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USING COMPUTATIONAL FLUID DYNAMICS AND FINITE ELEMENT ANALYSIS TO DETERMINE BOLT STRESSES DUE TO THERMAL CYCLIC LOADING

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ABSTRACT

This paper details the procedures necessary to accurately determine the stress in the bolts on a coke gasifier inlet flange using current state-of-the-art practices. Using accepted ASME Code practices (ASME [1]), the stress results are then used to justify the elimination of the spacers that were specified in the original design. Computational fluid dynamics (CFD) is employed to determine heat transfer coefficient distributions in the areas of interest. Finite element (FE) analysis is used to compute the transient assembly temperatures and related bolt stresses.

By evaluating the bolt stresses as specified in ASME Div. 1 [1], these analyses were used to determine that the spacers could safely be eliminated during operation.

INTRODUCTION

The original design for the inlet head on a coke gasifier called for long bolts with spacers between the nut and the top of the flange. These spacers were deemed necessary to limit the stress in the bolts during temperature cycling of the vessel.

At startup, the flange had to be disassembled and reassembled to change from the pre-heat burner to the process burner. The spacers made this procedure difficult and, more importantly, made achieving an even preload on the bolts almost impossible. Uneven preload often resulted in a failed gasket with subsequent leaks.

The primary emphasis for this paper is on the procedures used to conduct the analysis. Some of the operating parameters are considered proprietary. Therefore, specific values are not presented. Omitting these parameters does not detract from the presentation of the procedure.

A schematic of the gasifier installation is contained in Figure 1. In this figure the process stream enters through the burner location at the top of the vessel, is reacted in the vessel, and exits through the outlet location.

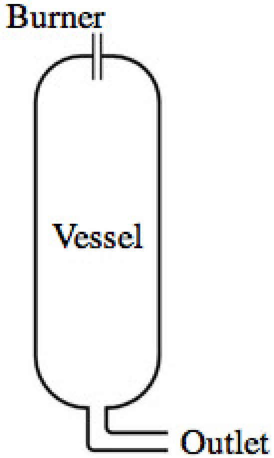

FIGURE 1 – PROCESS SCHEMATIC OF GASIFIER

The inlet assembly, shown in Figure 2, is composed of two separate flanges and an associated burner. The larger flange is bolted to the vessel, while the smaller flange supports the burner. During startup, the gasifier uses a natural gas burner for preheating and refractory dry-out. Once the vessel is preheated, the gas burner is replaced with a coke burner for steady-state process operation.

During the process, the coke (a by-product of a refining process) is converted to slurry. The slurry is reacted with pure gaseous oxygen within the gasifier where temperatures reach

2400 to 2700 °F. The product of this reaction is syngas, a mixture of hydrogen, carbon monoxide, carbon dioxide and hydrogen sulfide (Ferguson [2]). Further downstream, process equipment is used to convert the stream to high grade ammonia.

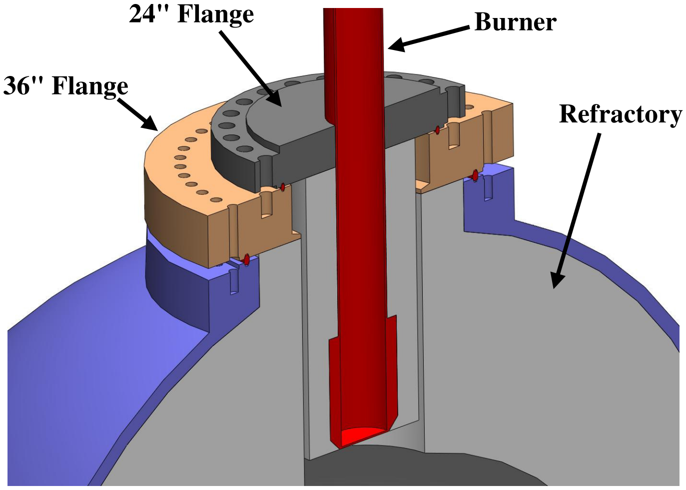

FIGURE 2: BASIC CAD MODEL OF GASIFIER INLET

In the original design, a temperature differential of 200 °F between the flanges was assumed. This differential induced bending stresses in the bolts due to a difference in radial displacements of the two flanges. The design calculations indicated that the bending stresses in the bolts were above acceptable levels. To reduce the bolt stresses, the design was altered with longer bolts with spacer sleeves, shown in Figure 3.

