Solving Noise Problems in the Process Industry

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Abstract

Combustors have been known to "sing" or to "roar" in various applications under diverse operating conditions. This paper is aimed at investigating the underlying physics controlling noise in combustion equipment. Last year, we presented a paper at the virtual AFRC meeting discussing the thermal-acoustic coupling inside a Reaction Furnace of a Sulfur Recovery Unit used in refineries to recover elemental sulfur [1]. Early work related to thermo-acoustic coupling was observed by glass blowers when they heated a blub of gas joined to a cooler tube. [2] As reported in our earlier CFD analysis, we identified noise frequency for this experiment of 8-9 Hz frequency (see Figure 1) which compared well to the calculated resonant frequency of 8.6 Hz. Coupling between combustion reactions and the natural acoustic behavior of a reactor is known to generate noise inside combustion equipment in the process industry.

During my career, I have observed this "roaring" phenomenon that literally shook an incinerator off its stand during startup. The vendor eliminated the problem by adjusting the burner tip location thus altering the resonate frequency inside the chamber. Previous CFD analysis of an incinerator identified conditions that led to reverse flow through the stack when combustion gases from the incinerator cooled as they rose up the stack which increased their density (and weight) which caused the heavier gas to flow back into the incinerator. This puffing created uneven refractory cooling that increased refractory wear and associated maintenance costs. LES based CFD transient analysis has allowed us to investigate difficult noise problems not possible using RANS based CFD steady state analysis.

This paper presents recent work involving an enclosed combustion device with nearby structures that altered wind conditions at the stack exit and created low frequency "combustion roar". Previous work to eliminate high noise created in a catalytic reactor of a nitric acid plant required us to design and install a Helmholtz resonator to cancel reactor noise at the stack. In the present work, we used the LES CFD code C3d to simulate various operating conditions to match observed noise levels and frequency. Our analysis confirmed no combustion noise for no wind conditions and moderate noise that died away over time for uniform wind conditions but when nearby structures were included together with their impact on wind speed at the stack exit (i.e., non-uniform wind from ground level to the stack exit elevation), noise levels increased by three times and the predicted noise level and frequency matched observations. We used the CFD code to identify design changes that decoupled the wind from combustion noise to solve this problem. Our proprietary CFD code, initially used to model pool fires [3], has been tailored for analysis of

flares, incinerators and process heaters. [4] [5] With it, we solve the most difficult problems related to thermal-acoustic phenomena in combustion equipment.

Introduction

Thermoacoustic vibrations always require the presence of two key features: 1) a large temperature gradient, and 2) a gas-filled cavity capable of supporting Helmholtz resonances. A wide variety of industrial furnaces, boilers, enclosed flares, and turbomachinery fit these requirements. As a result, thermoacoustic noise and vibration can affect and is a problem in many industrial applications.

Combustors have been known to "sing" or to "roar" in various applications under diverse operating conditions. It has also been observed that nearly identical furnaces have different acoustic behavior. One application may resonate while another nearly identical application may not. Therefore, it is often quite difficult to diagnose the source of acoustic vibrations. This paper is aimed at investigating the underlying physics controlling noise in combustion equipment. The earliest work related to thermo-acoustic coupling was observed by glass blowers when they heated a blub of gas joined to a cooler tube. More recently coupling between combustion reactions and the natural acoustic behavior of a reactor is known to generate noise inside combustion equipment in the process industry.

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Previous CFD work in the thermo acoustic field can be summarized into two categories.

Type 1: Thermal-Acoustics Coupling

A CFD combustion model is used as a source term with some type of transfer or coupling model to connect the source term to a Helmholtz wave equation solver to analyze the acoustic behavior. [6], [7]

Type 2: Compressible Thermal Acoustics Coupling

A coupled fully compressible solution of the momentum, energy and species equations applied to the application along with suitable boundary conditions. This type of analysis can vary widely in assumptions, grid refinement, combustion models etc. [8], [9], [10], [11]

The second category may require a significant amount of CPU compared to the first, however it is more applicable to a wider range of scenarios. This second category is addressed in this paper.

Some issues associated with the fully compressible CFD approach include:

- Chemical reaction and physical modeling approximations,

- Grid refinement requires upward of a million or more cells,
- A fully transient solution with small time steps required to resolve the acoustic waves, and
- A long transient generally required to identify the self-sustained pressure oscillations associated with acoustic behavior and to allow time to dissipate any sudden startup waves.

