North Carolina Agricultural and Technical State University

UNC Charlotte

THE APPLICATION OF IN740H ALLOY FOR ENHANCEMENT OF OPERATIONAL FLEXIBILITY OF POWER PLANTS

Ahmed Megri, NC A&T
Alireza Tabarraei, UNC Charlotte

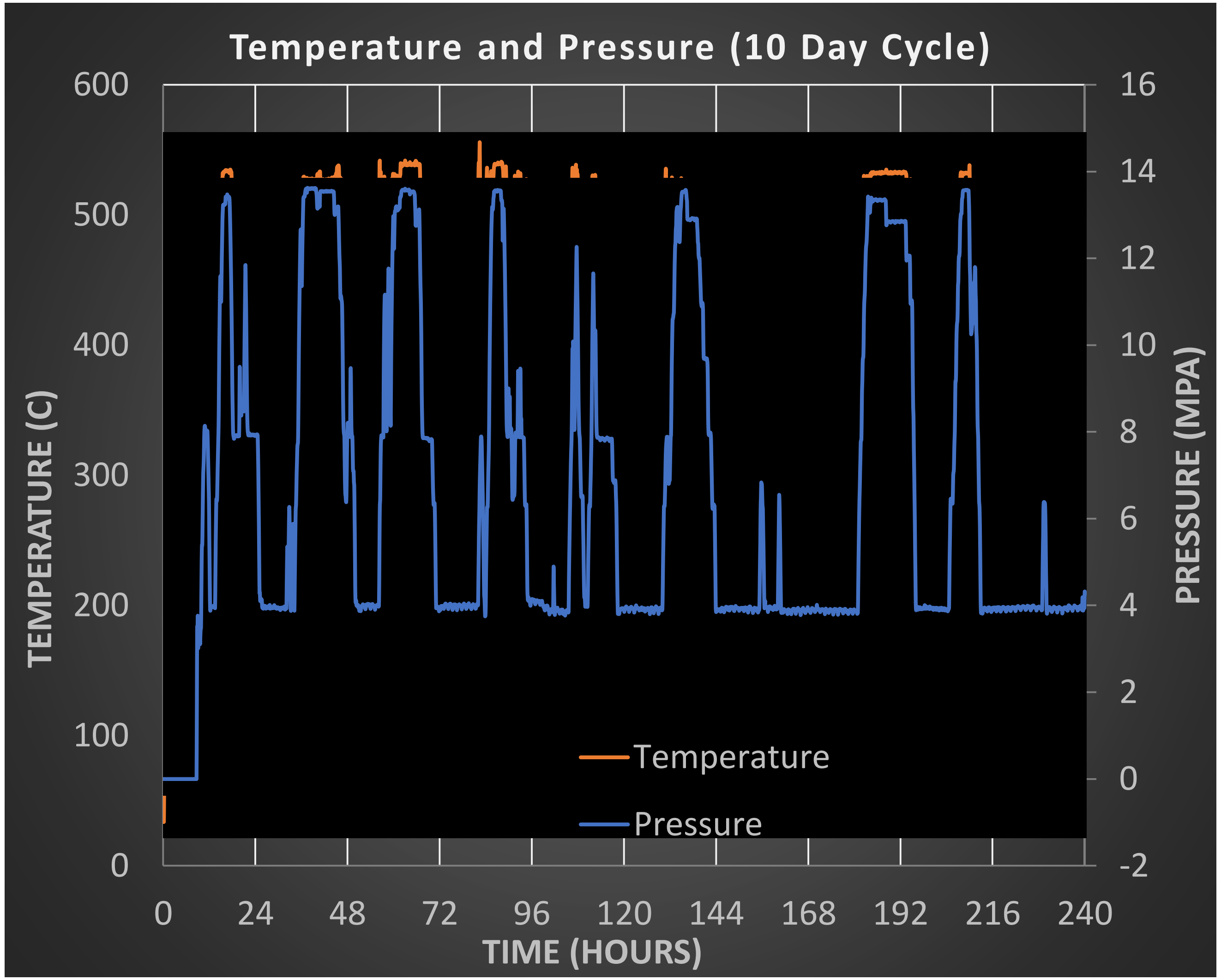
July 2021

Introduction

- Most fossil power plants in the U.S. were designed for a baseline steady state operation.

- The development of other power supply resources such as intermittent renewable generation, has forced power plants to adopt flexible operating strategies.

- The flexible operation mode includes shut-downs and start-ups which leads to a significant increase in the occurrences of thermal transients in the material of critical high-temperature boiler and turbine components.



Issues associated with flexible loading

These transients adversely affect the power plant assets by causing several issues such as:

- Increased rate of wear on high temperature components
- Decrease thermal efficiency at low loads
- Challenges in maintaining optimum steam chemistry.
- Increased fuel cost due to shut-down and start up
- Higher risk of human error in operating the power plant

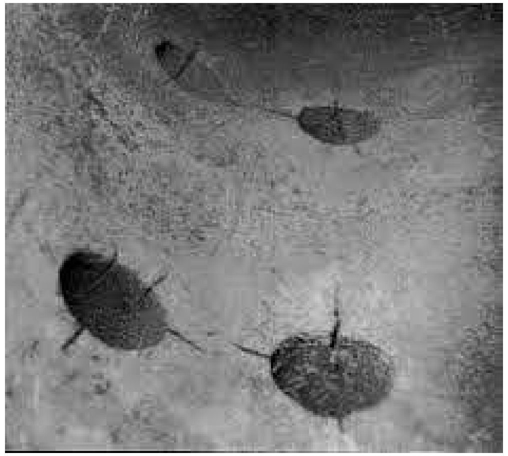
In this project we focus on the damage on boiler headers due to flexible operation

Damage in Boiler Headers

- Boiler headers are critical components of power plants which operate under high pressure and temperature.
- Due to high wall-thickness, thermal stresses are important in steam headers.
- The shut-down and start up can lead to a high range cyclic stress in headers
- The cyclic stress leads to the nucleation and growth of fatigue and fatigue-creep cracks in headers

Damage Mechanisms: Creep-Fatigue crack initiation

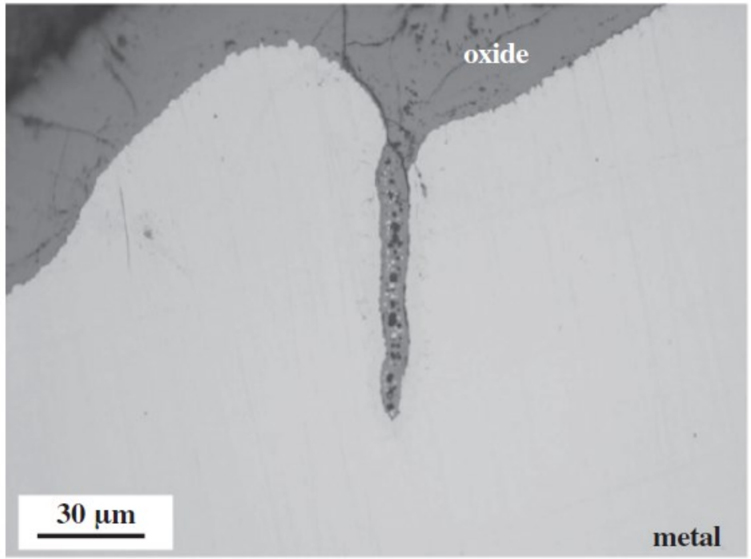
Axial cracking [1]

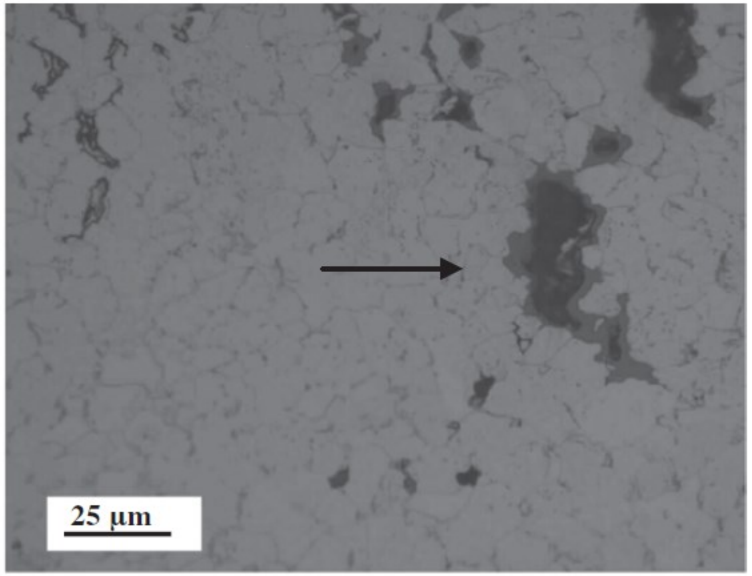


Circumferential and axial ligament cracking in a header [2]

1- Steve Hesler, Mitigating the Effects of Flexible Operation on Coal-Fired Power Plants
2- M. Hovinga G. Nakoneczny, Standard Recommendations for Pressure Part Inspection During a Boiler Life Extension Program, ICOLM, 2000

Damage Mechanisms: Oxide Notching





A. Almazrouee et. al, “Role of oxide notching and degraded alloy microstructure in remarkably premature failure of steam generator tubes”, Engineering Failure Analysis, 2011

