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Procedia Engineering 00 (2013) 000–000

Procedia Engineering

www.elsevier.com/locate/procedia

2nd International Symposium on Innovation and Technology in the Phosphate Industry
[SYMPHOS 2013]

Spray Injectors within Large Capacity Molten Sulfur Combustion: Fluid-Structure Interaction Study

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Abstract

An efficient combustion process of large molten sulfur volumes is a requirement in current and future phosphate production technology. The use of precision spray injectors in the combustion of molten sulfur represents an active and growing field. Over the past decade there have been rapid advancements in computer and software technologies for simulation of complex applications. These strides have allowed for more complex simulations at a reasonable cost point for industry engineers, such as the design of spray injectors with stress analysis coupled with fluid dynamics and heat transfer.

A Fluid-Structure Interaction (FSI) study of molten sulfur injectors into a large capacity sulfur combustion chamber was performed with usage of Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA). This work focuses on the FSI results of the detailed spray injector to evaluate suitability of the design to withstand the harsh combustion environment. The structural loads (obtained via FEA) due to stresses exerted by molten sulfur, gas flow and combustion process (obtained via CFD) were combined to define worthiness of the injector for the long term application of up to 25 years of continuous service.

Keywords: Fluid Structure Interaction (FSI), Sulfur Combustion, Sulfur Burning Injectors, Sprays, Computational Fluid Dynamics (CFD).

Nomenclature

General Symbols

St	Strouhal number
f_v	vortex shedding frequency
D	diameter of the cylinder
U_g	fluid flow velocity
Q_g	Gas Flow Rate
T	Operating Temperature
g	gravitational constant
f	natural frequency

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E	Modulus of elasticity
I	Moment of Inertia
l	span length
A	pipe cross-sectional area
P	Operating Pressure
Greek symbols	
λ	frequency factor
μ	weight per unit length
ρ	density

1. Introduction

Sulfur trioxide (SO3) is commonly used in the manufacturing of sulfuric acid, oleum, chlorosulfonic acid and other compounds. One method of attaining SO3 gas for these processes is through the combustion of molten sulfur.

The sulfur is liquefied and fed into the combustion chamber of a furnace through one or injectors. These precision spray injectors are a critical component in the process. The injectors convert large quantities of molten sulfur into an atomized spray of sulfur particles. These injectors have a significant role to maintain over long time periods, in a harsh environment. The environment exhibits extremely high temperatures and turbulent flow conditions. The injectors are fairly long and must remain in operation, maintenance free, for a period of up to 25 years.

In order to optimize design and verify proper material selection, FSI is required to ensure performance and reliability for the designed life of the injectors. This work outlines the design considerations for a successful sulfur combustion injection system. The process details injector design verification, based on the selection and preliminary design of previous work. These simulations address velocity profiles, temperature profiles, flow induced vibration and other relevant characteristics of the application.

2. Theoretical Considerations

2.1. Flow Induced Vibration

As fluids flow around structures, the motion of the fluid around the solid can exert oscillating forces on the structure. There are many areas of study relating to flow induced vibration. One subset of flow induced vibration relates to vortex shedding, which this study is focused around. Vortex shedding describes the unsteady flow that occurs as a fluid flows past a solid body, as shown in Fig1. Vortices are created at the back of the body and detach with an oscillating pattern from the body. If the body is rigidly mounted; when the frequency of the vortex shedding matches the resonance frequency, the structure can resonate leading to eventual failure.

Many studies have been documented in recent history relating to vortex shedding around cylindrical objects. This oscillating behavior is highly dependent on shape and Reynolds number (Re) of the flow around the structure. The results of these studies are heavily documented in figures such as Fig. 2.

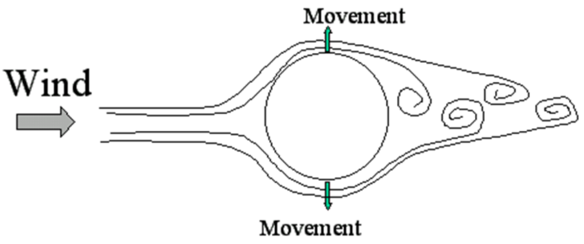
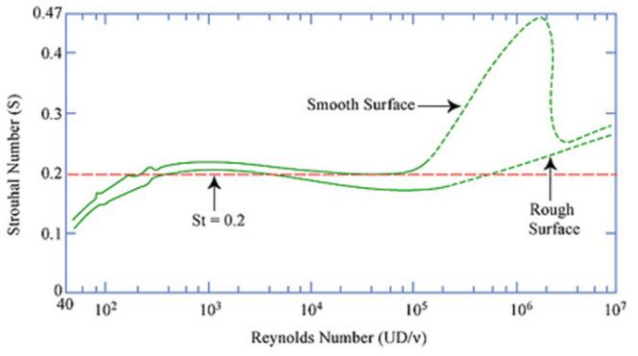


Fig. 1. – Vortex Shedding.



