M. SOARE, I-S. MINEA, M. V. PREDOI, C. BUNESCU and C. DIBA, Nuclear NDT Research & Services Srl, Bucharest, Romania

Fatigue damage assessment of coke drums based on temperature monitoring

Coke drums are expensive equipment with a long manufacturing cycle, so a realistic and accurate life prediction can save significant time and money.

Coke drums are special pressure vessels subjected to large cyclic stresses resulting from thermal distributions that are generated by coke bed interactions and random local flows through the coke bed and around it near the wall.[1] It is vital for owners to know as much as possible about the condition of these drums to devise or update plans for operation, inspection, repair and replacement.[2,3]

Full-scale visual inspection, as well as localized inspections like ultrasonic (UT) and dye penetrant (PT) inside the coke drum, are time consuming, require scaffolding and may be performed only during turnarounds. Meaningful information about the required time and the most probable areas of the appearance of cracks can help.[4]

The main problem in the fatigue damage assessment of coke drums is the irregularity and unpredictability of thermal loads during the cooling phase of the technological cycle. To address these issues, a stress assessment method is proposed based on temperature monitoring using thermocouples.[5] Using this method, it is possible to provide a complete image of the temperature field on the entire coke drum surface and to calculate the stress at every point within the coke drum with accuracy. The temperature monitoring of the walls should extend over a time period long enough to be considered as representative for the coke drum functioning.

Method presentation. The input to the assessment method is represented by the temperatures continuously monitored by thermocouples mounted on the coke drum's external surface.

The first step is the design of a temperature monitoring system and establishing an optimal distribution of the thermocouples. Only a minimal removal of coating is required to attach the thermocouples. The temperatures are stored in a database but can also be displayed in real time using proprietary software that allows coke drum operators to see the temperature variations on the surface and is linked to technological parameters including mass flow, material inflow temperature, etc. The temperatures on the surface of the coke drum are obtained from a two-dimensional (2D) interpolation in cylindrical coordinates. The angular interpolation along the recorded values at the same height is done using spline functions for a set of grid angles (e.g., 0°, 10°, 20°, …360°). Then, an interpolation along each generatrix of the coke drum is done, also using spline functions, for a set of heights (e.g., –5 m, –4 m, ….27 m, 28 m).

A snapshot of the interpolated temperature map at the beginning of the cooling is shown in FIG. 1. The geometry of the coke drum is initially defined in a file, as are the locations of the thermocouples. The month and day of the record are indicated on the left side. An animated, rotating, three-dimensional (3D) model of the

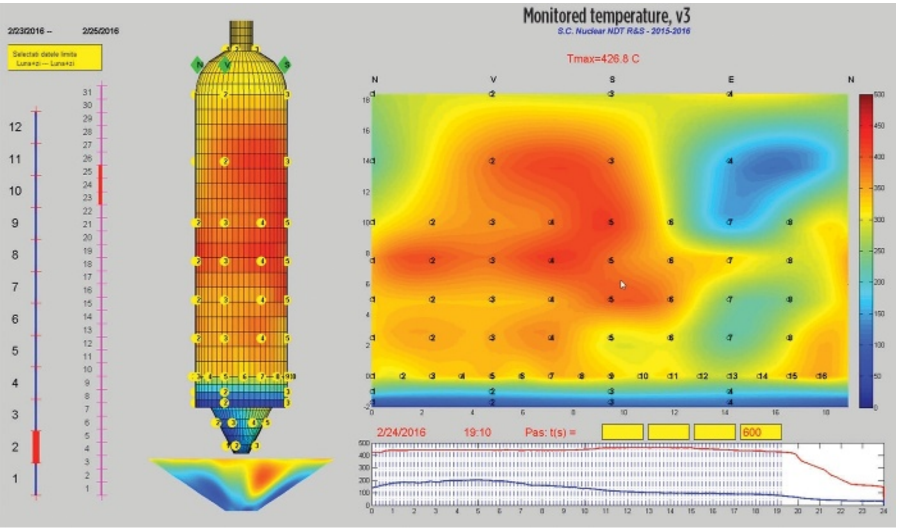

FIG. 1. A user interface with date, temperatures on the rotating model of the coke drum, unwrapped surface of the cylindrical parts (right) and cone (below 3D model), and a plot of extreme temperatures in time (low, right).

coke drum shows the interpolated temperatures. This information is also presented on an unwrapped surface of the cylindrical part of the skirt and drum on the right side of the window. For the unwrapped surface of the cone, the minimum and maximum temperatures are indicated below the 3D model on a 24-hr plot with a selected period (5 min in this case).

