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COMPUTATIONAL FLUID DYNAMICS INVESTIGATION OF A HIGH TEMPERATURE WASTE HEAT EXCHANGER TUBE SHEET ASSEMBLY

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ABSTRACT

Many modern Sulfur Recovery Unit (SRU) process waste heat recovery exchangers operate in high temperature environments. These exchangers are associated with the thermal reactor system where the tubesheet/tube/ferrule assemblies are exposed to gasses at temperatures approaching 3000 °F. Because sulfur compounds are present in the process gas, the carbon steel tubesheet and tubes in the assembly will be deteriorated by sulfidation as the operating metal temperature rises above 600^o F. Ferrule systems are used to protect the carbon steel from exposure to excessive temperatures. The temperature distribution in the steel tubesheet/tube/ferrule system is affected by process gas flow and heat transfer through the assembly. Rather than depend upon "assumed" heat transfer coefficients and fluid flow distribution, a Computational Fluid Dynamics (CFD) investigation was conducted to study the flow fields and heat transfer in the tubesheet assembly. It was found that the configuration of the ferrule installation has a large influence on the temperature distribution in the steel materials and, therefore, the possible sulfidation of the carbon steel parts.

INTRODUCTION

The waste heat exchanger studied is a typical ASME Boiler and Pressure Vessel Code Section VIII [1] design with a flexible tube sheet. The carbon steel tube sheet is protected by a two-piece solid head ferrule system. For modern SRU waste heat exchangers, the tube sheet design temperature is typically in the range of 650 to 700˚ F for Code tube sheet calculations. The carbon steel component materials are SA 516-70 plate for the tubesheet and SA 106B for the tubes. The ferrules are a 94% alumina content ceramic material. The ferrule heads are arranged such that the cold assembly gap closes at operating temperatures due to thermal expansion. The cold assembly gap is set on the basis of the differential thermal expansion of the tubesheet and the ferrule heads.

The ferrule is a two-piece style with a solid head portion and a second piece that forms the gas path into the exchanger tube. The outside of the solid head periphery is wrapped with a high alumina paper, as is the outside of the second piece. The process side of the tube sheet is covered with a high alumina ceramic material of a felt type construction. See Figure 1 for a cross sectional view of the assembly.

This investigation was limited to the tube filled area of the tubesheet assembly. The exchanger has a square tube pitch pattern dictating a square head geometry for the ferrules. The peripheral area around the solid head ferrule field and the inside of the exchanger channel uses a high alumina castable refractory.

Knowing the temperature profile of the system is critical to the mechanical design of the tube sheet and the prevention of sulfidation of the steel components, as discussed by Martens et al [2]. The thermal profile of a tubesheet protection system using a ferrule and castable refractory system on the face of the tubesheet is investigated in the Martens paper. However, in the current configuration, the possible effect of hot process gas passing through the porous insulating ceramic paper in the gaps around the solid head ferrule peripheral gaps presented a concern that had not been previously quantified.

The process gas properties, temperatures and flow rates, refractory and steel properties used were specific for the unit under study and are typical for SRU units designed by the authors.

The ferrule head peripheral gap used for this investigation was assumed to be 1/16 inch, and was either filled with suitable ceramic paper or considered open to simulate an improper assembly gap or failure of the ceramic paper. This expansion gap is typically not grouted as the grout interferes with ferrule head expansion during original heat up and such grout can be expected to fail in operation and during thermal cycles. The tube-to-tube sheet joint uses a specialized strength weld and tube rolling procedure that was modeled as homogenous for heat flux considerations. As discussed by Hudson and Grigson [3], the joint formed by the OD of the tube and the ID of the tubesheet hole may present a resistance to heat flux resulting in increased tube temperatures. However, the authors' experience supports that the use of a suitable strength weld and tube-rolling procedure does not produce any significant resistance to heat flux.

The investigation was conducted in two steps. First, an axisymmetric Finite Element (FE) study was conducted to establish a temperature profile with no process gas bypassing through the peripheral gaps between the solid head ferrules. The FE results were used to benchmark the CFD results and for comparison to previous investigations [2]. Second, a CFD study was conducted to establish the temperature profiles with varying peripheral gaps. See Figure 2 for the ferrule configuration used in the CFD study

FINITE ELEMENT STUDY

The FE study was conducted with Algor, Ver. 14, FE software using a two dimensional axisymmetric model of the ferrule/tubesheet/tube using the materials as described above. The model consisted of approximately 5200 nodal points defining approximately 4900 linear axisymmetric elements. The model is illustrated in Figure 3.

