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A HYBRID APPROACH FOR THE EVALUATION OF THE RADIATED NOISE FROM A TURBULENT NON-PREMIXED JET FLAME BASED ON LARGE EDDY SIMULATION AND EQUIVALENT SOURCE & BOUNDARY ELEMENT METHODS

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Abstract
A hybrid approach based on large eddy simulation (LES) and the equivalent source method (ESM) as well as the boundary element method (BEM) is applied to evaluate the noise radiation of open turbulent non-premixed jet flames. Hybrid approaches are well known and often used for classical non-reacting turbulent flows. The extension to turbulent reacting flows is presented here. For an open flame there is no strong influence of the acoustic field onto the flame. This is in contrast to enclosed flames, where the acoustic waves can easily induce combustion instabilities. Therefore, the flow simulation can be decoupled from the acoustic simulation. Furthermore, the very low Mach number of turbulent jet flames allows for an efficient incompressible formulation of the LES. From the instationary flow field resulting from the LES, the required information on a control surface or interface to the

acoustic method (ESM/BEM) can be extracted. By using two separate and specialized methods for the flow simulation and the acoustic simulation the large disparity of lengthscales in this problem can be exploited and the far field noise emission of the turbulent flame can be predicted at reasonable computational cost. The hybrid approach discussed above is shown to yield good results. Diluted non premixed hydrogen flames are considered and the results are compared to measurements of the flow field, the thermodynamical state of the fluid, as well as to acoustic measurements of the radiated sound power. These extensive comparisons validate not only the different numerical methods used, but also the complete hybrid approach presented.

INTRODUCTION

Hybrid approaches for the investigation of noise resulting from flow phenomena are widely used and a well accepted approach in the area of aeroacoustics [1], [2]. Especially in low Mach number flows, the fluid dynamical and acoustical lengthscales are separated by more than an order of magnitude. This allows the application of specialized techniques for each domain, namely the source region using computational fluid dynamics (CFD) and the acoustic propagation region all the way into the far field using computational aeroacoustics (CAA). Such a hybrid approach of an incompressible large eddy simulation (LES) for the fluid part and equivalent source or boundary element methods (ESM/BEM) for the acoustic part is applied to open, non-premixed turbulent jet flames in the present contribution. Especially for open turbulent combustion systems, the low Mach number approximation is applicable and hence an incompressible simulation saves computational costs and yields good results [3].

The use of instationary CFD such as the LES method is preferable, since here the turbulent spectrum does not have to be modeled completely. Therefore, conclusions of the sound output of such configurations can directly be drawn. In the case of a stationary RANS approach for the CFD part, the turbulent spectrum and therefore also the noise producing structures have to be modeled, limiting the general applicability of the hybrid approach. Finally, a direct approach, such as DNS of the flow field is beyond any feasible computational cost for technically relevant systems.

CONFIGURATION AND NUMERICAL APPROACH

The goal of this work is to predict and describe the direct combustion noise generated by turbulent non-premixed flames. For this purpose well investigated benchmark flames are used as a first target of investigation. The so called H3 flame, a benchmark flame of the TNF Workshop [4], as well as a slightly modified version, the HD flame [5], are simulated by means of LES and ESM/BEM. The flames consist of a simple round nozzle through which the fuel jet is injected coaxially into a slow coflow of air. The different parameters of the two flames are summarized in the following table 1.

Flame	Fuel [$vol\%$]	$D\,[mm]$	$U_{jet}\,[m/s]$	$U_{coflow}\,[m/s]$	Re	f_{stoic}
H3	50/50 H_2/N_2	8	34.8	0.2	10,000	0.310
HD	23/77 H_2/N_2	8	36.3	0.2	16,000	0.583

Table 1: Parameters of the two standard flames studied.

Large Eddy Simulation of the Flow Field

The well known Favre-filtered (Favre: density weighted) transport equations for mass and momentum, as well as the conserved scalar mixture fraction are solved. Here, the mixture fraction stands for a dimensionless enthalpy or element conservation equation. This is a well known approach for turbulent non-premixed combustion systems, usually called the Shvab-Zeldovich formalism [6]. The required chemical state, like the density or temperature is mapped as a function of the mixture fraction and then coupled back into the solver. Using this approach, a low Mach number approximation can be used for the reacting flow, where the density is not constant, but no function of the pressure at the same time. This is the characteristic property of an incompressible formulation with variable density.

