A Robust SRU Waste Heat Boiler Design

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ABSTRACT:

As documented by the authors, it is well known in industry that sulfur recovery unit waste heat boilers (WHBs) can fail due to a wide variety of reasons. The primary modes of reported failure include departure from nucleate boiling (DNB) and sulfidation corrosion. From experience, there are several design variables that must be considered in developing a robust design. For example, limiting the mass velocity limits the peak heat flux and the driving potential for gas bypass in tubesheet ferrule and refractory systems. While general design guidance for WHBs exists, it is the authors' experience that few boilers represent genuinely robust designs.

This paper explores a robust WHB design that has been in service for almost a decade without significant corrosion or unscheduled outages. The authors first describe general design rules that were incorporated in the subject WHB that should be considered in all WHBs where reliability is a major consideration. By examining the results of Computational fluid dynamics (CFD) analyses performed to study this WHB's historical operation and to determine limits for future operation, the authors will demonstrate how incorporating design results affects the WHB's performance.

The paper will conclude with a discussion of how complex, state-of-the-art CFD analyses can be used to determine - with a high degree of certainty - operational limits for existing WHBs and design evaluation of proposed new WHBs.

INTRODUCTION:

Flint Hills Resources' Pine Bend Refinery in Rosemount, Minnesota, is among the top processors of Canadian crude in the United States and a leader in providing cleaner-burning, high-performance fuels. The Pine Bend Refinery has a crude oil processing capacity of about 320,000 barrels per day. The refinery produces fuels such as gasoline, diesel, propane and butane, used throughout Minnesota and the upper Midwest.

In June 1993, the Pine Bend 525 LTPD SRU No.5 was started up using a typical two pass in a single shell Waste Heat Boiler (WHB) design generating nominally 600 psig saturated steam. The WHB first pass used 400 2-1/4" OD SA 213-T11 tubes and the second pass used 400 2-1/4" OD SA 210-A-1 tubes and the inlet tubesheet was 2" thick SA 516-70N. The tubes were rolled, seal welded and re-rolled and a 7/16" tube projection beyond the tubesheet was used. A castable refractory and ceramic ferrule system was used for the inlet tubesheet protection.

The following is a chronological summary of the SRU No. 5 WHB service:

- May 1994: Unplanned shutdown due to WHB tube leak. The root cause of the tube leak was determined to be tubesheet refractory degradation caused by inadequate anchoring system combined with reaction furnace vibration. The failure of the refractory/ferrule system resulted in the need to replace 73 tubes in the first pass. A redesigned tubesheet refractory and ferrule system was installed.

- May 1999: First planned turnaround for No. 5 SRU. The WHB had first pass inlet tube leaks and tube-end-corrosion. This necessitated the replacement of all 400 first pass tubes. The 310ss refractory anchors on the tubesheet had "burned up", allowing the refractory and ferrules to separate from the tubesheet[1].

- July 2002: Unplanned shutdown occurred due to WHB tube leaks. This problem required extended downtime to repair the WHB and the accompanying unplanned shutdown reduced the refinery's sulfur recovery capacity by about 50%. The first pass tubesheet and tube-ends had severe corrosion (see picture below) resulting in many tube leaks that required weld build-up of the tubesheet and replacement of all 400 first pass tubes. The original design castable refractory and ceramic ferrule inlet tubesheet protection system was replaced using Industrial Ceramics two-piece, hex-head ferrules with 1" insulating board and ceramic paper wrapping of the ferrules.

FRONT FACE OF TUBESHEET AFTER FAILURE IN 2002
(after scale removal and sandblasting)

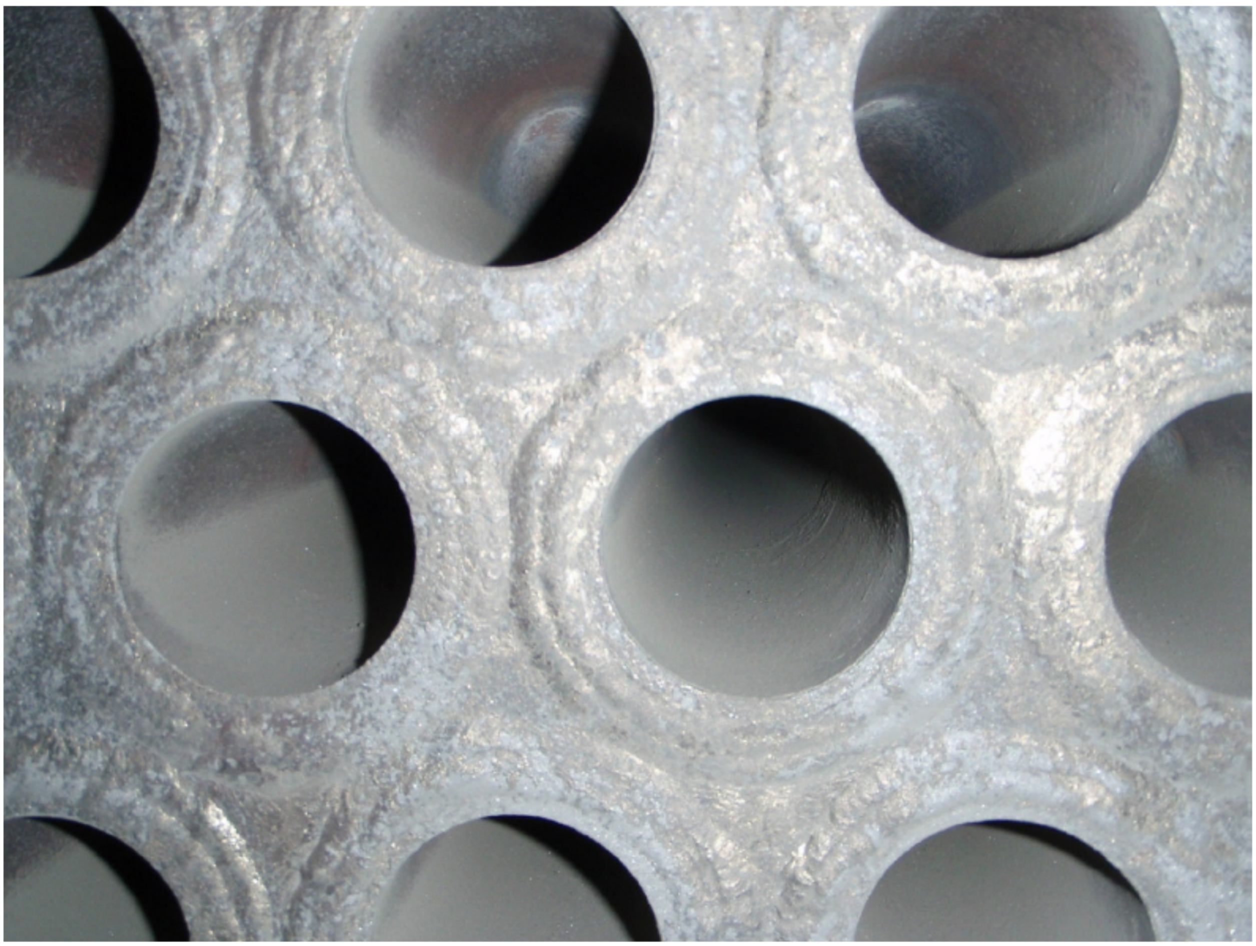
[1] It should be noted that the authors' experience is that the 310ss castable refractory anchors are typically melted off all the way to the face of the tubesheet quickly upon putting the WHB into service. For the typical castable refractory and ceramic ferrule system, the separation of the castable refractory from the tubesheet is typically not a direct result of the loss of the anchors. The separation is usually attributed to shutdown and start-up frequency and water leaks that flash to steam at the refractory-to-tubesheet interface.

