ASME-NH Code considers cyclic failure modes at elevated temperatures and provides creep-fatigue interaction rules and damage limits. CC 2605-1 outlines a procedure and acceptance criteria for conducting fatigue evaluation of 2.25Cr-1Mo-0.25V steels at limited part of the creep range i.e. for operating temperatures greater than 371°C (700°F) and less than or equal to 454°C (850°F). ASME-NH Code provides design fatigue curve for temperatures up to 595°C (1100°F) for 2.25 Cr-Mo steels.

ASME-NH Code provides both elastic and inelastic analysis methods for creep-fatigue evaluation. Generally, criteria based on elastic material models are more conservative than those based on time dependent inelastic models. The Code has provided comprehensive guidance on elastic analysis method, but the application procedures of assessment are very complicated. Although, the evaluation of creep-fatigue damage using inelastic analysis is conceptually straightforward, the Code has not provided any specific guidance on inelastic methods. The elastic methods make use of a number of interaction diagrams and rules expressing the effects of primary stresses and cyclic secondary stresses on cyclic strain accumulation. Due to the complexity of effects they represent, the rules are complex and have to err on the side of conservatism wherever it is necessary. Some of the complexities are mainly due to the requirement of stress linearization and classification, usage of graphically provided isochronous stress-strain curves, lack of specific guidance on elastic follow-up and estimation of creep strain increment, etc. In this paper, creep-fatigue damage under elevated temperatures is investigated for process reactor components using elastic analysis method of ASME-NH Code for a defined representative load cycle. Also the complexities in application procedures of ASME-NH rules with thermal and structural analysis results are described in detail.

2. Creep-Fatigue Design Studies for Process Reactor Components as per ASME-NH

2.1 Description of Process Reactor Components

Creep-fatigue design studies for pilot plant process reactor components are carried out using elastic analysis method of ASME-NH Code. The process reactor, schematic shown in Fig. 1, consists of several structural discontinuity components. The major structural discontinuities are inlet nozzle to top head junction, outlet nozzle to bottom head junction, quench nozzle to shell junction, catalyst nozzle to shell junction and skirt-shell-head junction. The reactor components are designed in accordance with the design Code, ASME VIII-1 [4], for the design conditions and other design loads. Although the design Code does not recommend any explicit design and fabrication details for cyclic service, all special fatigue resistant features i.e. integrally reinforced forged nozzles and skirt, blend radii on corners, smooth transition between the variable thicknesses, machined or ground welds, advanced inspection methods in accordance with ASME VIII-2 and tight tolerances on fabrication, etc. are considered in the design and fabrication. Creep-fatigue damage is evaluated for the operating conditions using elastic analysis method of ASME-NH Code for a defined representative load cycle. In this paper, creep-fatigue evaluation of inlet nozzle to top head junction and outlet nozzle to bottom head junction with thermal and structural analysis results are presented.
2.2 Design Data

The inside radius of the reactor shell is 500 mm and the thickness at the top and bottom portion of the reactor shell / ellipsoidal head are 30 mm and 36 mm, respectively. The inside and outside diameter of self-reinforced inlet nozzle (20 inch) are 480 mm and 710 mm, respectively. The inside and outside diameter of self-reinforced outlet nozzle (12 inch) are 299 mm and 419 mm, respectively. The material of construction is 2.25Cr-1Mo low chrome alloy steel. The design pressure is 2.6 MPa and design temperature is 550 °C. The typical operating pressure and temperature cycle is shown in Fig. 2. The total cycle time is 240 hrs and the time duration above the creep range is 115 hrs. Typical external piping loads are also considered for the inlet and outlet nozzles. The design life of the reactor is 20 years.

