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HP | Heat Transfer

A. GUPTA, Petro-Chem Development Co. Inc., Houston, Texas; and **M. R. GENTRY,** Airflow Sciences Corp., Livonia, Michigan

Flow modeling as a tool for WHRU performance optimization

Greenhouse gas (GHG) emissions have become a growing concern for many industrialized countries over the past few years. Beyond the specific issues of GHG and general environmental considerations, there is a global tendency for improved energy efficiency. Whether the price of energy is high or low, controlled and reduced energy consumption will naturally improve operators' margins. As a result, the use of energy is minimized by heat integration, heat recovery and reduction in heat loss to atmosphere.

A waste heat recovery unit (WHRU) is a type of heat exchanger that recovers waste heat from hot flue gases and integrates heat into the balance of plant operations. The WHRU can generate steam/superheating steam, as well as heat thermal fluid, natural gas, various hydrocarbon fluids, and regen gas (cyclic operation).

WHRU is utilized at a wide range of industrial applications, including:

- LNG plants
- Carbon monoxide (CO) incinerator boilers for FCC
- Catalytic reforming units
- Hydrocracker units
- Ethylene crackers
- Steam methane reformers.

An LNG plant utilizes gas turbines to generate power and run turbines/compressors for refrigeration systems. The gas turbines burn natural gas to generate power, and waste heat in the hot flue gas (at a temperature of approximately 1,000°F/538°C) is recovered in a WHRU downstream of the gas turbine by heating a thermal fluid.

Normally, a WHRU consists of gas turbine exhaust ductwork, a silencer to reduce noise, a bank of heat recovery coils (finned) and an exhaust stack. The efficiency of heat transfer depends on the amount of surface area provided, the temperature differential available and the even distribution of flue gases over the finned coils.

A case study is presented here to show the effectiveness of flow modeling in optimizing the performance of a WHRU.

Flow modeling for WHRU performance optimization.

In this case study, flue gases from a gas turbine are used to heat a thermal fluid (hot oil). In turn, this thermal fluid provides heat (approximately 200 MMBtu/hr) to various other units and equipment in the LNG plant. The flue gas distribution pattern from the exhaust of the gas turbine was not uniform. Optimal operation of the WHRU is dependent on the gas flow characteristics across the tube banks of the hot oil coils.

A company was contracted to carry out computational fluid dynamics (CFD) and physical model flow studies to optimize flow control devices within the WHRU system. The CFD model was primarily used to design flow control devices and assess velocity patterns. The physical model was used for confirmation of the flow control device design and for assessment of velocity uniformity. The primary goal of the project was to achieve a uniform gas velocity distribution upstream of the tube banks for improved heat transfer, with the secondary goal of minimizing pressure loss.

Baseline design.

A wireframe of the baseline design is shown in **FIG. 1.** The hot gas exiting a gas turbine flows through the WHRU, heat transfer occurs across the tube banks and then the gas exits the stack. To accurately assess the flow characteristics, both the CFD and physical models include:

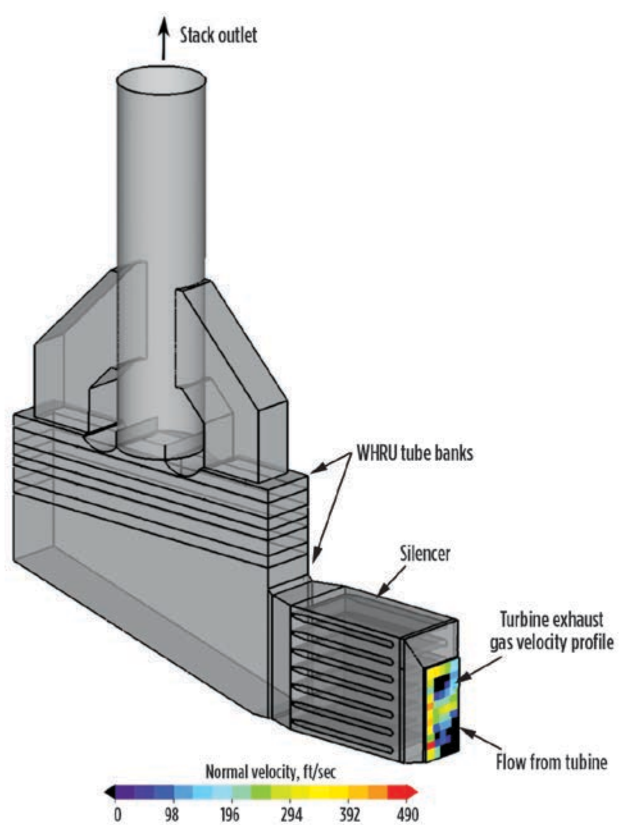

FIG. 1. The baseline design of the WHRU showing the turbine exhaust gas velocity profile.