- Sept. 2003: Second planned turnaround. Installed new single-pass WHB.

- Oct. 2006: Out-of-cycle shutdown due to hot spots on reaction furnace caused by refractory failure. New WHB tubesheet removable ferrule system was intact. Removed some ferrules for tubesheet inspection. No adverse corrosion conditions were found.

- July 2008: Low level (< 28%) O2 enrichment in No. 5 SRU began.

- Sept. 2008: First planned turnaround on new WHB. Tubesheet removable ferrule system was intact and inspection of 100% of the tubesheet found no significant tubesheet or tube-end corrosion (see picture below).



FRONT FACE OF TUBESHEET FROM ROBUST WHB DURING 2008INSPECTION

The service experience of the original two pass WHB was not satisfactory for supporting FHR's intended shutdown interval. The replacement WHB has the intended turnaround service cycle with no indication of corrosion and, to date, has not been a source for an unscheduled shutdown of SRU No. 5.

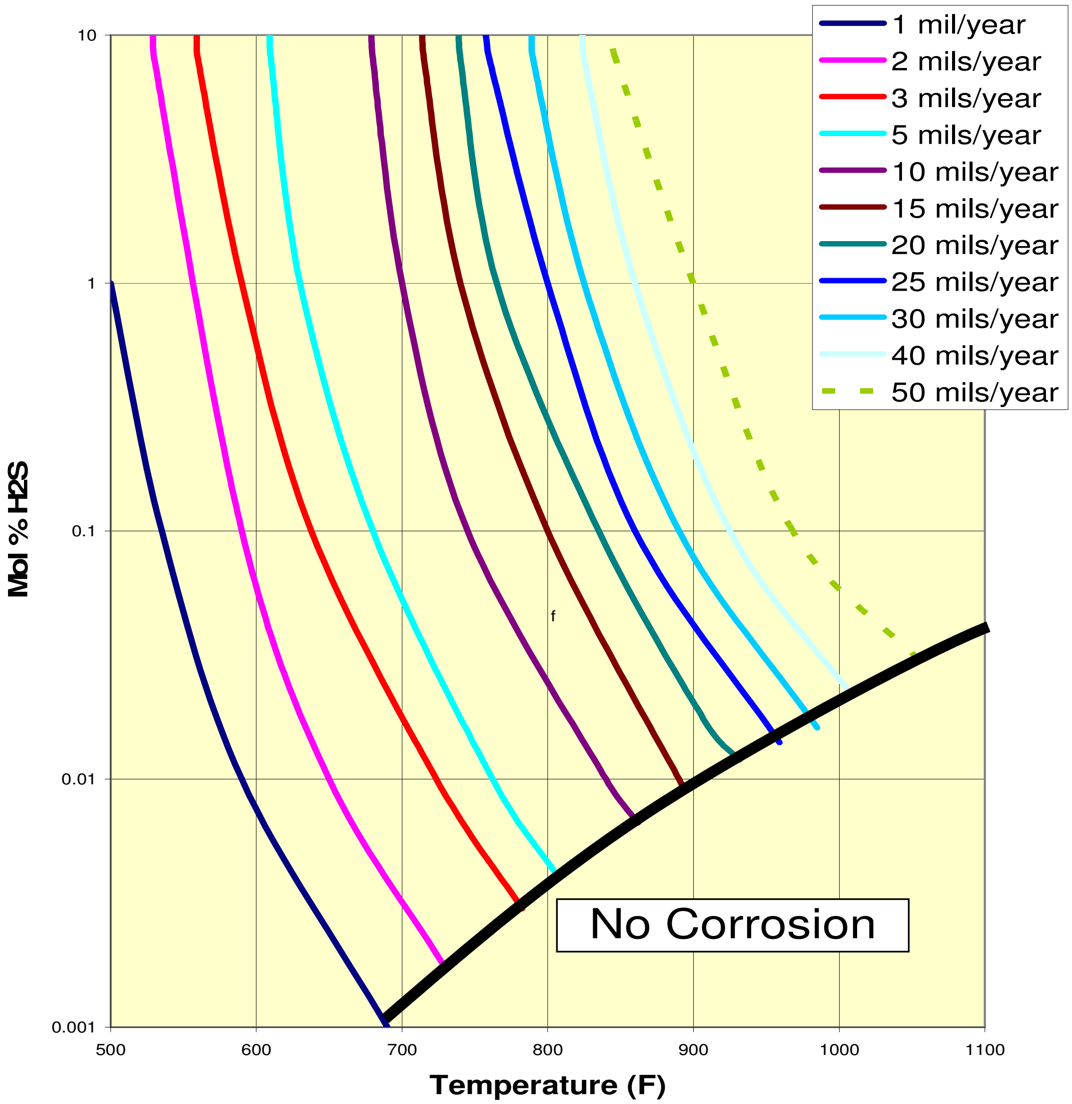
DISCUSSION:

Design Review of the Original WHB:

Significant tubesheet and tube entrance corrosion occurred throughout the life of the original WHB design that may have resulted from many factors. Prior to the 2002 unplanned shutdown, the most apparent cause for the corrosion was the lack of serviceability of the original refractory and ferrule tubesheet protection system. The authors' experience is that failures of this type of protection system are typically caused by improper design, installation and dry out procedures, or burner vibration and other operational parameters (such as heat-up and cool-down rates, maximum firing temperatures and number of shutdowns and restarts). In FHR's opinion, the 2002 unplanned shutdown corrosion resulted from a very complicated failure. Pressure drop had significantly increased across the WHB and metal restrictions had reduced the inlet ferrule ID to the size of a pencil. The tubesheet refractory was impregnated with contaminants. The FHR root cause analysis did not achieve consensus for determining a single mode of failure – with this paper we leave this as a point of future discussion.

The most severe corrosion occurrence - due to tube joint leakage -resulted in the July 2002 unplanned shutdown. The corrosion indicated in the associated picture above was due to high temperature sulfidation of the carbon steel during exposure above 600°F. In the authors' experience, the most likely scenario is that a local failure of a ferrule or refractory caused a local tube-to-tube joint failure leaking boiler water behind the refractory. In this case, water flashed to steam and perpetuated additional refractory, insulating ceramic paper/board and ferrule damage that caused the refractory "wall" to be pushed away from the face of the tubesheet. The authors note that the high pressure drop resulting from the reduced ferrule ID would be a driving force for hot process to pass through refractory at cracks and penetrations and flow across the face of the tubesheet. The high mass flux for the original WHB produced a significant pressure drop at the ferrule entrance, which provided a driving force for hot gas to pass through the damaged refractory and ferrules, heating the tubesheet. This then drove greater tubesheet heat flux and increased metal temperature on the face of the tubesheet resulting in accelerated corrosion.