Project Objective

- Investigation of the applicability of IN740H in steam headers of subcritical coal-fired power plants
    - The allowable stress of IN740H is significantly higher than conventional steel (Gr 22) and creep strength enhanced ferritic (CSEF) steels including the Gr 91
    - Due to its higher strength, the header designed with IN740 are significantly thinner, hence the thermal stresses generated in the header walls are lower
    - The lower thermal stress range cycles will lead to a higher fatigue lifetime of the header
    - IN740 is significantly more expensive than other types of steel (about 10 times more on a weight basis)
    - Repair or replacement of header is very costly for the power plants (~ 4 million dollars)

In this project, finite element analysis along with CFD calculations are conducted to investigate if using IN740 will enhance the operational flexibility of power plants

Strategic alignment of project to Fossil Energy objectives

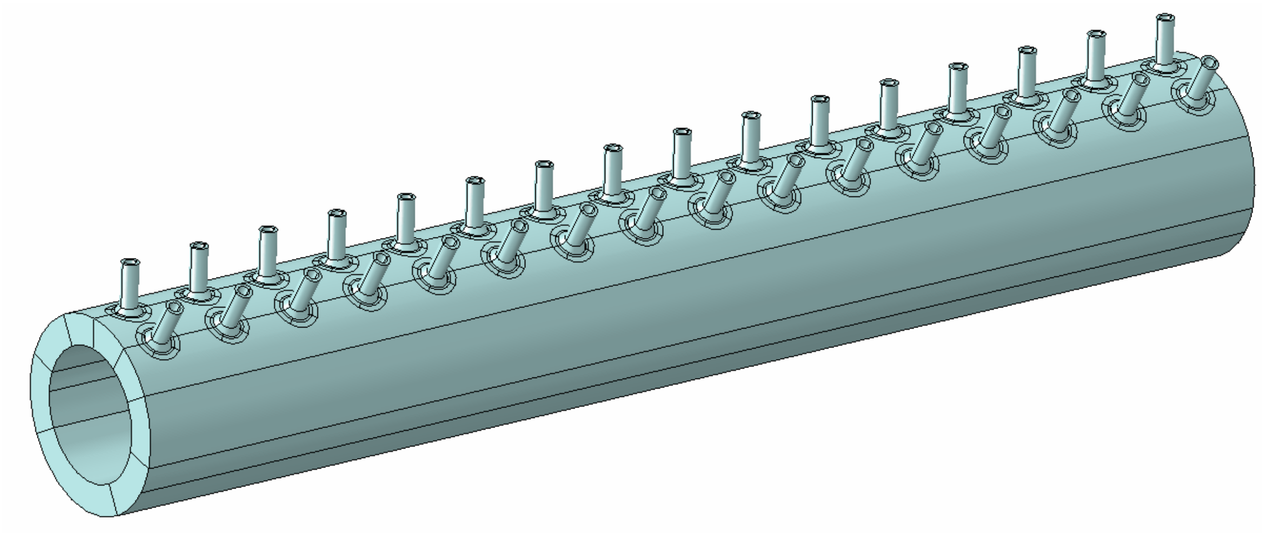
- FE STRATEGIC GOAL 1 Develop secure and affordable fossil energy technologies to realize the full value of domestic energy resources
- Improve existing and new power plants through better understanding of the header behavior, through heat transfer, stress and fatigue analysis studies
- Advance R&D on new material (IN740H Alloy) usage in power plant installation, which is cost effective and durable, and reduce the maintenance cost.
- Develop next-generation of headers, and systems to improve the performance, reliability, and efficiency of the existing coal-fired power plants.

Strategic alignment of project to Fossil Energy objectives

- FE Strategic Goal 4 - Develop and maintain world-class organizational excellence
- Modernize infrastructure through the Life Extension of the power plants installation, through the use of new header generation
- Cultivate and maintain a highly qualified, diverse, and well-trained workforce capable of achieving the FE mission and objectives, through training qualified undergraduate and graduate students
  - <u>Current Status of project</u>
    - **Industry/input or validation** – the measured information related to an exiting power plant has been provided by EPRI. These information have been used to conduct stress analysis and estimate the life cycle of header. The operating data is also used to predict the heat transfer coefficient using CFD calculations.

Designing the headers

- ASME B&PV Section I, A-317 is used to design the header using Gr 91 and IN740.
- Material properties are extracted from ASME BPVC Section VIII Div 2 Part D.
- Header is designed for a maximum allowable working pressure of 2450 psi (16.9 Mpa) and temperature of 1005 °F (541 °C).
- The header wall thickness in the model using Gr 22, Gr 91 and IN740 are respectively 3.5 in, 2.1 in and 0.95 in.



Designing the headers

- According to A-317, the minimum wall thickness of headers can be obtained from

$$t = D_i\left(e^{(P/SE)} - 1\right)/2 + C + f$$

P: Maximum allowable working pressure (2450 psi)

D_i: Inner Diameter = 1.219 in

C: Minimum allowance for threading stability = 0

f: Thickness Factor For Expanded Tube Ends = 0

E: Efficiency

$$E = \frac{p - d}{p}$$

p = Pitch = 6 in
d = Diameter of opening
The through hole diameter is 1.219 in
E = 0.797