The next step is the analysis of temperature records to extract the data needed for the stress calculation. The stored temperatures in all recording points for a monitoring representative interval of several months—or even continuous monitoring—are processed offline.

The amount of time spent at various temperatures on each measuring point was calculated, allowing the evaluation of the creep damage.

The data needed to evaluate the fatigue damage in the coke drum walls were extracted. A second software was developed for processing the temperature records covering months of coke drum operation. The purpose of this second software is to determine the temperature variations at each point of the structure that lead to peak thermal stresses.

The two kinds of temperature variations are:

1. A slow variation of the average temperature during the technological process, specific to each level height where the thermocouples are mounted (**FIG. 2**). The temperature fields obtained for all structure points are corroborated with the pressure on the walls due to the technological process and the hydrostatic pressure. These represent input data for a finite elements, quasi-static analysis to determine the average stress-state stresses in the entire structure at each moment.
2. A rapid and local temperature variation producing high-temperature gradients which, in turn, generate high local thermal stresses. Using the proprietary software, the high-gradient events are recorded for each location on the coke drum.

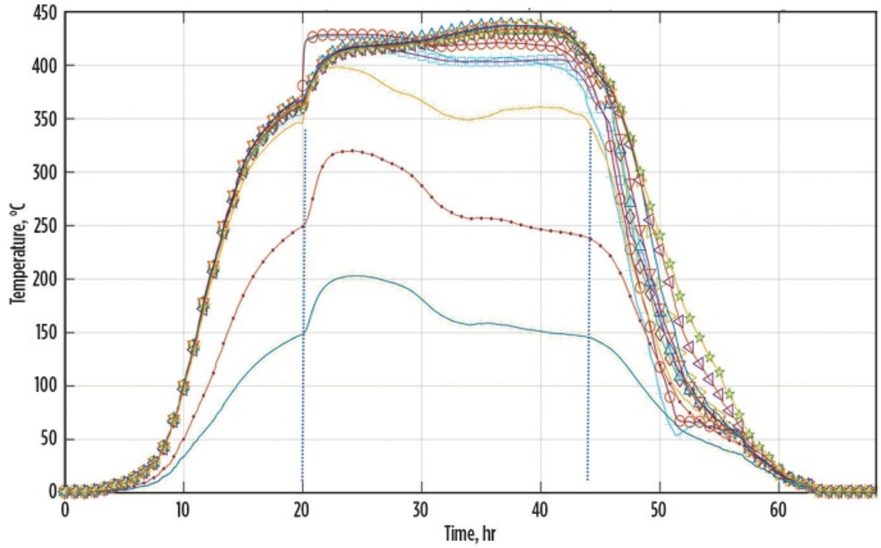

FIG. 2. Temperature average variation vs. time (hr) at the heights where thermocouples are installed.

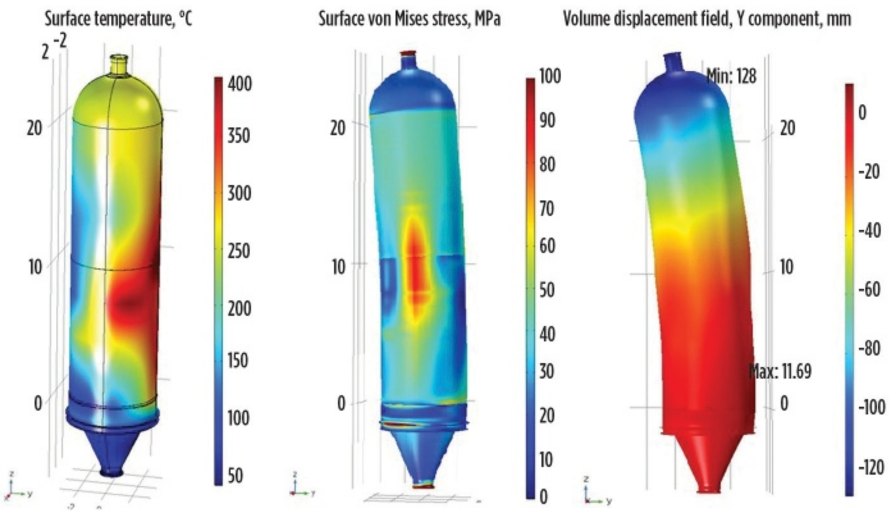

FIG. 3. Temperature map and corresponding stress map on the deformed shape of the coke drum at a selected moment during the cooling process.