Relationship between Strouhal number and Reynolds number for circular cylinders. Data from Lienhard (1966) and Achenbach and Heinecke (1981). S~0.21 (1-21/Re) for 40<Re<200, from Roshko (1955).

Fig. 2. – Strouhal Number versus Reynolds number for a cylindrical body.

Many factors, in addition to cross-sectional shape and Reynolds number, have been shown to have an effect on vortex shedding as well. Hence these calculations should be used with caution in determining safety of the design. Shedding frequency is commonly related to the Strouhal number (Sh) by the following equation:

$$St = \frac{f_v D}{U_g} \tag{1}$$

The Strouhal number is dependent on the cylindrical body and the Re number as aforementioned.

2.2. Frequency Calculations

Calculations of natural frequency were performed to aide in the design phase of the injector.

$$U_g = \frac{0.086 Q_g T}{PD^2} \tag{2}$$

$$f = \frac{\lambda}{2\pi}\sqrt{\frac{gEI}{ul^4}} \tag{3}$$

2.3. Fluid Considerations

Molten sulfur is highly influenced by temperature and thus temperature of the liquid feed through the injector is required to be tightly controlled. This is achieved by means of steam jacketed lining. Steam must be continually circulated to maintain the expected physical properties of the molten sulfur and corresponding spray performance. Figure 3[7] detail the temperature dependent nature of sulfur density and viscosity. Under normal operation in this application, density was determined to be 10.59 kg/m3 with viscosity of 2.266e-5 kg/m*s, based on temperature profiles.

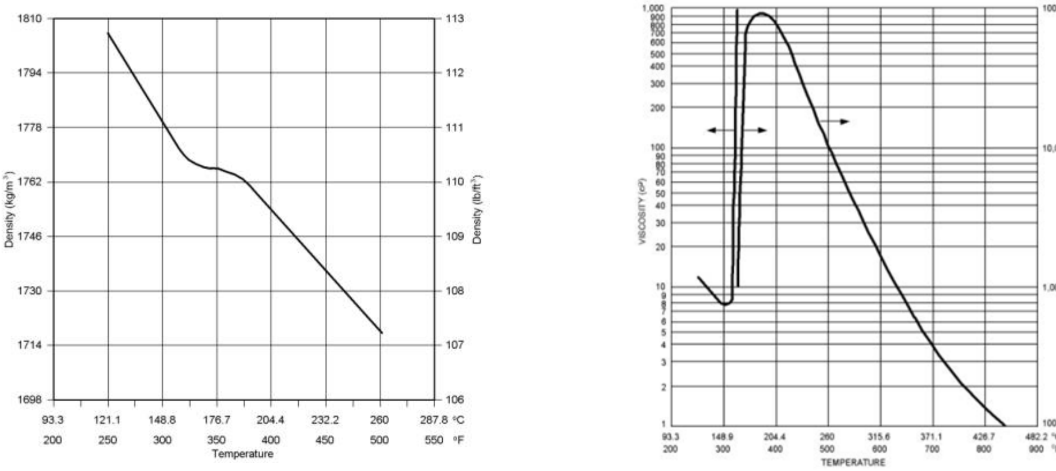


Fig. 3. – Molten sulfur physical properties based on thermal conditions.

2.4. Injector Material Considerations

Nozzle construction materials may vary from light weight plastics to case hardened metals. The material which is most suited to an application directly depends on the spray substance, spray environment (corrosive, heated, etc.), and desired spray characteristics.

Typical furnace temperatures are in the range of 900°C - 1500°C. In order to function properly the injector must withstand the external temperatures, internal temperatures, exposure to process fluids and internal forces. There are many readily available heat-resistant injector materials such as 310SS, 304SS, 316SS or 309SS or similar materials; the combination of material and design must be evaluated and optimized for each application.