The SRU environment high temperature sulfidation corrosion rate versus carbon steel temperature is characterized by the graph below as presented at the 2011 Brimstone conference by Dennis Martens [1].



AUTHORS' PROPOSED CLAUS SRU SERVICE SULFIDATION CARBON STEEL CORROSION CURVE

The inspection information and failures reported for the original WHB did not indicate that a departure from nucleate boiling (DNB) event had occurred. A DNB typically occurs at the downstream end of the ferrule and results in significant tube damage such as tube collapse [1].

The typical industry rule of thumb for Mass Flux used to be: WHB's range from 2 to 5 lb/sec-ft^2, depending on the type of boiler and the designers' experience. In this case, the 4.3 mass flux for the original design was at the high end of this range and may have been a contributing factor for the tubesheet corrosion observed. In a 1996 technical paper by Dennis Martens et. al. [2] the relationship between mass flux and tubesheet temperature was noted. For the application under study, a 2.5 lb/sec-ft^2 mass flux was determined to be suitable.

The original WHB tube to tubesheet joint used a seal weld and tube rolling with two grooves. The 2002 unplanned shutdown inspection picture above indicates that seal welds were essentially corroded away and that the tube roll was the principle resistance for the boiler water leakage into the process. Although the 2” thick tubesheet provided a significant tube roll engagement length, this engagement was not sufficient. Also, the 2” thick tubesheet was considered to contribute to a higher tubesheet face temperature and was possibly a significant contributor to the corrosion occurrence.

Replacement WHB Design Criteria for a Robust Design:

As the original SRU No. 5 WHB required substantial repairs during the unscheduled shutdown in 2002, FHR decided to replace this boiler during the scheduled 2003 turnaround. The reliability criteria for the replacement WHB - a 5 year interval scheduled turnarounds and a 20 year life - was of prime importance. Using a root cause analysis of the problems with the original WHB, FHR determined their principle considerations for achieving the intended reliability to be the use of larger and thicker tubes, thinner tubesheets and full penetration weld at the inlet tubesheet, and strength weld at the outlet tubesheet.

NOTE: TEMA indicates that acceptable performance can be achieved with a maximum tube penetration of 1/8” past the front face of the tubesheet. Based on the results of previous analyses, any penetration past the front face of the tubesheet will result in higher tube operating temperatures. When practical, the tubes should be terminated at the front face of the tubesheet.

The replacement WHB process conditions were established to be similar to the original WHB with consideration for an increased operating temperature caused by the use of oxygen enrichment. The replacement WHB was to fit in the available space in the existing SRU plot space without moving the reaction furnace or the sulfur condenser(s). All options were considered for the design of the replacement WHB. After careful consideration, the selected replacement design for the WHB was a long single pass kettle type. The mechanical aspects of the original and replacement WHBs are compared in Table 1.

FHR had adopted the use of two piece removable ferrules as standard practice for the tubesheet protection system and this practice was followed for the replacement WHB. The two piece removable ferrules were supplied by Industrial Ceramics and Flint Hills used the Industrial Ceramics-recommended design and installation procedures, including the use of 1” ceramic insulation board on the face of the tubesheet and 3/16” ceramic paper wrap for the ferrule OD.

The use of a thinner tubesheet using a stayed design was considered to be significant in reducing the maximum tubesheet operating temperature. The design tubesheet thickness became 1- 1/4”. This was considered to be a reasonable reduction from the original 2” thick tubesheet and the corresponding reduction in the tubesheet operating temperature.

Table 1 – Comparison of WHB Designs

Item	Original WHB	Replacement WHB
Type of WHB	2 pass in single shell kettle type	1 pass in single shell kettle type
Diameter of tubes	2 ¼ " OD first and second pass 2.03" ID first pass and second pass	3" NPS pipe 2.9" ID
Number of tubes	400 in first and second pass	479
Tube length	15' –0"	36'- 0"
Tube specification	SA 213-T11 12 Gage First pass SA 210-A-1 12 Gage Second pass	A 106B Sch 80
Mass Flux – ID tube Lb/sec-Ft^2	4.3	1.75
Tubesheet (TS) thickness	2"	1 ¼"
Tubesheet material spec	SA 516-70N	SA 516-70N
Inlet tubesheet-to-tube joint	Seal weld and roll with 2 grooves	Full penetration
Tube projection beyond TS	7/16" projection	No projection
TS protection system	Castable refractory and ferrules	Removable two piece Ferrules

The use of larger tubes, low mass flux and low heat flux (transfer rate) was considered to be significant for the design of a robust replacement WHB. The design mass flux of 1.75 lb/sec-ft^2 was achieved through use of 479 3" sch 80 pipes. It is noted that this mass flux produces a minimal pressure drop at the entrance to the ferrule. This, in turn, limits the driving force for hot gas passing through cracked refractory and ferrules or around the head of removable ferrules and flowing through the ceramic paper insulation. The effect of hot gas flowing around the head of a removable ferrule was investigated. A 2005 technical paper by Dennis Martens et. al. [3] reported that this could potentially significantly increase the tubesheet to tube junction temperature. It is reasonable to consider a low mass flux to be a positive parameter for designing and maintaining a suitable tubesheet protection system. The authors recognize that limited data is available for the evaluation for determining reasonable mass flux and ferrule entrance pressure drop values with respect to the possibility of tubesheet corrosion occurrence. However, the authors suggest this aspect should be considered when establishing a WHB design.

Developing a Replacement Design for an Existing Problematic Boiler:

It was known that the existing WHB replaced in 2003 was problematic for reliable operation, and that the SRU replacement WHB had delivered excellent reliability. Therefore, FHR commissioned a study of the process gas side of the robust replacement WHB to capture the best practices of the WHB for future design considerations. The CFD results were then used to develop operational limits guidance (as detailed in this paper).

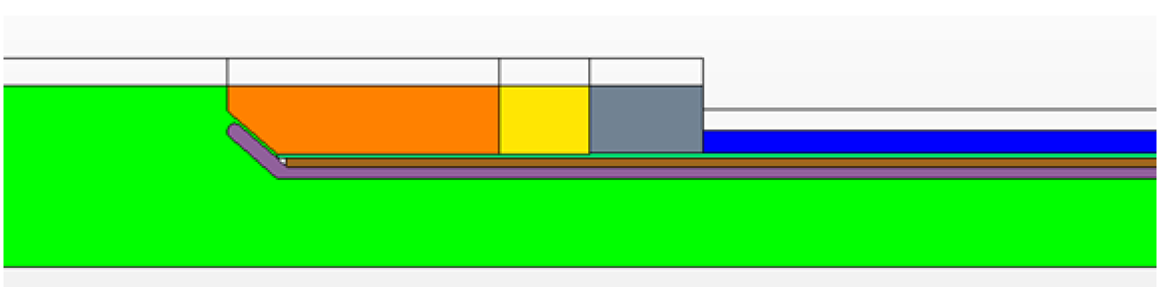
The ability to evaluate the operational characteristics of an SRU WHB was the subject of 2009 and 2011 technical papers by Sean McGuffie et. al. [4] [5]; the aforementioned 2005 technical paper by Dennis Martens et. al. [3]; and the 2009 Brimstone technical paper presentation by Mike Porter et. al. [6].