The Rijke and Sondhass Tube Problem

A very popular problem that many investigators have simulated is the Rijke and/or the Sondhauss tube problem. [12], [13] The Rijke tube has both ends open whereas the Sondhauss tube has one end closed. The latter case involves a long tube with a heat source, such a hot wire mesh, placed at the closed end and the other end open to the atmosphere. When the wire is hot enough, a loud sound is produced due to thermoacoustic effects. Last year we presented our solution to this same problem which was observed to agree with theory for the fundamental frequency of the device. The two figures shown below illustrate our solution (see Figure 1 and Figure 2).

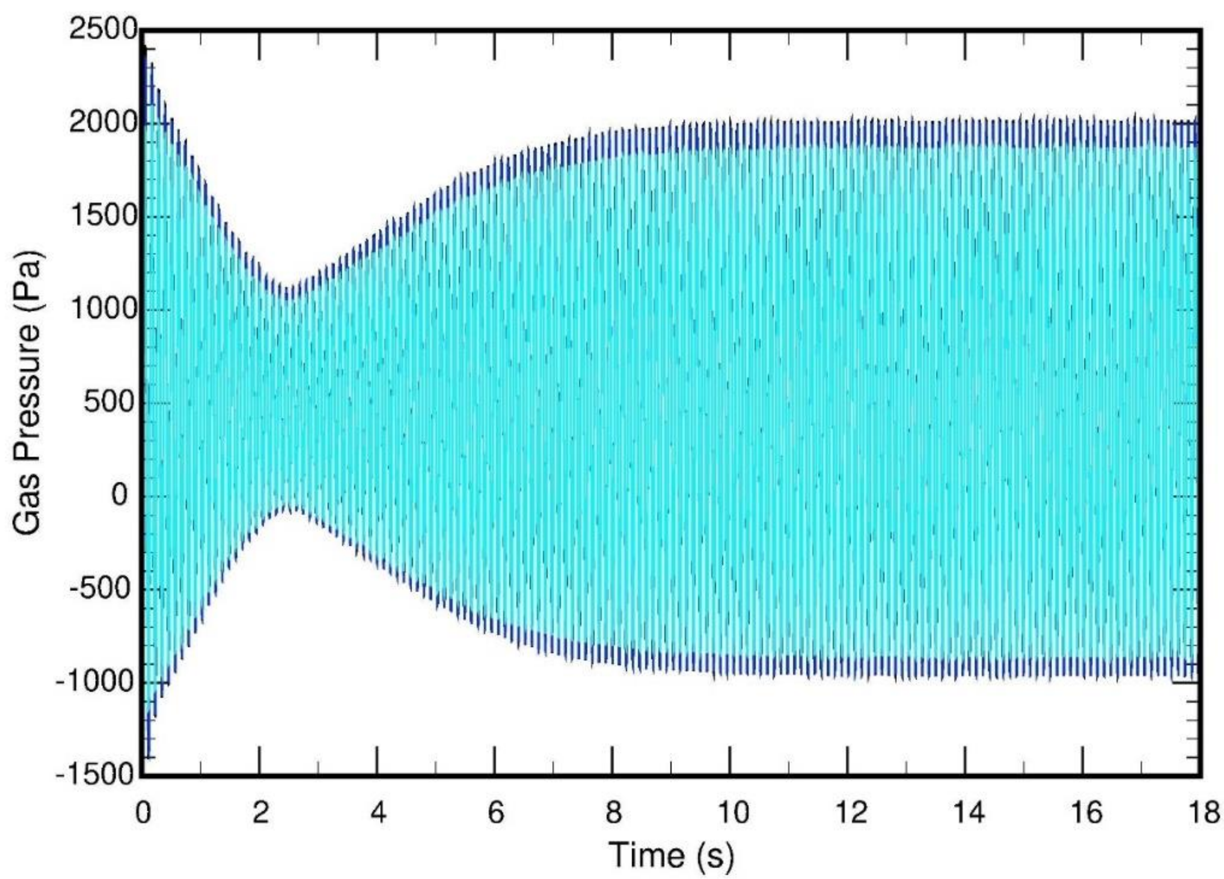

Figure 1 – The pressure response of a simulated Sondhauss tube illustrating an initial transient that decays and later amplifies to the steady sustained oscillation [1]

