Originally appeared in:
August 2020, pgs 21-25
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CFD modeling of mixing tees—Design of a thermal sleeve

Mixing tees—in which two fluid streams with different physical and/or chemical properties mix—are widely used in the petrochemical industry. When there is a large temperature difference between two streams, large metal temperature fluctuations can occur in the region where the two streams meet if proper design steps are not taken. The temperature fluctuations in the metal can lead to thermal fatigue of the pressure boundary piping. If through-wall cracking occurs, the fluid may leak, possibly causing a fire and damage. Therefore, it is imperative to ensure that the piping system can withstand the temperature fluctuations. Options can include improving the mixing of the two streams to reduce the temperature fluctuations through redesign of the piping system such that the momentum ratio of the two fluid streams is favorable to rapid mixing, or installing devices that protect the pressure boundary piping (e.g., injection quills or thermal sleeves in the region where the temperature fluctuations are higher than a thermal fatigue threshold). This region includes the T-junction and a length of differing main pipe diameters downstream from the T-junction. For thermal sleeves, different approaches exist to determine the needed sleeve length, which are briefly discussed in this article.

Empirical correlations in the literature may be used to estimate mixing effectiveness or the uniformity of the fluid concentrations over the pipe cross-section downstream from the T-junction,[1] whereby the length of the pipe that needs protection can be determined. However, these correlations were developed based on experiments typically using air or water as working fluids and a chemical agent as the tracer to indicate the mixing uniformity. The temperature differences between the two fluid streams in these experiments were usually small. Therefore, these correlations should be used with caution when the actual fluid conditions are well outside of the range in which the correlations were developed.

Computational fluid dynamics (CFD) modeling, such as wall-resolved large eddy simulation (LES), can provide accurate predictions of the mixing behavior—including velocity, concentration and temperature fields—in a mixing tee.[2] Therefore, the variations of the transient fluid temperature can be used to identify a location in the main pipe downstream of the tee, after which the circumferential maximum temperature difference is less than the thermal fatigue threshold.

Advanced CFD modeling can predict the fluid temperature fluctuations at the mix point, as well as characterize the corresponding temperature variations in the pipe wall. Specifically, LES is required to capture the time-varying turbulent behavior at the mixing point, which is significantly more time- and resource-intensive than traditional two-parameter (e.g., k-ε and k-ω) Reynolds-averaged Navier-Stokes (RANS) simulation, which is the workhorse of most industrial CFD simulations.

In this article, both the conventional LES approach and a new hybrid RANS-LES method are used to predict the mixing of the two fluid streams, and the results are compared with test data reported in the literature for validation purposes. The new hybrid model is the stress-blended eddy simulation (SBES) and has recently been included in commercial software.[a] SBES retains most of the fidelity of the conventional LES approach in a fraction of the time for typical problems. The SBES approach is then used in an actual industrial application to predict temperature fluctuations in a mixing tee. The simulation is used to determine the length of the thermal sleeve required to protect the pipe from thermal fatigue.

Model validation. The test data utilized is from an experiment specifically designed to investigate thermal mixing in a mixing tee.[3] The data has been used to validate different turbulence scale-resolving simulation models, such as LES, scale-adaptive simulation (SAS) and delayed detached eddy simulation (DDES).[4,5]

In this paper, the data is used to validate the conventional LES approach, as well as the new SBES approach. The model consists of a horizontal pipe with an inner diameter of 140 mm (D) for a cold-water (19°C) flowrate of 9 l/sec and a vertical branch pipe with an inner diameter of 100 mm (D_0) for a hot-water (36°C) flowrate of 6 l/sec. The inlets are located at 3.1 D_0 and 3 D upstream of the junction for the hot and cold water, respectively. The model outlet is at 22 D downstream of the junction. The model is composed of 2.78-mm and 6.08-mm hexahedral cells for the SBES and LES approaches, respectively. The inlet velocity distributions are based on measurements.[3] The water's physical properties, such as density, viscosity, specific heat and thermal conductivity, are treated as functions of the local water temperature. A time step of 3×10^{-3} sec and 1×10^{-3} sec is used for the SBES and LES methods, respectively, which corresponds to an average CFL number of 0.36 and 0.98. Both the LES and SBES models were run with a flow time of 10.32 sec, which is approximately 3.3 times the flow residence time from the tee to the model exit. Statistic properties, such as mean temperature and mean velocity components, are obtained by averaging instantaneous flow fields over the total flow time.