A summary of the temperature profiles developed in the FE analysis is listed in Table 1. The results, based on no gas bypassing through the ferrule solid head periphery, indicate that the maximum steel temperatures do not exceed 600˚ F, the typical maximum temperature for the carbon steel components.

Table 1 FE Indicated Temperature Results

Process gas ˚ F	Shell water ˚ F	Temp @ RP-1 ˚ F	Temp @ RP-2 ˚ F	Temp @ RP-3 ˚ F
2800	495	570	506	565
3000	495	580	507	571

COMPUTATIONAL FLUID DYNAMICS STUDY

The CFD study was conducted with Fluent v 5 software. An initial steady-state analysis was performed on a three-dimensional model of the ferrule/tubesheet/tube. The model consisted of nearly 200,000 brick elements, the configuration of which is illustrated in Figure 4.

For the initial analysis, the inlet was treated as a mass flow boundary condition. The outlet was set to an outflow boundary condition, which dictates a zero diffusion flux. Based on the pressure profile data developed from this analysis, the outlet boundary condition was then set to a pressure-outlet boundary with the pressure specified using the value determined in the base analysis. This change allows for either fully or partially developed flow to occur at the outlet location, rather than the flow required for a zero diffusion flux. Radiation was accounted for through the use of the Discrete Ordinates radiation model with all solid materials treated as opaque.

The three dimensional model results indicated that the cross sectional temperature distribution was essentially uniform. Based on this information, the study was continued using a two-dimensional axisymmetric model, illustrated in Figure 5. The use of a 2-D grid allowed implementation of a more refined grid in the areas of interest while minimizing computational costs.

Several analysis cases were conducted employing varied values of the gap at the peripheral of the solid head and the radiation heat transfer. The first goal of these studies was to develop information related to the amount of process gas that could be expected to bypass the primary flow path and travel through the gap between the ferrule and tube. The second goal was to study the amount of radiant heat transfer occurring within the assembly. This information was used to quantify the performance of the paper in preventing radiant heat transfer by limiting the view factor between the components.

The pressure drop through the ferrule system is the driving force for process gas to bypass the main flow path through the ferrule and flow through the peripheral gap between the ferrule heads. The CFD analysis allowed determination of this pressure drop and predicted the amount of process gas expected to bypass the main flow path.

For the base case studied, the pressure drop at the ferrule end was determined to be 0.23 psi with zero process gas flow through the solid head peripheral gap. Assuming a 1/16" open gap, analysis indicated that process gas mass flow-through would be approximately 7% of the total mass flow.

Detailed temperature profiles for the system were developed. For comparison reasons, the temperatures indicated by CFD analyses were queried at the same locations used for the FE study and are listed in Table 2.

Table 2 CFD Indicated Temperature Results
For 3000 ˚ F Process Gas Temperature

Peripheral Head Gap	Temperature ˚ F			
	Shell	RP-1	RP-2	RP-3
Solid (1)	495	537	503	573
1/16" paper filled (2)	495	612	515	561
1/16" open gap (3)	495	835	600	540

Notes:
(1)- Direct comparison to FE results in Table 1 as no gas flow is allowed through the porous ceramic paper
(2)- Gas flow is allowed through the porous paper and gap radiation is considered to be effective
(3)- Gap considered open with no paper gasket remaining, no remaining gasket at ferrule to tubesheet area or between the ferrule and tube, radiation considered

At the 7% mass flow bypass condition, the CFD study indicates a temperature of 835˚ F at the tip of the tube. This temperature is well above the 600˚ F maximum design temperature typically used for carbon steel components to assure acceptable service life. The rate of sulfidation that would be expected to occur at 835˚ F would not be considered an acceptable service life.

DISCUSSION OF RESULTS

Comparison of FE and CFD results given in Tables 1 and 2 indicates differing temperature values at the point designated as RP-1. The authors concluded that this difference is due to the effects of heat transfer by radiation that were addressed in the CFD analysis and not addressed in the FE analysis.

Inspection of the FE and CFD analysis results makes it apparent that the temperature at the tip of the tube-to-tube sheet junction, noted as RP-1, is highly dependent on the amount of process gas that passes through the peripheral gaps of the solid head of the ferrule system. It is also apparent that the actual gap width during operation and the condition of the insulating ceramic paper in this peripheral gap and throughout the system, are very important to controlling the process gas bypassing and for the successful protection of the carbon steel components.