2.3 Finite Element Analysis

A sequentially coupled transient thermal and linear elastic structural stress analysis has been carried out using general purpose commercial finite element software ABAQUS, version 6.11-1. The temperature dependent mechanical and heat conduction properties of 2.25Cr-1Mo steel are taken from Section II, Part D of the ASME Code. Figure 3 shows FEA model of inlet and outlet nozzle which includes the head and portion of shell and is meshed using 3D solid brick elements (DC3D20 for heat transfer analysis and C3D20R for structural analysis). An identical mesh is used for both the heat transfer and structural models to allow direct mapping of calculated nodal temperatures.
For heat transfer analysis, time-varying heat transfer coefficients are calculated for each operating event, based on the expected temperatures and flow rates. Conservatively the calculated maximum heat transfer coefficient of 2000 W/m²°C is applied on inner surface of the model. An equivalent heat transfer coefficient is applied on outer surface of the model representative of the combined effect of thermal insulation and natural convection in air. A heat transfer analysis has been carried out from 0 to 240 hours in thirteen Time-Load Steps. Automatic time incrementation is used. The thirteen Load Steps are selected in such a way that they gave finer time mesh near the transients. Also the maximum allowable temperature change per increment and minimum time increment size are specified for each Load Step appropriately. Figure 4 shows the typical temperature distributions during first transient at time point of 124 hrs.

The obtained temperature distribution is mapped on the structural model, and stress analysis is performed. For structural stress analysis, the reactor shell end nodes are fixed in all directions. The stress analysis also includes internal pressure and nozzle loads due to external piping. The operating pressure load cycle is defined using amplitude curves in ABAQUS. Care has been taken to ensure that the times in the structural stress analysis step and in the previous thermal analysis are the same. The external piping loads are varied in accordance with temperature in the analysis. Figure 5 shows typical von-Mises stress distributions during first transient at time point of 124 hrs.

![Temperature Distribution](image1.png)

Fig. 4: Temperature (°C) distribution during first transient at the time point of 124 hrs

![Stress Distribution](image2.png)

Fig. 5: von-Mises stress (Pa) distribution during first transient at the time point of 124 hrs

2.4 Generation of Input Data for Creep-Fatigue Evaluation

To evaluate creep-fatigue damage from the elastic analysis results, it is necessary to calculate the linearized stresses/strains for the selected critical sections for the entire operating cycle. To determine the critical locations, results of the primary and secondary stresses are analyzed in detail. Also, various other parameters such as location of weld zone, maximum stress, maximum stress range, maximum temperature and hold time at maximum temperature are considered while selecting the critical locations [5]. Based on the above parameters, the evaluation
sections are selected at the nozzle-head junction (see Fig. 3). It may be noted that the ASME-NH uses stress intensity based on Tresca’s maximum shear stress theory, whereas ASME VIII-2 uses equivalent stress based on von-Mises theory. In this paper, to be consistent with ASME VIII-2 rules, the ASME-NH procedures are used in conjunction with the ASME VIII-2 equivalent stress definition. The linearized stresses are calculated based on the von-Mises criterion that is deemed to be adequate for ASME VIII applications.

ASME-NH requires linearization of stress/strain components for the entire operating cycle to calculate the various stress parameters such as \((P_L+P_B/K_t)_{\text{max}}, (Q_R)_{\text{max}}, (P_L+P_B+Q), (P_L+P_B+Q+F)\) and \(S_{\text{nl}}/(\Delta e)\). The parsing of FEA results to determine stress categories is a major problem in elastic analysis method of ASME-NH. The linearized stresses have been calculated using ABAQUS stress linearization module and are classified in accordance with NH-3217. A Macro is used to automate and extract data from ABAQUS stress linearization module at different time points of entire operating cycle. The linearized stresses for the outlet nozzle are shown in Fig. 6. Figure 7 shows the variation of \((P_L+P_B+Q)\) and \((P_L+P_B+Q+F)\) for the outlet nozzle. The strain range \((\Delta e_{\text{max}} = 2S_{\text{nl}}/E)\) is determined using the stress difference procedure described in NB-3216.