2.5. Injector Design

Spraying Systems Co. patented (PAT# 6,098,896) design of an “Enhanced Efficiency Nozzle for use in Fluidized Catalytic Cracking” provides a refined solution to the FCC feed injection process. The use of an impingement pin, along with a transversely intersecting steam flow, greatly improves the efficacy and efficiency of the FCC feed injection process. In addition to these elements, the patented FCC unit provides specification for exit nozzle configurations to improve the post-discharge atomization of the fluid. Figure 4, provides a schematic representation of one of the Spraying Systems Co. FCC unit design configurations.

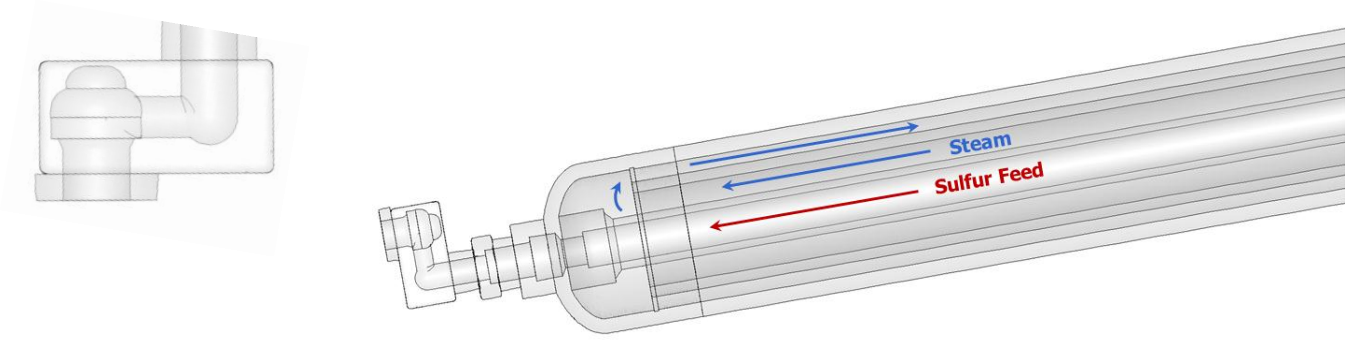


Fig. 4. Illustration of (a) injector whirl chamber design and (b) upstream steam and sulfur supply.

These tests were conducted using a 2" CS FCC feed, single slot orifice injector nozzle, which was modeled after a commercial unit. The production size unit’s liquid inlet flange-to-exit orifice OAL centerline distance is 54". The results of these tests help to determine design limits of this injector. The numerical simulation conducted for this work helps to characterize the internal mechanisms which could not be investigated experimentally. These results provide a better understanding of the output of this nozzle and the mechanisms which allow it to perform as it does.

3. Numerical Simulations

3.1. CFD Methods

Computational Fluid Dynamics (CFD) is a numerical method used to numerically solve fluid flow problems. Today's CFD performs use extremely large number of calculations to simulate the behavior of fluids in complex environments and geometries. Within the computational region, CFD solves the Navier-Stokes equations to obtain velocity, pressure, temperature and other quantities that may be required by a tackled problem.

The commercially available CFD package ANSYS FLUENT (version 14) was used for the simulation of the gas flow in the combustor domain and internal injector flow. Air and combustion resulting gases inside the horizontal combustion chamber were simulated using an Eulerian approach. Temperature, velocity and pressure profiles were mapped to the injector surface for the one-way FSI simulation. Internal steam and molten sulfur flow were similarly modeled. The primary phase used coupled models (momentum, turbulence, energy, and species mixing) which required boundary conditions (BC's). Inlet for the molten sulfur was set as a mass-flow inlet based on required fluid delivery of the injector. The steam jacket inlet was modeled as a pressure boundary condition..

3.2. FEA Methods

FEA is a numerical technique used to approximate a solution for partial differential equations. The domain is divided into finite nodes where systems of equations are developed to approximate the physics of the whole domain. The material used for lance construction was ASTM A312 TP304L seamless stainless steel. The properties of which are included in table 1.