This leads to the conclusion that careful consideration must be given to the design of the gap. Additionally, assurance that the correct gap is achieved during installation is absolutely necessary.

The temperature profile in the tube end, as indicated in the analysis, has a considerable gradient. The gradient results in the highest temperature occurring at the tip of the tube at the area of the tube-to-tube sheet attachment weld. This is the area that is usually observed to have sulfidation corrosion when the tubesheet/tube protection system is not adequate. From a practical engineering viewpoint the possible elevated temperature at the tip of the tube-to-tube sheet joint is a greater concern for sulfidation corrosion failure than for exceeding the tube sheet design temperature.

CONCLUSIONS

The use of CFD provides the design engineer considerable insight into the critical temperature profile at the tip of the tube-to-tube sheet junction. The CFD analysis provides qualification and quantification of this critical temperature profile and assures the design engineer that a suitable design temperature is utilized for ASME Code calculations. The development of upper and lower bounds for this temperature profile can be achieved to assess the temperature profile variability of due to (paper) installation effects.

The authors recognize that all ferrule systems used to protect the carbon steel tubesheet and tubes of these SRU waste heat exchangers are critical and require considerable design and installation expertise and routine follow up inspections.

ACKNOWLEDGMENTS

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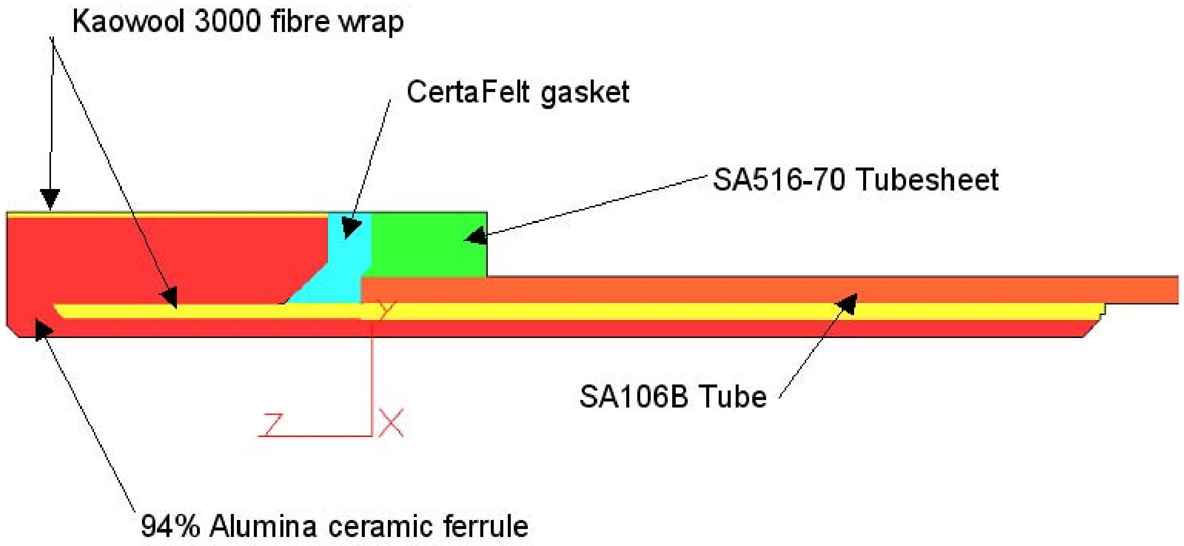