The temperature distribution on the coke drum surface when peak stresses occurred in the walls will be used as primary data—in addition to pressure, hydrostatic pressure and weight—for the finite element stress analysis of the coke drum (**FIG. 3**).

The needed data were extracted to evaluate the fatigue damage of the cladding. The thermal shocks were counted and classified at filling and cooling for every measuring point.

The third step is the stress analysis of the coke drum and cladding. Stress analyses were performed in all critical moments of each technological cycle, and the stress variations were obtained in the chosen points of the coke drum over the monitored period.

The finite element analysis calculated the stress generated by thermal shocks in the drum walls, focusing on the cladding. **FIG. 4** shows the variation of the equivalent stress in the cladding over time during a strong thermal shock generated by the impact of the cooling fluid on the coke drum wall. **Note:** The magnitude of the stress increased in a very short time.

The fatigue damage that accumulated over the monitored period in the drum walls and in the cladding was assessed using the EN 13445-3 standard.[4] The damage was calculated by extrapolation, considering the monitored period of time as representative for the entire service duration.

Case study. The Petromidia refinery in Romania, a member of KazMunaiGas Group, decided to assess the remaining life of its coke drums following a major repair to plan future investments in the delayed coking unit (DCU). The unit has four medium-sized coke drums made of C–½Mo steel, with a diameter of 6.3 m and a height of 26 m.

To solve the problem, the engineering company[a] entrusted with the project applied the stress assessment method based on temperature monitoring of the coke drum walls.

An acquisition system with 80 thermocouples was designed and installed in 2015 on one of the coke drums in operation at Petromidia. The system gathered data for 1 yr, and all records were kept in a database for subsequent analysis. During this time, the temperature distributions on the coke drums could be visualized both in real time and offline using the proprietary software.

The data needed for the stress calculation were extracted from the temperature records and used to gain a better understanding of the process developing inside the coke drum.

The amount of time spent at various temperatures on each measuring point allowed the evaluation of the creep damage. In this case, it was negligible, although the allowable stress of the C–½Mo steel of the coke drum walls at the design temperature was obtained from time-dependent properties.

By analyzing each cycle record, it was observed that the cooling fluid may touch the wall at any point below the coke level. Initially, it was assumed that the fluid flow inside the coke drum during the coking process was random, but the analysis of all temperature records highlighted the existence of flowing patterns within the coke drum, both at filling and cooling.

Using this method, the fatigue damage in any point of the coke drum can be assessed. This requires the extraction of the needed data for every chosen point on the model from every stress analysis. By following the step-by-step method presented here, the following results were obtained.

TABLE 1 presents the total fatigue damage in 64 points of the coke drum walls, both on the inner and outer faces. The fatigue damage is visibly higher than average on one sector of the cone wall and on an area of the cylindrical wall. TABLE 2 presents the fatigue damage in 32 points of the skirt welding, as a percentage of the allowable value. On the skirt welding, two points were subjected to higher stresses and, consequently, accumulated much more fatigue than average.