S: Maximum Allowable Stress at Design Temperature

S = 108.4 MPa at 541°C for G 91
S = 275 MPa at 600°C for IN740

Designing the headers

- Using Efficiency E = 1, the tubes wall thickness is obtained as

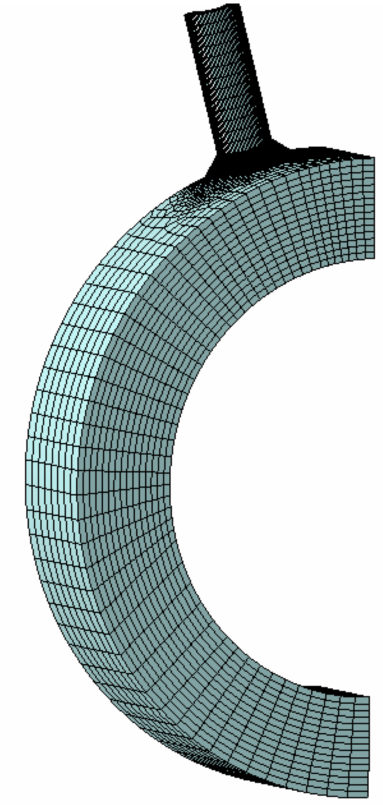
Calculated tubes Wall Thickness

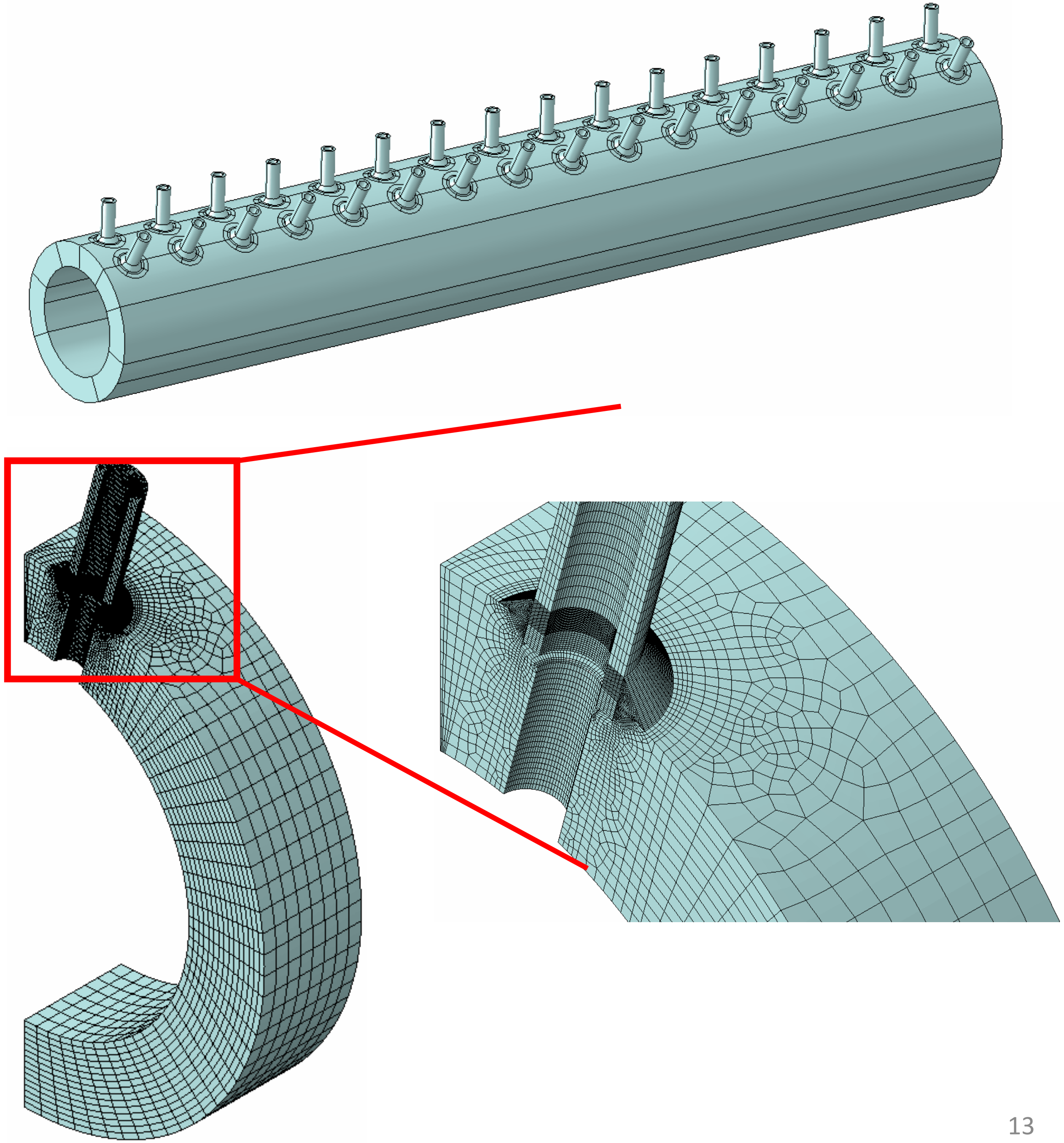
$t = 0.103$ in for header made of Gr 91

$t = 0.0386$ in for header made of IN740

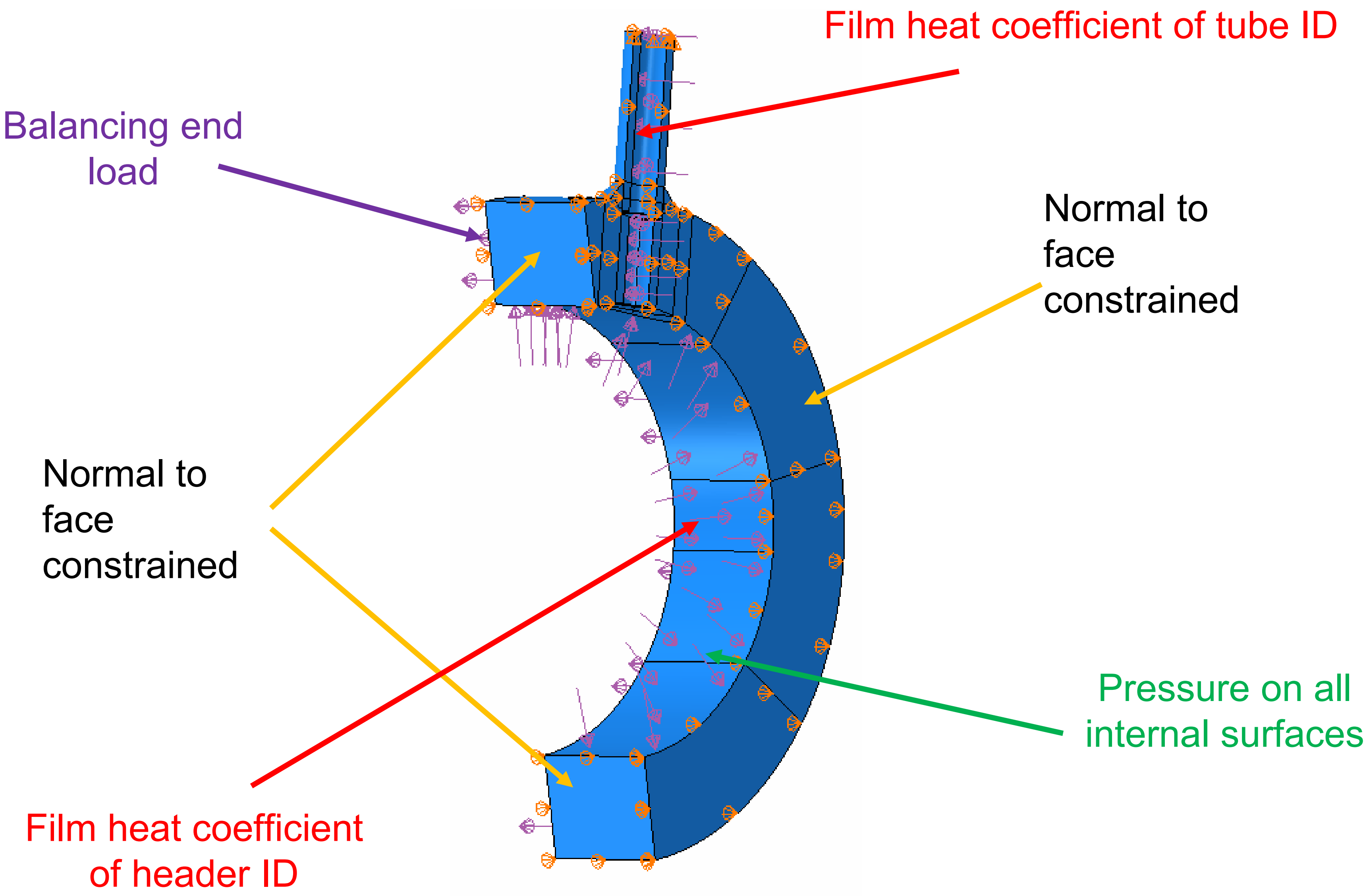
Due to their thin walls, thermal stresses are not high in tubes