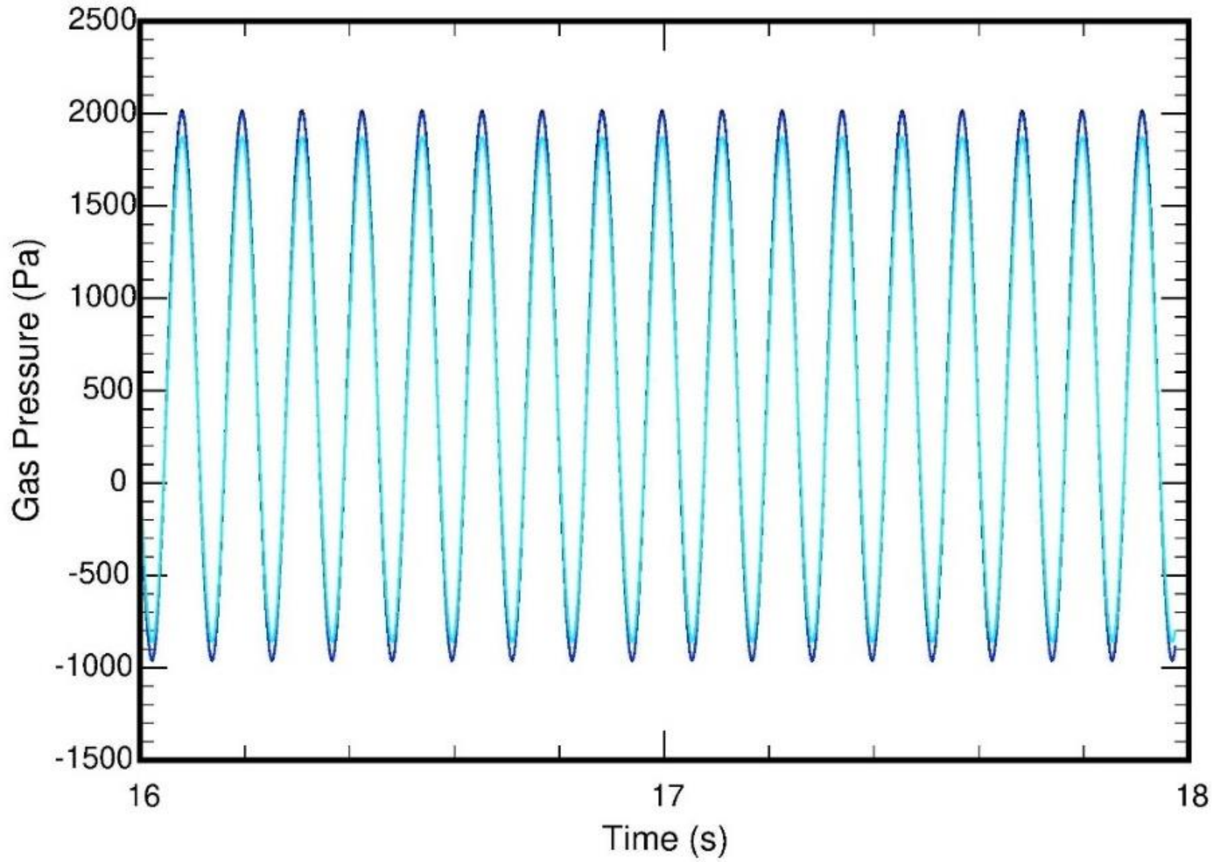

Figure 2 - Expanded time scale of the steady pressure waves allowed frequency to be determined [1]

A characteristic of our solution was that the heat transfer from the wire mesh had to be increased otherwise the initial sound wave decayed away and no steady oscillations were observed. Last year, we also presented a thermoacoustic solution for a reaction furnace in a Klaus Process used to recover elemental sulfur. [14] The paper showed results of acoustic oscillations in the reaction chamber caused by the burner used in this system. All results presented in this paper were generated using the C3d code. A brief discussion of the previous work is given below but reader is referred to full paper for additional details.

The LES CFD code C3D

The LES based CFD code C3d is a fully compressible code we use in our CFD work. To generate solutions that simulate sound wave production, propagation, and cavity resonance effects, a fully compressible CFD code is required (Type 2 problem). However, for this case flow velocities are subsonic, so the amplitude of pressure waves ranges from small to quite large (10's to 1000's of Pascals). To simulate small amplitude sound waves with a compressible CFD code in the subsonic regime, the code must suppress numerical dissipation so that the sound waves do not artificially disappear. Removing numerical dissipation requires a relatively fine mesh and small timesteps. These same requirements exist for thermoacoustic CFD simulations in three dimensions. The interested reader is referred to the C3d LES user manual for additional details regarding the code.[1]

Thermoacoustic application to a flare

For this paper, the C3d code was used to analyze the thermoacoustic oscillations found inside an industrial enclosed ground flare (see Figure 3).

