Computational Fluid Dynamic Modeling of a Ground Flare

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ABSTRACT

A major ethylene plant under construction in Al-Jubail, Saudi Arabia found itself under pressure from neighboring facilities and regulatory agencies to reduce flare emissions, flame visibility, and noise. Plant personnel contacted a company that had pioneered and commercialized a grade mounted, multipoint flare burner system that eliminates the need for an elevated flare which historically contributes to increased noise levels, inhibited efficiency, limited service life, increased flame visibility, and increased smoke formation. Computational Fluid Dynamic (CFD) simulation of the flare system was used to aid in the design of the flare system by predicting fence temperature, grade temperature, air flow to the burners, and flame and radiation characteristics of the flare system. Installed during the plant's 2004 startup, the flare burners were designed, fabricated, and tested on a fast track schedule. Production tests and operating data show that the flare burners achieve the predicted CFD results and the required increased smokeless capacity, reduction in noise levels, decreased visibility of the flames and enhanced operational efficiency, while simultaneously resisting the failures typically associated with elevated flares.

INTRODUCTION

In 2004, construction of a major ethylene plant in the Middle East faced challenges to find workable methods to reduce flare emissions, flame visibility, and noise. Plant personnel solved their dilemma by turning to a company with expertise in environmental emission control and combustion that had pioneered and commercialized a ground mounted, multipoint flare system. By eliminating the need for an elevated flare, the proposed system not only resolved all issues, but provided the added benefit of enhanced service life.

By using Computation Fluid Dynamic (CFD) simulation the flare system supplier predicted fence temperature, grade temperature, air flow to the burners, and the flame and radiation characteristics of the flare system. The flare burners were designed, fabricated, and tested on a fast track schedule to meet installation requirements of the 2004 plant startup.

Production tests and operating data confirm the flare system achieved the predicted CFD results, with all reduction criteria met, and the added advantage of enhanced operational efficiency that has resisted the failures associated with elevated flare systems.

Modeling Approach and Assumptions

The design engineers used specifications furnished by the plant to perform CFD modeling of the multipoint ground flare, utilizing a flare system comprised of nearly 1000 burners, and confirmed temperature for the surrounding fence, grade temperature, air flow to the flare burners, flame length and the radiation characteristics of the flare system. After a three-dimensional equipment representation was built using the CFD software, a mesh comprised of hexahedral and tetrahedral elements was used to achieve the finite-volume solution of the flow field. This solver concurrently solved flow, turbulence, oxidation chemistry and radiation models over the entire area of calculation.

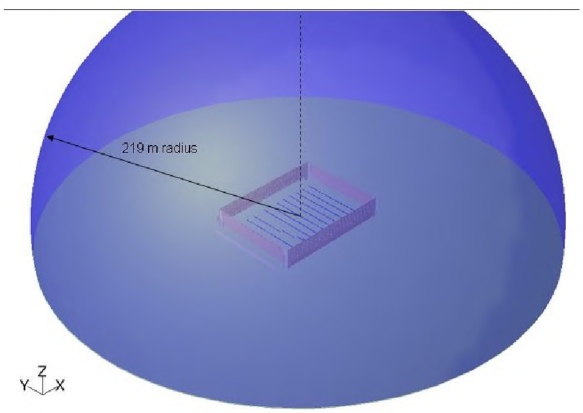

Figure 1 – Pressure boundaries represented by the blue, semi-transparent surfaces.

Waste gas flow was set at a rate of 14,105 megawatts. The air in the model was composed of 0.21% oxygen and 0.79% nitrogen, and set at a temperature of 27˚C. The gas lower heating value was set at 14,092 kcal/Nm^3, the mole fraction composition at 1.00 C_2H_4, and matched to the air temperature of 27˚C.

The large scale difference between the fuel gas orifices in the multipoint tip, and that of the domain limits required to capture the performance of the flare, is such that it is computationally infeasible to capture the detail at a sufficient level near the burner tips and carry the mesh throughout the domain. Therefore, the assumption made, in order to model the flare as a combined system, is that the area immediately around the burners can be represented by "source terms" applied to a grid structure that is somewhat coarser than that required to dimensionally capture the fuel gas orifices.

The model for the Middle East ethylene plant verified flow to the flare was adequate, peak temperatures for the flare system were acceptable, and radiation was both within acceptable levels and dissipated within the boundaries of the flare fence. To verify that visibility limits were met, contours of static temperature, different contours of the mole fraction of CO_2, velocity vectors, and iso-surface rates that ranged from 1.58 kW/m² to 15.77 kW/m² were used in the modeling. Peak fence temperatures were measured to be less than 250 ˚C on the interior of the inner-fence structure. The peak mole fraction of ethylene measured at the top of the fence was 3.57×10^{-5}. The model proved almost complete destruction before the flare met the top of the fence, as well as adequate oxygen supply to the burners. Peak radiation levels that were directly by the fence were predicted to be 3.14×10^{-1} kW/m^2, dissipating to 1.86×10^{-1} kW/m^2 in the far-field regions.