Turbulence is characterized by eddies with different space and time scales. In the LES approach, large eddies are resolved directly, while small eddies are modeled using a subgrid model. The LES approach requires significantly finer meshes and a smaller time step than those for a RANS model. SBES is a hybrid RANS-LES turbulence model, in which the boundary layer is modeled using an unsteady RANS model, while the LES model is applied to the core turbulent region where large turbulence scales play a dominant role. As such, SBES allows a coarser mesh and a larger time step than LES.

FIG. 1 shows unsteady flow structures, as predicted by the SBES model (iso-surfaces of Q-criterion colored by time-averaged temperature). The results indicate the formation of unsteady turbulence structures emanating from the initial mixing of the two streams, forming a "horseshoe vortex." In the mixing zone, additional turbulence is formed, which then dominates the downstream mixing process. **FIG. 2** shows the instantaneous velocity and temperature, as well as time-averaged velocity and temperature based on the SBES model. The velocity field indicates the presence of a large recirculation region extending approximately 1 D downstream of the junction. The results indicate that the SBES approach can resolve the turbulent eddies generated by shear layer instabilities where the hot and cold streams meet. The instantaneous temperature field shows that the thermal mixing is highly turbulent.

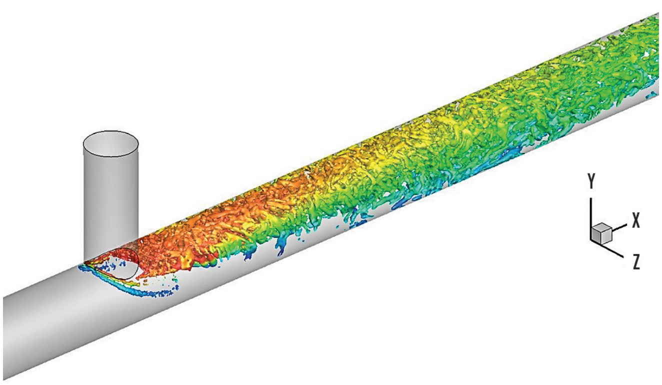

FIG. 1. Iso-surfaces of Q-criterion colored by time-averaged temperature in the SBES model.

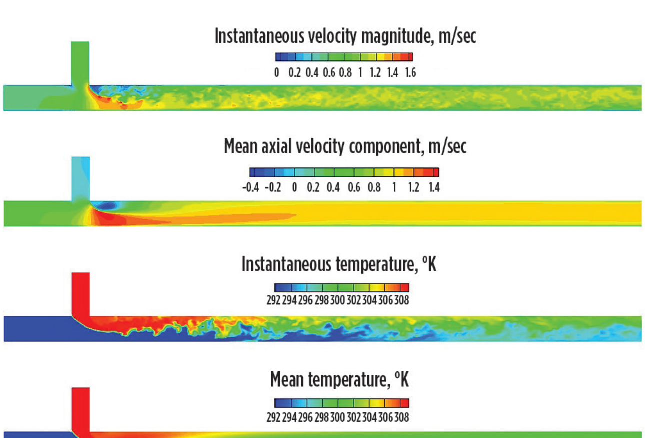

FIG. 2. Time-averaged and instantaneous velocity and temperature on a vertical plane in the SBES model.

As previously mentioned, both the LES and SBES simulations are carried out for 10.32 sec of flow time using 16 computer processors. The LES model contains approximately twice the computational cells of the SBES model and requires slightly more than three times the computational time (wall-clock time) for the SBES analysis. The SBES model is also run for a total of 37.3 sec of flow time. The results for a longer flow time are very similar to those with 10.32 sec of flow time and are not presented here.