Table 1. Material Properties of Stainless Steel

Young's Modulus	2.7992e+007 psi
Poisson's Ratio	0.31
Density	0.28021 lbm/in³
Thermal Expansion	9.4444e-006 1/°F
Tensile Yield Strength	30023 psi
Compressive Yield Strength	30023 psi
Tensile Ultimate Strength	84992 psi
Compressive Ultimate Strength	0 psi
Thermal Conductivity	2.0196e-004 BTU/s·in·°F
Specific Heat	0.11455 BTU/lbm·°F

3.3. Geometry

The CFD simulation problem called for assessment of injectors used for liquid sulfur combustion inside the combusting chamber. The sulfur is atomized via spray nozzles in order for efficient burn off. The injectors must withstand the harsh environment of the combustion chamber. The geometry of the chamber can be seen in Fig.5. It consists of a horizontal cylindrical section with the injectors extended into the chamber. A detailed image of the injectors is shown in Fig. 4.

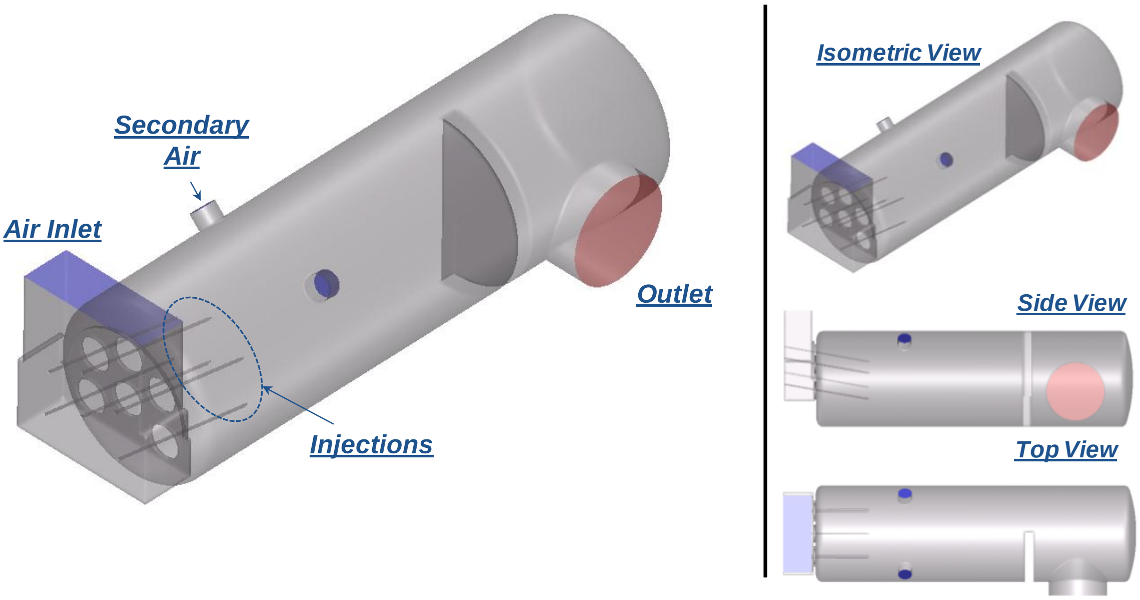


Fig. 4. Illustration of combustion chamber and injectors.

A single injector was selected for FSI analysis to allow for a tractable simulation. Temperature profiles, velocity and pressure profiles from the combustion chamber were mapped to the face of the connected injector. Hence, internal face connections were assured to enable FSI capability through ANSYS workbench.

4. Results

4.1. CFD (internal and external flow)

CFD analysis was performed to determine temperature, pressure and velocity flow around the injectors. The results of this work are shown in fig.5-8. Temperatures were determined to peak at 570°C, which is within the expected range for this application. The main body of the injector has well controlled temperature range, due to the recirculating steam design. The highest temperature occurs at the outer edge of the injector tip.