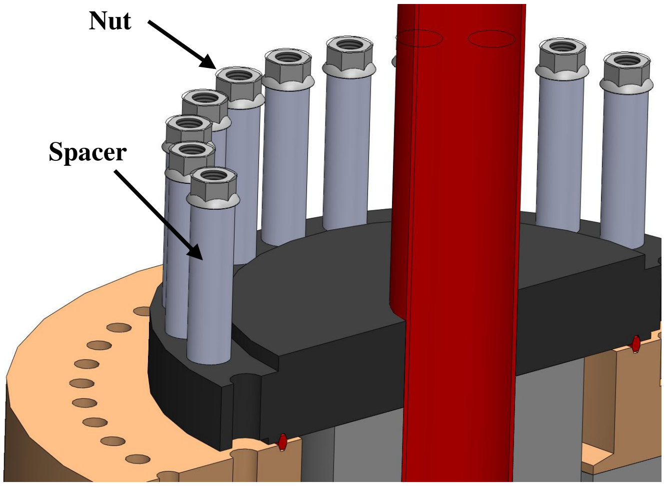

FIGURE 3: CAD MODEL SHOWING SPACERS

The longer bolts and spacers proved to be problematic. During the startup process, it was difficult to establish and maintain a consistent preload in the bolts when using the spacers. This variable preload caused uneven gasket loads, leading to gasket failures with subsequent leaks. Because of these problems, a study was initiated to determine if it was possible to eliminate the spacers using modern analysis techniques. The effort used CFD and FE models to develop a better understanding of the operational temperature profiles and associated stresses.

Once again, it should be noted that the analyses presented in this paper represent procedures employed to analyze specific design and operating conditions. Specific values related to the analyses are not presented. The analyses presented in this paper should not be used to qualify any other designs or operating conditions. The procedures presented in this paper represent good practice for a design of this type.

NOMENCLATURE

DP = Design Pressure
RNG = Renormalization of Groups
Y+ = u^*y/ν, used in defining the law of the wall
u* = Friction velocity
y = Distance to nearest wall
ν = Local kinematic viscosity
k-ε = Two-equation Reynold’s Averaged Navier Stokes (RANS) turbulence model

ANALYSIS PROCEDURES

The focus of the analysis was to determine whether or not the spacers are necessary for this flanged assembly. Meeting this mandate required an analysis to characterize the temperature differentials and the associated differential expansions between the 24” and 36” flanges. As it was not known *a priori* where or when the maximum temperature differentials would occur, a complete design analysis would require evaluation via a transient thermal investigation. The boundary conditions for this analysis would include convection on the inside and outside atmospheric surfaces of the gasifier and, as discussed in the **THERMAL ANALYSIS** Section, body-to-body radiation. The flow patterns within the gasifier did not match design book cases (Hodge [3]) for estimation of the internal convection coefficients within the annular passage between the flanges, refractory, felt and burner (see Figure 4). For this reason, a CFD model was deemed most appropriate for estimating these coefficients for the transient thermal analysis performed via FE analysis.

Temperatures calculated during the transient thermal analyses were verified through a comparison to infrared thermal images provided by the operator.

The peak temperature differentials were transferred to a structural model. To determine the tensile and bending stresses within the bolts, this model was then analyzed with the inclusion of the mechanical loads specified in UG22 LOADINGS [1]. These stresses were then evaluated using Section VIII, Div. 1 allowable stresses [1].