Figure 1 – Tubesheet Assembly

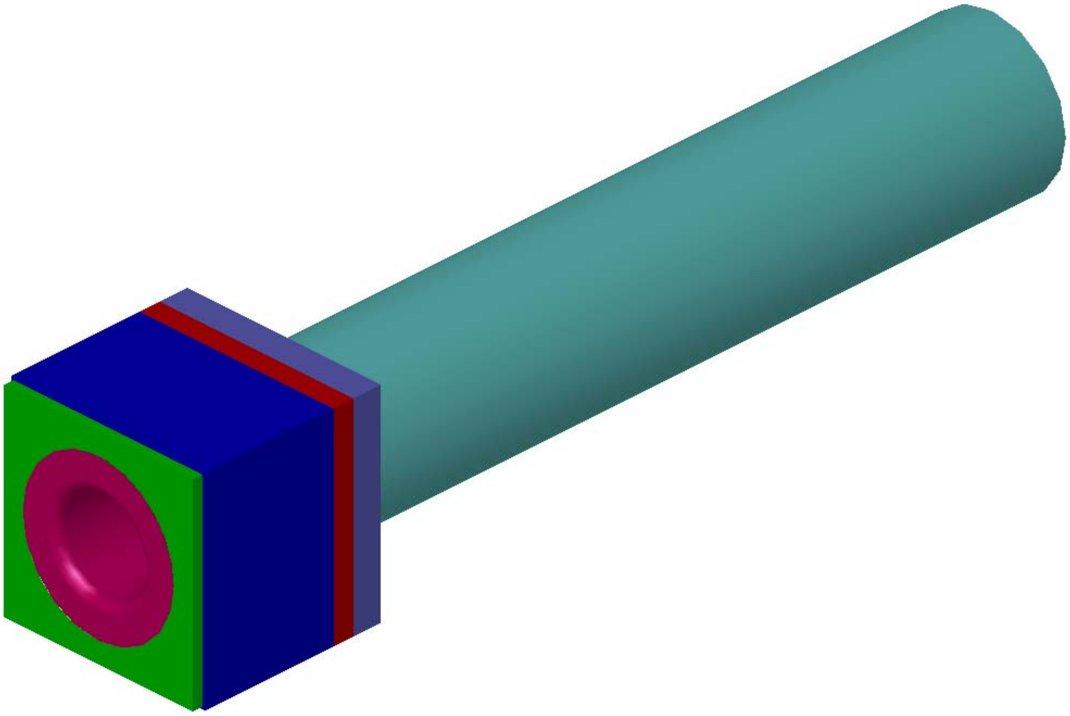

Figure 2 – Ferrule Configuration

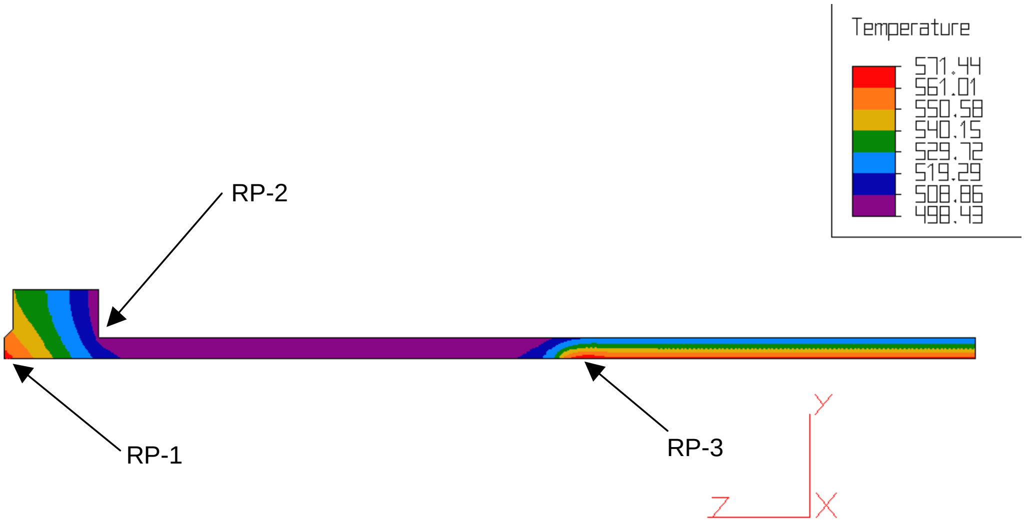

Figure 3 – FE 2-D Axisymmetric Model Indicated Temperature Profile