FIGS. 3–7 compare the modeling results (labeled LES and SBES) with test data (labeled exp.) obtained in different locations downstream of the junction. The model predictions of the time-averaged water temperature (approximately 1 mm away from the inner wall of the pipe) are in good agreement with the test data at both the bottom and the top of the pipe. The LES results appear to compare somewhat better with the test data than those from the SBES approach. The predicted temperature fluctuations compare favorably with the test data, as shown in **FIG. 4** where the root-mean-square-error (RMSE) temperatures are plotted as a function of the axial distance from the junction. In **FIG. 4,** "pipe front" denotes the 3 o'clock position when looking downstream from the tee. Again, the LES results show a slightly better agreement with the test data than the SBES results.

The predicted time-averaged axial velocity component (u) and vertical velocity component (v) compare satisfactorily with the test data at both x = 1.6 D and x = 4.6 D for both the LES and SBES approaches (**FIGS. 5** and **6**). The predicted fluctuations of the velocity components are also in good agreement with the measurements for the LES and SBES approaches (**FIG. 7**). It is worth noting that the SBES approach takes only approximately one-third of the computational time for the LES approach.

The model predictions show that the results from both the LES and SBES models are in reasonable agreement with the measurements of the time averaged and RMSE temperature and velocity components of the flow in a mixing tee. The SBES model can predict turbulent flow structures in the thermal mixing process. Since the SBES model requires a much lower computational cost and provides a faster turnaround of challenging problems than the LES model, this approach will be used to predict temperature fluctuations in a mixing tee—which blends light gasoil with a recycle gas—to determine mixing uniformity

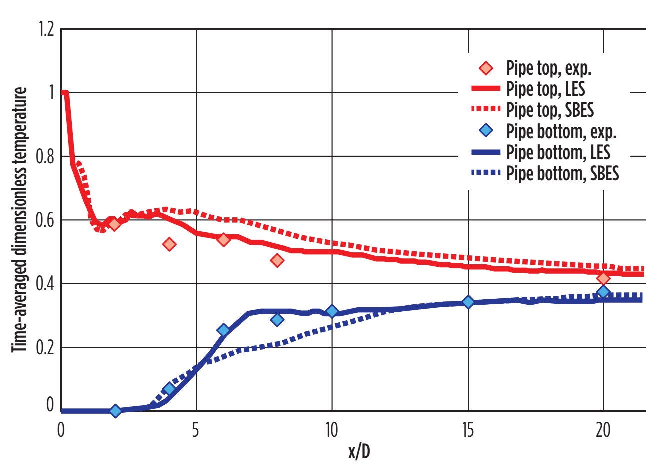

FIG. 3. Modeling results and experimental data for time-averaged dimensionless temperatures along a horizontal pipe.

and the length of a thermal sleeve, which is used to protect the pressure boundary piping.

Industrial application. In the following, a mixing tee that blends light gasoil with a recycle gas is modelled using the SBES approach. The light gasoil temperature is 316°C, and the recycle gas temperature is 516°C. The large temperature difference between the two streams is expected to cause large temperature differentials downstream of the junction, which may lead to thermal fatigue of the piping if the pipe is not properly protected.

The operating pressure of the mixing tee is 117 bar. The recycle gas enters the mixing tee from the vertical branch and the light gasoil from the horizontal main pipe. Under the operating conditions, both the recycle gas and the light gasoil are supercritical fluids. The Peng-Robinson real gas model[6] is used to describe the state of the mixture. This model requires the critical temperature, critical pressure and acentric factor for each fluid as model inputs and can predict vapor, supercritical fluid and liquid properties.

The molecular weight of the recycle gas (mostly hydrogen) is calculated based on the operating conditions and the measured density. However, other properties, including critical properties and thermal properties, are based on the properties of hydrogen. The boiling point temperature of a light gasoil may vary from 370°C–550°C. It is assumed that the boiling point temperature of the light gasoil in this work is 426.7°C. The critical properties and molecular weight are then estimated using the Lee-Kesler correlations,[7,8,9] which are functions of the boiling point temperature and the specific gravity of the light gasoil—the latter is 950 kg/m^3. The thermal conductivity is calculated based on a correlation given in literature.[10] The specific heat of the light gasoil is estimated using a simple equation provided in literature.[11] The correlations for the thermal property estimations are functions of the specific gravity and the temperature of the light gasoil.

