1pEAa3. Analyzing the impact of the inlet temperature on the acoustic noise production form a supersonic jet using large eddy simulations

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Non-ideal expanded supersonic jets emerging from a nozzle produce three different types of noise, i.e., shock-associated broadband noise, screech noise, and the turbulent mixing noise. The screech tone occurs due to self-excitation in a feedback-loop of flow propagating downstream and acoustic wave interaction. In downscaled laboratory experiments often the screech noise occurs, while the real applied exhaust jet of a gas turbine engine does not show this phenomena. Apart from a geometric scaling difference, usually a lower temperature is employed in experimental studies. The compressible Navier-Stokes equations are simulated numerically by a large eddy simulation approach to investigate the effect of jet operation temperature onto the noise development in a supersonic jet originating from a convergent-divergent nozzle. The jet-exit mach-number is 1.56, while the total temperature ratios are 1.27, 2.46, and 3.65. The differences in the acoustic near-field will be presented and the interaction of flow-field with acoustic waves will be analyzed and compared to each other.

Published by the Acoustical Society of America through the American Institute of Physics
INTRODUCTION

Accurate measurements of acoustic jet-noise relay often on anechoic chambers. However, only a few existing acoustic test facilities are equipped with anechoic chambers in which investigations on supersonic jets with realistic temperatures are practicable. There are several reasons for downscaling the jet-temperature in experimental jet-analysis. One is that the realistic jet temperatures are difficult to handle in these acoustic test facilities. Furthermore, the flow-field of hot jets, especially under supersonic conditions, is hard to examine experimentally by direct methods. The sensitive flow measurement instruments would need to sustain the high jet temperatures. Usually only pressure measurements of the near-field and far-field are performed. Via the gained acoustic spectra the hydrodynamic generation process is deduced, as shown by Tam et al. (2008).

To develop a scaling-law to account for temperature, the differences and changes of the acoustic noise production due to temperature reduction need to be identified and a mathematical relation needs to be found. With his acoustic analogy, Lighthill (1952) showed that the radiated total acoustic output is proportional to the eighth power of the velocity. This observation was picked up by many researchers, e.g. Fisher et al. (1973); Viswanathan (2006), and they suggested different, but similar acoustic-intensity scaling-laws. For this purpose an acoustic Mach-number $M$ was defined as the ratio of the jet-velocity and the ambient speed of sound. These were verified by the collapse of the experimentally measured spectra from cold and hot jets. The acoustic intensity scales with the jet-velocity, while the disturbance travels through ambient media. Viswanathan (2006) suggested to include the temperature effect by modifying the constant exponent of the acoustic Mach-number to a function depending on the jet temperature and directional radiation angle.

For subsonic jets the turbulent mixing noise is dominant. Therefore, it is not unexpected that with a scaling-law depending only on the quadruple noise source reasonable estimations can be gained (Morfey et al. (1978)). However, for supersonic jets there are three acoustic noise radiation mechanisms known, i.e. turbulent mixing noise, broadband shock-associated noise, and the screech tones. These additional acoustic noise sources could require more difficult scaling laws, since each of those could show a different temperature dependence. However, Viswanathan (2008) could show that for a substantial temperature ratio range even on supersonic jets could be shown that scaling-laws perform.

The issues that the high temperature of a heated supersonic jets causes in the framework of the experiments, are not so serious when setting up a numerical investigation. Using numerical simulations details of a supersonic jet can be investigated and distinguished. Such examples are the studies on the understanding of the screech tone generation mechanism (Berland et al. (2007); Suzuki and Lele (2003)). Also the temperature effect to this acoustic noise source was simulated and a shift of the tonal frequencies was reported by Shen and W. Tam (2000). A consistent accepted theory regarding jet-temperature effects on the flow-field and acoustic noise generation is not yet in place.

This study focuses on the changes caused by an increased jet-temperature to the flow-field and the acoustic noise sources of a supersonic jet exhausting from a convergent-divergent (C-D) nozzle. Therefore, Large Eddy Simulations solving the compressible Navier-Stokes equation have been performed for three different total temperature ratios. The differences in the flow-field are analyzed and the changes in the acoustic sources are investigated.