The governing equations are solved on a staggered cylindrical grid of $513 \times 32 \times 60 \approx 1.0 \cdot 10^6$ cells in axial × tangential × radial direction by the incompressible LES code *FLOWSI*. The code uses a 2nd order central scheme for the spatial derivatives in combination with a non-linear total variation diminishing (TVD, here CHARM) scheme for the steep gradients in the convective scalar transport. The time integration is performed by an explicit 3rd order low storage Runge-Kutta scheme. A Smagorinsky model with the dynamic procedure by Germano is applied to model the unclosed subgrid scales [7]. The chemical system is described by a steady flamelet approach integrated in a pre-processing step with a presumed β-PDF to model turbulence chemistry interaction [6]. The mean inflow profiles are superposed by artificially generated turbulence [8], while at the outflow a Neumann condition is applied. The circumferential outer boundary is described with a simplified momentum equation to allow for entrainment of fluid. For a detailed description of the current LES approach, please refer to the following publication [9].

Simulation of the Acoustic Far Field

Based on the velocity data prescribed on a control surface, which encloses the flame source region the equivalent source method (ESM) as well as the boundary element method (BEM) are able to determine the acoustical field outside the control surface by evaluating the surface data [10], [11]. This is less computationally expensive than the evaluation of volumetric data by using Lighthill's Analogy for example.

The ESM replaces the original sound sources with a system of acoustical elementary sources inside the control surface which satisfy the wave equation and radiation condition in the ambient medium and fulfil the boundary conditions on the interface, here the given velocity in normal direction of the surface. The acoustical field outside the control surface is described by the superposition of all the acoustical elementary sources. Details for the used ESM, like positioning and characteristics of the equivalent sources can be found in [12] and [13].

The BEM can be regarded as a special kind of equivalent source method. The equivalent sources are no longer located inside the control surface, but are moved to the surface itself. They are restricted to monopoles and dipoles. The elements of the discretized surface represent a set of a monopole and a dipole sources, respectively. By means of the Helmholtz-Integral-Equation (HIE) a system of equations can be set up for the pressure $p(x)$ on the Kirchhoff-Surface.

$$\iint_S \left[-p(y)\frac{g(x,y)}{\partial n(y)} - j\omega\rho v_{nS}\, g(x,y) \right] \mathrm{d}S = \frac{1}{2}p(x); \quad x,y \text{ on the surface} \tag{1}$$

The Green's function $g(x,y)$ in the HIE is given by the fundamental solution of the wave equation in the unbounded three dimensional space,

$$g(x,y) = \frac{e^{-jkr}}{4\pi r} \quad \text{and} \quad r = r(x,y) = \left\| y - x \right\|. \tag{2}$$

After solving the system of equations the pressure and normal velocity on the Kirchhoff-Surface are known and the sound field in the ambient medium can be calculated directly from these variables [11].

Coupling the two Approaches

The coupling between the LES and the ESM/BEM methods requires the exchange of instationary velocity data. Since both acoustic techniques use a control surface to extract the appropriate source terms, the same cylindrical interface can be used. As an important restriction, the interface needs to enclose the complete source region of the flame and must be located in a flow region where no more influence of the flame takes place and hence the fluid is nearly quiescent. The spatial as well as the temporal resolution need to be matched accordingly.

In the present case samples over a real time period of approximately 0.2 s with a resolution of 10 kHz were collected from the LES. The temporal signal is converted to the frequency domain by Fast Fourier Transform (FFT), using sections of 250 samples with a 50% overlap for subsequent averaging, still maintaining a resolution of 40Hz. A detailed description of the coupling technique can be found in [14].

ACOUSTIC MEASUREMENTS

To validate the numerical results the acoustical sound power of the flames was measured. The radiated sound power was obtained by measuring and integrating the sound intensity on a surface mesh around the flames. Additionally, the sound power of the isothermal flow was quantified for comparison.

Figure 1 shows the measured sound power density for the H3 und HD flame. The combustion process turns out to be the main source of sound. The sound power of the reactive flow is around 20 dB larger than that of the isothermal flow. While the isothermal flow shows distinct peaks of higher sound radiation, the flames emit broadband noise in a wide frequency range without tonal characteristics. Due to the strong similarity of the flames, the sound power spectra of the two flames do not vary substantially.

