Practical Vessel System Force/Moment Analysis Using Finite Element Techniques

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ABSTRACT

In the design of a sulfur recovery plant incorporating three closely coupled pressure vessels, differential thermal growth of the vessels was perceived as a potential stress problem for the vessel connections. Due to the size of the vessels, the anchor point locations, the foundation stiffness and the type of connections, the results obtained from a typical piping flexibility analysis were deemed to be of questionable accuracy. Design questions were answered using Finite Element techniques that, due to advances in the software, were both timely and cost-effective for use in the design process. The process employed and the results obtained are presented as an example of the tools currently available to the design engineer.

DESCRIPTION OF PROBLEM

A typical Claus Sulfur Recovery Unit (SRU) has a reducing transition cone connection between the Claus thermal reactor and the first pass Claus process cooler. The first pass of the cooler is closely interconnected to the second pass of the cooler. The system has its fixed anchor at the inlet to the second pass and the entire unit is supported on piled foundations. Figure 1 illustrates the layout of the system.

The thermal reactor is 15 feet in diameter and the Claus process coolers are 6 feet in diameter each. Typically the equipment is joined by a butt welded connection between the thermal reactor transition cone and the first pass cooler inlet channel. Although the operating pressure is 9 psig, the equipment is designed for deflagration conditions with a design pressure of 75 psig. The unit is Code stamped and National Board registered.

Normally the field connection for these types of units would consist of a weld end connection at the transition cone outlet and the cylinder/offset inlet. A field butt weld completes the installation. The design of this particular unit included a carbon steel round-up ring welded to the end of the transition cone. A bevel weld was used to join the cylinder/offset ring on the inlet channel of the first pass cooler to the face of the round-up ring. The round-up ring maintained cone roundness and allowed for some misalignment during field installation.

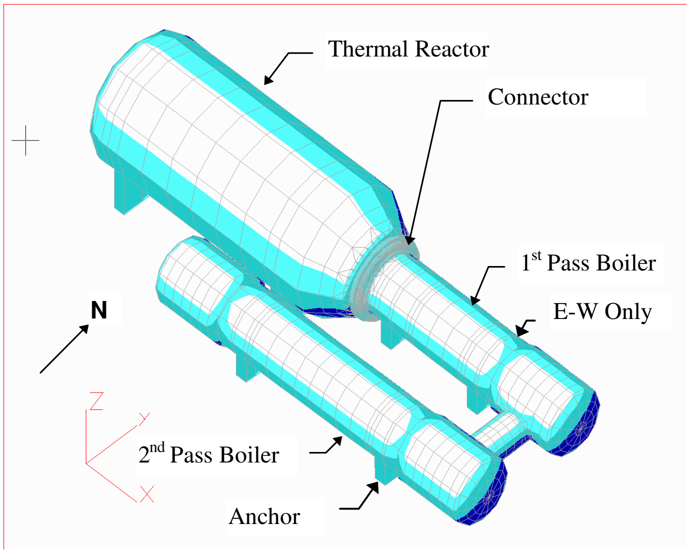

Figure 1

The equipment centerline is in the east-west (E-W) direction. The system anchor point is at the inlet to the second pass cooler on the east end. The outlet of the first pass cooler (east end) has stop bars that only allow north-south (N-S) movement. Except for the fixed support, all supports have teflon slide pads. With this arrangement, bending stresses on the crossover connection are eliminated but the stop bars on the first pass cooler outlet causes over six inches of axial movement in the thermal reactor and first pass cooler. There was concern that the force causing the axial movement combined with the vertical thermal movement would overstress the connection between the thermal reactor and the first pass cooler.

Because of the size difference between the thermal reactor and the first pass cooler, there is an elevation difference of 4 feet between the vessel supports. The thermal reactor refractory system is designed to maintain a maximum skin temperature of 650°F. The first pass cooler has a skin temperature of 493°F. The difference in support elevations coupled with the differential thermal growth of the vessels caused the thermal reactor to try to lift the first pass cooler from its support. There was concern that the thermal growth would lead to excessive stress in the connection between the two units. Spring supports are sometimes used to solve this problem. The weight of the refractory lined thermal reactor, however, made the use of spring supports impractical.

During fabrication, shop measurements showed there would be larger than anticipated misalignment at the field connection. There was concern that the bending stresses caused by this offset would overstress the ring on the end of the transition cone. Based on prior work documented by Porter et al. (1995), there was an additional concern that the pipe stress programs normally used to study equipment movement and anchor points would not provide an adequate prediction of the equipment movements and the bending stresses being imposed on the connection.

The Thermal reactor transition cone and the first pass cooler channels are refractory lined with a hot face layer of high alumna firebrick and two backup layers of castable. The operating temperature in the refractory lined cone is approximately 2,700 °F. There was concern that excessive movement of the joint could cause cracking of the castable refractory, loosening of the firebrick, and possible refractory failure.