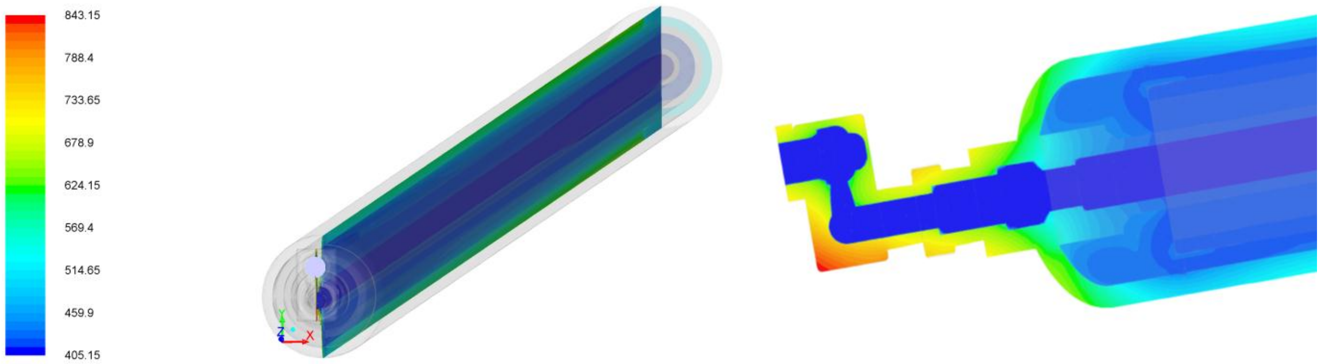


Fig. 5. Temperature distribution (°K).

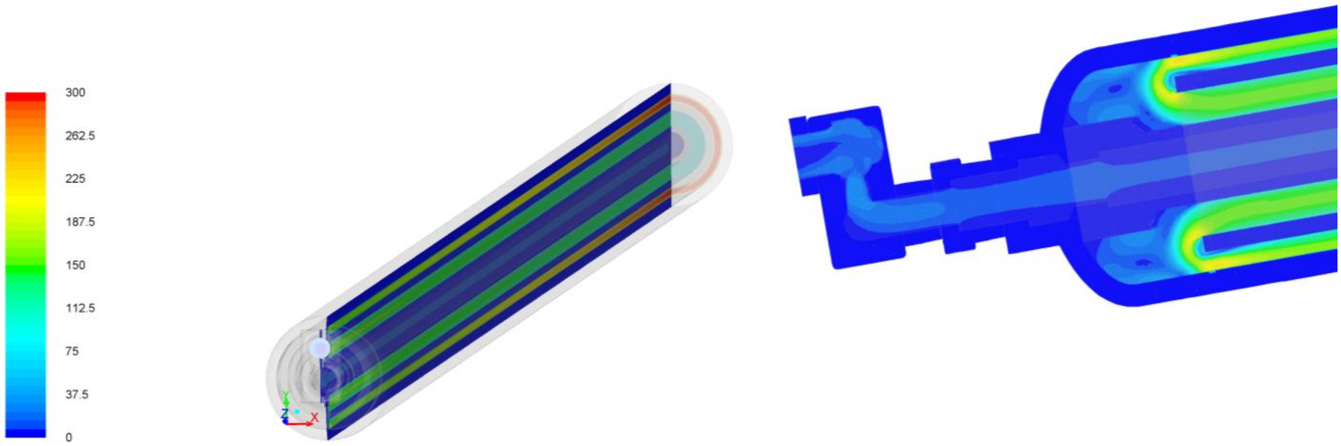


Fig. 6. Velocity distribution (m/s) with steam focus.

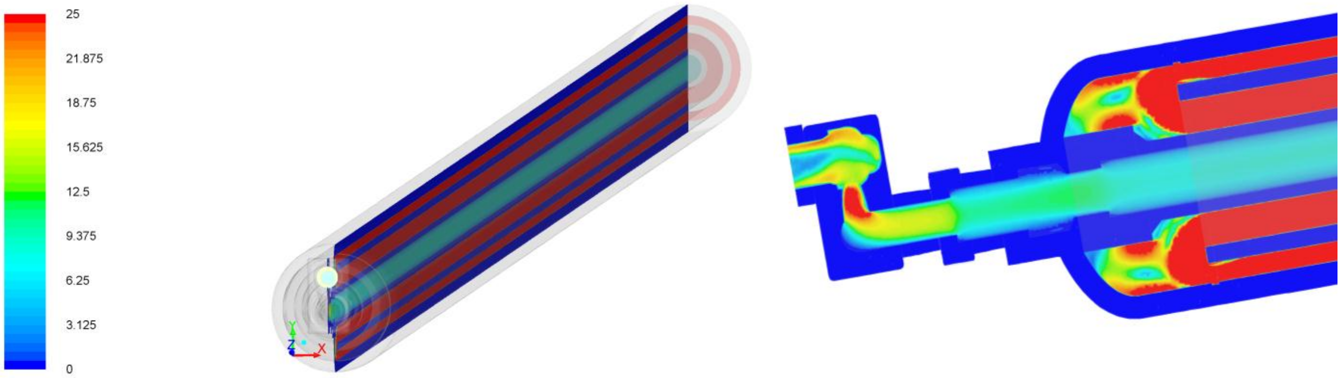


Fig. 7. Velocity distribution (m/s) with nozzle focus.