CASE DESCRIPTION

The geometry of the nozzle used in the simulations is shown in Fig. 1. The inner nozzle wall has a sharp C-D shape and is shown in Fig. 1 (colored in red). The C-D nozzle is characterized by
the exit diameter $D_e$ of about 57.5 mm and an area ratio of 1.23. The nozzle lip thickness is 0.5 mm. The outer nozzle covers the inner nozzle and is shown in green in Fig. 1.

A total pressure source, representing the pressure downstream of the turbine, is driving the nozzle acting at the inlet. The pressure source is quantified using the nozzle pressure ratio, which is 4, i.e. at the inlet plane acts a four times higher total pressure than the ambient pressure. The total temperature at the inlet $T_{j,0}$ was varied as a ratio to the ambient temperature for three cases, 1.27 (warm), 2.46 (intermediate), and 3.65 (hot). The inlet total pressure has been kept constant for all cases.

The jet expands into stagnant ambient conditions. The ambient temperature $T_\infty$ was 288.15 K and the ambient pressure $p_\infty$ was 101,325 Pa. The operating media is air, which is assumed to behave like an ideal gas and the isentropic exponent $\kappa$ is 1.4. The temperature dependency of the dynamic viscosity $\mu$ was modeled using Sutherland’s formula with standard coefficients.

**Numerical simulation procedure**

The numerical simulations were performed using a finite volume code, solving the three-dimensional Favre-filtered Navier-Stokes equations. To ensure the conservation of mass and energy, the conservation equations have been solved. Due to the problem specific high Reynolds-numbers, the resolution of all turbulent scales would be numerically too expensive. Hence, fine enough numerical grids were used, to represent at least the substantial fluid-motion within the inertial subrange. This approach is commonly known as Large Eddy Simulation (LES). The subgrid flow scales, smaller than the mesh cell size, are low-pass filtered by the mesh grid. No explicit filter is applied and the small-scales are assumed to be represented implicitly by the numerical dissipation of the solver.

A low-storage four-stage Runge-Kutta scheme using standard coefficients is applied for the time integration. Explicit time-stepping was used for time advancement, where the time-step $\Delta t$ was chosen to be $6 \cdot 10^{-9}$ s for the warm, $2.5 \cdot 10^{-9}$ s for the intermediate, and $1.5 \cdot 10^{-9}$ s for the hot case.

A second order accurate central difference scheme is used for the spatial discretization of the convective terms. For artificial dissipation, a blend of second and fourth order differences is employed. This ensures that serious numerical overshots collateral to sharp gradients are damped out.

Characteristic boundary conditions, specifying the total pressure and total temperature, have been applied on all in and out-flow boundaries to avoid wave reflections from the boundaries. Adiabatic no-slip boundary conditions have been applied to the nozzle walls.

The computational domain extends over about eight nozzle diameters in radial direction and about thirty nozzle diameters downstream from the nozzle exit. The outer shape of the mesh-grid is optimized to allow a low cell growth-factors and refinement zones in important sections.
The mesh-grid was created with a hexahedral block-structure, where 90 blocks were used. The computational size of the grid is about 30 million cells.

(a) mid-plane cut of the entire domain (b) zoomed mid-plane cut close to the nozzle exit

**FIGURE 2:** The numerical grid of the nozzle geometry is visualized.

At the nozzle walls, no-slip conditions are implied. It is intended to capture the location of shocks inside of the nozzle as accurate as possible without any underlying assumptions required for modeling of the boundary-layer. Also the potential shock movement should not be influenced by any modeling. Hence, no wall-functions where applied and the boundary-layer was reasonably resolved.

A locally high mesh resolution is required, to resolve the relevant small scale phenomena of interest. The cell-size distribution of numerical grid was designed to be as homogenous as possible with low cell growth-factors to avoid high dissipation or dispersion errors from the numerical scheme.

**RESULTS**

In this section the results obtained by the LES describing the temperature dependence of the super-sonic jet originating from a C-D nozzle are presented. Three different cases are analyzed, where the total temperature at the nozzle inlet was varied.

The consequences of changing the inlet total temperature of the nozzle are analyzed. The driving source, applied as total pressure inlet condition at the inlet, is kept constant over all cases. For three cases, the total temperature of the jet at the inlet is varied. In agreement with the ideal gas law, the density adapts for the given static temperature and static pressure. Hence, at the inlet a high density of about 3.8 kg/m³ establishes for *warm* case, while for the *hot* case the density is only slightly higher than in the ambience.