The recycle gas pipe has an inner diameter of 216 mm connected to a 325-mm × 216-mm reducer, while the light gasoil pipe has an inner diameter of 257 mm with a 325-mm × 257-mm reducer. The pipe downstream of the mixing point has an inner diameter of 325 mm. The model outlet is at 15 times the main pipe inner diameter downstream of the junction. The model comprises 2.82 MM control volumes. A time step of 1×10^{-4} sec is used in the simulation, corresponding to an average CFL number of 0.54. The time-averaged statistic quantities are based on a flow time of 0.9 sec, which is approximately 1.2 times the flow residence time, lower than what typically is required.

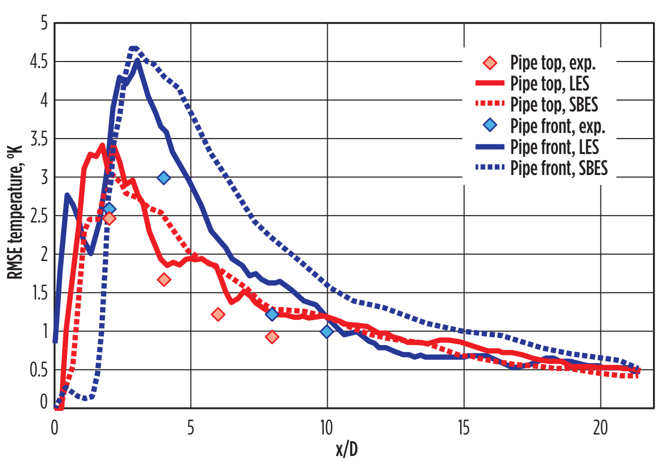

FIG. 4. Modeling results and experimental data for temperature fluctuations along a horizontal pipe.

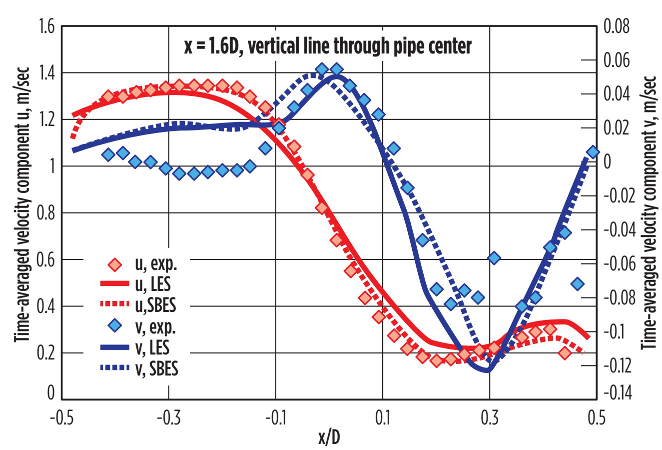

FIG. 6. Modeling results and experimental data for time-averaged axial and vertical velocity components along the y-axis at x = 1.6 D.

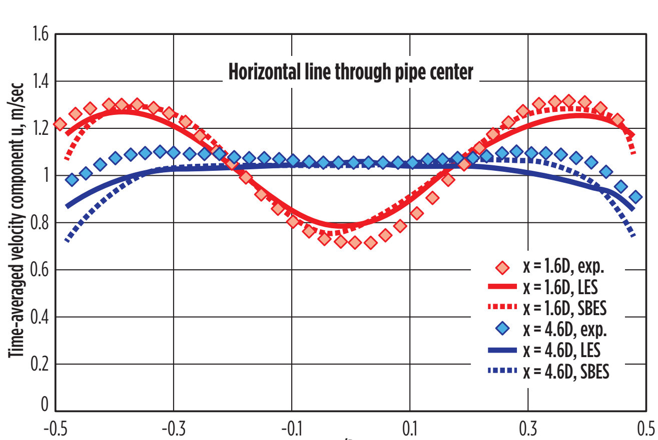

FIG. 5. Modeling results and experimental data for time-averaged axial velocity components along the z-axis.