Finite Element Model

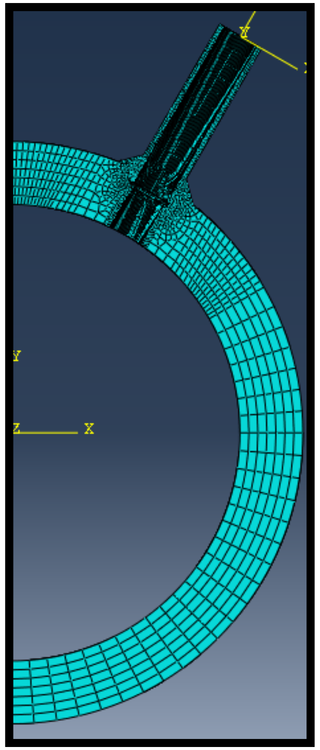


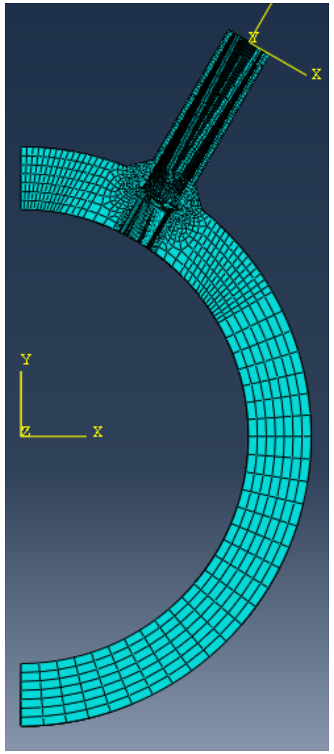


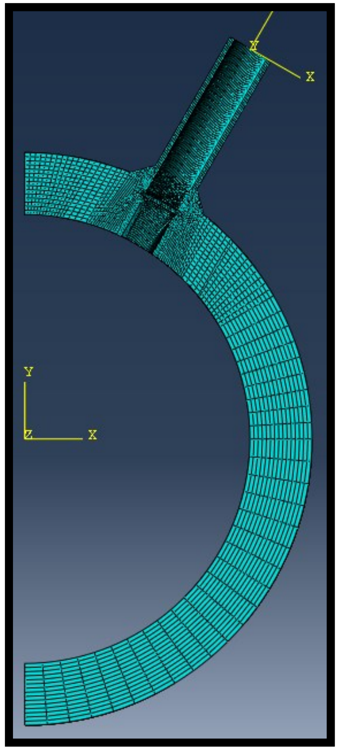
Boundary Conditions



Mesh Convergence Study







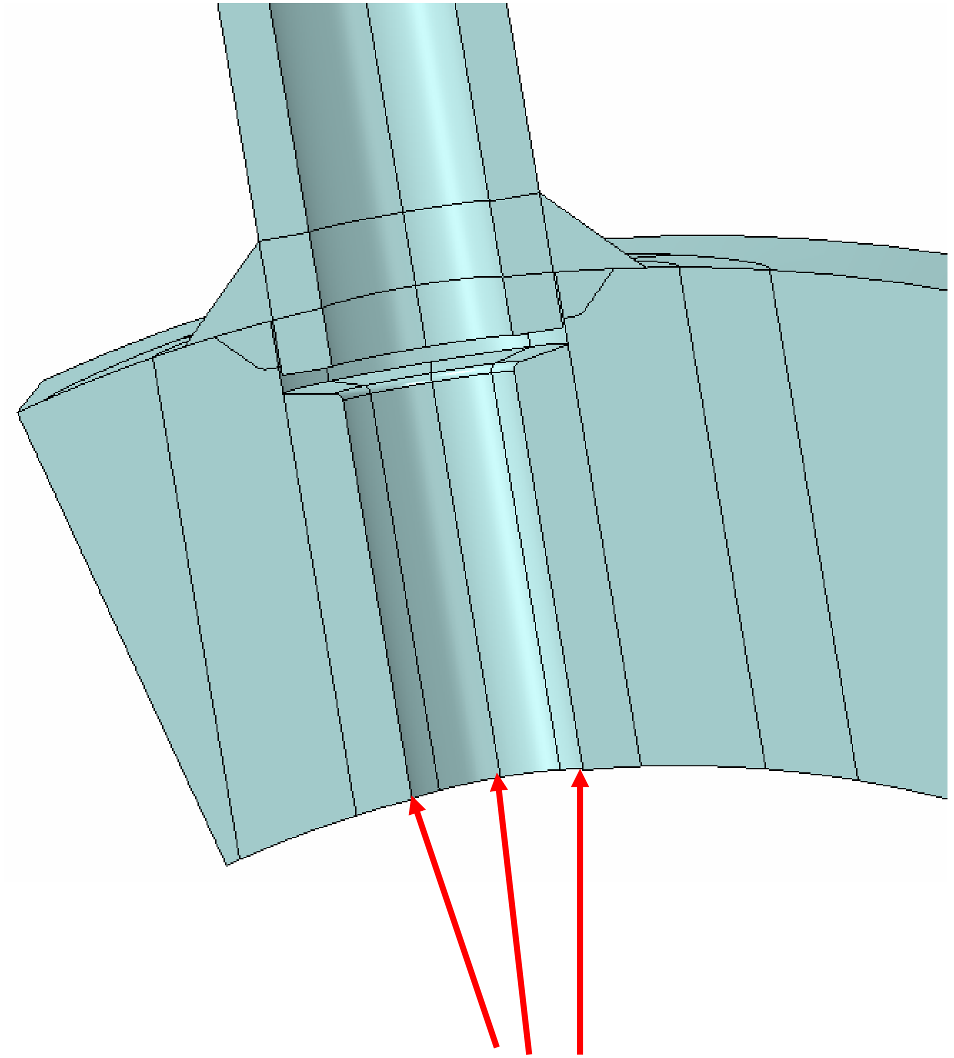
The finite element mesh is refined until the results converge. Six different meshes are prepared for each header

Number of Elements						
Material	Mesh 1	Mesh 2	Mesh 3	Mesh 4	Mesh 5	Mesh 6
Gr 91	41,367	56,501	56,859	68,992	76,191	91,222
Gr 22	55,111	53,730	55,440	65,100	72,960	88,080
IN740	41,181	43,248	57,330	65,965	78,010	88,420

Fatigue analysis

The convergence of stresses at three critical points are used for the verification of results convergence

- A 10-day operating period (~250 hours) of the power plant is used in the stress analysis
- Fifteen load cycle is recognized in the 10-day operating period. This is equivalent of 180 load cycle in one year (typical operating of 3000 hours per year is assumed)

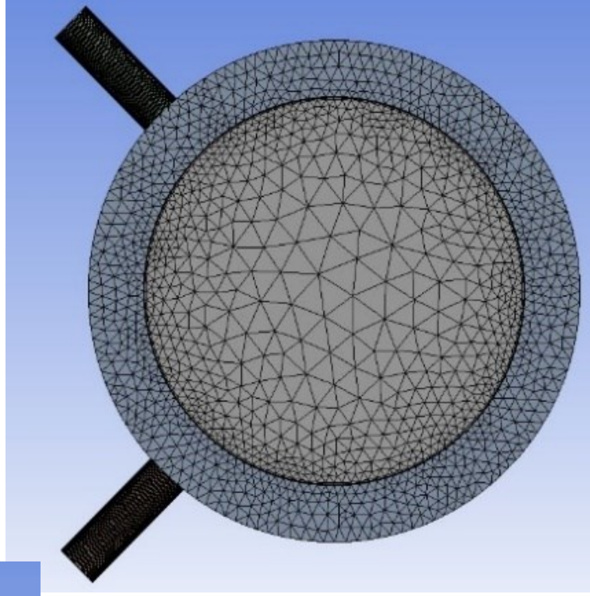


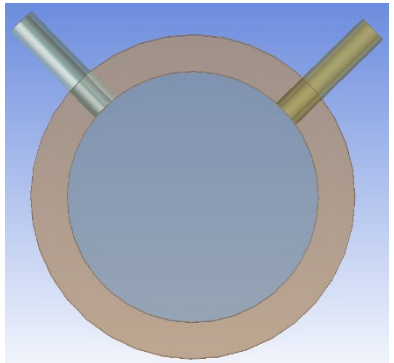
Critical points used for checking stress convergence

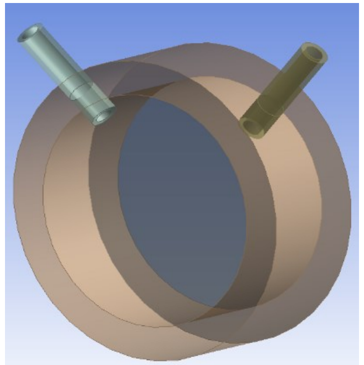
Fatigue analysis

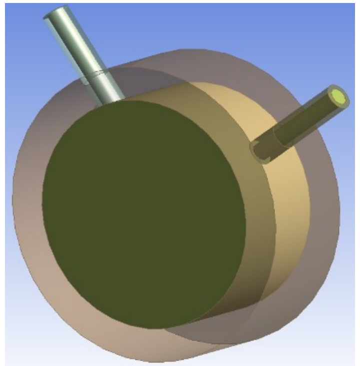
- Our results predict that if fatigue is the only damaging mechanism, it will take many years for crack initiation
- We are considering other damage mechanisms such as creep and oxide notching

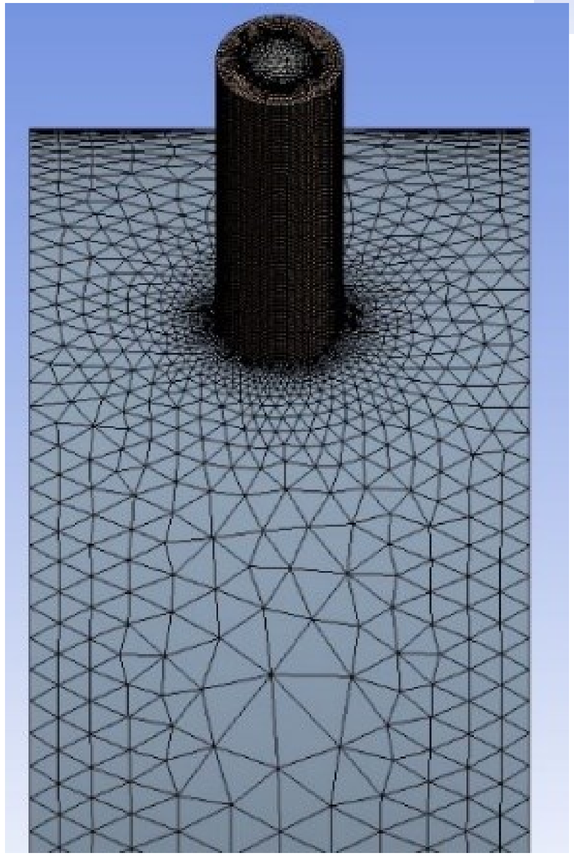
HEADER ASSEMBLY (HEAT TRANSFER ANALYSIS)

