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Global and Local Elastic-Plastic Stress Analysis of Coke Drum Under Thermal-Mechanical Loadings

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Coke drums are critical equipment in the petroleum industry. The failure modes of coke drums include excessive bulging deformation and fatigue cracking. The elastic-plastic behavior of a coke drum, subjected to both thermal and mechanical loadings, is analyzed for a complete cycle of operation. The effects of multiple operational cycles and localized hot/cold spots are also investigated. It is found that yielding of the clad layer starts at the very early stage in an operating cycle and permanent deformation is caused in the first operating cycle. Plastic shakedown occurs in the clad layer under combined operating thermal and mechanical loadings. It is also found that both hot and cold spots will cause bulging of the shell and the cold spot can cause more severe deformation than the hot spot. [DOI: 10.1115/1.4002802]

Keywords: coke drum, cyclic thermal loading, elastic-plastic analysis, elastic/plastic shakedown, hot/cold spot, finite element analysis (FEA)

1 Introduction

Coke drums are important equipment in the delayed coking process. In routine operation, coke drums are heated up by steam, vapor, and hot oil and then cooled by quenching water and, therefore, experience severe cyclic thermal and mechanical loadings. The prevention of failure and the design and service improvement of coke drums have been high priority topics in the relevant industry and professional organizations for decades.

Bagdasarian et al. [1] indicated in the summary of the American Petroleum Institute (API) survey that coke drums are in cyclic fatigue service and the operating conditions and practices have a larger effect on the integrity of a coke drum than materials selection or design parameters. They revealed that alloy upgrade, specifically, increasing the Cr–Mo contents in alloys, does not yield a longer service life for coke drums. It can be concluded from the survey that the nature of the failure mechanisms and the direction of the design improvement toward failure prevention have yet to be investigated. Penso et al. [2] identified the locations of the cracks and bulges in the coke drum and suggested means to improve coke drum life covering design, fabrication, operation, and maintenance. Ramos et al. [3] presented the mechanical integrity evaluation of coke drums made of Cr–Mo alloys. Failure mechanism analysis, field measurement, and numerical studies were also included in the works of Penso et al. [4] and Ramos et al. [5].

Relevant work on cyclic thermal loadings of pressure vessels was also reported by Kussmaul et al. [6]. The consequences of hot spots on the structural integrity of pressure vessels were investigated by Seshadri under the framework of codes and design standards [7].

Xia et al. [8] developed a thermal model for the heat transfer analysis of the coke drum for an entire operational cycle. Based on the computed temperature history, stress analyses for pure thermal and combined thermal-mechanical loading cases were carried out and stress and strain distributions and time history of the entire coke drum during a complete operational cycle were obtained and analyzed. They found that the clad layer experiences yielding in the load cycle and, therefore, more accurate elastic-plastic analysis is needed.

This study is the continuation of the authors' previous research [8]. The objective of the study is to investigate the elastic-plastic behavior of a coke drum under both thermal and mechanical loadings. ABAQUS finite element analysis (FEA) codes [9] are used in this study for stress analyses. A simple one-course model is also developed to study the mechanical behavior of the drum shell subjected to multiple cyclic thermal and mechanical loadings. Furthermore, the effect of a hot and cold spot on the integrity of the coke drum is investigated. It is found that the yielding of the clad layer starts at the very early stage in an operational cycle and permanent deformation and residual stresses are caused in the first operational cycle. Elastic/plastic shakedown occurs in the clad layer under combination of operating cyclic thermal and internal pressure loadings. It is also found that both hot and cold spots will cause bulging of the shell and the cold spot can cause more severe deformation than the hot spot.

2 Coke Drum Geometry, Mesh, and Materials

Figure 1 shows the geometry and main dimensions of a real coke drum currently serving in industry. The overall height and diameter of the coke drum are respectively 27.87 m and 7.92 m. The thickness of the base layer is 25.40 mm for courses 1, 2, and 3; 22.225 mm for courses 4 and 5; and 19.05 mm for courses 6 and 7, while the thickness of clad is 2.54 mm for all courses. The numbers in the circles indicate data point locations, which are 100 mm above the corresponding welding lines between two courses.

Due to the nature of the geometry and loading and boundary conditions, axisymmetric elements are used to model the coke drum, while the mesh density and distribution vary with the geometrical details of the drum as shown in Fig. 1. The termination of the skirt is assumed to be fixed in the finite element computation.

The materials for the clad and the shell (base) are respectively TP 410S stainless steel and SA387 low alloy steel and their

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