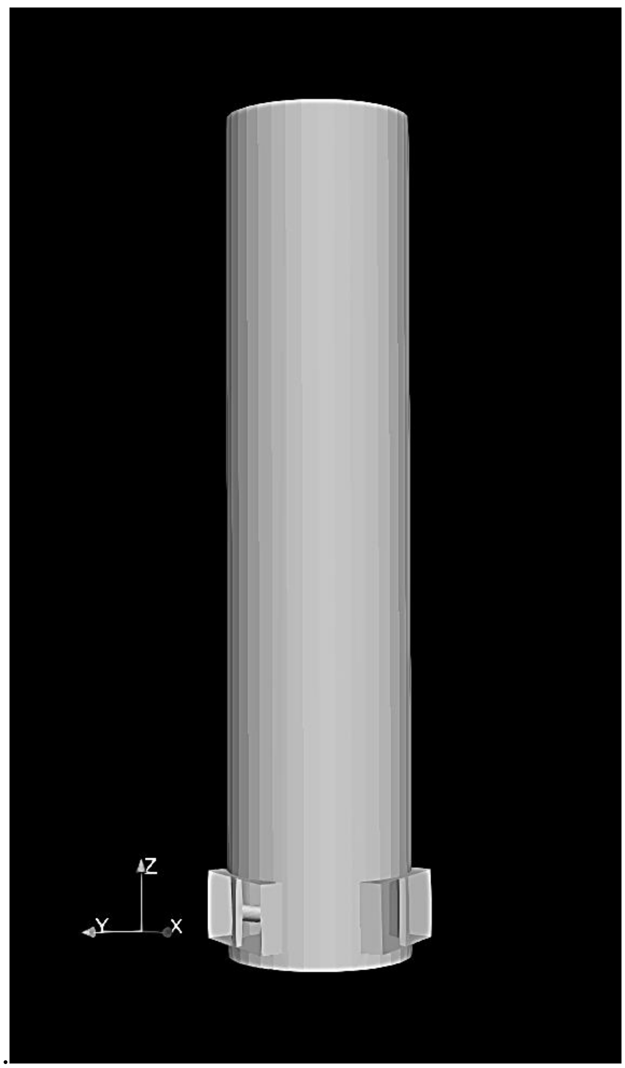

Figure 3 – The flare used in this thermoacoustic simulation has a height of 15 meters with a diameter of 3 meters and louver openings at bottom for air inlets

[1] See https://www.researchgate.net/publication/330485597_C3D_Theory_and_User_Manual

When the flare operates at design conditions, excessive sound is produced similar to the pressure pulsations from a helicopter. However, it was also noted that the sound was not produced in all conditions. Further, it was noted that similar flares did not produce any sound under any condition. Such non-uniform behavior is very difficult to analyze because of these inconsistencies. When setting up the CFD model, the user cannot tell if the solution is simulating the "*No-Sound*" condition or the "*Sound-On*" situation. To resolve the dilemma numerous simulations have been made with variations in operating conditions and boundary conditions.

Numerical Model Details

The C3d LES based CFD model considered the flare enclosure, the burners within the flare and an exterior domain to account for their impact on ambient wind conditions. Figure 4 and Figure 5 below depicts the computational domain and associated grid used in this work.

The 3-dimensional CFD model consisted of 350,000 hexahedral cells with an additional 50,000 subgrid cells to resolve heat transfer within the stack refractory and to simulate the fuel injection ports in the burners. The grid structure was refined in regions with the burners to resolve fuel injection ports and resulting flames above the burner. To create a resonant cavity, it is important to resolve the sound reflection characteristics. The top of the flare is open to the atmosphere which represents a free boundary for reflecting sounds waves. Although a constant pressure boundary condition could be used, that create an artificial constraint and would not allow for the inclusion of ambient wind effects. As the wind blows across the stack exit, it creates flow recirculation inside the stack. This recirculation zone both on the leading edge inside the flare stack and on the downwind side of the flare stack are important flow features that must be included in the analysis. Thus, the grid was also refined near the top and above the flare stack exit to insure a good free boundary for pressure wave reflection.

Finer grid models were also run (up to a million cells) to better resolve the flames and sound waves within the flare, and to confirm that the 350,000-cell simulation was sufficiently accurate to resolve the thermoacoustic coupling.

Other boundary conditions used in the simulation included a no wind (or cross wind) blowing from the X minimum boundary toward the X maximum boundary. All other boundaries used a hydrostatic pressure boundary.