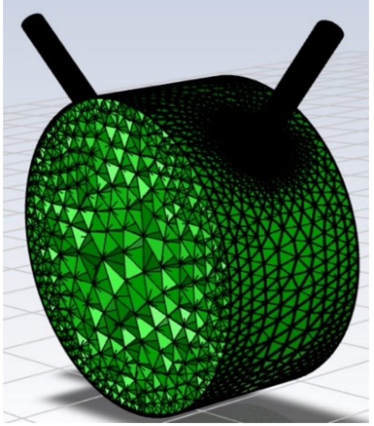


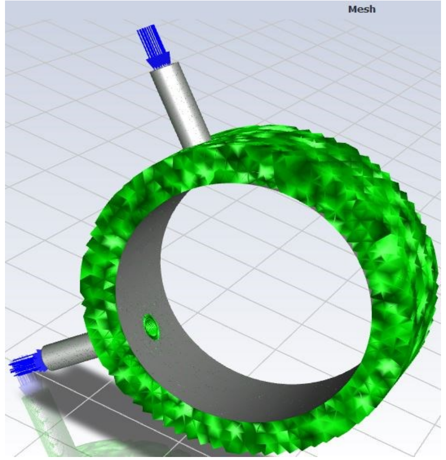


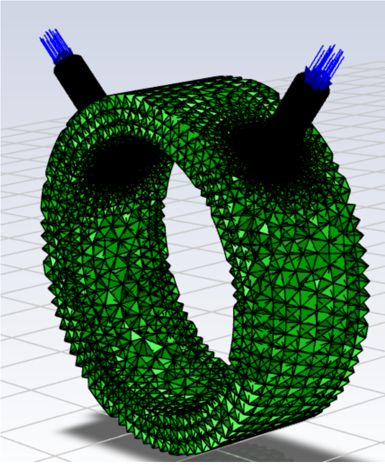






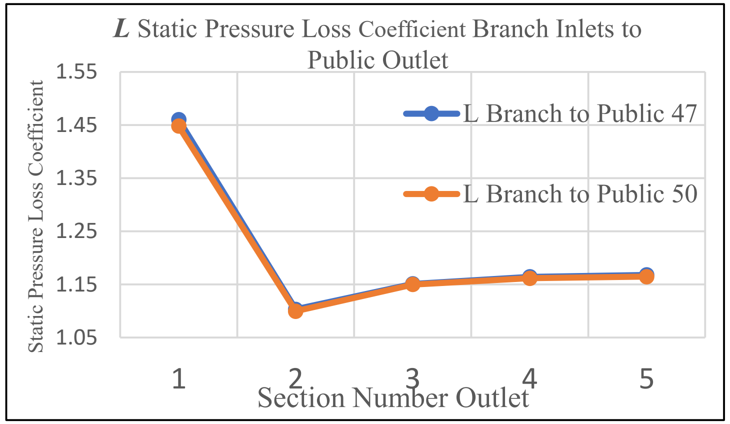




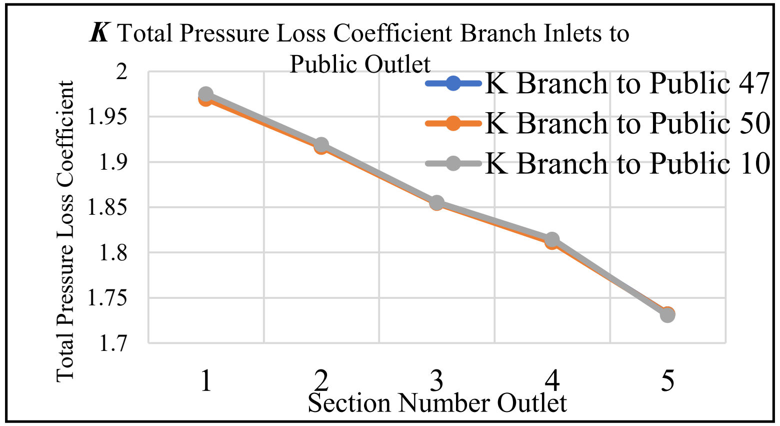


Pressure Loss Coefficient

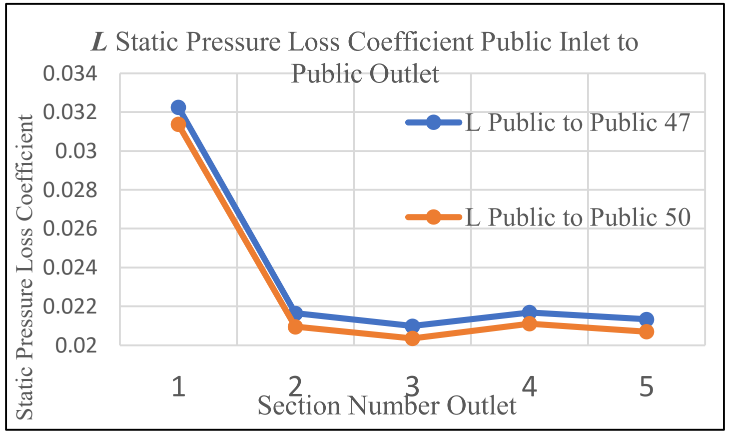
L Static Pressure Loss Coefficient **Branch Inlet** to **Main Outlet**



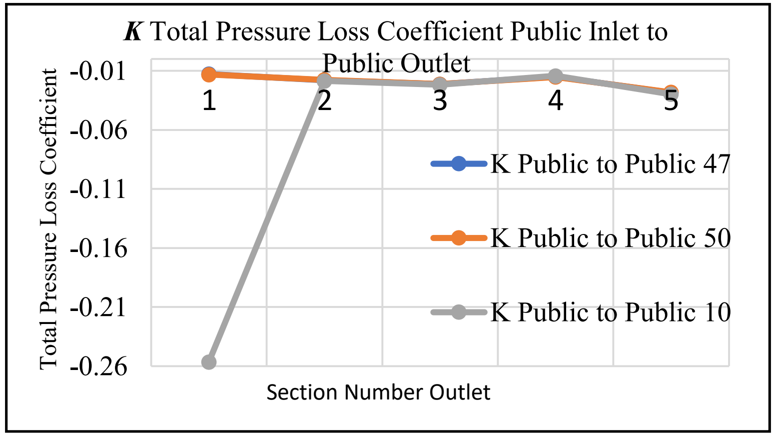
K Static Pressure Loss Coefficient **Main Inlet** to **Main Outlet**



L Total Pressure Loss Coefficient **Branch Inlet** to **Main Outlet**



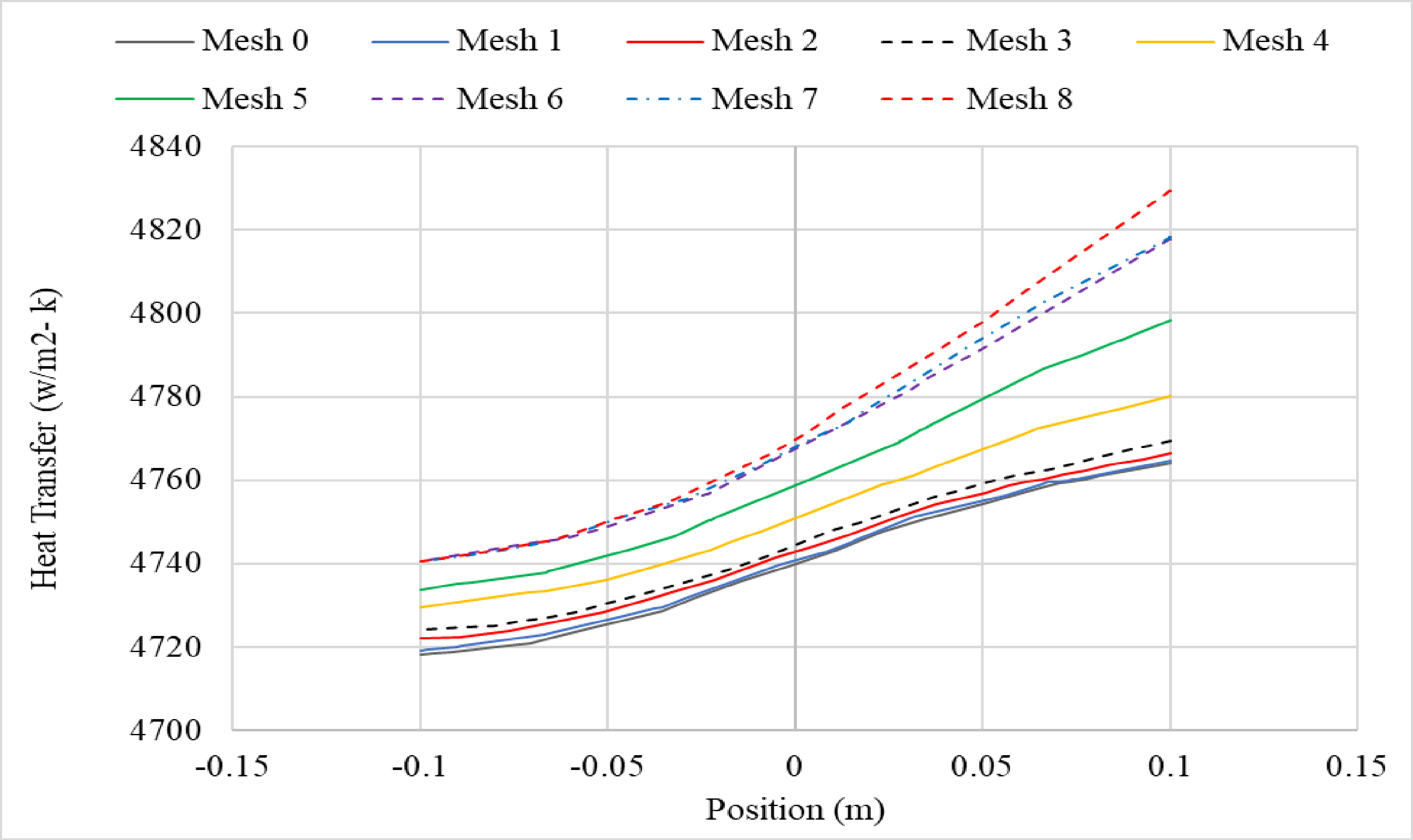
K Total Pressure Loss Coefficient **Main Inlet** to **Main Outlet**