Reliable operation requires that operators understand the fluxes and temperatures that occur at all operational states of the WHB. This enables operators to determine how changes in firing temperature or mass flow through the boiler, likely caused by plant upsets, affect the temperatures and fluxes through the boiler. This allows margins before significant sulfidation corrosion rates or a DNB event occurs to be established. While estimates can be established using empirical methods, these methods require simplifications for the radiative fluxes and "ballpark" estimates for the maximum heat flux multiplier occurring immediately downstream from the ferrule termination. The use of radiation simplifications and the estimates applied for the heat flux multiplier necessitate that a degree of conservatism be applied to the empirical calculations. This may result in reduced utilization of the WHB design. To reduce the conservatism inherent in empirical calculations, CFD models have been successfully used to provide significantly better estimates of the maximum fluxes and temperatures occurring in the WHB, as presented in the technical references [3, 4 and 5]. The numerical results from CFD analyses can then be used to determine the limits of operation for the WHB using the techniques described in this paper.

CFD Analysis of FHR's Robust WHB:

As the first step in the CFD analysis of existing WHBs, the historical DCS data must be analyzed. This is done to determine the operational parameters associated with the maximum WHB operating conditions and to produce data usable as inputs for the CFD analysis. In this case, PMI partnered with KPS Technology and Engineering LLC to perform the DCS data reduction required to determine the operational periods of interest and to derive the data required for the CFD model inputs. Determining the operational periods of interest required data mining of 6 years of DCS data to determine periods of maximum pseudo-duty for the WHB. The CFD input information was then derived by performing process combustion models (using Sulsim 7) based on the periods of interest and inlet gas composition data.

As the behavior at the ferrule inlet location can be considered to be fully coupled heat transfer, all components must be considered in the analysis. For two-piece ferrule assemblies, the models must include: gas (green), ferrule (purple), Kaowool paper wraps (brown and green), hex head refractory (orange), insulating board (yellow), tubesheet (grey) and tube (blue), as shown in the figure below.

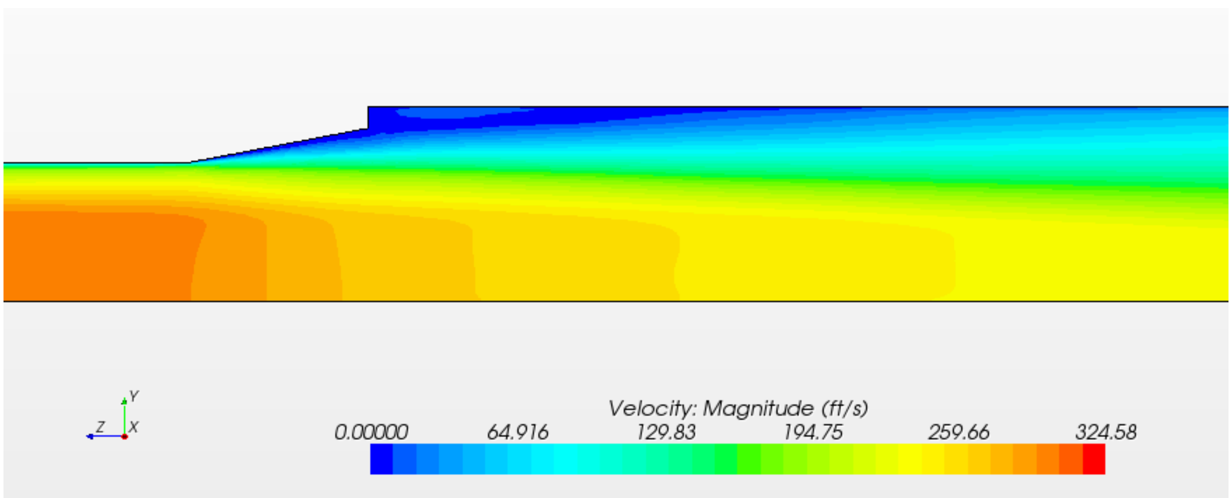


GEOMETRIC MODEL DEVELOPED FOR PROCESS SIDE FERRULE ANALYSIS

Material properties for the solid components were defined based on industry-accepted values.

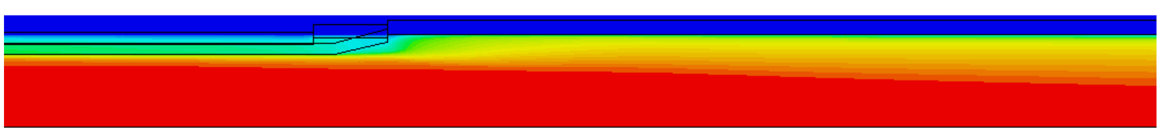
Initially, three cases were identified to be of possible interest based on the DCS. Input data for the CFD model - including mass flow, temperature and the gas density, thermal conductivity, specific heat and viscosity - were developed using process combustion models. Steady-state analyses were then performed.

The image below shows the velocity profile downstream from the ferrule's termination. As can be seen from the image, recirculation occurs. This recirculation increases the turbulent energy in the flow and results in a higher convection coefficient at this location. This then increases the flux through the tube above values that would be predicted without knowledge of the flow field at this location. It should be noted that the standard turbulence models are ill-suited to model the detached, recirculating flow occurring at this location. Design decisions based on numerical values of the heat flux multiplier occurring at this location must be based on well-formed models, using the proper turbulence closures, with the understanding that even the best model might be 10% from the actual values that occur.



VELOCITY PROFILES CALCULATED DOWNSTREAM FROM THE FERRULE LOCATION

The image below shows the temperature profiles calculated downstream from the ferrule's termination. As can be seen, the temperature varies with a smooth profile. This result is typical for a steady-state analysis.



TEMPERATURE PROFILE DOWNSTREAM FROM FERRULE TERMINATION FROM V2F RANS MODEL

The two most severe process conditions were analyzed concurrently. Based on the results of these analyses, the third, less severe case was abandoned. Analyses were conducted to determine the design's sensitivity to changes in firing temperatures and mass flows that were much greater than any conditions captured by DCS. The following statements can be made regarding the results of the CFD analyses performed on the WHB.

- The CFD-reported peak heat flux occurring at the end of the ferrule for all cases studied was below $\pm$ 50,000 BTU/hr-ft^2. This is the value that PMI considers to be sufficiently conservative for a properly designed kettle type boiler to not require a water-side CFD evaluation for DNB.
- The CFD-reported maximum metal temperature at the tubesheet-to-tube end location for the current WHB operational temperature was ~ 600°F, which is considered reasonable for avoiding significant high temperature sulfidation corrosion.
  - The sensitivity evaluation for increasing the process gas operating temperature 200 to 400°F above the current operating temperature into the WHB indicated an increased metal temperature of 20 to 40°F or more. This is enough to give concern for significantly increasing the high temperature sulfidation corrosion potential. Evaluation of possible changes to the existing tubesheet protection system design was not conducted as part of the CFD study.
  - The mass flux and resulting pressure drop at the ferrule entrance is relatively low for all cases studied and an evaluation of potential gas bypassing the removable ferrule head and the effect on the maximum temperature at the tubesheet to tube location was not conducted as part of the CFD study [3].