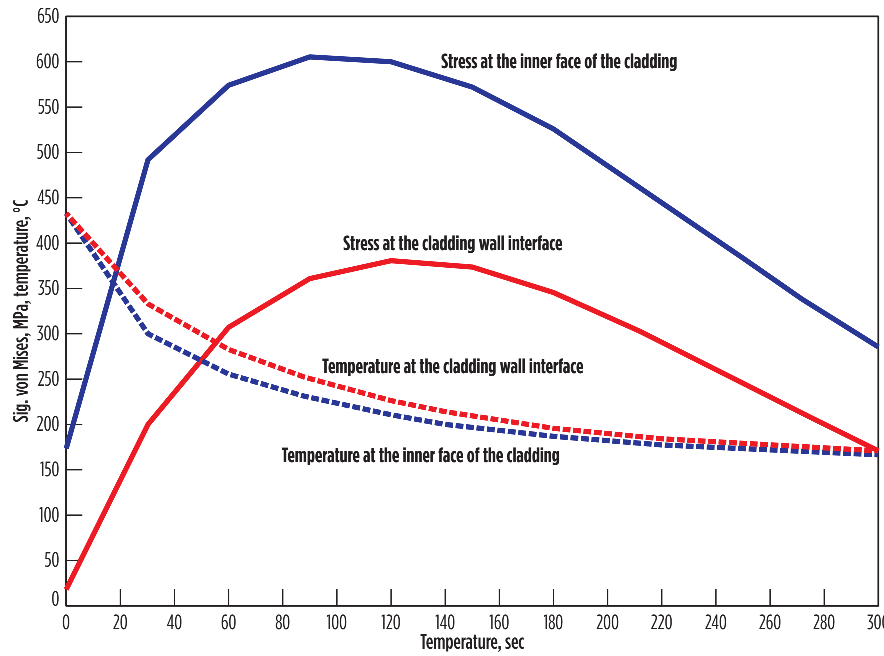

FIG. 4. Temperature and stress variation over time in the cladding during a thermal shock.

TABLE 1. Fatigue damage accumulated by the coke drum walls

Number	Level	Circumferential position															
		0°		45°		90°		135°		180°		225°		270°		315°	
		Ext.	Int.	Ext.	Int.	Ext.	Int.	Ext.	Int.	Ext.	Int.	Ext.	Int.	Ext.	Int.	Ext.	Int.
1	Cone, –3 m	5	4	9	18	14	5	3	1	3	1	1	6	8	4	2	1
2	Cone, –4.5 m	13	15	13	19	5	2	2	1	0	0	1	1	2	1	1	0
3	Level, 0 m	3	1	1	1	1	1	2	1	1	1	1	1	1	1	3	1
4	Level, 2.5 m	3	3	4	8	2	2	2	1	2	1	1	2	1	3	3	1
5	Level, 5 m	5	6	8	18	4	3	3	1	1	1	2	2	6	5	1	1
6	Level, 7.5 m	6	6	9	23	4	4	3	2	1	2	3	2	4	5	1	1
7	Level, 10 m	67	4	47	9	7	5	4	1	2	1	2	3	7	6	1	1
8	Level, 12.5 m	3	3	3	5	2	2	1	1	1	1	1	1	2	2	1	1

The distribution of thermal shocks at cooling, by temperature rate, on each level of the coke drum as a percentage of the total number of shocks counted, is shown in TABLE 3.

The effects of thermal shocks on the accumulation of fatigue in the cladding at each level where temperatures were measured (by percentage) are shown in FIG. 5. The reference value is the fatigue damage without shocks on the lower part of the coke drum, from Level 0 to Level 10, which is 35 mm thick. The wall thickness of the cone is 40 mm, and the upper part is 30 mm thick. The fatigue damage of the cladding is in red (considering the thermal shocks) compared to the blue columns, which represent the fatigue damage of the cladding accumulated without considering them.

The calculations show that 12%–67% of the total fatigue damage of the cladding (depending on the level) come from thermal shocks, while the rest is due to the cyclic warming at the vacuum residue temperature.

Takeaway. The methodology presented here enables the user to evaluate the low cycle fatigue and remaining life for the entire coke drum, highlighting the critical zones. Detailed inspection plans focused on the critical zones can be elaborated as a basis for the preventive maintenance of the coke drum.

The data gathered and analyzed during this assessment can also be used in the optimization of operating procedures and the modernization of coke drums to extend their lifetime. The main results of the case studied using this methodology are:

- By monitoring the coke drum wall temperatures, the existence of flow patterns within the coke drum, both at filling and cooling, were observed. The study of these patterns led to the discovery of their cause.
- The fatigue damage to the coke drum was calculated with a special focus on the skirt welding and the cladding. The results highlighted the effect of the flow patterns on the coke drum structure, showing the areas subjected to higher stresses and accumulating more fatigue damage.
- Based on the information gathered, proposals for the optimization of the DCU operation were made.
- Considering the results of the fatigue damage assessment, the oil refinery management decided to extend the service life of the coke drum. HP

TABLE 2. Fatigue damage accumulated by the skirt welding

Number	Skirt welding	0°	45°	90°	135°	180°	225°	270°	315°
9	Exterior	2	2	2	5	1	3	2	8
10	Middle	31	3	8	10	13	3	4	7
11	Interior, lower corner	52	58	74	179	44	57	50	135
12	Welding concentrator	153	194	237	696	137	185	138	468