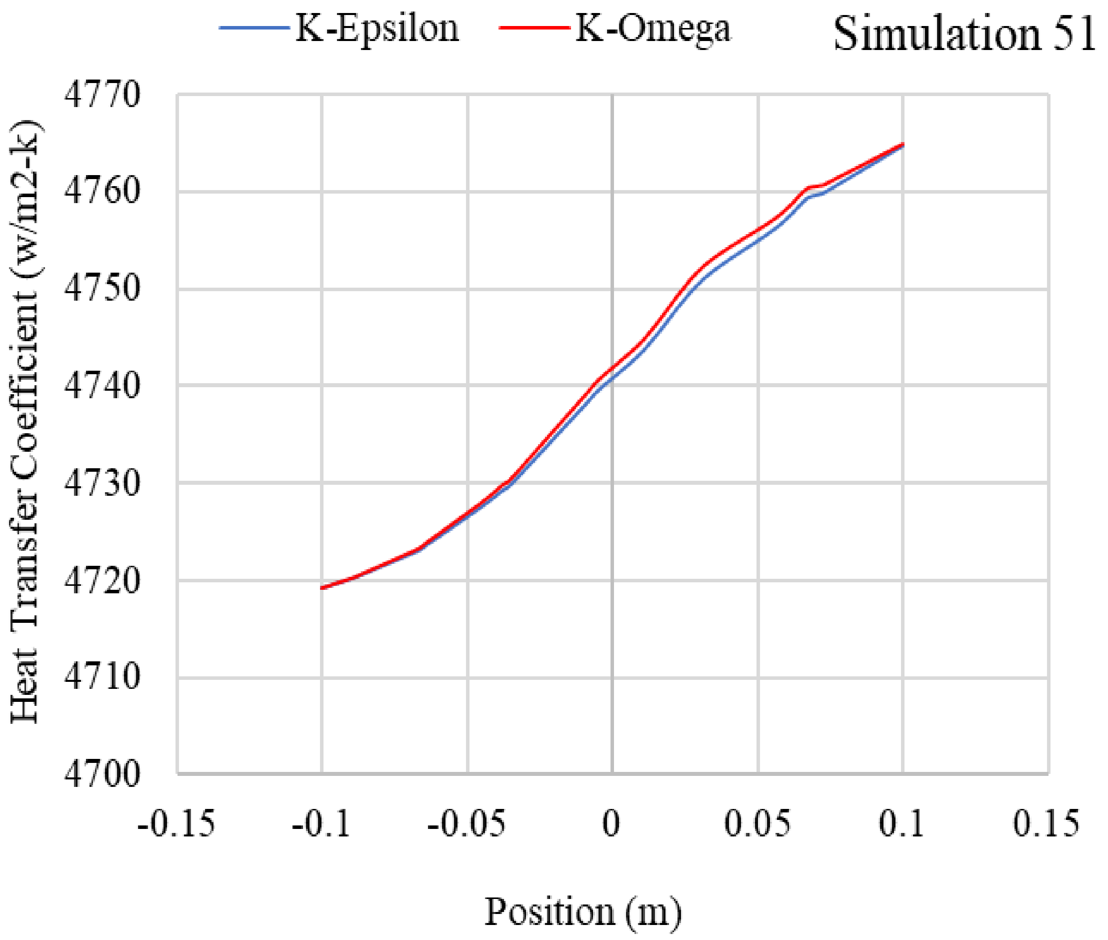
MESH ANALYSIS

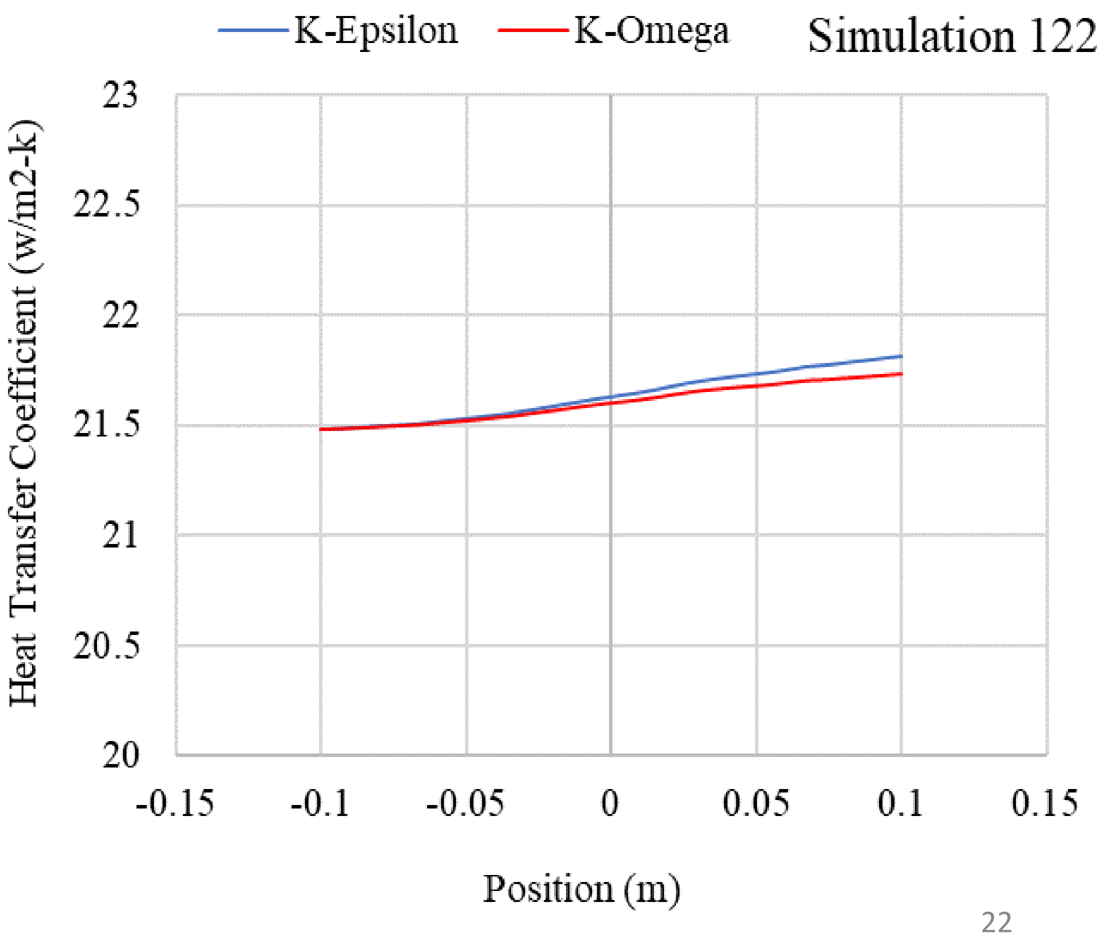
No	Mesh 0	Mesh 1	Mesh 2	Mesh 3	Mesh 4	Mesh 5	Mesh 6	Mesh 7	Mesh 8
Size	120-140	60-80	50-70	40-60	30-50	20-40	10-20	5-10	1-2
Number of Elements									
All Domain	1627593	433979	325126	191151	140084	80413	78209	78023	77969
Number of Nodes									
All Domain	854069	192955	142525	69574	53878	30623	29804	29782	29782

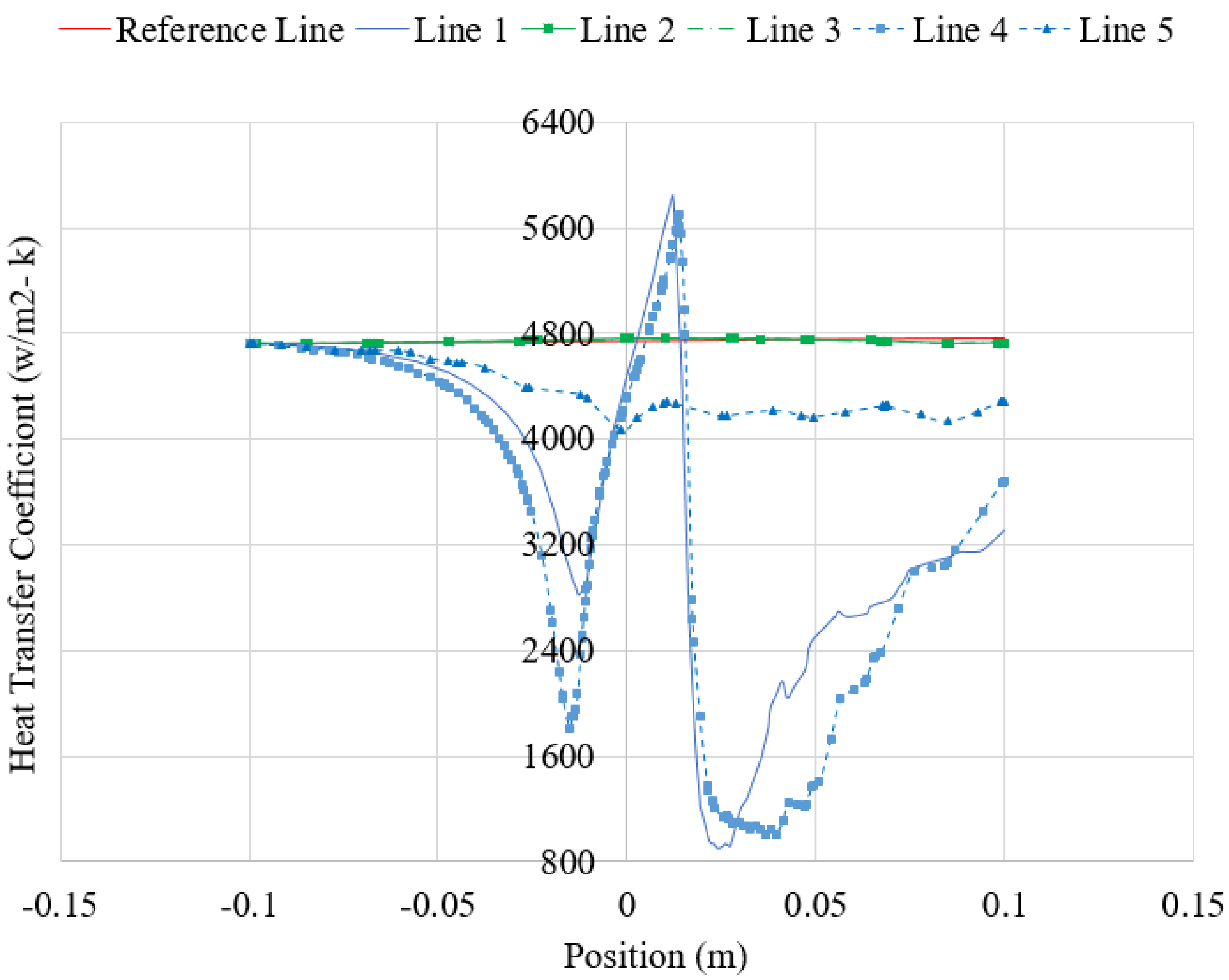
The Mesh Study Results for Heat Transfer Coefficient