CFD ANALYSIS

The purpose of the CFD analysis was to determine if the flows from the high speed (~50 m/s) gas exiting the burner would introduce flow within the annular passage between the flanges, refractory, felt and burner. If recirculating flows occurred in this passage they would result in a higher convection coefficient on the inside surfaces of the gasifier, and consequently, higher heat transfer. Since the primary purpose of the CFD analysis was to detect recirculation in the annular passage, it was not necessary to include combustion in the analysis. The flame front exists a considerable distance from the burner exit and does not affect flow in the annular passage.

To perform the analysis, an axisymmetric CFD model was built based on the gasifier geometry. The model geometry is illustrated in Figure 4. Steady-state analyses were performed using the procedures detailed below in Star-CCM+ (CD-Adapco [4]).

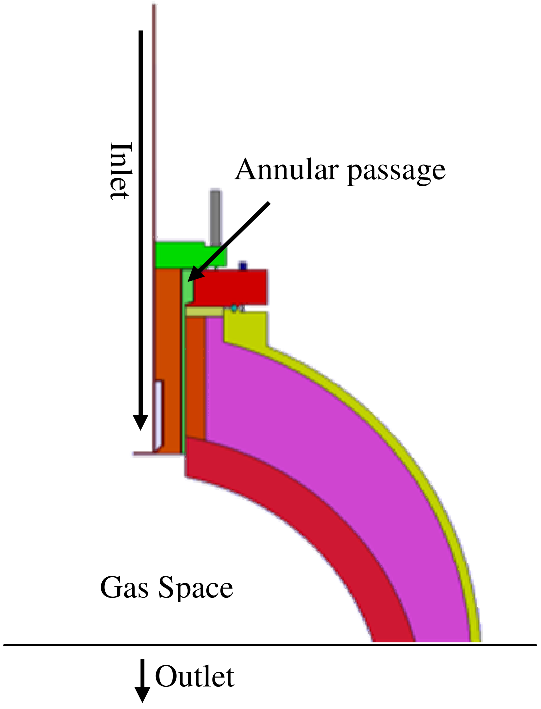

FIGURE 4: AXISYMMETRIC VIEW OF GASIFIER

Two separate analyses were conducted using two gas mixtures. A stoichiometric mixture of methane and air was used to represent the heatup process and a stoichiometric mixture of coke and oxygen was used to represent the operating conditions. These gases were used to define an inlet velocity boundary condition. The velocity values were defined using flow rate information supplied by the operator.

The outlet was defined as a pressure outlet with the pressure defined as the DP of the vessel. The analyses modeled the species as ideal gases. Turbulence was included through the use of the RNG k-ε turbulence model. Near wall boundary layer refinement was used in the annular passage so that the wall Y+ values were less than 10 for both analyses.

The analysis indicated that almost no recirculation was introduced in the passage, even at high burner flow rates. The velocity magnitudes computed in the analysis are shown in Figure 5. Additionally, the convection coefficient at the walls within the passage was queried from the model. The maximum value of this coefficient was found to be ~0.1 BTU/(hr*ft2*°F).

Modeling of the heat transfer across the flange using standard resistance network modeling [3] indicated that the thermal resistance across the internal convection boundary was at least 20 times all other resistances in the network. Little error was introduced in the calculations through the use of a singular convection coefficient in this passage. Slight variations in this convection coefficient did not significantly affect the overall resistance. For this reason, the maximum convection coefficient within the annular passage calculated via CFD was applied to the walls of the annular passage for the remainder of the analyses.