TABLE 3. Thermal shocks distribution on the coke drum walls at cooling

Level, 22 m	48.3	45	6.2	0.5						
Level, 18 m	64.3	24.7	8.4	2.2		0.3				
Level, 14 m	45	38.4	12.1	3.5	0.8	0.3				
Level, 10 m	41.1	35.6	12.5	6.2	2.6	1.3	0.6		0.1	
Level, 7.5 m	46.4	37.5	10.3	3.7	1.3	0.1	0.4	0.1	0.3	
Level, 5 m	49.1	33.3	9.8	4.7	1.7	0.8	0.6			
Level, 2.5 m	64.7	25.7	5	2.3	0.6	0.6	0.1	0.4	0.4	0.1
Level, 0 m	87.2	10.7	1.2	0.7	0.1	0.1	0.1			
Level, –3 m	42.9	40.8	12.5	2.6	0.9	0.3				
Level, –4.5 m	38.4	46.3	10.4	3	1.3	0.8				
Temperature rate, °C/min	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100

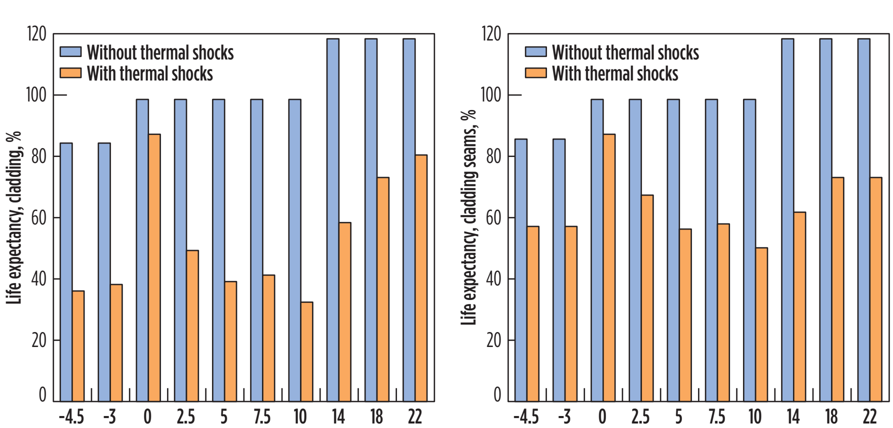

FIG. 5. Reduction in life expectancy of the cladding due to thermal shocks.

NOTES

[a] Nuclear NDT Research & Services

LITERATURE CITED

1. "Delayed Coker Unit Basics," Coking.com, Resources.
2. Mzad, H. and R. Khelif, "Numerical approach for reliability-based inspection periods (RBIP) of fluid pipes," *Case Studies in Thermal Engineering*, Vol. 10, 2017.
3. Zhaoa, J., H. Donga, X. Wang and X. Fu, "Research on heat transfer characteristic of crude oil during the tubular heating process in the floating roof tank," *Case Studies in Thermal Engineering*, Vol. 10, 2017.
4. EN 13445-3 Standard: "Unfired pressure vessels—Part 3: Design."
5. Soare, M., I-S. Minea, M. V. Predoi, C. Bunescu and C. Diba, "Comprehensive life assessment of a coke drum," REFCOMM Conference, Valencia, California, October 1–5, 2018.

MARIAN SOARE is the General Manager of Nuclear NDT Research & Services Srl. He is a research scientist in structural integrity characterization of materials, and has been working in research in the nuclear field for 20 yr. In 2000, Dr. Soare founded Nuclear NDT Research & Services, continuing the research work on projects carried out within this company.

ION-SORIN MINEA is a Research Engineer and has been working with Nuclear NDT since 2013. He has 28 yr of experience in thermomechanical and vibration analysis of piping systems and pressure vessels, as well as finite elements simulations.

MIHAI VALENTIN PREDOI is a Research Engineer involved in the activities of the Thermomechanical and Technical Inspection (TMTE) Engineering Department. He specializes in finite elements simulations and software development. Dr. Predoi also lectures at the University Politehnica of Bucharest in Romania.

CONSTANTIN BUNESCU is a Research Technician with Nuclear NDT. He has more than 40 yr of experience, specializing in automatic control systems, applied electronics, the IoT and Oracle programming.

IOAN CRISTIAN DIBA is a Mechanical Engineer with Nuclear NDT. He is involved in the activities of the design and technical expertise engineering department, and specializes in boilers and pressure vessels.