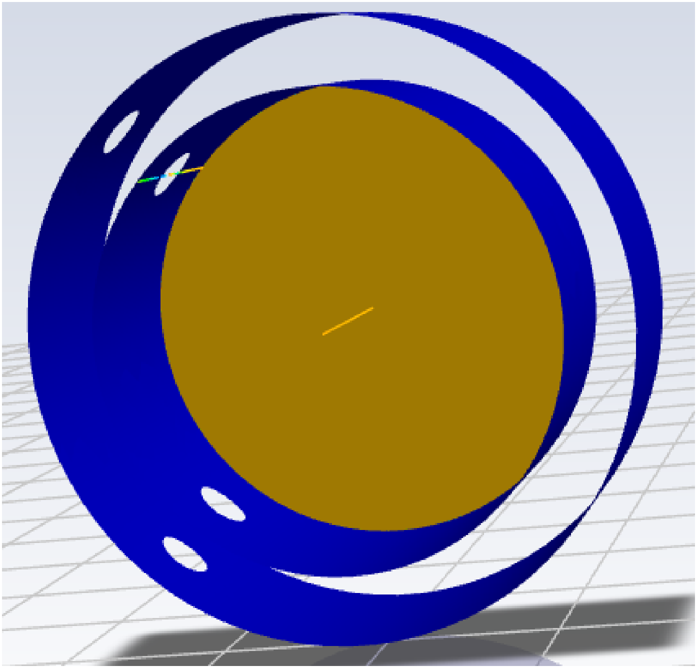
Viscosity Models



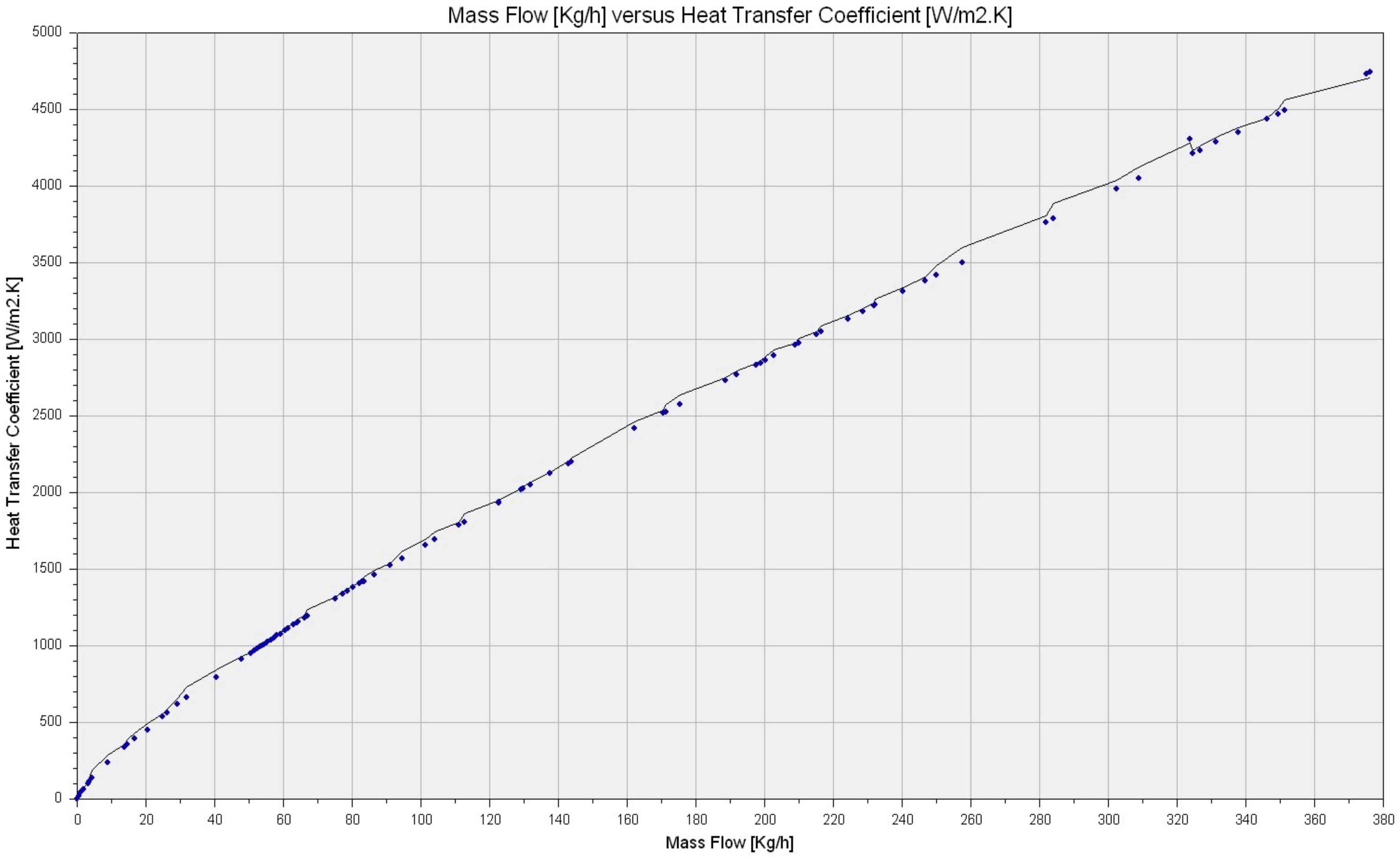




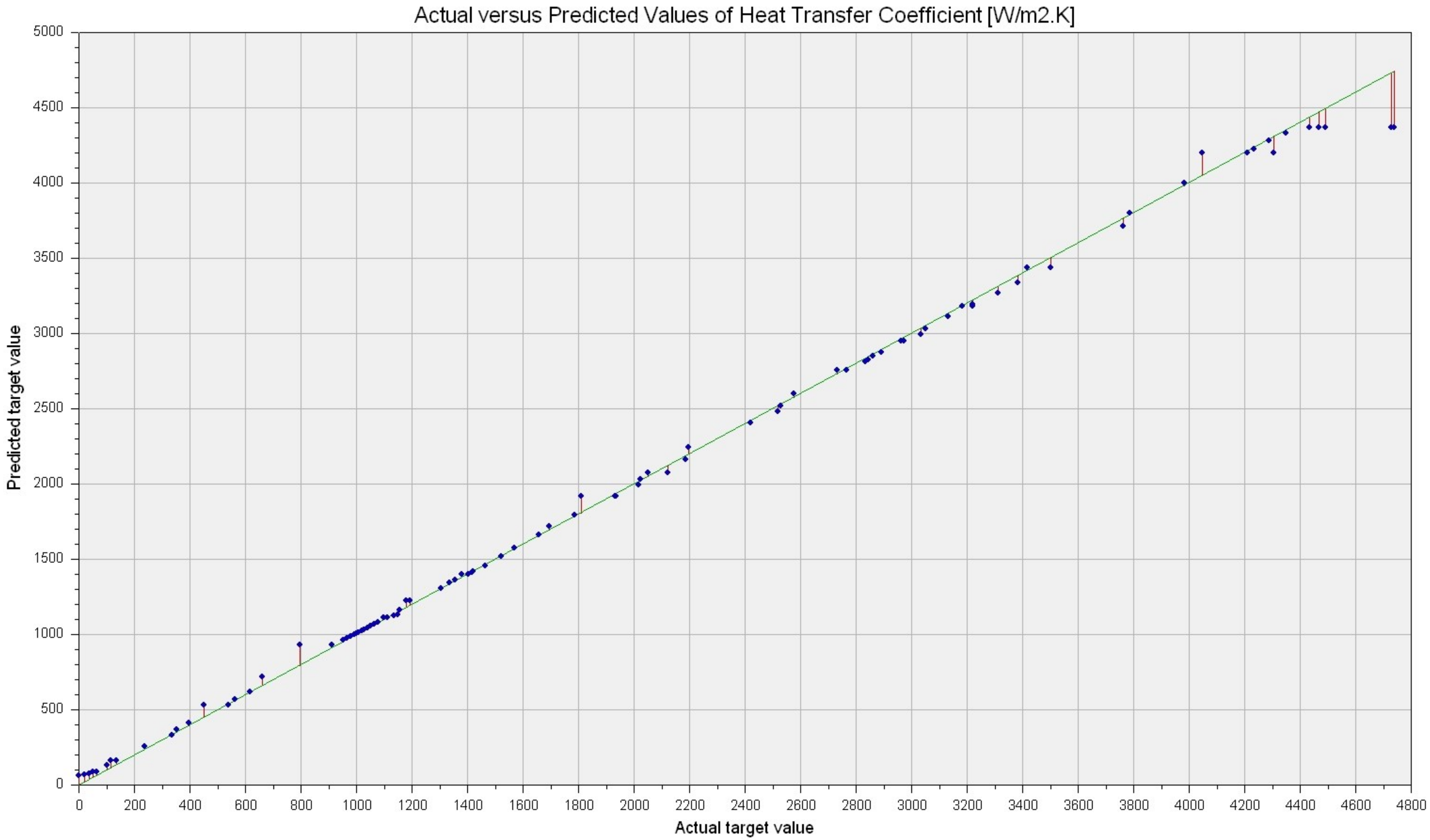
Effect of Heat Transfer Location



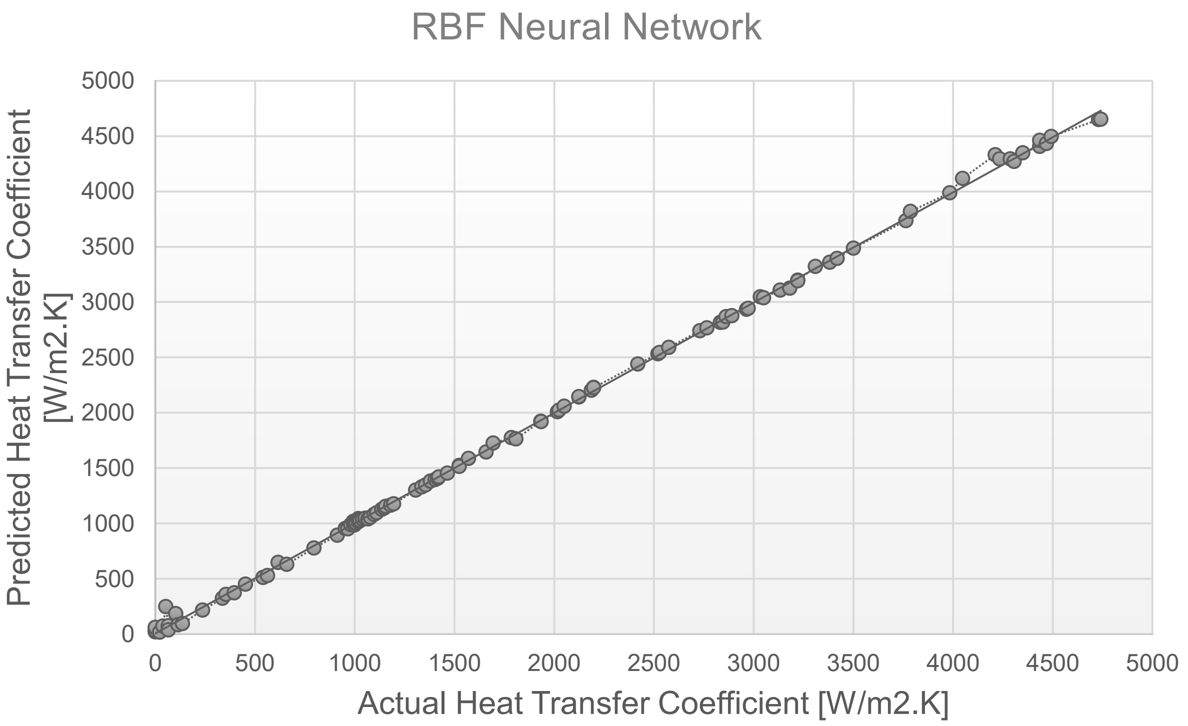
- Prediction of heat transfer coefficient using Predictive models, such as "Tree Forest Prediction"

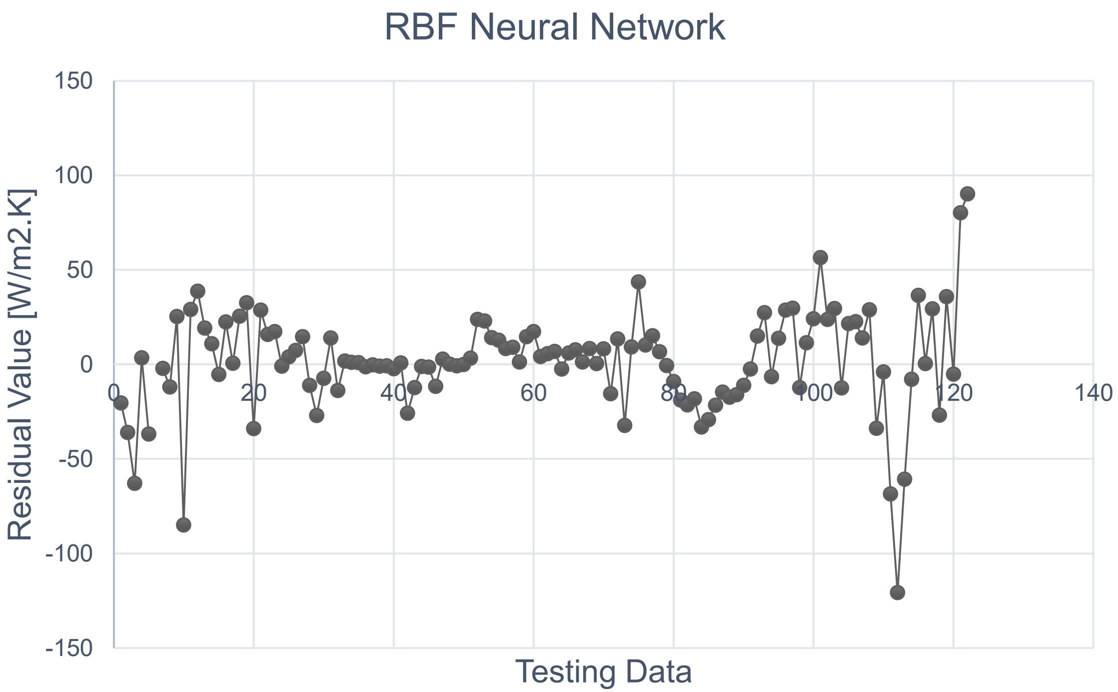


Prediction of heat transfer coefficient using Predictive models, such as “TreeBoost”.



Prediction of heat transfer coefficient using Predictive models, such as “RBF Neural Network”.





Market Benefits/Assessment

- A critical component in power plants is steam outlet headers. A main concern regarding the structural integrity of headers is the ligament cracks occurring between tube penetrations. A major conclusion from previous studies is that a main reason for the initiation and propagation of ligament cracking is the fatigue damage accumulation as a result of a large quantity of thermal stress cycles.
- Current headers are not designed for cyclic thermal stresses and pressure cycling, hence fatigue damage due to cyclic loading is not considered in their design. The radical changes in the operating practices which imposes cyclic loading on headers has raised concern regarding the medium- and long-term structural integrity of headers. Inter–ligament cracking between stub penetration has been observed in headers and are attributed to the high frequency start–up shut–download operating strategies. A header leak can result in a four–day power plant outage with an associated cost of $500,000 per day for a 500-MWe power plant. Such high replacement cost along with the risks associated with loss of life in a catastrophic failure of headers necessitates special attention to the design and lifetime assessment of headers.

Market Benefits/Assessment

- Studying fatigue damage in headers designed using IN740H to quantify the benefits of IN740H over other CSEF steels such as Grade 91 in designing headers under cyclic loading. – Using CFD analyses and machine learning to obtain an accurate description of fluid velocity profile and heat transfer coefficients – Using the heat transfer coefficients in the thermo–mechanical analysis of steam header to obtain the stress distribution in the header – Using the stress distribution to approximate fatigue damage in header due to cyclic loading