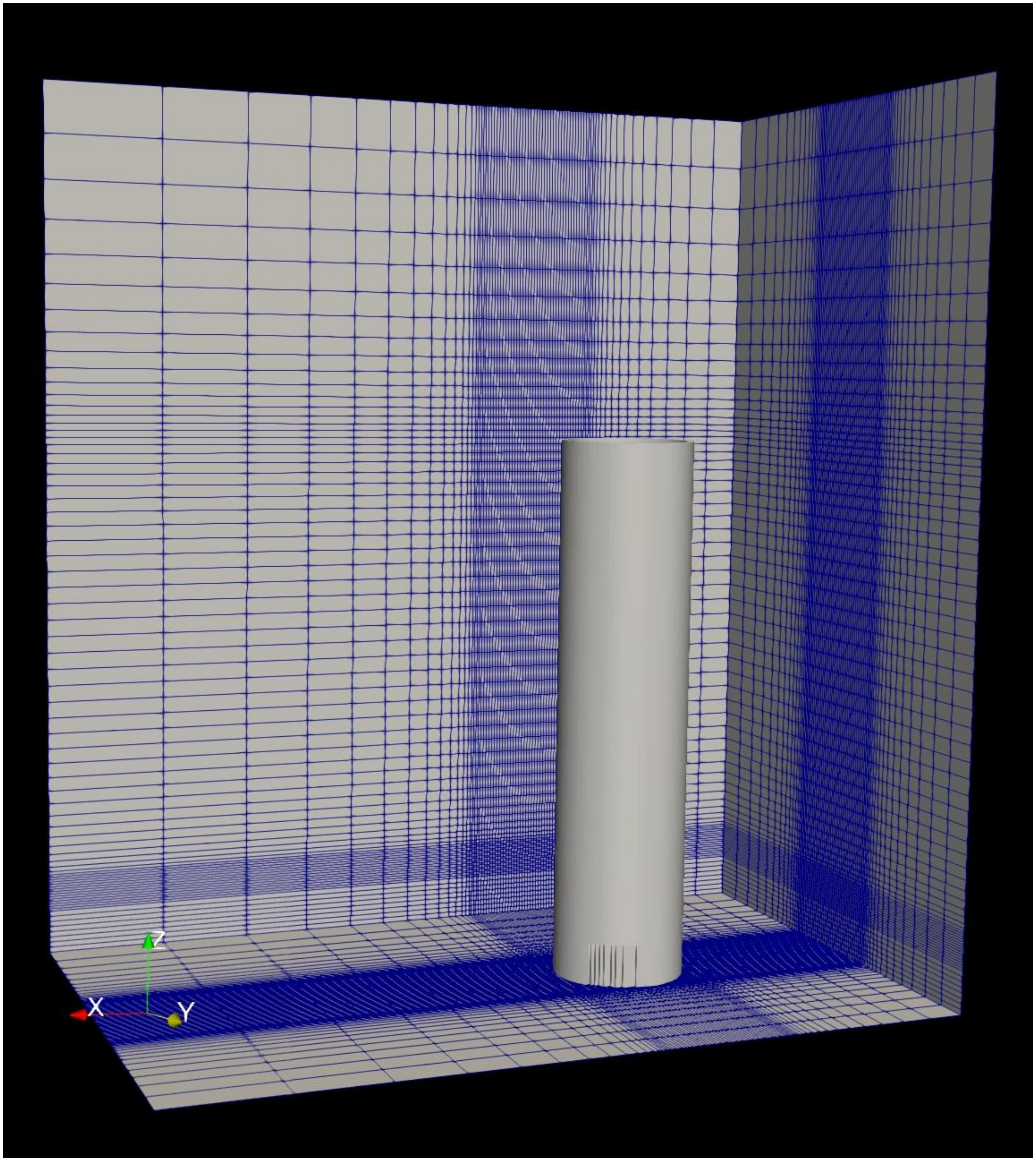

Figure 4 - The full computational domain for the flare CFD simulation. Lines depict the grid structure