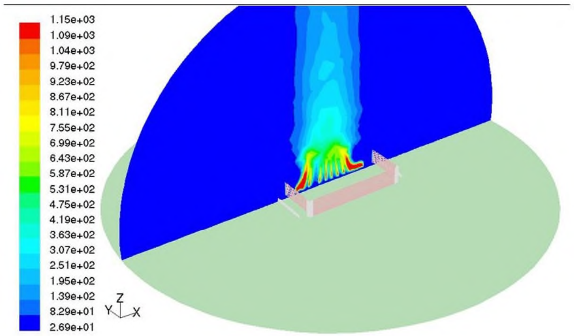

Figure 2 – Contours of Static Temperature (°C).

Ethylene Field Flare Specifications

With the employment of ground level linear burner configurations, visible flare emissions were eliminated. Dedicated gas lines send waste gas to the flare fields. These lines are in turn fed by a flare staging manifold. The first-stage burners are air assisted to ensure the operation remains smokeless at low rates of flow. Subsequent burner stages achieve smokeless burning through the use of gas pressure.

The multipoint burners were organized in ten solid rows and one staggered row, with each burner row served by two continuous burning pilots. Two additional pilots were installed on the field's single air assisted flare, to handle ethylene flow rates occurring below the staging pressure for the first stage of the multipoint array. The air flare design maintains continuous operation whenever the ethylene flare field is online, handling low pressure minimal flow rates, as well as higher gas pressure ranges. On each row, there is an automated staging valve with a pressure relief device for bypass in the event the staging valve doesn't open.

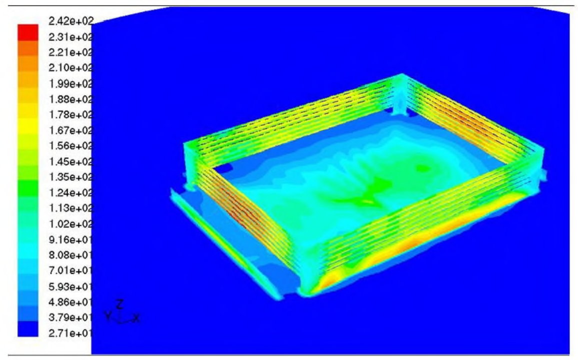

Figure 3 – Contours of Wall Temperature (°C).

Design features are built-in to add burner capacity through the staging control system, and limit turndown by removing burner capacity at lower pressures. The model used a pre-calculated ethylene flow rate of more than 1.0 million kg/hr, and applied it on a volume average basis over the analogous coarse-grid burner region. On each burner tip, the port area was used to allocate the total flow to each row of burners in the flare system. The adiabatic flame temperature of ethylene at 12% oxygen was pre-calculated and used as the peak allowable temperature in the model in order to compensate for the inability of the coarse grid to properly represent the mixing in the near burner domain. Additionally, a single flare tip was modeled and run individually in order to use the volume average turbulence kinetic energy and turbulence dissipation rate scalars calculated from the fine-scale model in the large-scale model.

Low Visibility Design Provisions

The burners are enclosed by a radiation fence. Beyond shielding sight of the flares during burner operation, the fence also protects personnel and equipment from radiant heat, especially at the staging manifold where operator access is required for maintenance.

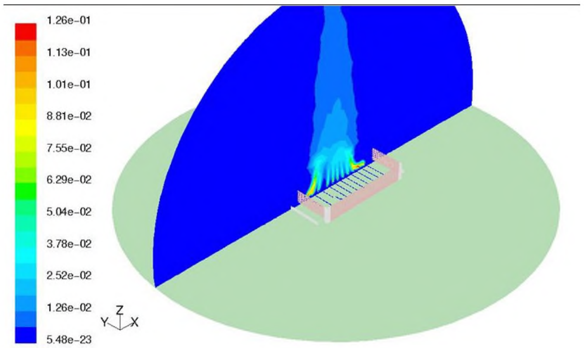

Figure 4 – Contours of Mole Fraction of CO_2.

Access and radiation through vented sections is eliminated by fencing panels supported by the main fence knee braces. The fourth side of the fence faces staging headers, and is solid to provide plant personnel complete access to the area during flare operations.

Service Life Considerations

In addition to the expertise of the design team, the modeling provides the data to fine-tune the plant flare system through features and components that predict the potential for trouble-free operation over a long service life. Per the team's specifications, the burners are investment cast to ensure dimensional accuracy and performance repeatability. An added benefit of utilizing castings is that they remove the necessity to drill orifices. Casting the holes leaves behind no sharp edges, eliminating the risk of stress risers and, thus, the cracks commonly found in conventional flare burners.