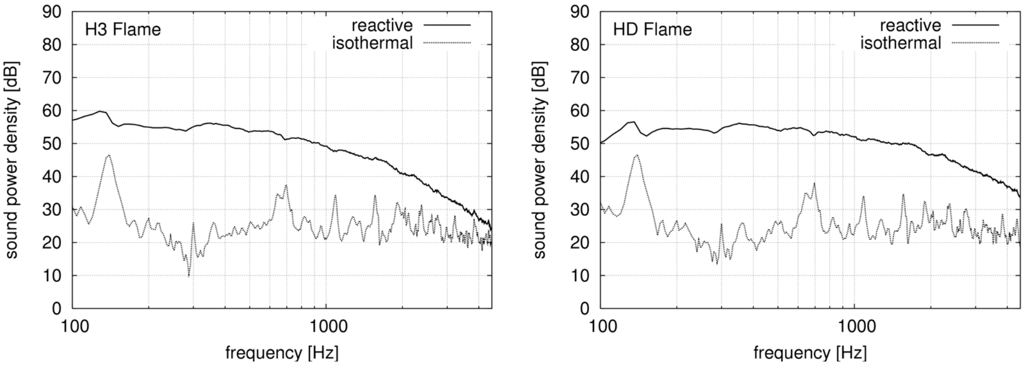

Figure 1: Measurements of the sound power density of the H3 and HD flame as well as the corresponding isothermal cases.

RESULTS

The use of LES allows the extraction of instationary views of the flow field. As mentioned before, this is one of the reasons, why such a simulation technique is that attractive for acoustic hybrid approaches. As an example of such fields, the mixture fraction, the temperature and the mass fraction of OH are shown in figure 2 for a single timestep. Large structures, as well as small structures can be observed.

Validation of the LES

In order to assess the quality of the LES, a detailed comparison of the statistics with experimental findings has to be performed. Here, the results of the TNF-workshop can be used to validate the flow field, as well as the distribution of chemical properties. In figure 3, the mean and standard deviation of different quantities in axial direction are presented for the H3 flame as a representative example. The agreement between experiment and simulation is evident. Only close to the nozzle, the level of velocity fluctuations is slightly overpredicted. This relates to the nozzle shear layer, which is not resolved properly by the LES. The effect is well known and reduces with grid resolution of the LES, but cannot be overcome otherwise.

Further radial comparisons at different axial positions are shown in figure 4. Mean values are presented in the left half of the graphs, while standard deviations are on the right side. Here the previous agreement of the LES is confirmed. The good agreement of the temperature distributions is directly coupled to the mixture fraction, since only the chemistry model plays a determining role.

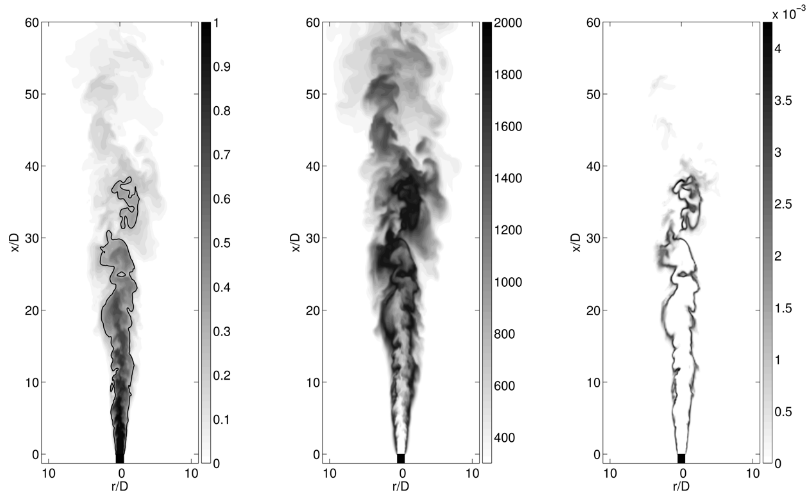

Figure 2: Instationary views of the mixture fraction [-] with the stoichiometric value highlighted by an iso-line, the temperature [K], and the OH mass fraction [-] as a marker for the flame front of the H3 flame.

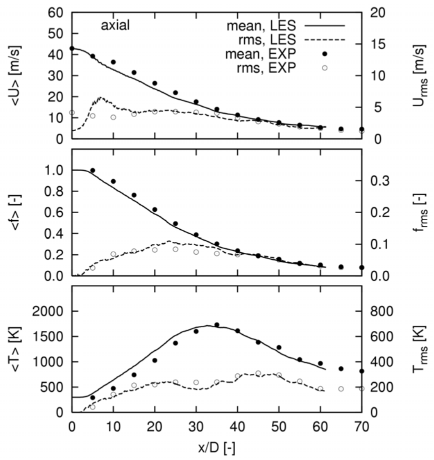

Figure 3: Axial distribution of mean and standard deviation of the axial velocity [m/s], the mixture fraction [-] and the temperature [K] for the H3 flame.