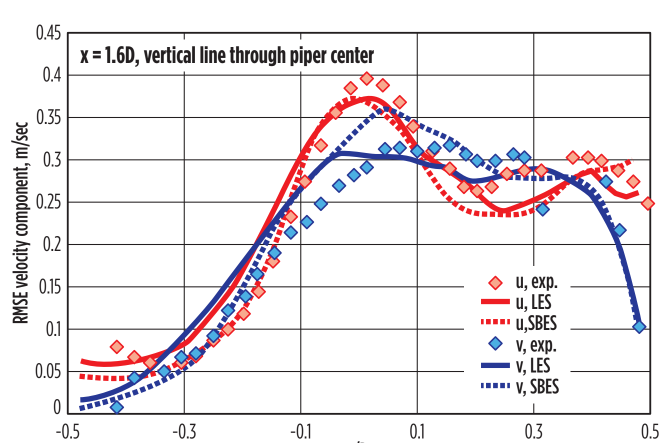

FIG. 7. Modeling results and experimental data for fluctuations of velocity components along the y-axis.

Nevertheless, the results presented here are still indicative of the nature of the turbulent mixing process.

FIG. 8A shows the distributions of the instantaneous temperature and RMSE temperature on the vertical plane through the pipe centerline. The instantaneous temperature distribution shows intensive mixing between the two streams downstream of the junction. The momentum of the branch flow is much lower than that from the main pipe inlet: the latter sweeps past the former and forces the branch flow to bend toward the top portion of the horizontal pipe. The RMSE temperature distribution indicates large temperature fluctuations at the interface where the two streams come into contact. Downstream of the junction, the fluctuations are relatively small in the bottom portion of the pipe, and the recycle gas tends to stay in the upper section (**FIG. 8B**), which illustrates the concentration distributions of the fluids at the vertical plane through the pipe centerline. This is not surprising, given that there is a large difference in the densities of the two streams.

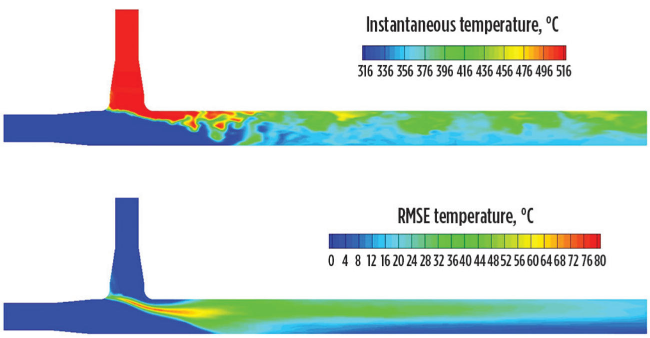

FIG. 8A. Temperature distributions on a vertical plane through the pipe centerline.

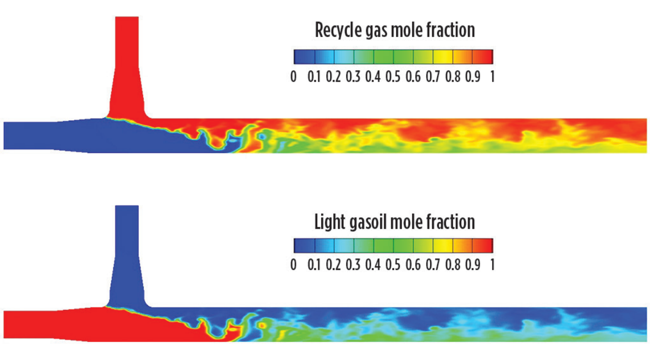

FIG. 8B. Distributions of recycle gas and light gasoil concentrations.

FIG. 9 shows the instantaneous temperatures at different locations. Temperatures at four locations are presented. Looking in the main flow direction, the locations at the 12, 3, 6 and 9 o'clock positions are denoted as top, right, bottom and left, respectively. Distance (x) is the distance from the junction, and D is the main pipe diameter.

The temperature sampling locations are 1 mm away from the inner surface of the pipe. The results show that the minimum temperature is always at the bottom of the pipe and the maximum temperature is usually at the top of the pipe. Local temperatures oscillate rapidly in the mixing tee. The maximum temperature difference for the pipe cross-section at x = 5 D is 155°C.