The above concerns, developed during the detailed engineering design, lead to the conclusion that a Finite Element Analysis (FEA) was required to study this complex problem.

FE MODEL

The finite element (FE) model constructed for the study of the above system focused particularly on the connection between the reactor and the first pass cooler. The connection between the reactor and the first pass cooler was modeled using approximately 8200 three dimensional brick elements. A cross section of the connection portion of the model is illustrated in Figure 2. The remainder of the reactor and cooler assembly was modeled using approximately 2600 three dimensional plate elements. A relatively coarse mesh was employed except in the connection area described above in order to hold the model size to a minimum.

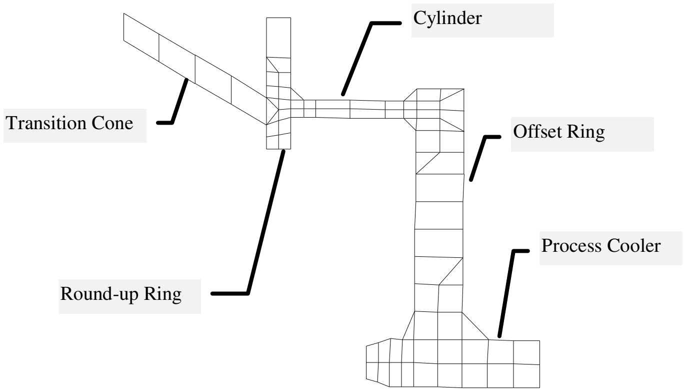

Figure 2

Despite the effort made to minimize the model size, the assembled model had approximately 46,500 degrees of freedom and required approximately 6.5 hours on a P-100 and 500 Megabytes of storage per run to solve. Approximately 10 runs were required to arrive at the final solution. The multiple runs were required for model debugging, mesh refinement necessary to achieve convergence, and to achieve balance on the foundation stiffnesses as will be discussed in a later section. The FEA portion of the project required approximately 80 man hours of analysis effort.

The loads that were examined on the model were:

Table 1 - FE Model Loads

Case	**Loads**
A	Combination of all Operating Loads
B	Thermal Reactor at Design Pressure (75 psig)
C	Operating Pressure (Reactor at 9 psig, Coolers at 625 psig)
D	Operating Pressure (as above) + Gravity
E	Thermal Load Only (Reactor at 650° F, Cooler at 493° F)

SUPPORT LOADS

The initial runs with this model were made using the assumption that the supports were rigid. The support reaction forces obtained using this assumption indicated that the foundations for the reactor and first pass cooler would be overloaded due to the "lifting" of the first pass cooler by the thermal reactor. Subsequently, the soil spring rates for the piles (Figure 3) were substituted for the rigid supports in the model. Using the soil spring rates for the support stiffness resulted in more realistic support loadings.

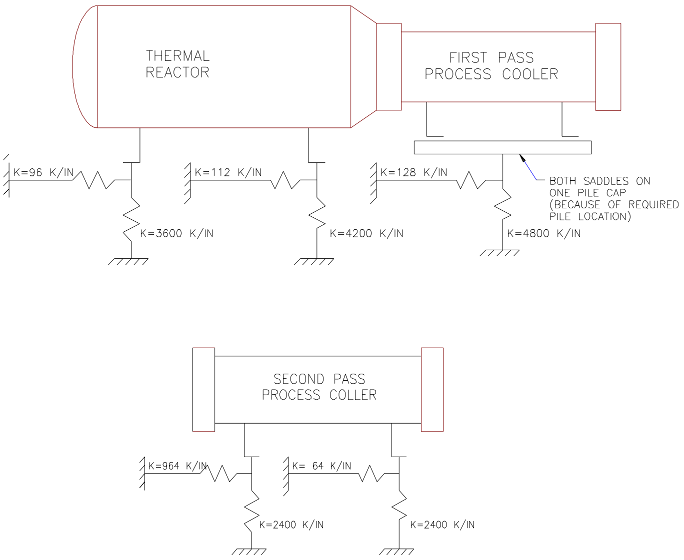

Figure 3

Table 2 illustrates the loads on the saddles computed for the cold "operating weight" and the hot "operating weight" conditions. While these numbers accurately represent the output of the analysis program, they likely do not represent the true values that will be seen in the field because of the method of installation. The FE model assumes that the entire reactor/cooler assembly is connected and placed on the saddle supports, which then deflect according to their respective stiffnesses.

Table 2

Saddle Loadings - LB

	West End Saddle			East End Saddle		
Vessel	**Cold**	**Change**	**Hot**	**Cold**	**Change**	**Hot**
Reactor	314,060	30,490	344,550	180,680	38,420	219,100
1st Pass Boiler	209,940	-41,870	168,070	128,430	-46,980	81,450
2nd Pass Boiler	91,680	21,340	113,020	115,630	-1,400	114,230

In actuality, the reactor and process coolers will be placed on their saddles separately and then joined after the initial settlement has taken place. The result of this difference between the model and the actual field conditions is that the indicated "Cold" saddle loads are probably inaccurate, representing a distribution of weight that will not likely take place. The "Cold" distribution was used for foundation analysis. The shift of weight to and from the various saddles, represented by the "Change" column is, however, likely to take place. Thus, the load on the reactor supports may be expected to increase by 30-38,000 lbs. The second pass cooler will see a substantial decrease in loading. In other words, the reactor will support a substantial portion of the first pass process cooler weight through the connection.