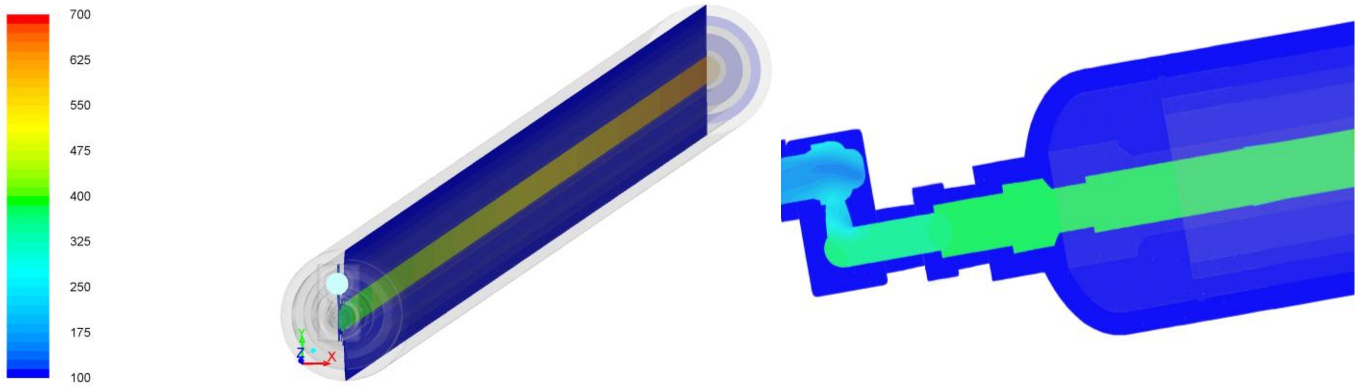


Fig. 8. Pressure distribution.

Velocity results are shown in Figs. 6-7. Multiple scales are used to investigate the steam flow initially, and the injector tip. Velocity in the steam line far exceeds the flow of the molten sulfur through the nozzle. Due to the high viscosity of the molten sulfur, the velocity at the exit orifice is 25m/s. This is as expected for the injector style and operating conditions.

The pressure distribution through the injector is shown in Fig 8. Again due to the high viscosity of the molten sulfur, there is a significant pressure drop across the injector.

4.2. *Thermal Analysis*

The thermal load on the lance has multiple sources. Heat transfer from the combustion process and gas stream acts on the outer surface of the injector. Additional the recirculating steam supplies further heat from the internal chamber of the steam jacketed injector. The final contribution to the thermal load is due to the molten sulfur feed. The maximum temperature of the injector of 570°C is well below the melting point for stainless steel.

4.3. *Structural Analysis*

The cantilevered injector was modeled using a fixed surface at the flange location. The pressures were accounted for: from the combustion chamber, steam jacket, and internal sulfur flow. The maximum stress concentration is located at the base of the lance, near the flange. The stress results are contained in fig. 9. The maximum stress, of 271 ksi, exceeds the yield strength of stainless steel of 33ksi. It is evident that supports will be required for this application.