The results of the analyses were used to develop operating limit curves using the procedures described in this paper.

What is CFD? - in Less than a Page:

NOTE: The cited tutorial [7] is available for download. As a warning, there are equations, *lots* of equations. It's only 110 pages of trying to convey CFD as quickly as possible. We tried to go with the KISS philosophy for this paper, since refinery engineers already have enough to worry about.

CFD is a method used to solve a system of partial differential equations (PDEs) to determine the numerical solution to a flow problem. The minimum subsets of PDEs required to solve the most basic flow problem are known as the Navier-Stokes equations. These equations are developed from the conservation of momentum coupled with conservation of mass, energy and possible equations of state. In their non-reduced form, they create a complete model of the fluid's motion. The Navier-Stokes equations for an incompressible fluid, expressed in 3-dimensional Cartesian coordinates are shown below.

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\rho g_x$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\rho g_y$$

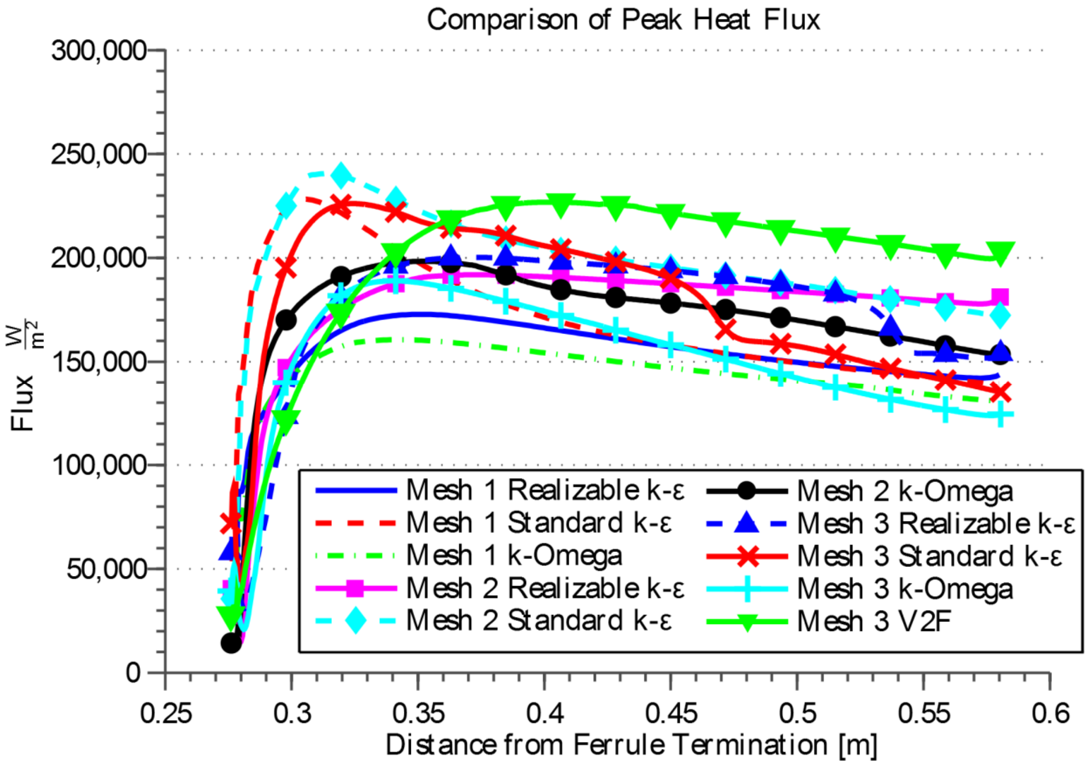
$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g_z$$

A review of the equations shows that their form is similar to the simplified case expressed by Bernoulli for flow along a streamline, with the major exception being the expansion of gradients into 3D coordinates. In their expanded form, the Navier-Stokes equations are nonlinear, making their analytical solution for all but the most trivial of cases impossible. In addition to the basic Navier-Stokes equations, additional equations may need to be solved depending on the specific physics of the problem under consideration. For this reason methods were developed to allow their numerical solution, creating the framework we know today as CFD.

What are the Limits of CFD?

Most CFD models of engineering significance require a major simplifying assumption – that turbulence within the flow can be modeled using a closed form solution rather through direct, transient integration.

These major simplifying assumptions (required to solve for the turbulent nature of the flow) present significant difficulties for bounding the quantities of interest to determine the maximum operational envelope for evaluating WHBs. Consider the following graph that was prepared for similar geometry to FHR's WHB geometry for the tutorial, "The Use of CFD in Design", developed for the 2012 ASME Pressure Vessels and Piping Conference [7].



SAMPLE OUTPUT FROM TUTORIAL ANALYSIS OF FERRULE ASSEMBLY

As can be seen from the figure, the choice of grid topology (mesh) and turbulence model (k-ε, k-ω) used in the analysis can affect the predicted results by as much as 25%. In cases where this level of variance is unacceptable, it may be necessary to adopt more rigorous analysis techniques such as detached eddy simulation (DES) or large eddy simulation (LES). Both DES and LES are transient analysis techniques that attempt to resolve the near-wall behaviors of the flow with less strict grid and time-step requirements than direct numerical simulation (DNS). As will be shown later these methods require more than an order of magnitude more effort to conduct. That said, they are possible with a reasonable level of engineering effort.

Other limitations inherent in CFD analyses are typically caused by limits in engineering knowledge related to the phenomena under consideration. For WHB-related phenomena, these limitations include, but are not limited to:

- DNB – Most knowledge about the initiation of DNB events was developed by the nuclear industry for flows occurring around fuel rods. The flow in this case is significantly different than the flow that occurs in kettle type boilers. First, reactor flow is mechanically driven rather than only relying on buoyancy effects in the flow. Second, the flow in reactors typically has bulk velocities of 1.5 – 2 m/s whereas the flow in kettle type boilers typically occurs at velocities less than 0.5 m/s. Finally, the flow in reactors travels longitudinally along the cylindrical surface, while boiler tubes are exposed to cross flow situations. For these reasons it is not known with certainty whether the limits on maximum flux and local void fraction developed in the nuclear industry are directly applicable to the flows occurring in WHBs.