- Ductwork downstream of the turbine (with silencer)
- The WHRU inlet plenum and tube banks
- The exhaust stack.

Additionally, any internal flow control devices, such as vanes and gas distribution devices required to improve flow, were incorporated into the models.

The gas flow exiting the gas turbine is highly turbulent and energetic. The primary challenge of the design process is to sufficiently control this flow. The flow enters a duct silencer, with horizontal panels, before exiting into a plenum upstream of the heat transfer tubes.

The baseline geometry included the duct silencer, but no other flow control devices. The turbine exhaust gas (TEG) flow is highly stratified, with much higher velocities on the right side of the duct, also shown in **FIG. 1.** This stratification is due to the side turbine outlet diffuser, which has limited flow control devices and results in the gas flow bunching up on one side of the duct. A primary challenge of the design was to reduce this significant side-to-side TEG stratification prior to the tube sections.

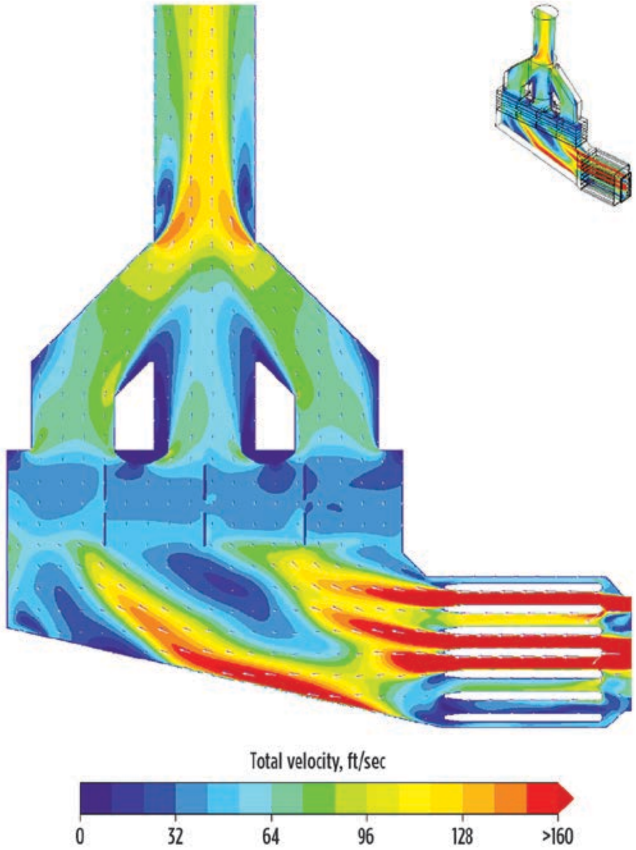

FIG. 2. Centerline velocity profile of the baseline WHRU design without the flow control devices.

Since the design objective is to produce uniform and optimized heat transfer through the tube banks, the velocity profile through the WHRU is closely monitored. The baseline CFD model centerline velocity profile is shown in **FIG. 2.** In addition to the side-to-side issues, significant stratification is evident vertically through the silencer baffles. The velocity is, therefore, very non-uniform at the inlet to the tube banks. Note the extremely low velocities (dark blue), indicating a dead zone with little flow.

FIG. 3 provides CFD results for velocity at the plane immediately upstream of the tube banks. In this plan view, side-to-side stratification is evident, with higher velocities on the right side of the unit (top of **FIG. 3**) due to the TEG profile. The red circles indicate the locations of velocity measurement points. This "grid" of points is used to provide statistical values of flow uniformity, as well as a comparison to field test or physical model flow data. The velocity uniformity is reported as root means square (%RMS), also referred to as coefficient of variation. The %RMS is a normalized value, defined as the standard deviation of velocity divided by the average velocity over the selected grid of points. A typical goal for %RMS is less than 15% to achieve uniform flow and efficient heat transfer. For this baseline WHRU model, the velocity uniformity at the tube bank inlet plane is 27.9%, which is well outside the goal.