FIG. 10 shows the maximum temperature differences at different locations downstream of the junction. As the distance from the junction increases, the maximum temperature difference decreases. At x = 6 D, the maximum difference is 141°C, while at x = 10 D, the maximum difference is 116°C. The results suggest that it may take more than 15 times the inner diameter of the pipe downstream of the tee to achieve adequate thermal mixing of the two streams (e.g., the circumferential temperature differential is less than 100°C). However, for thermal fatigue mitigation with a sleeve, the sleeve does not have to cover the pipe section downstream of the tee until the temperature differential is as low as 100°C. A higher temperature difference may be acceptable for the pipe material. If more rapid thermal mixing is desired for the process, then other options, such as installation of an injection quill or a static mixer, must be considered. These options will increase the construction cost. However, they typically result in a shorter thermal sleeve than the case when there is no injection quill or static mixer.

While the actual temperature of the exposed metal will depend on the frequency of the temperature fluctuations, the results shown in **FIG. 10** illustrate how CFD modeling results can be used to determine the distance from the junction, over which the temperature fluctuations are higher than the thermal fatigue threshold and the pipe section needs a thermal sleeve. The modeling results show a stratified flow of the two fluid streams downstream of the junction, where the recycle

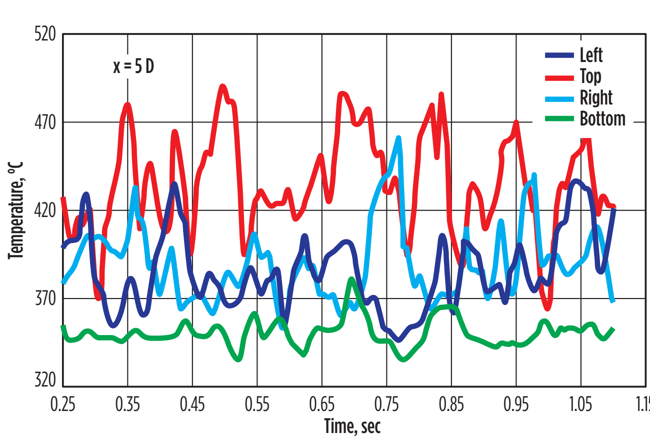

FIG. 9. Instantaneous temperature as a function of flow time: x = 5 D.

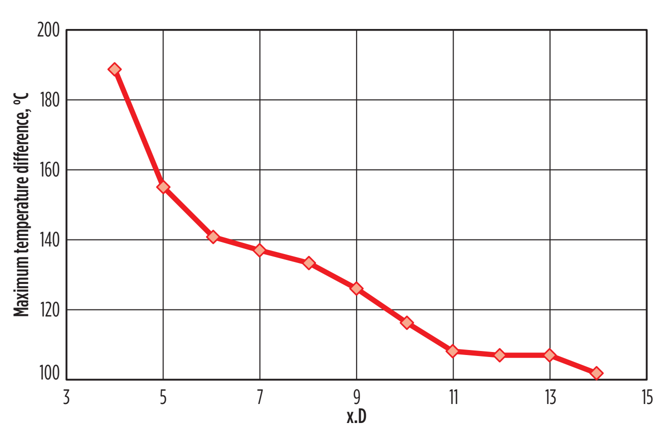

FIG. 10. Maximum temperature difference along the main pipe.

gas tends to stay at the top part of the pipe and the light gasoil tends to remain at the bottom part, even after 15 pipe diameters. However, the circumferential maximum temperature difference is only 116°C at the plane 10 times the pipe diameter downstream of the tee.

Takeaway. The LES and SBES approaches have been validated against test data obtained from a mixing tee. Both approaches have been shown to predict the average and transient behavior of the fluid velocity and temperature in a mixing tee. The LES predictions show a somewhat better agreement with the test data than the SBES approach. However, the computational cost and model turnaround time are considerably higher for the LES approach.

The SBES approach has been used to predict temperature fluctuations in an industrial mixing tee where light gasoil mixes with a recycle gas. The predicted temperature fluctuations can be used to determine mixing uniformity and the pipe length downstream of the mixing junction, for which the temperature variations are greater than the thermal fatigue threshold and a thermal sleeve is needed to protect the pipe to avoid thermal fatigue. HP

NOTES

[a] ANSYS Fluent flow modeling and CFD simulation software

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