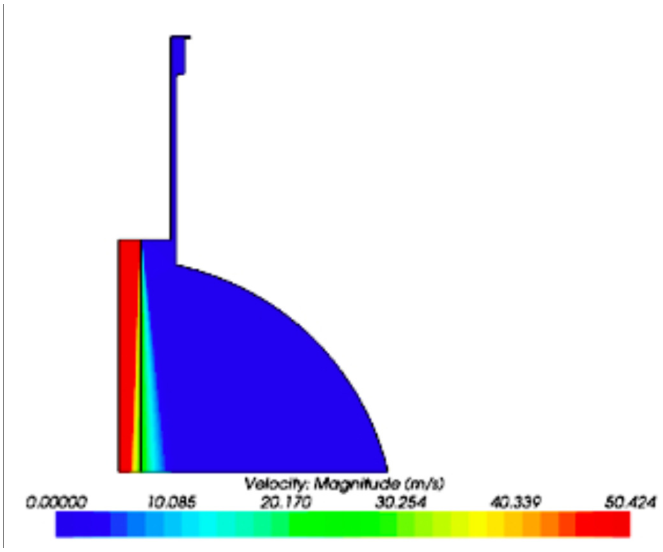

FIGURE 5: VELOCITIES DUE TO JET AT BURNER LOCATION

Calculations performed using resistance network modeling indicated that the majority of the temperature drop (> 2300 °F) would occur at the internal convective interface and a temperature drop across the flange and external convective boundary would be only about 100 °F. However, thermal imaging during startup (similar to that shown in Figure 6) indicated that temperature drops greater than 200 °F were occurring at the external convective interface. Consequently, it was clear that a second heat transfer mechanism was occurring during service.

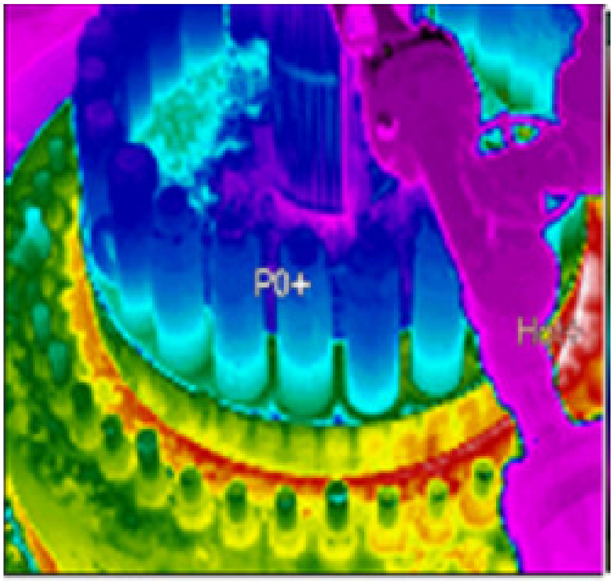

FIGURE 6 – SAMPLE THERMAL IMAGING SCAN FROM OPERATIONAL GASIFIER

Radiation Considerations

Hottel (Hottel [5]) has shown that typical emissivity values lie between 0.08 to 0.10 in hydrocarbon combustion environments where only trace amounts of water are produced.

An FE model was developed to evaluate the radiation effects within the environment. This model included all of the previously described solid gasifier components, as well as an approximation of the air in the annular passage. The exterior of the burner contained cooling water traces and so would operate at a low enough temperature that radiation between the burner and flanges was considered negligible.

Inspection of the geometry of the model indicated that the view factor of the flanges to the bulk of the gasifier refractory was near zero. Thus only the top portion of the vessel needed to be included in the model. Thermal resistance calculations indicated that the inner wall temperature would be very close to the combustion temperature. Rather than computing the radiation and convection effects on the inside surface, this wall temperature was simply set to the combustion temperature. This approximation did not introduce significant error in the transient thermal model, but did significantly reduce the complexity of the required models.