The rules for strain limits in T-1330 and creep-fatigue in T-1430 cite stress with elastic follow-up i.e., pressure induced membrane and bending stresses and thermal induced membrane stresses are classified as primary (load controlled) stresses for the purpose of applying their respective rules. ASME-NH offers no specific rules for evaluating elastic follow-up. This conservative approach severely restrict the applicability of the elastic analysis rules [6]. As recommended by Jetter (2008) [6] in the subsection ASME-NH technical basis document, only pressure-induced membrane stresses and thermal-induced membrane stresses are classified as primary stresses for implementation of the rules for stress limits and creep-fatigue damage.

In the ASME-NH rules, the evaluation of inelastic strain and creep-fatigue damage is based on isochronous stress-strain curves which are given for every 28°C and specific time points. This may result in inaccurate structural evaluations due to the problem of graphical determination of stress and strain values from these curves, especially for a design strain range less than 1%. Zhao (2010) [7] has carried out creep-fatigue analysis of reactor nozzle based on CC 2605-1 and concluded that for merely a 2.3% increment of temperature, the creep life with fatigue is reduced by 65%. Therefore, it may be noted that the calculated creep-fatigue life is very sensitive to the loading, especially, the temperature.

In ASME-NH rules, the evaluation of creep strain increment, \(\Delta e_c\), is based on either one stress cycle time or entire service life divided by the number of stress cycles and no guidance is provided on applicability of these methods. For the inlet and outlet nozzles, the creep strain increment based on one cycle is almost twice than that of total life. Conservatively, the creep strain increment based on one stress cycle is used for these nozzles. One stress cycle is treated as entire operating load cycle for calculation of total strain range \((\varepsilon_t)\). Various parameters required to obtain total strain range are presented in Table 1.
Table 1: Parameters for Total Strain Range Calculation

| Parameter                                      | Inlet Nozzle | Outlet Nozzle |
|-----------------------------------------------|--------------|---------------|
| Max metal temp. (°C)                          | 480.0        | 480.0         |
| Cycle duration (hr)                           | 240.0        | 240.0         |
| Time duration above the creep range (hr)      | 115.0        | 115.0         |
| Number of cycles                              | 730          | 730           |
| Alternating stress, $S_{alt}$ (MPa)           | 52.0         | 55.5          |
| Max elastic strain range, $\Delta e_{max}$ (%)| 0.058        | 0.063         |
| Equi. stress concentration factor, $K$        | 1.61         | 1.28          |
| Modified strain range, $\Delta e_{mod}$ (%)   | 0.095        | 0.080         |
| Stress ratio factor at yield, $K_e$           | 1.0          | 1.0           |
| Factor, $(K_e)(K)(\Delta e_{max})(E)/modified-3S_m$ | 0.76        | 0.76          |
| Creep strain increment, $\Delta e_c$ (%)      | 0.016        | 0.016         |
| Total strain range, $\delta_t$ (%)            | 0.121        | 0.100         |
| Initial stress, $S_i$ (MPa)                   | 186.0        | 173.0         |

3. Results and Discussion

Prior to performing the creep-fatigue damage evaluation, the ASME-NH requires the check of elastic ratcheting rules of T-1320 or T-1330 and the modified $3S_m$ limit compatible with the NB-3222.2. The creep-ratcheting evaluation and creep-fatigue evaluation results are presented in the following sections.

3.1 Creep-Ratcheting Evaluation

To satisfy the strain limits by the elastic analysis method, the A-2 test (T-1320) is used in this study. For this test, it is important to determine the maximum value of the primary stress, $(P_L+P_y/K_e)_{max}$, and the maximum range of the secondary stress, $(Q_R)_{max}$, during the cycle being considered. Figure 8 shows the maximum value of the primary stress and the maximum range of the secondary stress.