Final design from CFD analysis.

ASC carried out different CFD simulations, resulting in the addition of several flow control devices to create a final design. These changes include:

- Perforated plate
- Ladder vanes
- Inlet duct addition of kicker plate
- Layout of silencer baffles.

FIG. 4 shows the CFD centerline velocity profile for the final design. The ladder vanes were added upstream of the tube banks to better distribute the gas flow while reducing the gas velocities. The perforated plate was added just downstream of the turning vanes to further smooth out the flow profile heading into the tube banks. The purpose of the perforated kicker plate at the entrance of the silencer is to mitigate the effect of the stratified TEG flow, spreading out the flow prior to the duct silencer.

The final CFD profile upstream of the tube banks can be seen in **FIG. 5.** The increased uniformity near the lower tube bank is

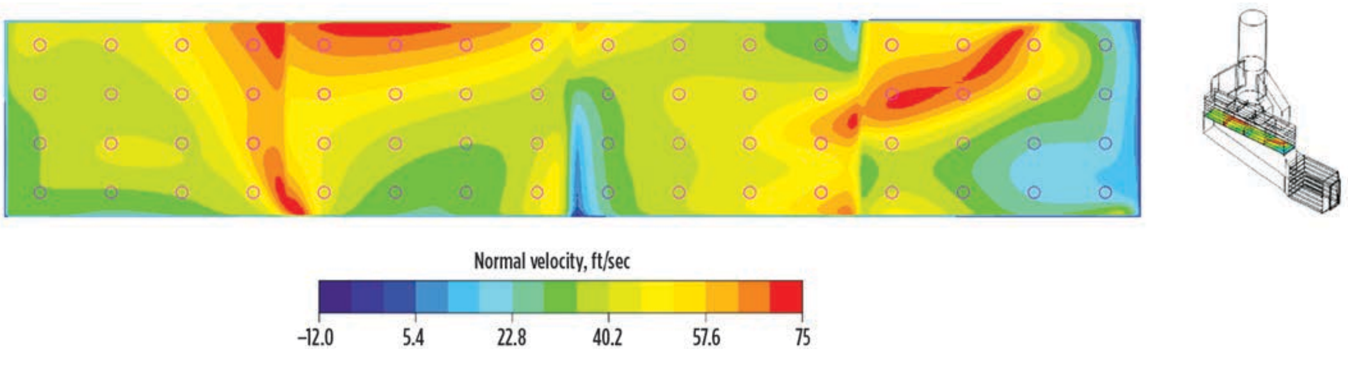

FIG. 3. Velocity just upstream of the tube bank in the baseline design.

evident, as indicated by the elimination of the higher velocities (orange and red colors). The %RMS in the final design at the plane just upstream of the tube banks was 11.2% compared to 27.9% in the baseline CFD version—a significant improvement.

The uniform velocity field will result in improved heat transfer performance, as the mass flow of gas past each heat transfer tube will be more equal, rather than some areas having high or low velocity where the heat transfer would not be optimized. Potential structural issues are also mitigated, as stresses due to uneven thermal expansion are reduced. Although the addition of flow control devices resulted in a larger system pressure loss, the improved flow provided by these devices resulted in a reduction in pressure loss through the tube banks. Overall, the pressure loss target was still met.

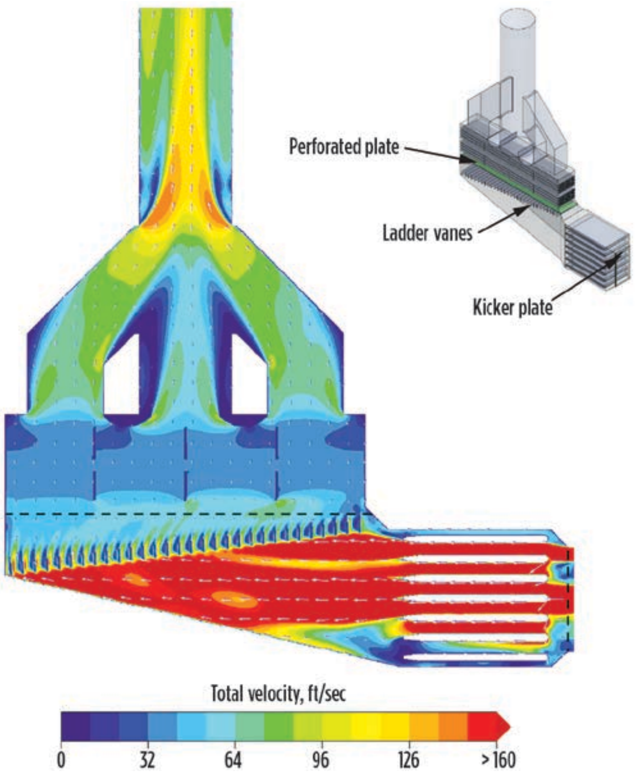

FIG. 4. Centerline velocity profile of the final WHRU design.