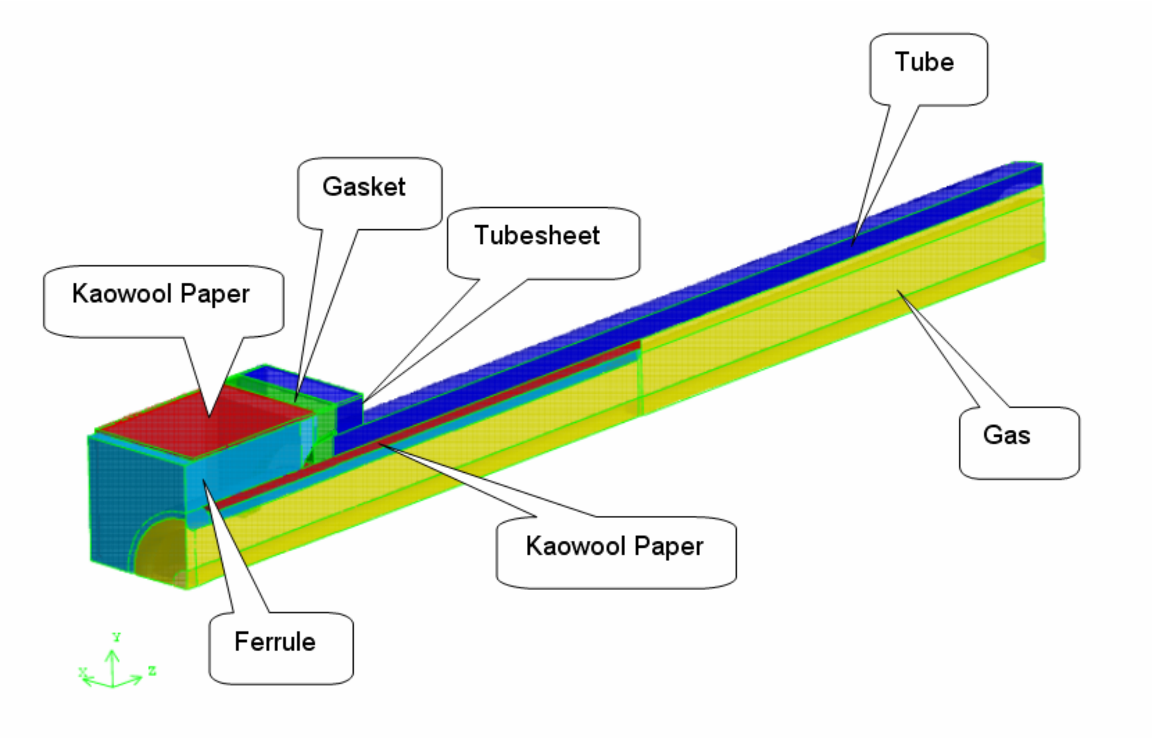

Figure 4 – CFD 3-D Model Configuration

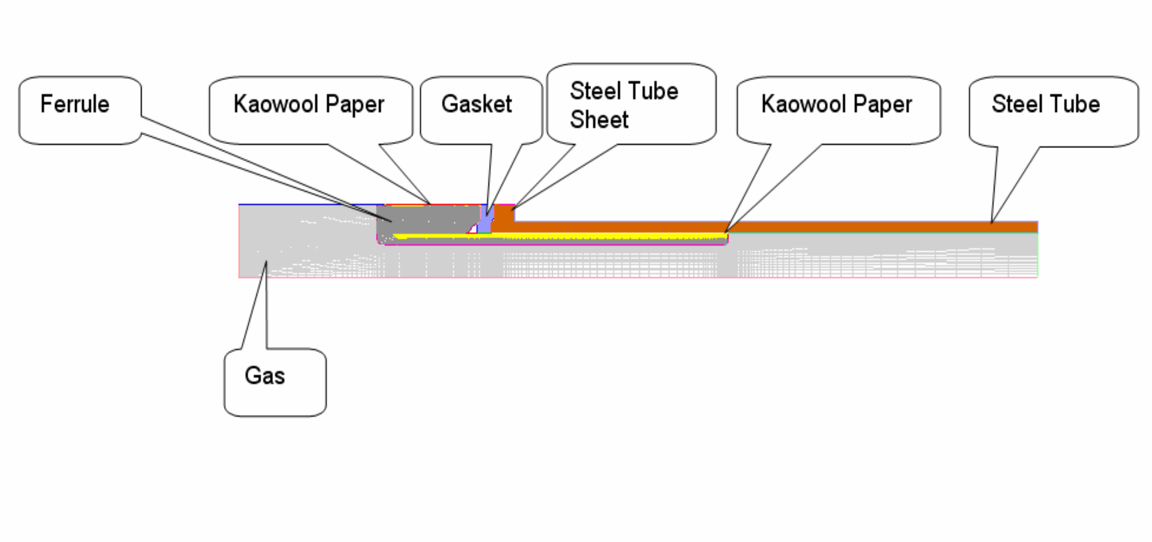

Figure 5 – CFD 2-D Axisymmetric Model Configuration