A steady-state analysis was performed using the 0.1 BTU/(hr*ft^2*°F) convection coefficient computed during the CFD analysis of the passage. For the analysis, the gas in the annular passage was defined as a transparent emitter with an emissivity of 0.09 and at the combustion temperature. The results (seen in Figure 7) agree very well with the temperature profiles shown in thermal images for the colder steady operating temperature. These analyses were performed using Algor v. 20 (Algor [6])

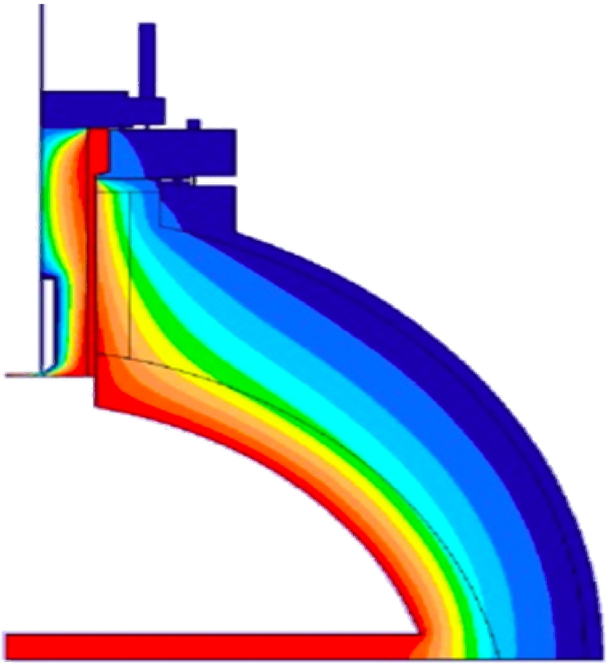

FIGURE 7: TEMPERATURE CONTOURS WITH EMISSIVITY OF 0.09

These results confirmed that the primary mode of heat transfer into the flanges during normal operation was radiation from the hydrocarbon combustion byproduct. However, it was still unknown why the emissivity of the gas increased during reactor startup.

Water vapor, carbon dioxide and nitrogen are the primary products of the combustion of natural gas (methane) in air. It is known that the emissivity of nitrogen is almost zero at all temperatures. At a partial pressure of 1 atm and above, water vapor can have an emissivity as high as 1 (Staley [7]). Since water has the lowest molecular weight of any of the combustion products, it will tend to segregate at the top of the vessel due to buoyant forces. Therefore, it can be concluded that the emissivity of the gas at startup with high levels of water vapor near the flanges could approach 1.

Another FE analysis was conducted using a gas emissivity of 1. This produced temperatures much higher than indicated in any of the thermal images. An iterative analysis procedure was then used to determine the gas emissivity required to produce temperatures seen in the thermal images during startup. These analyses indicated that a gas emissivity of 0.7 would produce temperature profiles that were almost exactly the same as those seen in the thermal images. Figure 8 contains the temperature profiles calculated during the 0.7 emissivity value analysis.