- Employing the finite element analysis and CFD to optimizing the header geometry for the purpose of minimizing the weight of header. Considering that IN740H is ten times costlier than other CSEF steels, the material cost of optimized shaped headers is expected to be significantly lower than headers with conventional shapes.
- Conducting a cost–benefit analysis of fabricating headers with IN740H versus fabricating them with Grade 91.

Technology-to-Market Path

- The end result:
    - *Improve existing and new power plants through better understanding of the header behavior, through heat transfer, stress and fatigue analysis studies*
    - *Advance R&D on new material (IN740H Alloy) usage in power plant installation, which is cost effecitive and durable, and reduce the maintenance cost.*
    - *Develop next-generation of headers, and systems to improve the performance, reliability, and efficiency of the existing coal-fired power plants.*

- Identify needed or already identified industry collaborators:
    - EPRI and ST

Concluding Remarks

- *Highlight applicability of technology to Fossil Energy and alignment to strategic goals.*
  - Improve existing and new power plants through better understanding of the header behavior, through heat transfer, stress and fatigue analysis studies
  - Advance R&D on new material (IN740H Alloy) usage in power plant installation, which is cost effective and durable, and reduce the maintenance cost.

- *Define project's next steps and current technical challenges.*
  - Improve the prediction of heat transfer/ stress and fatigue through using machine learning analysis studies
  - Design a new header, using the new material (IN740H Alloy), which is cost effective and durable, and reduce the maintenance cost.

- **Acknowledgment**: “This material is based upon work supported by the Department of Energy Award Number DE-FE0031747.”

- **Disclaimer**: "This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.“