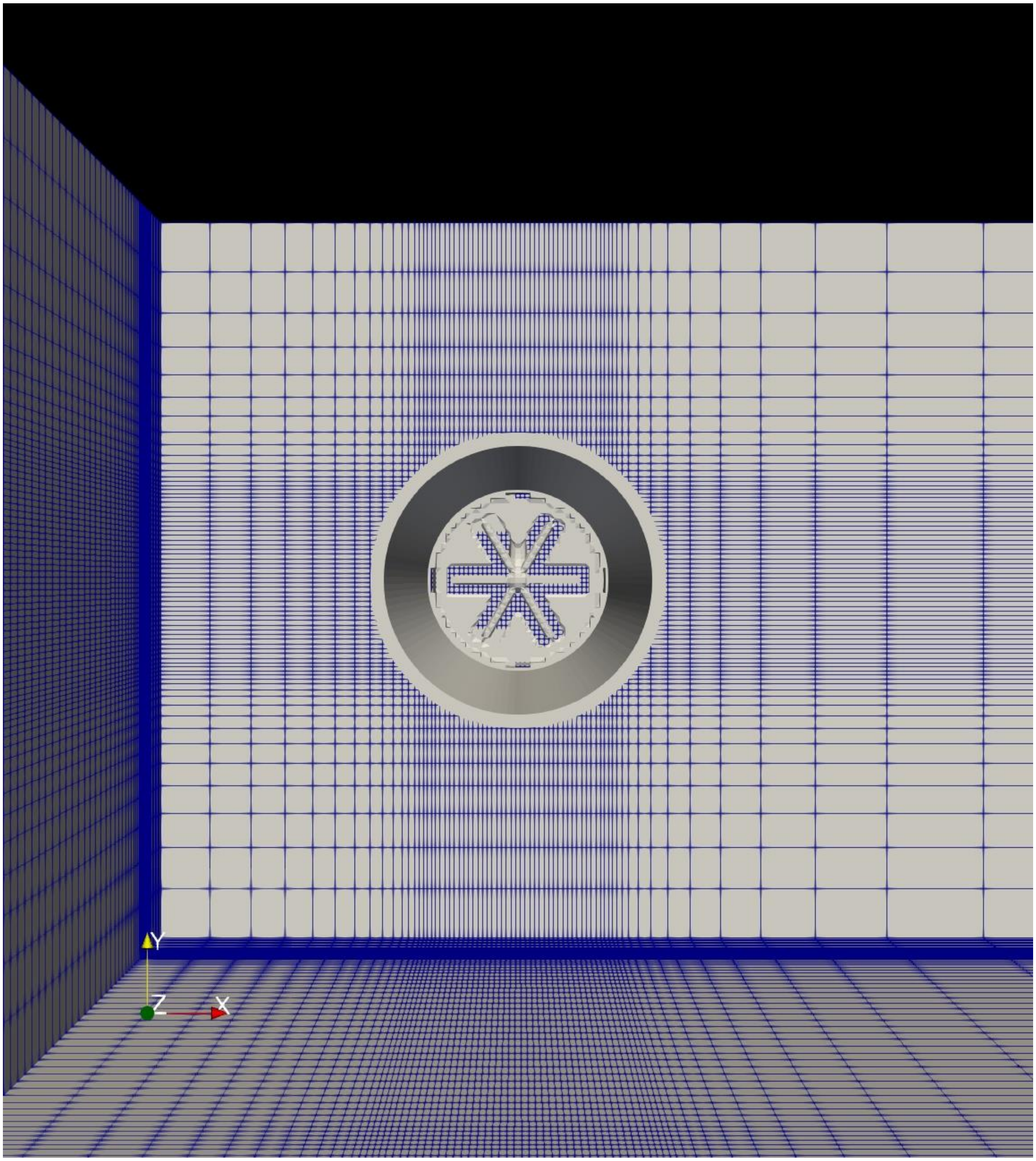

Figure 5 – Expanded view from above showing the grid structure and some burner details

Results

The first simulation considered a no-wind condition and fuel injection rates where sound had been observed in the field. These conditions resulted in the flare operating as expected without excessive noise (Figure 6). The initial sound waves associated with starting the flare (related to the sudden onset of flow through the stack) rapidly decayed leaving no persistent sound during continued operation observed beyond normal combustion noise.