Resulting Acoustics

The calculation of the radiated sound power provides a direct comparison to the acoustical measurements. Figure 5 shows the resulting sound power density for the ESM and BEM simulations, compared to the measurements. The ESM and the BEM simulations lead to nearly the same results, only in the lower frequency range the ESM results differ slightly from the BEM results due to ill-conditioned matrices at these frequencies.

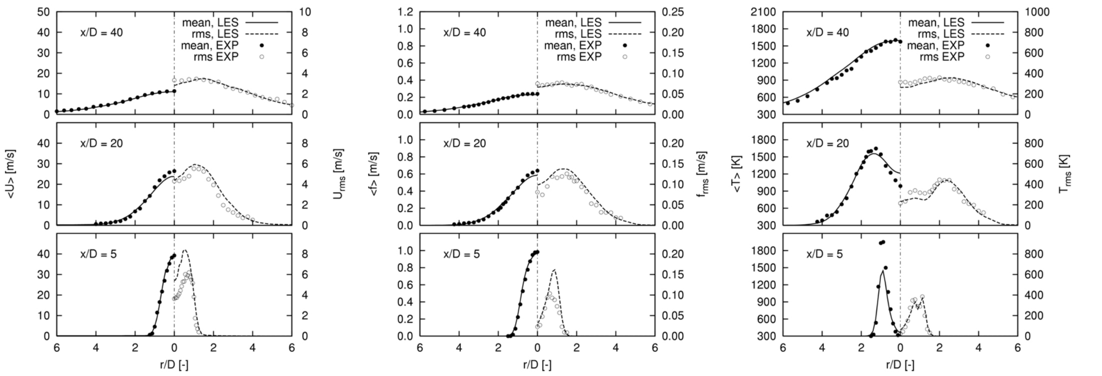

Figure 4: Radial distributions of mean and standard deviation of the axial velocity [m/s], the mixture fraction [-] and the temperature [K] at different axial positions for the H3 flame.

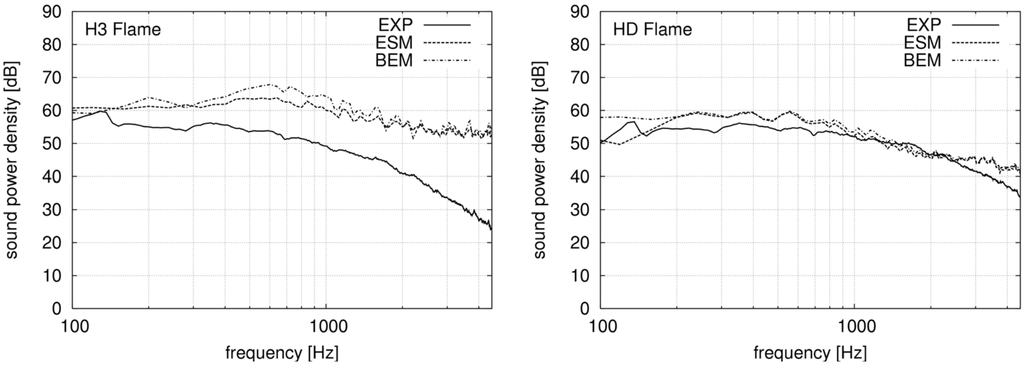

Figure 5: Comparison of the sound power density for the two configurations computed by ESM & BEM to the experimental results.

For the HD flame the resulting sound power is in good agreement with the measured spectra. The differences between simulation and measurement do not exceed 3 dB up to 2 kHz. Above 2 kHz the decrease of the sound power is not well reproduced by the simulations. In contrast the simulation results for the H3 flame differ notably from the measured spectra. The sound power is strongly overestimated in the considered frequency range. Here a turbulent velocity distribution of the closed control surface at the downstream end may disturb the acoustic simulations. The control surface encloses the entire source region, i.e. it enters the non-linear region at the downstream end of the domain. For the HD flame, which is the shorter flame, the turbulent sources have weakened sufficiently in this region. In other words, the ratio of the stoichiometric flame length to the axial extension of the LES domain was not the same in both simulations and might lead to such differences.

CONCLUSIONS

The use of a hybrid approach combining an incompressible LES with ESM and BEM was shown to yield good results for the acoustic far field of open turbulent non-premixed jet flames. Certainly, further improvements are required in order to allow a detailed prediction of the combustion noise stemming from such configurations. Nevertheless, the approach is computationally efficient and very promising.

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