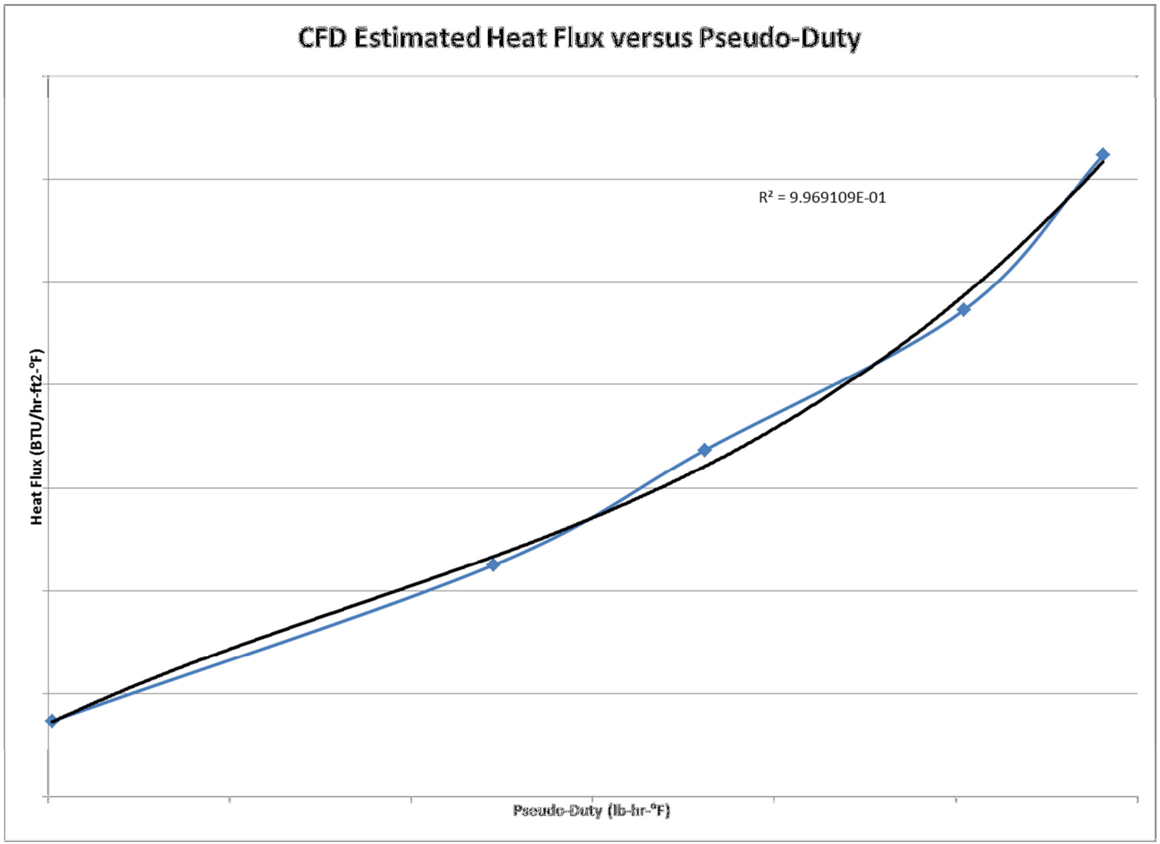
- Gas bypass – Gas bypass in WHBs with multi-piece ferrule assemblies that is known to occur due to the pressure differential through the ferrule is significantly affected by the shape of the assembly components when assembled. No method is available to actually measure what the installed geometry is for the ferrule and insulating paper. Because of this, it is generally accepted that the assembly should be modeled in a "perfect" condition. The pressure drops across the perfect model can be compared to the predicted pressure drops from models developed of ferrule assemblies where gas bypass is known to occur.

- Sulfidation – Whether sulfidation will occur and at what rate is typically predicted through a Couper-Gorman type curve, shown earlier. (These curves were developed based on industry experience with corrosion in previous SRU services.) In most cases the operational temperatures at a given rate of corrosion were predicted by adjusting a Couper-Gorman curve to observed SRU sulfidation rates. This means that the temperatures on these curves are, at best, estimates. This presents challenges in designing systems to run at maximum capacity without causing corrosion.

How is CFD Used to Determine Operational Limits?

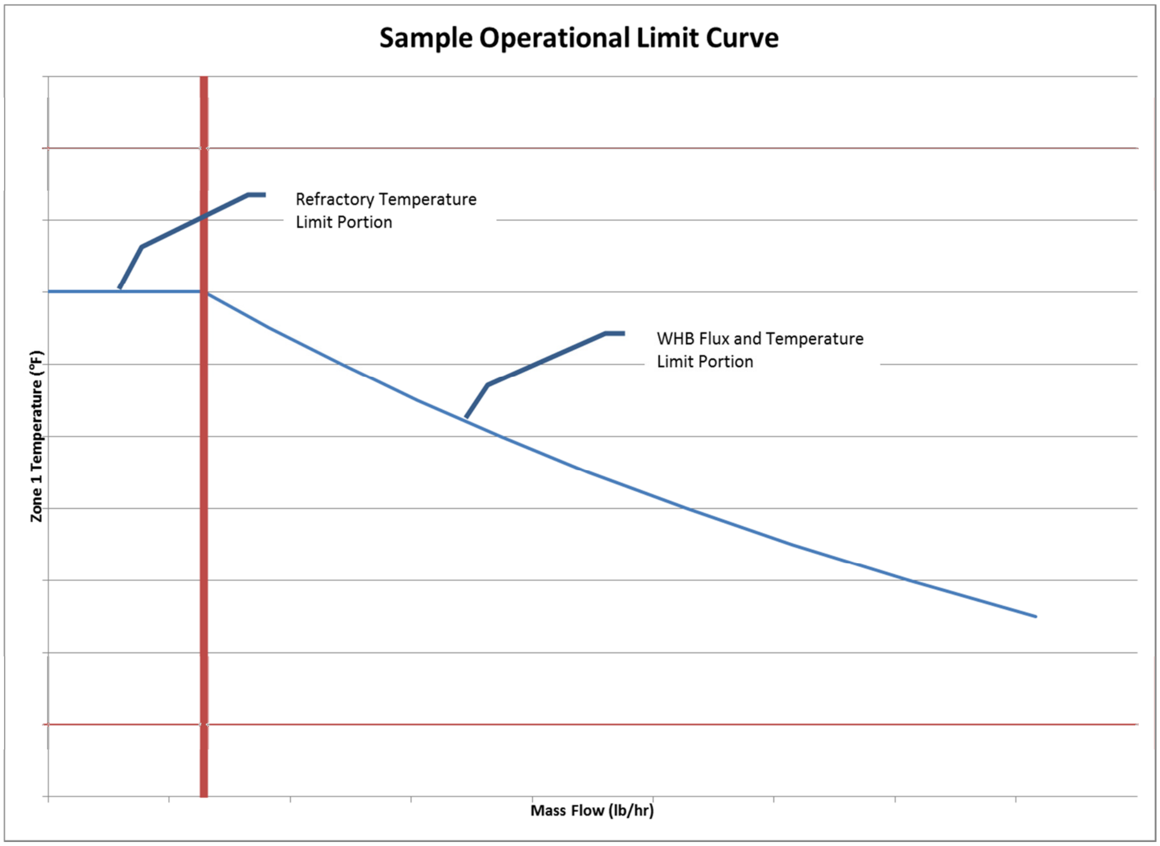
Once a CFD model for an SRU WHB that sufficiently captures the physics under consideration has been developed, engineering judgment can be used to determine the maximum safe operating envelope for the WHB. Developing the envelope requires a series of analyses to determine how measurable operational parameters - typically firing temperature and mass or volumetric flow rates - affect the maximum heat flux into the boiler and its associated peak operational temperatures. Typically, the product of mass flow and temperature, referred to in industry as pseudo-duty, can be related to the maximum heat flux and the associated temperatures. Levels can then be established to limit operational temperatures below the parameters associated with the onset of sulfidation and DNB. Typically both the mass flow rate and temperature are important so that the rate of sulfidation does not affect the WHB's design lifetime - typically 20 years.