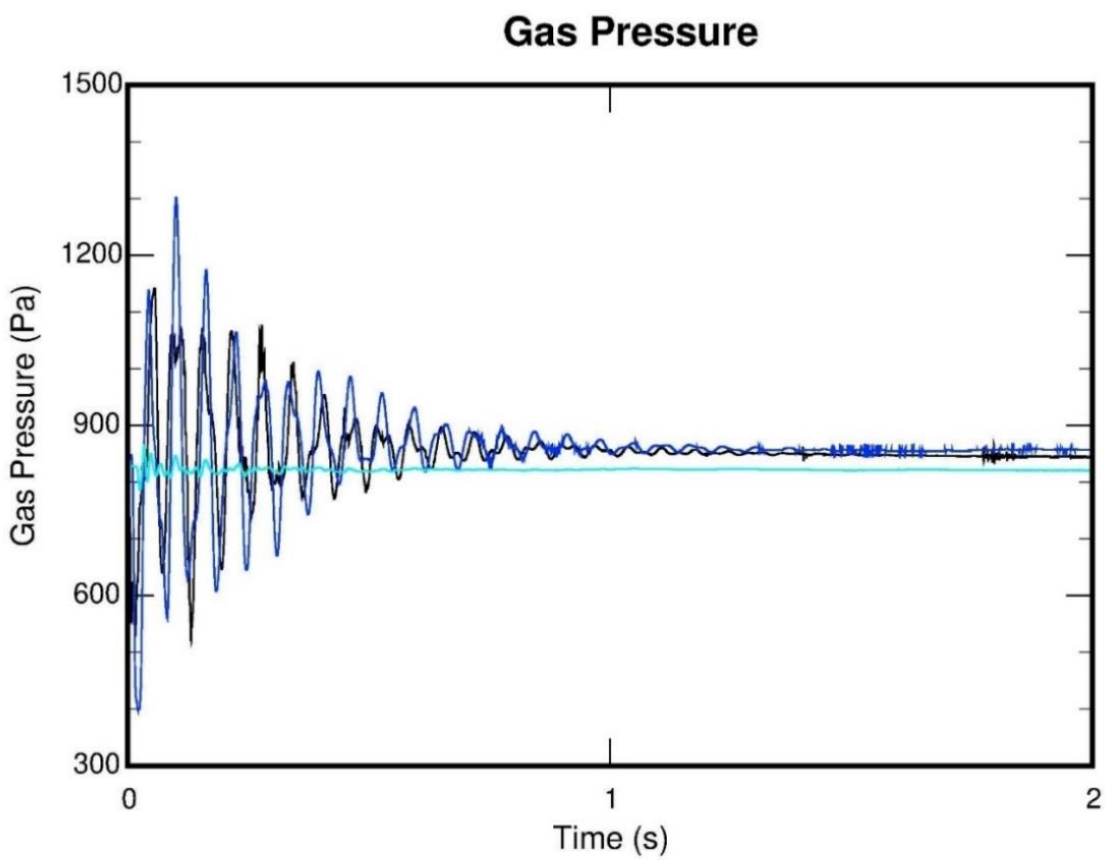

Figure 6 - The pressure waves within the flare caused by the sudden onset of flow decay rapidly a sound free condition under no-wind conditions

The next simulation used the same fuel flow rates but considered a 5 meter/sec cross wind. Under these conditions a low amplitude persistent sound wave was observed to form, but the predicted amplitude seemed to be low and was not considered to be a problem (see Figure 7).

The next simulation included the effects of surrounding terrain and nearby buildings. The nearby buildings could block wind from the bottom of the flare which would reduce air flow to the inlet louvers whereas nearby hillsides and could also create downward flow at the top of the flare. Thus, a wind gradient of zero flow was imposed at the flare bottom and a crosswind with a downward component was applied to the top of the flare. This combination of boundary conditions created a significant pressure wave inside the operating flare (see Figure 8).

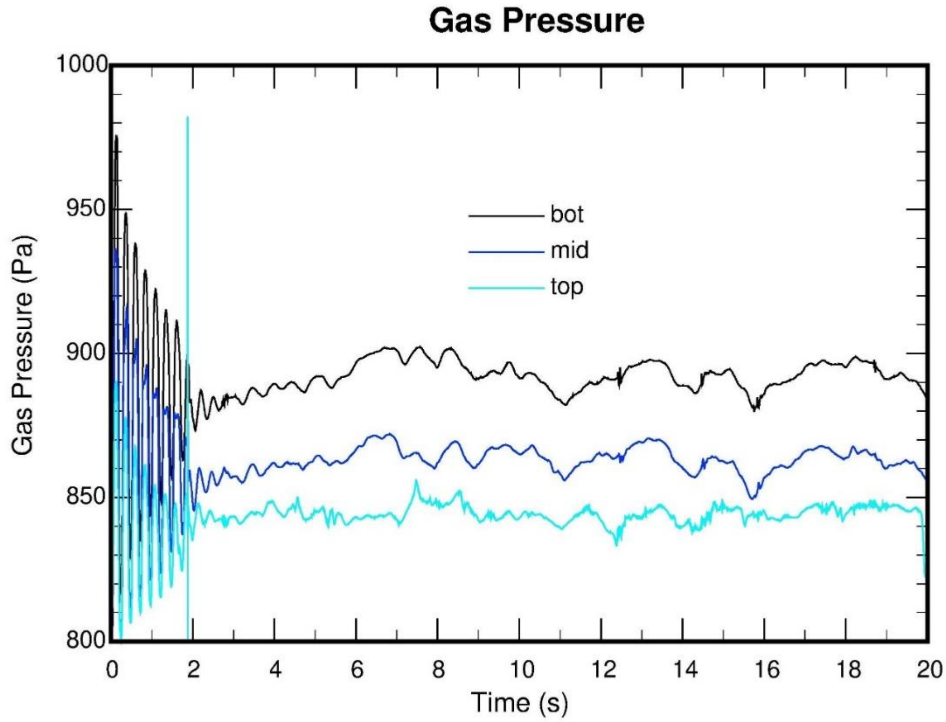

Figure 7 - The gas pressure at various elevations with a cross wind showing low amplitude persistent sound waves within the stack