At the narrowest cross-section, the chocked flow-condition develops. Using, according to the data in table 1 isentropic relations the mass-flow $\dot{m}_{iso}$ through the nozzle can be approximated. The discharge coefficient $C$ encounters for the real mass flow rate compared to the ideal mass flow rate. With increased jet inlet temperature, the mass-flow through the nozzle decreases drastically for this temperature variation. However, the thrust $F$ of the nozzle increases with increased inlet temperature. The obtained values are presented in table 1.

**TABLE 1:** The estimation for the mass-flow $\dot{m}_{iso}$ using the isentropic formulation is compared to the mass-flow $\dot{m}_{sim}$ obtained by the simulations. The discharge coefficient $C$ and the thrust $F$ calculated based on the computations is tabulated.

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_j/T_\infty$</th>
<th>$\dot{m}_{iso}$ (kg/s)</th>
<th>$\dot{m}_{sim}$ (kg/s)</th>
<th>C (-)</th>
<th>F (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>warm</td>
<td>1.27</td>
<td>1.807</td>
<td>1.71</td>
<td>0.95</td>
<td>642</td>
</tr>
<tr>
<td>intermediate</td>
<td>2.46</td>
<td>1.299</td>
<td>1.23</td>
<td>0.95</td>
<td>663</td>
</tr>
<tr>
<td>hot</td>
<td>3.65</td>
<td>1.066</td>
<td>1.01</td>
<td>0.95</td>
<td>672</td>
</tr>
</tbody>
</table>
After the sharp transition of the convergent part to the divergent part of the nozzle, an expansion-fan establishes. Slightly downstream, a separation bubble occurs, which is longer but flatter for the hot case than for the warm case. On the separation bubble, the first oblique shock establishes and merges in the middle to a Mach-disk. The Mach-disk has about an equal size for all the cases. However, the occurring peak Mach-number differs insignificantly. Since the separation bubble varies in its shape, the formed shock-pattern is moved slightly downstream with increased temperature. As a consequence of that, the flow separates later from the nozzle with increased jet-temperature. The second shock-diamond pattern emerges with separation and the temperature effect shifts the pattern with the separation slightly downstream.

Figure 3 shows that the flow-field in terms of the Mach-number and the shock-pattern shows a similar general behavior. However, there are small differences visible, e.g. the boundary-layer thickness in the nozzle. The jet-plume shows a significant flapping motion for the intermediate and hot case, which can be seen in figure 3 by comparing two time instants (c) $t_1$ and (d) $t_2$ with each other. This is not that distinct visible for the warm case.

As mentioned before, the density in the inlet duct of the nozzle is significantly higher for the warm case than for the hot case. A higher density-gradient develops in the nozzle for the warm case, which causes higher shock-strengths in this case. In figure 4 the higher density-gradient over the shock-pattern in the warm case (a) compared to the hot case is visible.

**FIGURE 3:** The Mach-number in a mid-plan view is shown.

**FIGURE 4:** Snapshots of the numerical Schlieren data. The upper half of the picture shows the density gradient for the warm case, while the lower half shows the hot case.
In the shear-layer the density-gradient for the hot case is higher than in warm case. Thus, the emitted acoustic fluctuations are altered in amplitude with temperature. In table 2 the characteristic jet values in the nozzle exit plane are shown. The averaged density over the nozzle exit plane is higher than ambient conditions for the warm case. Correspondingly, the static temperature in the jet is lower than ambient conditions for this case. For the intermediate and hot case the situation is the opposite. The jet-temperature is higher than in the ambience and the density in the jet-plume is lower than in the ambience. Hence, the temperature and density-gradient changes sign when the jet is heated.

The jet-velocity increases with the increased jet-temperature. On the other hand, the static density is significantly higher for the warm case than for the hot case. However, also the dynamic viscosity $\mu$ increases with increased temperature. Thus, the Reynolds-number $Re$ based on the nozzle exit diameter $D_e$ changes from $2.358 \cdot 10^6$ for the warm case to $0.674 \cdot 10^6$ for the hot case.