STRESSES

The lifting of the first pass process cooler by the thermal reactor, as confirmed by the FE study, contributes significantly to the stress in the thermal reactor/cooler joint. Figure 2 illustrates a cross section of the reducing transition cone connection between the reactor and the cooler showing the mesh employed for the brick elements used in this area. Figure 4 illustrates the indicated stresses generated by all loads on the joint.

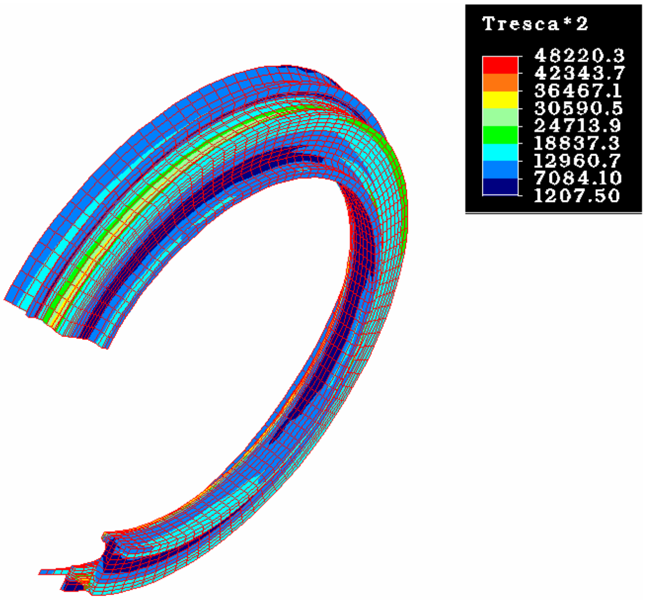

Figure 4

Despite load added to the connection from the lifting of the first pass cooler by the thermal reactor, the analysis indicated that the connection had adequate flexibility and strength to allow for the differential motion and to support the added load. The indicated Primary stress on the connection was below the allowable stress defined by ASME Section VIII, Division 1. Table 3 presents a summary of the stresses as computed. Table 4 presents the Factor of Safety Summary using the Division 2 methodology.

Table 3

Thermal Reactor/Process Cooler Joint Stress Summary

Load Case	**A**	**B**	**C**	**D**	**E**
Load	All Loads	Reactor at Design Pressure	Operating Pressure	Operating Pressure plus Gravity	Thermal Load Only
Stress Intensity	35,926	31,422	7,310	12,243	34,850

Table 4
Factor of Safety Summary

Allowable	**Stress Intensity**	**Factor of Safety**
Sm = 17,500 psi	Primary (D) = 12,243 psi	1.43
3Sm = 52,500 psi	Secondary (E) = 34,850 psi	1.51
Sa = 105,000 psi @ 500 cycles	Peak (A + B) = 67,348 psi	1.56

CONCLUSIONS AND RECOMMENDATIONS

The results of the FEA showed that for all stress cases (primary, secondary, and peak) the predicted stress values were within the allowable values for SA-516-70 material as defined in ASME Section VIII, Division 1 when applied to the methodology of ASME Section VIII, Division 2. The allowable stress values from ASME Section 1, Division 1 were used for design criteria. The methodology from ASME Section VIII, Division 2 was used to evaluate the Secondary and Peak stresses.

The FEA also showed that the deflection of the joint caused by the various load cases was within Pritchard's allowable deflection criteria of 1:150. This criteria is similar to that used in concrete design. It was determined that the joint was rigid enough to resist refractory failure.

The FEA results verified that the decision to perform the analysis on the joint was justified. The analysis showed that while high stress areas do exist within the joint, by performing the FEA, the stress levels were within the allowables of Division 1. Piping analysis programs currently on the market cannot accurately predict the bending stresses within the joint. Without the ability to analyze the joint by FEA, undesirable options such as spring can supports would have to be seriously considered.

For complicated, highly loaded joint configurations, as demonstrated by this example, FEA should be considered as an analysis tool available to the design engineer.

REFERENCES

ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 and 2, 1992, The American Society of Mechanical Engineers, New York, NY.

Porter, M. A., Martens, D., and Korba, A. C., 1995, "Improving the Accuracy of Piping Programs When Analyzing Closely Coupled Equipment," PVP Volume No. 315, *Fitness-for-Service and Decisions for Petroleum and Chemical Equipment,* , M. Prager et al. Editor, July, 1995, The American Society of Mechanical Engineers, New York, NY., pp 335-340.