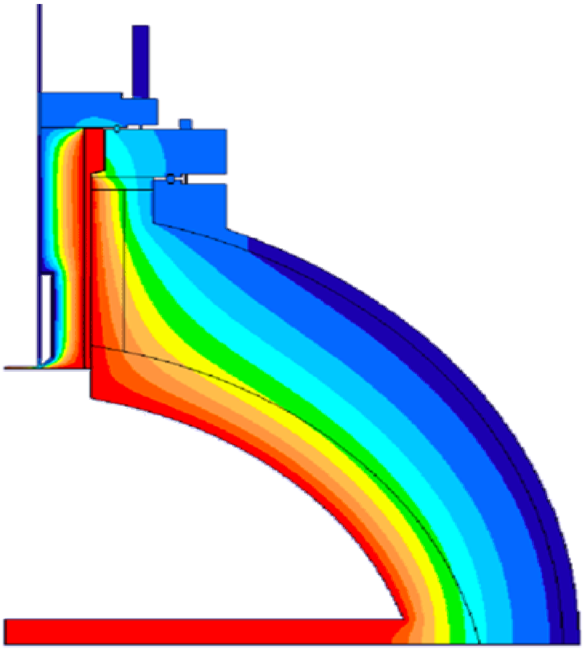

FIGURE 8: TEMPERATURE CONTOURS WITH GAS EMISSIVITY OF 0.7

When the gas burner is replaced with the coke burner, the products of the coke reduction reaction are lower in molecular weight than water. As a result, the water vapor will eventually be replaced with these lighter gases due to mixing and will lower the gas emissivity value to Hottel's hydrocarbon combustion byproduct values of ~0.1. Thus, the flange will heat up during initial operation with the coke burner. It is expected that the flange's temperature will decrease over time due to the replacement of the water vapor.

THERMAL ANALYSIS

The primary purpose of the overall analysis was to justify the elimination of the spacers. These spacers were used to reduce the bending stresses in the bolts produced by the temperature differential between the flanges. Consequently, a transient analysis was performed to determine when the maximum temperature difference would occur. Due to the time-scales involved in the gasifier preheat and transition to operational temperatures, it was decided to perform these analyses with an FE package. This would allow for a much greater, stable time-step during solution than could be achieved through CFD analyses.

To perform the analysis, a steady-state analysis was first conducted on a 3-D model to produce the temperature profiles that are evident at startup, after preheating with the natural gas burner. The results from this analysis were used to initialize a transient analysis using the higher internal temperature associated with the coke reduction. The higher temperatures overall resulted in an increase in the differential temperature between the flanges. Once a steady-state temperature profile had been achieved during this transient analysis, the gas emissivity was step-changed from 0.7 to 0.09. A step-change of the emissivity was used since there was no information on the rate of replacement of the water vapor with the coke reduction products. Figure 9 shows the average temperature difference vs. time between the two flanges. The graph indicates that the maximum temperature difference occurs at the hottest condition and is approximately 60 °F.

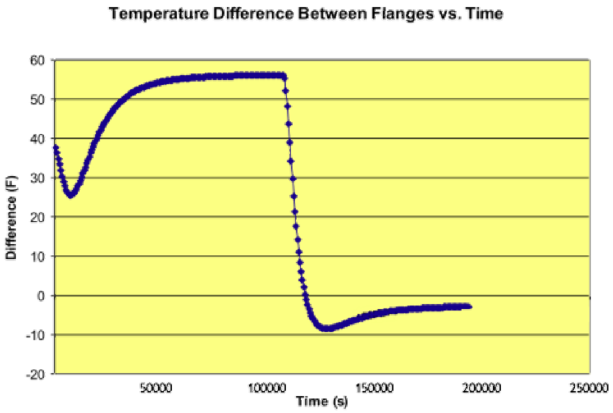

FIGURE 9: AVERAGE TEMPERATURE DIFFERENCE BETWEEN FLANGES

Structural Analysis using FEA

To determine the bending stress in the bolts due to the temperature difference between the flanges, a 3-dimensional 1/8th symmetry model of the vessel was constructed. See Figure 10.

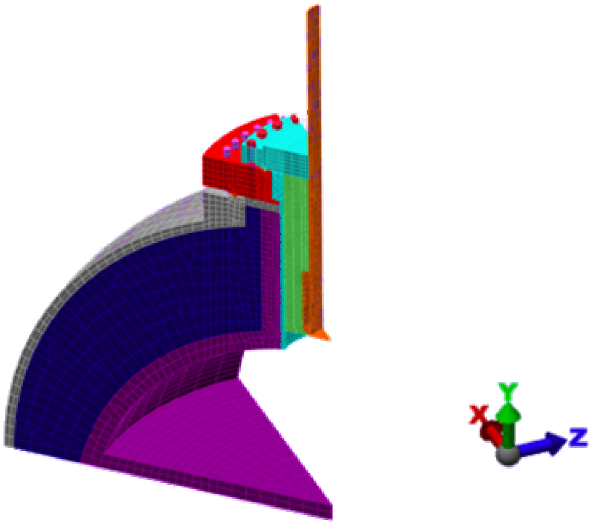

FIGURE 10: 3-D 1/8TH SYMMETRY MODEL USED FOR BOLT ANALYSIS DURING TRANSIENT ANALYSIS

The temperature results of the thermal analysis at the peak temperature differential between the flanges were transferred to a static model. A stress analysis was then performed. This temperature profile is shown in Figure 11. During the structural analysis, operational loads specified in Paragraph UG 22 [1] were also applied to the structure. The bolt preloads were taken as 30% of minimum yield to match the field practice for this vessel.