Curve fits of the pseudo-duty versus the maximum heat flux can be developed, as illustrated for the tutorial [7] boiler in the figure below.



TYPICAL PSEUDO-DUTY / FLUX CURVE DEVELOPED FROM CFD ANALYSIS

The ability to predict the maximum flux and the associated temperatures based on the measurable operational parameters can then be combined with established limits to determine the maximum operational envelope for the WHB through an algebraic solution. As demonstrated previously by the authors [2] the maximum flux should be limited to 50,000 to 70,000 BTU/hr-ft^2 to avoid a DNB event. The temperature should be limited to no more than 615 °F to avoid significant sulfidation corrosion. The figure below shows a sample of an operational limit curve developed using this methodology.



TYPICAL OPERATIONAL LIMIT CURVE DEVELOPED FROM CFD RESULTS

As shown in the figure, a limit firing temperature must be established to prevent refractory and tubesheet short-term damage from an over-temperature condition. It should also be recognized that the curve (solved for using algebraic techniques) will typically be derated. This action is based on the uncertainties in facility process measurements and those associated with the CFD model inputs and modeling techniques implemented

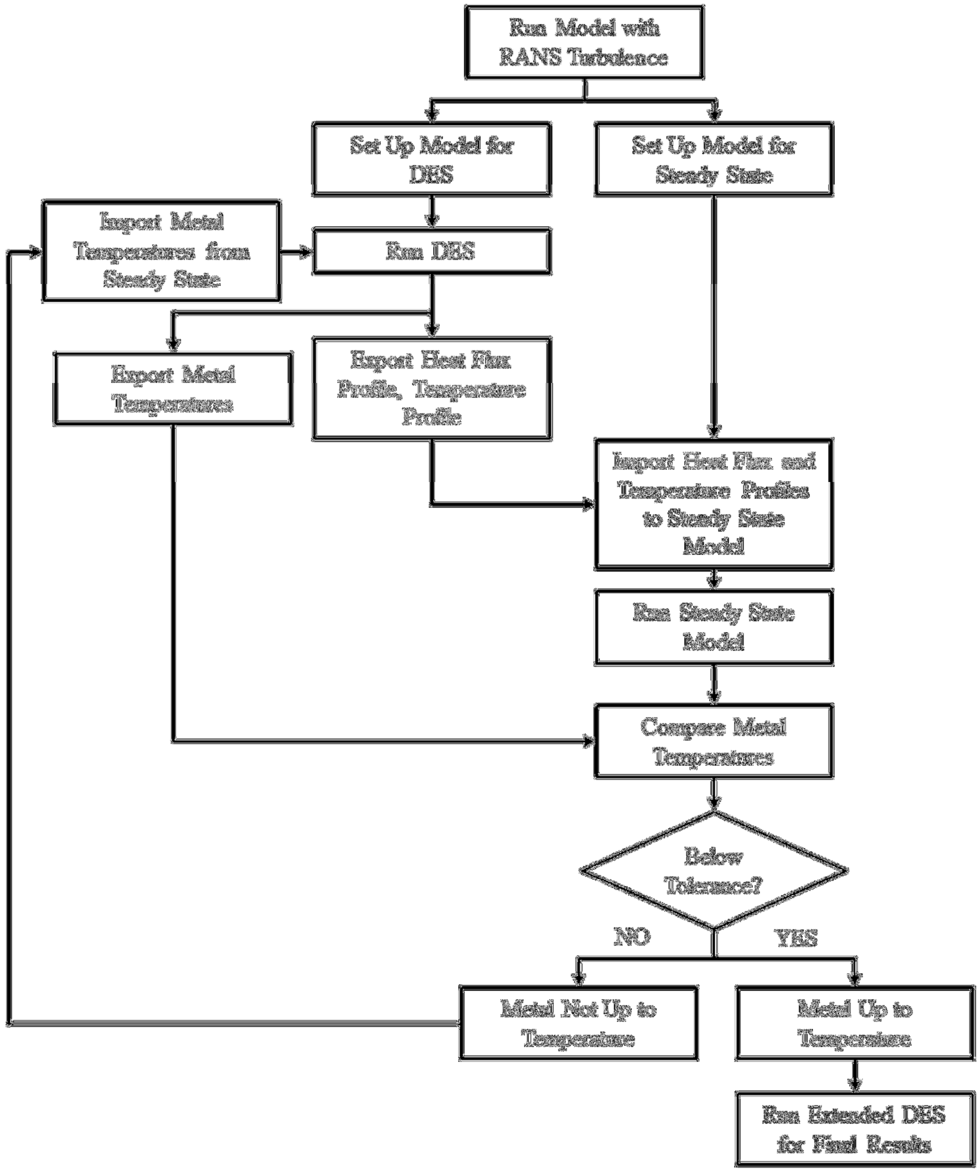
That's a long discussion, outside of the scope of this paper. If you plan on pushing a WHB, you need to have a similar talk with your analyst and with your process people.

What if More Accurate Turbulence Modeling is Required?

While it is outside of the scope of this paper, and has only be alluded to, the flow situation that exists at the ferrule termination is not well suited to conventional analysis. Standard, steady-state turbulence closures are known to be unsuitable for this flow condition, especially if care has not been exercised in the model development. While in most cases engineering decisions can be made based on past experience with similar equipment, when the design is new and the desire is to push the limits of the metal, more complex analysis techniques may need to be employed. As previously mentioned, analysis techniques (DES and LES) have been developed to allow better consideration of the turbulent nature of the flow.

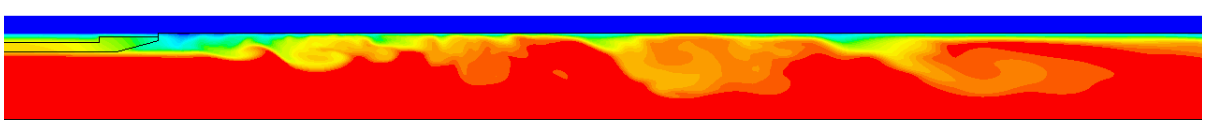
In a critical situation, it may be advisable to conduct a CFD analysis to better estimate the maximum fluxes and temperatures occurring in the assembly. Performing these analyses when only considering flow is often considered to be an expert level task, given the correct resources, they are accomplishable. The coupled heat transfer problem considered in this paper presents an additional complication, dissimilarity in time scales. Based on the authors' past experience, it is known that the transient nature of the flows that occur in ferrule assemblies occurs at frequencies between 20 and 50 Hz. The thermal time constant for the large thermal mass presented by the tubesheet, tube and thermal protection is on the order of minutes. Therefore, capturing the transient nature of the flow and how it impacts the quasi-steady-state temperature of interest in the assembly would require an insurmountable number of time-steps to model explicitly. Instead, a modified procedure has been developed that allows the consideration of the disparate time-scales. It should be noted that the advent of this procedure is a recent development, spurred by developments in both computing hardware and software. Although the procedure is intensive, for critical design applications it can now be considered.