Physical model analysis. A scale model was built of the final design geometry to confirm the findings of the CFD analysis. The physical model is the same geometry as the final CFD design, but at a 1⁄12 scale. The model was primarily constructed of clear acrylic. The flow control devices, tube banks and silencer are constructed of formable plastic, acrylic, sheet metal or wood. The physical model data were collected at scaled operating conditions that could be compared to the CFD.

Velocity and pressure measurements were taken at critical planes in the model, including:

1. Upstream of silencer/model inlet
2. Downstream of silencer/WHRU inlet
3. Upstream of tube banks
4. Downstream of tube banks
5. Stack outlet.

Modeling summary. The goal of the project was to optimize the following requirements:

- Uniform flue gas velocity distribution upstream of the lower tube bank (target: 15% RMS)
- Optimize system pressure loss.

Both the CFD model and the physical model results confirm that the above requirements were met with the final design geometry.

The WHRU was constructed with these design elements. Feedback from the operating plant indicates the WHRU is operating within design parameters. As the presented case study shows, flow modeling is essential for proper design and optimization of the WHRU. HP

AMIT GUPTA is the Director of Furnace Technology and Proposal with Petro-Chem Development Co. Inc. He has more than 24 yr of experience in the design of process fired heaters, cracking furnaces and emissions reduction systems. He has held positions at Engineers India Ltd. and Technip (KTI Corp.) before joining Petro-Chem Development Co. Inc., which was later acquired by Heurtey Petrochem. Heurty was acquired by Axens in 2017. Mr. Gupta holds a BS degree in chemical engineering from Panjab University in India.

MATTHEW R. GENTRY has worked for Airflow Sciences Corp. for more than 15 yr, performing flow modeling as well as laboratory and field testing. He has served as project manager for heat recovery steam generators, waste heat recovery units, selective catalytic reduction and sorbent injection projects, helping optimize performance and pollution control in a wide variety of industrial applications. Mr. Gentry received his MSE degree in Aerospace Engineering from the University of Michigan in 2004, with a specialization in structural mechanics.

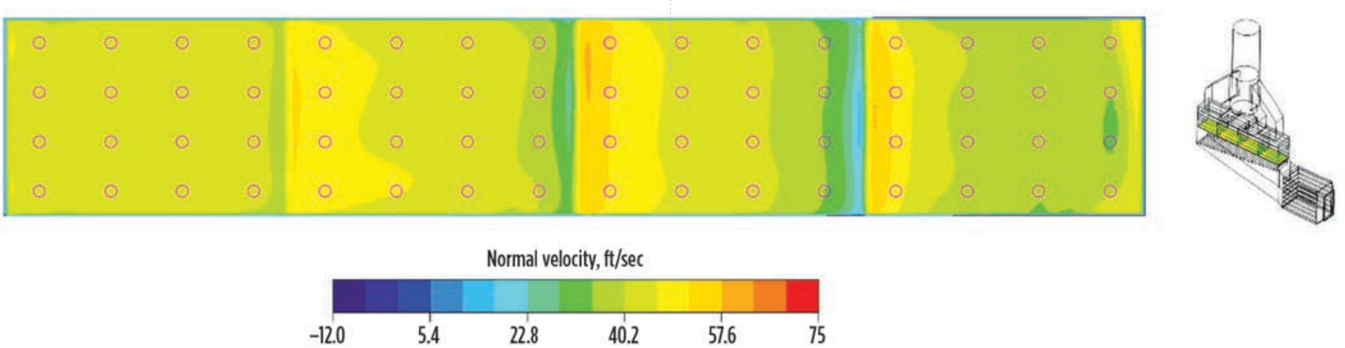

FIG. 5. Velocity just upstream of the tube bank in the final design.