Table 2 shows the strain limit check results for the inlet and outlet nozzle. The calculated sum of the stress parameters $(X+Y)$ at evaluation section are 0.56 and 0.57 for inlet and outlet nozzles, respectively. These satisfy the ASME-NH allowable limit value of 1. The calculated $3S_m$ value also satisfies the ASME-NH allowable limit value of 221 MPa and the results are shown in Table 2.

![Fig. 8: Primary and secondary stress (MPa) distribution](image)
Table 2: Summary of Creep-Ratcheting Evaluation

| Parameter                                      | Inlet Nozzle | Outlet Nozzle |
|------------------------------------------------|--------------|---------------|
| $(P_L+P_f/K_t)_{\text{max}}$ (MPa)             | 27.6         | 26.4          |
| $(Q_r)_{\text{max}}$ (MPa)                     | 104          | 109           |
| $X = (P_L+P_f/K_t)/S_Y$                        | 0.12         | 0.11          |
| $Y = (Q_r)_{\text{max}}/S_Y$                   | 0.44         | 0.46          |
| $X+Y$                                          | 0.56         | 0.57          |
| $(P_L+P_f+Q)$ (MPa)                            | 104          | 111           |

3.2 Creep-Fatigue Evaluation

To evaluate the fatigue damage, total strain range is calculated at the evaluation point (see Fig. 3) as per T-1432 of ASME-NH and is presented in Table 1 for the inlet and outlet nozzles. For these nozzles, the evaluation point is in the vicinity of a weld ($\pm 3$ times the thickness to either side of the weld centerline). Therefore, the allowable number of cycles, $N_d$, is considered as one-half of the value permitted for the parent material (T-1715). The calculated fatigue damage is 0.0015 for both nozzles. The calculated fatigue damages are negligible at the evaluation points because the obtained total strain ranges are too small to invoke fatigue damage.

To evaluate the creep damage, the stress relaxation time history should be generated based on initial stress, $S_0$. Single stress relaxation cycle is generated for the entire design life since the total strain range, $\varepsilon_t$, is less than $3S_0/E$ for all load cycles. Figure 9 shows the stress relaxation time history at evaluation points for inlet and outlet nozzle. In this figure, no further modification is done on the stress time history curve due to very short duration of the transient time and a lesser primary stress, but the maximum transient metal temperature is considered as per ASME-NH rules. Weld strength reduction factors are considered while calculating the allowable time duration, $T_d$ (T-1715). Figure 10 shows the calculated creep damage accumulation time histories. The calculated creep damage for the inlet and outlet nozzles are 0.77 and 0.38, respectively.

Table 3 shows a summary of the creep-fatigue evaluation results. As shown in this table, the calculated creep damages are much larger than the fatigue damage. From creep-fatigue interaction diagram for 2.25 Cr-1Mo provided by the ASME-NH rules, the calculated total creep damage meets an allowable creep damage of 1.0 (i.e. negligible fatigue damage).
Table 3: Summary of Creep-Fatigue Damage Evaluation

| Parameter       | Inlet Nozzle | Outlet Nozzle |
|-----------------|--------------|---------------|
| Fatigue Damage  | 0.0015       | 0.0015        |
| Creep Damage    | 0.77         | 0.38          |

4. Conclusion

ASME-NH Code provides comprehensive guidance on elastic analysis method for conducting creep-fatigue evaluation for pressure vessel components. However, the evaluation procedures and rules for obtaining creep-fatigue damage are very complicated. The complexities are mainly due to the requirement of stress linearization and classification, usage of graphically provided isochronous stress-strain curves, lack of specific guidance on elastic follow-up and estimation of creep strain increment. Therefore, understanding the complexities in the evaluation process is very important for an appropriate creep-fatigue damage estimation. In this paper, the creep-fatigue evaluation for process reactor components is investigated using elastic analysis method of ASME-NH Code for a representative operating load cycle. The evaluation procedures of ASME-NH rules are described in detail with thermal and structural analysis results and the complexities are highlighted.

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