The subject procedure incorporates two (2) models, the DES flow model that includes all solid components and a steady-state thermal model. These models are then iteratively analyzed, passing boundary conditions between models until a converged solution is achieved. The flow chart below shows the steps that occur in the process.



PROCESS FLOW DIAGRAM FOR COMPLETING COUPLED DES THERMAL ANALYSIS

As shown in the image below (comparable to the previous temperature plot), this methodology captures the actual transient nature of the flow rather than the time averaged component, thereby producing better estimates of performance.



TEMPERATURE PROFILE DOWNSTREAM FROM THE FERRULE TERMINATION FROM DES ANALYSIS

It should be noted that the authors made this discussion brief because a full understanding would require 100+ pages of eye-bleeding equations and very technical minutia. The take-away should be that it's possible to understand, when necessary, but it's not an afternoon walk in the park.

Conclusions and Comments:

This paper addresses the considerations for reliability and robustness of a replacement SRU WHB. The paper indicates how reliably can be improved by addressing the design guidance parameters for a WHB. As its original WHB was not considered sufficiently reliable, FHR changed the design parameters for the replacement WHB such that they have achieved significant improvements in reliability. The achievement of 5 year planned shutdown intervals, with no tube leaks or significant corrosion, all the while avoiding unplanned shutdowns for SRU WHBs is possible.

As presented in this paper, process design and operating limit parameters (such as mass flux, operating temperature and peak heat flux) in conjunction with the use of larger tube sizes and thinner tubesheets will have a significant impact on WHB reliability. Additionally, for the WHB designer, it should be noted that limiting the penetration of the tube past the front face of the tubesheet improves reliability. The guidance for these parameters is not well addressed in any industry consensus document and the consideration for these parameters is usually left up to the SRU licensor. Evaluation of capital costs and repair costs are often not brought to the forefront during the original design or replacement engineering effort.

The expert use of state-of-the-art computational fluid dynamic tools can provide considerable insight and understanding into the performance of WHBs. While only alluded to in this paper, it should be understood that "expert" level is a term not to be taken lightly. Having a copy of software and being able to produce results doesn't mean you should accept them for engineering decisions. The flow downstream of a ferrule is known to produce the conundrum where turbulence models break. It's possible to model the flow well, but it's not a task for a novice. The basic procedures referred to in this document can be used to model a wide variety of equipment.

The CFD author of this report would like you to consider that we don't know much about what goes on in WHBs, thermal reactors, condensers, incinerators, the associated piping, the amine units, everything. We should learn more; the technology is there! Or, as a rhetorical question, is no one concerned about reliability?

CFD provides several benefits over traditional physical flow testing, including:

- The results from CFD analyses are available even after the analysis is complete
- CFD allows the observation of flow quantities without disturbing the flow itself
- CFD allows observation of flow quantities at locations that may not be accessible with instrumentation
- CFD provides a framework for qualitative design evaluation early in the development process, and
- CFD allows modeling of phenomena that cannot be physically tested, including:
    - Large domains where building physical models is impractical

- Physics where it is impossible to achieve similarity, and
- When it is too dangerous to physically test (deflagration, explosion risk, etc.)

It is common for an owner to evaluate a WHB failure to provide guidance "to not make the same mistake again." It is very *un*common to evaluate a reliable WHB to understand why it is *not* failing and what parameter changes would cause for reducing reliability or what parameters changes increase reliability. Why look at something that isn't broken? So you can make other things that don't break. FHR took that step. By following these and similar protocols, operators can avoid unscheduled shutdowns, which, in this industry can be a very bad thing.

Based on the authors' past experience, and as discussed in this paper there are three (3) critical areas to consider when designing a robust WHB:

1. Avoid high temperatures at the tubesheet
2. Avoid tube-to-tubesheet joint leakage, and
3. Avoid tube damage downstream of the ferrules

Design features that should be incorporated in robust WHB designs include:

1. Use a properly engineered ferrule design – The design must be capable of limiting the heat flux, and associated maximum temperatures, to insure temperatures below where sulfidation corrosion will occur, typically accepted as approximately 615 °F.
2. Limit the mass flux – This control will limit the maximum heat flux downstream from the ferrule's termination, reduce the heat flux through the ferrule ID into the tube sheet and will reduce the pressure drop across the ferrule system. Previous papers by the authors [2] have indicated that the mass flux should be limited to 2.5 lb/sec-ft^2 for waste heat boilers at today's higher operating temperatures
3. Establish and manage process temperature – This step will once again limit the maximum flux in the system and should also limit the possibility of refractory damage. Based on past experience system start-up and shutdown processes must be considered.
4. Minimize or eliminate tube projection past the front of the tubesheet – Analyses of the inlet assemblies that did and did not include tube projections indicates that the inclusion of projections, even at the TEMA recommended 1/8" limit, significantly increased the tube metal temperature.
5. Minimize the tubesheet thickness – Additional tubesheet thickness, beyond the minimums required for structural considerations, will increase the temperature on the front face of the tubesheet due to the increased conduction resistance caused by the additional material.
6. Use full penetration welds – While successful WHBs have included rolled and seal welded tube-to-tubesheet joints, the inclusion of a full penetration provides additional strength and provides a larger leakage barrier than a seal weld. This can increase the time before failure if corrosion does occur. It should be noted that full penetration welds will require the incorporation of thick wall pipe rather than tube.
7. Limit the pressure drop through the ferrule – While not the focus of this paper, a previous paper by the authors [3] concerned a ferrule assembly where sulfidation corrosion likely could be caused by gas bypassing between the ceramic ferrule and the tube, through the paper wrap. The

predicted pressure drop from a CFD analysis of this assembly was 0.23 psi. For this reason the authors have established a general limit of 0.15 psi through the assembly.

It must be noted that the impact of original construction, repair/maintenance procedures/ workmanship and the control of operation parameters/limits are all critical to the reliability of any WHB. For example even a highly reliably designed WHB can fail if there is a high inlet temperature event, a failure of the tubesheet protection system, improper boiler water feed water control, or quality and inadequate maintenance or operating procedures.

The authors must caution that certain guideline numerical values should not be considered applicable to all WHB applications. For example a guideline mass flux value suitable for large diameter tubes and tube sheet protection system may not be suitable for a small diameter tube application as the tube sheet temperature and the turbulence effect on heat flux at the end of the ferrule could be significantly different. The understanding of how these guidelines affect and interact for various WHB applications is an important aspect to a reliable WHB application.

The old saying that “the height of stupidity is doing the same thing the same way and expecting a different result” is very applicable to many of our activities.

We should be saying that “the height of good engineering is determining what resulted in high reliability and doing the same thing the same way and expecting the same results.”

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