To promote mixing, it is critical for multipoint flares to operate with sufficient kinetic energy levels in their combustion zone, and the burner design determines its ability to provide mixing over the widest possible range of flow. The burner is a spider type configuration with a center hub acting as a stability point for the assembly, to ensure combustion through a wide range of compositions and turndowns.

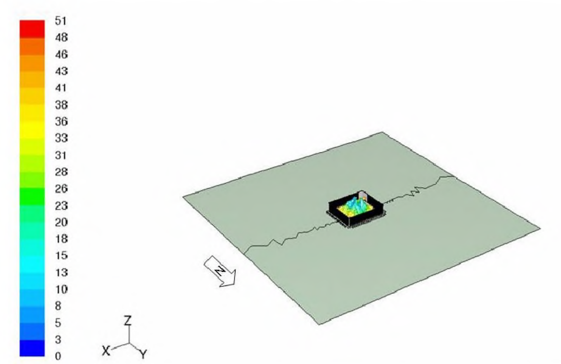

Figure 5 – Iso-surface of 2000 ppm CO (dry) believed to be a reasonable representation of the visible flame surface. The scale gives the radial coordinate from the flare centerline in meters.

Additionally, in a departure from conventional high pressure burner design, a web under each arm of the burner provides reinforcement to the arm limits thermal expansion. This also limits the resultant stresses which might otherwise form cracks where each arm meets the central hub. The hollow web supplies optimum flow to the outermost holes on the spider, which ensures that the gas will reach the arc of the burner with the greatest access to air.

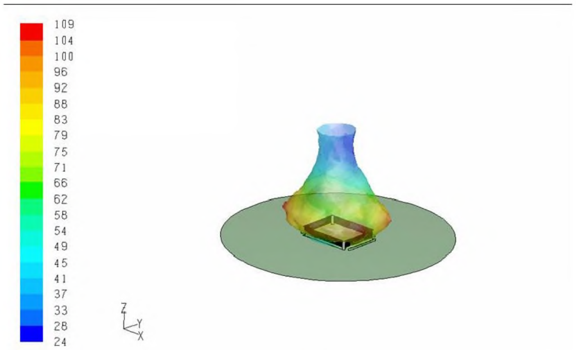

Figure 6 – Iso–surface of 1.58 kW/m^2. The scale is the radial position from the centerline of the flare in meters.

Controlling turndown, through the use of the burner staging system, proportions the number of burners in service to the flow rate of waste gas to be flared. This overcomes the likelihood of improper staging, which can result in excessive burner temperatures, reduced burner life, and smoking burners.

Performance Summary

CFD modeling and subsequent testing proved that by using a vertical, rather than angular burner orifice pattern, flame length is reduced and not only improves mixing, but also dramatically decreases recirculation on the hub. This, in turn, lowers hub temperature and lessens the potential for burner cracking and plugging.

Pulled burner connections on the manifolds minimize pressure drop to improve gas flow into the burner risers. Full penetration welds ensure solid mechanical connections. In comparison, conventional burner connections, unlike the spider design burners employed at the Middle East plant, can only provide access for welding from a single side, leaving crevices that invite the propagation of cracks during thermal cycling and ultimately lead to premature burner failure.

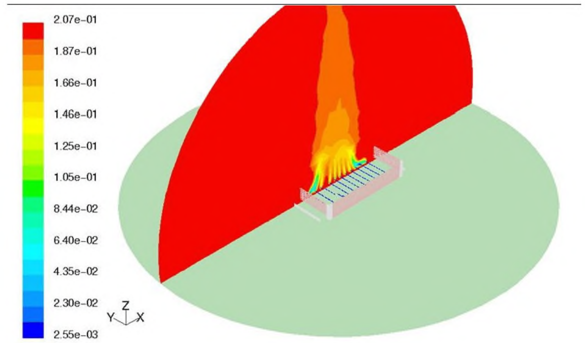

Figure 7 – Contours of mole fraction of O_2

Conclusion

The flare system the engineering team designed and installed for the Middle East plant has successfully demonstrated its ability, under all operating conditions, to meet the owner's requirement for safe operation and reduce noise, flare emissions and flare visibility. Although the system has already proven highly reliable in actual production operations, it is also capable of fully automated operation and is being cost effectively maintained with minimal downtime.

The efficient design, straightforward construction and provisions for future expansion, promises to combine with low operating costs and low burner flame visibility to enable environmentally friendly multipoint flare operations that are capable of meeting the Middle East plant's needs for many decades.

Brian Duck has been a flare system designer for more than 25 years. He is presently the Vice-President of Flares and Vapors Control for Callidus Technologies, L.L.C.