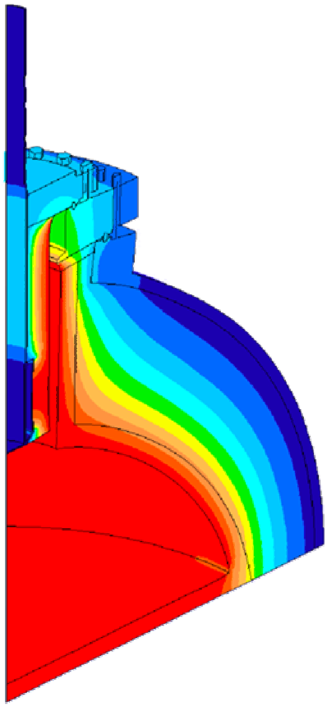

FIGURE 11: TEMPERATURE VALUES CALCULATED DURING 3-D ANALYSIS

RESULTS AND DISCUSSION

The maximum stresses from the analysis were output and evaluated using the procedures specified in Section VIII, Div. 1 [1]. The bolts were found to meet the stress requirements without the added length and spacers.

CONCLUSIONS

A procedure using current state-of-the-art analytical methodologies for qualification of the thermal stress profiles within flange bolts via ASME standards is demonstrated in this paper.

The procedure's analyses used CFD models and basic thermal analysis to establish that significant convective heat transfer was not occurring in the annular passage of interest. Thermal analyses performed with an FE package indicated that radiation emissions from hydrocarbon reactions reproduced the temperature profiles evidenced in long-term operation of the gasifier. The emissivity of products from the combustion of natural gas (specifically water vapor) used during the pre-heat of the gasifier could have a much higher value than during normal coke firing. It was shown that at emissivity values below the maximum values documented in literature, the maximum temperatures evidenced at the operator's facility could be achieved. Transient analyses were then used to determine the maximum temperature differentials that could occur between the flanges using information derived in the previous analyses.

The procedural analyses demonstrated that, indeed, significant conservatism – resulting in the recommended use of spacers – had been used in the initial calculations. The new analyses showed that the spacers could be safely removed. The operator has reported no problems since the spacers were removed from the gasifier several years ago.

The analyses presented within this paper document only a procedure that was used in a specific circumstance. Proper engineering judgment must be used to qualify other flange arrangements.

REFERENCES

[1] ASME, "ASME Boiler and Pressure Vessel Code," Section VIII - Division 1, The American Society of Mechanical Engineers, New York, NY

[2] Ferguson, Coleman R., "Refining Gasification: Petroleum Coke to Fertilizer at Farmland's Coffeyville, KS Refinery" Paper presented at the NPRA Annual Meeting, San Antonio, Texas, March 21-23, 1999.

[3] Hodge, B. K. 1990. *Analysis and design of energy systems*. New Jersey: Prentice-Hall

[4] CD-Adapco, Star-CCM+ v.2

[5] Hottel, H.C., The emissivities of the luminous flames and the radiative energy corresponding to these emissivities, taken from www.cookstove.grensy.info, 1954

[6] Algor, Algor v. 20+

[7] Staley, D.O., Jurica, G.M., "Flux Emissivity Tables for Water Vapor, Carbon Dioxide and Ozone", Institute of Atmospheric Physics, The University of Arizona, Tucson, 1969