<table>
<thead>
<tr>
<th>Case</th>
<th>$\bar{u}_j$ (m/s)</th>
<th>$T_{j,s}$ (K)</th>
<th>$\bar{\rho}_{j,s}$ (kg/m$^3$)</th>
<th>$\bar{\mu}$ (kg/(s · m))</th>
<th>Re (–)</th>
</tr>
</thead>
<tbody>
<tr>
<td>warm</td>
<td>476.7</td>
<td>246.7</td>
<td>1.37</td>
<td>$1.60 \cdot 10^{-5}$</td>
<td>$2.358 \cdot 10^6$</td>
</tr>
<tr>
<td>intermediate</td>
<td>669.4</td>
<td>468.2</td>
<td>0.72</td>
<td>$2.60 \cdot 10^{-5}$</td>
<td>$1.061 \cdot 10^6$</td>
</tr>
<tr>
<td>hot</td>
<td>818.7</td>
<td>692.9</td>
<td>0.49</td>
<td>$3.39 \cdot 10^{-5}$</td>
<td>$0.674 \cdot 10^6$</td>
</tr>
</tbody>
</table>

Inside the nozzle, the flow remains laminar until flow-separation from the nozzle occurs under laminar conditions. Hence, also the boundary-layer remains laminar for all three cases. However, figure 4 shows that for the warm case, the development of vortical structures can be clearly seen at the exit plane of the nozzle. For the intermediate and hot case, the flow remains laminar close before the first interaction of the first reflected shock and the shear-layer.

The screech tones are caused by a feedback-loop as described by Powell (1953). The interaction of coherent structures propagating downstream in the shear-layer and shock-reflections causes an acoustic event. Acoustic waves travel outside of the hydrodynamic region upstream to the nozzle-lip, where the acoustic waves stimulate the receptivity of the shear-layer to form the coherent structures. Since, the temperature effects the viscosity and the Reynolds-number of the flow, the receptivity of the shear-layer might be changed due to scaling of the temperature implied at the nozzle-inlet.

Figure 5 shows the static pressure distribution overlaid by the acoustic Mach-number, where values lower than $M < 1$ where coped. In the case of the warm jet, curved acoustic waves traveling downstream are generated immediately at the nozzle exit. It could be observed that the emitted acoustic waves increase in intensity with increased jet-temperature in all radiation angles, as displayed for two monitoring points in figure 6. The location of the motoring points $M_1$ and $M_2$ is displayed in figure 5 (a). The acoustic noise radiation into the upstream angles was significantly lower than into the aft angles, with can be seen by comparing figure 6 (a) and (b).

With increased jet-temperature Mach-wave radiation starts to appear. For the intermediate and hot case, high aptitude acoustic waves appear originating from the first interaction of shock-reflection and shear-layer. Tam et al. (2008) observed that the acoustic waves are generated by large-scale coherent structures traveling at supersonic speed relative to the ambient. This mechanism causes the parallel shaped waves in figure 5. Pressure statistics obtained by monitoring points in the radiation sector of the Mach-waves showed a high skewness for the intermediate and hot case, which is typical for a crackle event as described by Nichols et al. (2012); Baars et al. (2011). This was not observed for the warm case.
**CONCLUSION**

The effect of increased inlet temperature to the flow-field and acoustic noise production of a supersonic jet originating from a C-D nozzle was investigated using LES. The flow-field and acoustic near-field for three different jet temperatures has been analyzed.

It has been shown that with temperature downscaling the Reynolds-number and the mass-flow rate of the jet is increased, which resembles a situation closer to real-scale jet exhausting from a gas turbine engine. However, the boundary-layer separates laminar from the nozzle for
all simulated temperature cases, which is unlikely to happen in real-scale jets. The development of turbulent structures in the shear-layer is delayed with higher temperatures.

A higher density-gradient in the C-D nozzle and jet-core was observed for low temperatures, which lead to stronger shocks than for higher temperature cases. However, density-gradients got stronger in the shear-layer with increased temperature. The density-gradient changed sign between the warm temperature case and the increased temperature cases.

A temperature dependence on the occurrence of Mach-wave radiation has been seen. The high skewness of the pressure signal produced by the Mach-wave phenomena has been seen. However, temperature downscaling can influence the appearance of this acoustic phenomena.

ACKNOWLEDGMENTS

This work was supported by the Swedish National Infrastructure for Computing (SNIC 002-12-11) via PDC.

REFERENCES