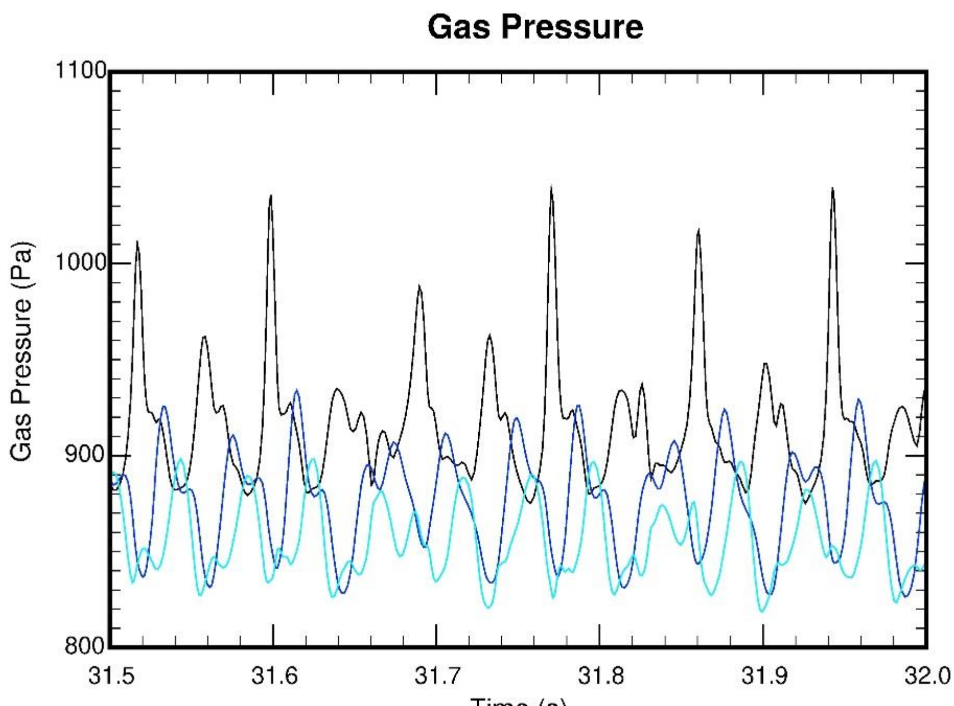

Figure 8 - Predicted pressure waves at various heights inside the operating flare considering non-uniform wind boundary conditions at the top and bottom of the flare

Having successfully predicted conditions which may lead to excessive noise from the flare, design modifications are possible to minimize the impact of non-uniform wind conditions around the flare. This result also shows the value of using CFD to estimate noise potential based on flare location for subsequent installations. In addition to the non-uniform wind effect discussed above, several other conditions were examined including:

- Inlet pipe length that might crease a 1-d pressure wave leading to surging inlet fuel flow,
- Nearby buildings built downstream of the flare in a crosswind,
- Partially closed top exit (i.e., an orifice exit),
- Oscillating chemical reaction rates (both high and low rates),
- Wide open and nearly closed inlet air louvers openings,
- High and low fuel flow rates,
- Fine grid resolutions to verify model accuracy,
- Burner hole orientation, vertical or horizontal firing,
- High (5mps) and low (2mps) wind speeds

CFD simulations considering each of these various operating conditions and/or geometry changes produced various degrees of noise in the flare, but none created sound waves of the same scale as non-uniform wind profiles along the flare stack.

Summary and Conclusions

Thermo acoustic sound is produced in various some types of industrial equipment where heat release affects local compressibility which couples with the resonant frequency of the enclosure, such as in furnaces, incinerators, and flares. The sound generated in these devices can have sufficient amplitude to disturb nearby residents or in more extreme situations can result in an unsafe work environment or even severe damage to nearby equipment. The LES based CFD code C3d is designed to properly capture this phenomenon. This code has been used to simulate an enclosed ground flare which produced a persistent loud sound under certain operating conditions. CFD simulations were run considering a wide range of operating scenarios and system designs to investigate this behavior and determine under what conditions thermoacoustic vibrations might occur so we could help to reduce or eliminate them. Under the "no-wind" conditions, the flare was predicted to perform as expected with no excessive sound emissions. When wind was added to the simulation, sound waves of low amplitude were predicted. When terrain effects were also included that created gradients in the wind directions and created non-uniform wind profiles along the stack height, then large amplitude sound effects were predicted.

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