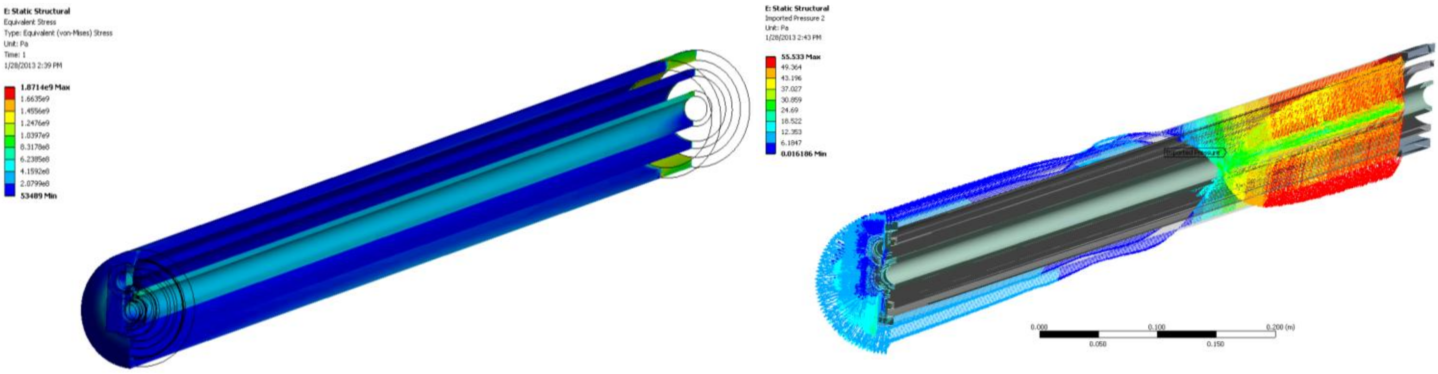


Fig. 9. Stress Results.

4.4. Modal Analysis

Modal analysis was performed to determine the dynamic natural response of our model when subjected to free vibration. Overall mass and stiffness are used to determine the various periods at which the injector will naturally resonate, leading to potential failure. The natural frequency is compared to vortex shedding frequency determined during failure analysis.

Six modes were used to analyze vibration in the injector, though the first is the most probable vibration mode. The six vibration modes are: 1- side to side vibration, 2 – up and down vibration, 3 – side by side vibration along a fixed point at the center of the lance, 4 – up and down vibration along a fixed point at the center of the lance, 5 – side by side vibration along two fixed points in the lance, and 6 – up and down vibration along two fixed points in the lance. The results of the modal analysis are contained in table 2.

Table 2. Modal Analysis

Mode	Frequency (Hz)	Maximum Stress (ksi)
1	2.167	37.3
2	2.168	37.4
3	2.516	44.6
4	2.923	51.8
5	14.212	231
6	14.212	231

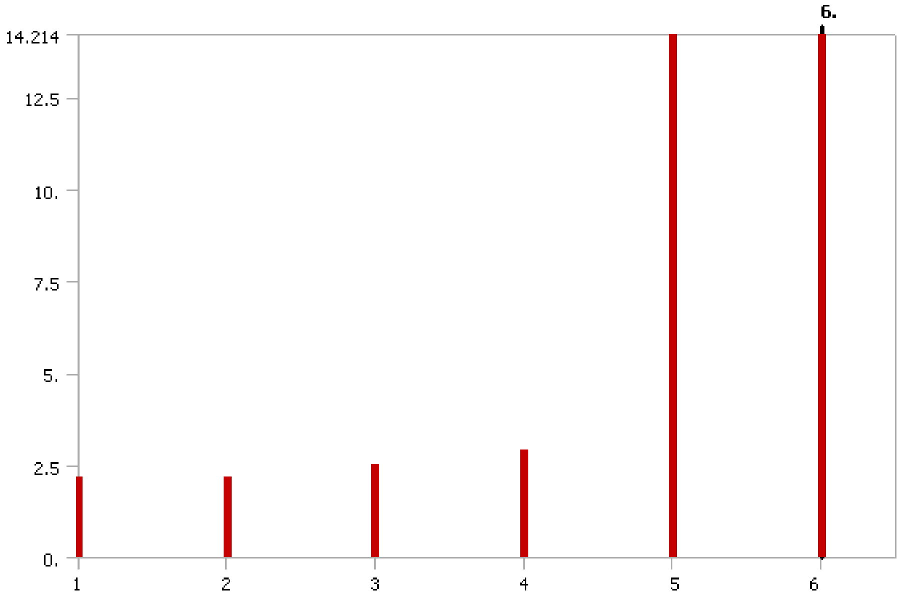


Fig. 10. Modal analysis results for the first 6 modes.

5. Conclusions

A sulfur burning injector was analyzed to determine its suitability in a combustion chamber at normal operating conditions. An optimized injector design was incorporated into a lance. Due to the length requirement of the injector, structural analysis was required to determine suitability for the long-term, maintenance free installation.

A full analysis was performed for the injector; including fluid flow analysis, structural analysis, and one-way fluid structure analysis. Thermal analysis results did not uncover any potential for failure. However both the structural and modal analysis of the injector, indicate potential for failure. This failure is due to the overwhelming weight per unit length of the steam jacketed injector for the extensive length requirement. These injectors are often supported internally using mounting supports from the refractory surface of the combustion chamber. Further analysis is planned based on the injector installation using support pads. This, in effect, shortens the cantilevered length of the injector. Hence the stress at the base of the injector is significantly reduced.

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