# Numerical investigations of the noise sources generated in a swirl stabilized flame

F. Zhang, P. Habisreuther, M. Hettel and H. Bockhorn[1]

[1] Engler-Bunte-Institute, Division of Combustion Technology, Kaiserstraße 12, 76128 Karlsruhe, Germany

E-mail: feichi.zhang@vbt.uni-karlsruhe.de, peter.habisreuther@vbt.uni-karlsruhe.de

## Introduction

Lean premixed combustion devices have been investigated since quite a time with respect to the flow instabiblities. The excess of air cares for a lower flame temperature to reduce NOx emission. Swirl generators are often used upstream of the burner to stablize the premixed flame at the burner exit. These cause a central recirculation zone by exceeding a critical value of swirl intensity and enhance the flame stability by feeding the hot gases into the root of the reaction zone. Unfortunately, unsteady flow oscillations, usually referred to as combustion or flow instabilities are often induced in such systems. These oscillations may interact with acoustic waves or cause unsteady heat release and may reach sufficient amplitude to modulate the burner outflow. The present work uses the LES (Large Eddy Simulation) method to adress the mechanisms of the combustion and flow instabilities. In this approach, the large scale turbulences are resolved until the cut-off level and the small ones are modelled via a so-called sgs (sub grid scale)-model. Since the large eddies carry the most of the energy in the flow and generally show a non-isotropic behaviour, it is adequate to model the small eddies, whereas these exhibit more universal features. Thus, the LES technique is well suited for studying instabilities in the combustor devices, because the flow field of concern is highly unsteady and dominated by turbulence motions that can be adequately resolved computationally.

## Numerical setup

Basics of the numerical modelling are the compressible Navier-Stokes equations and the energy equation[2]. To add combustion in the flow, an additional transport equation for the progress varialbe $\theta$ has to be solved, which describes chemical reaction progress in a first approximation. In the framwork of LES the transport equation of $\theta$ yields the form:

$$\frac{\partial \bar{\rho}\widetilde{\theta}}{\partial t} + \nabla \bullet (\bar{\rho}\widetilde{\vec{u}}\widetilde{\theta}) = \nabla \bullet (\frac{\mu_t}{Sc_t}\nabla\widetilde{\theta}) + \overline{\dot{\omega}}. \quad (1)$$

where overbars and tildes denotes the filtered scale and Favre-averaged scale. The source term $\overline{\dot{\omega}}$ can be given using a TFC (Turbulent Flame speed Closure) approach and the turbulent flame speed $S_t$ can be derived from theoretical or experimental analysis. This combustion model has been implemented in the commercial CFD code CFX which uses an unstructured finite volume method (FVM) to solve the compressible Navier Stokes equations and is capable to run LES. Habisreuther et al. [1] performed an isothermal LES with CFX for the strongly swirled burner used in this paper and achieved very good agreement with respect to the measured mean flow values and the Reynolds stresses.

## Lighthill's acoustic analogy

The Lighthill's acoustic equation for the density fluctuation results by conversion of the basic fluid mechanics equations without any approximation and linearization:

$$\frac{\partial^2 \rho'}{\partial t^2} - c_0^2 \Delta \rho' = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}, \quad (2)$$

$$T_{ij} = \rho v_i v_j - \tau_{ij} + \delta_{ij}(p' - c_0^2 \rho'). \quad (3)$$

$T_{ij}$ is the Lighthill's stress tensor and $c_0$ the sonic speed. The left hand side of eq.(2) has the form of a linear wave equation and the right hand side of this inhomogeneous wave equation can be considered as a source term presuming no viscous terms and small Mach numbers. While the turbulent reacting flow acts as a source, the acoustic waves propagate in a uniform acoustic medium. The transfer of informations from the sources to the external medium is achieved through the Lighthill stress tensor $T_{ij}$. In a turbulent reacting flow, the viscous stress $\tau_{ij}$ in $T_{ij}$ is very small in comparison to the other two terms and can be neglected. The velocity correlation term $\rho v_i v_j$ and $p' - c_0^2 \rho'$ represent the sources caused by the turbulent flow and by the unsteady heat release. An order of magnitude analysis of the Lighthill's tensor showed [3] that the ratio of both terms scales to $Ma^2$, which indicates further, that for turbulent reacting flows at low Mach numbers $Ma^2 << 1$, the dominant term will be the last one on the right hand side of eq.(3).

## Analysis of the LES result

The reacting flow field analysed in this section is a result from a compressible LES simulation of a double annular swirl burner [1](fig.1). The combustable mixture used here consists of air and methane. The total thermal energy of both pilot and main flow is 135 kW. Details of both inflows are listed in table 1. $\dot{V}$ is the volume flow rate and $\lambda$ the air equivalence ratio. The Reynolds-number based on the main flow nozzle velocity and diameter was $Re \approx 27000$. Furthermore, the sources in Lighthill's

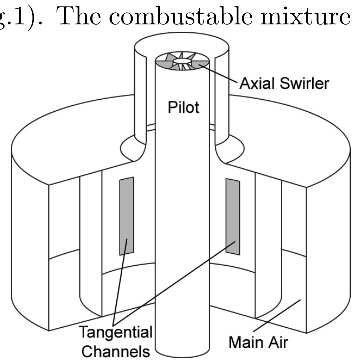

**Figure 1:** Scheme of the double-concentric swirl burner

equation are computed on the cartesian grid using the resolved quantities obtained by the interpolation from the LES directly. As this work focuses on the analysis, further details of the burner and simulation are omitted here, but can be found in [1].

**Table 1:** Inlet boundary conditions of the burner.

| | | | |
|---|---|---|---|
| $\dot{V}_{main}$ | $180 m_N^3/h$ | $\lambda_{main}$ | 1.5 |
| $\dot{V}_{pilot}$ | $20 m_N^3/h$ | $\lambda_{pilot}$ | 1.05 |

The slices shown in Fig.2 and Fig.3 give an overview of the caculated Mach number (Ma) and the progress variable $\theta$. The shape of the jet flame can be seen, the overall mach number is very small ($\max(\text{Ma}) \approx 0.06$) and a thin reaction zone is formed close to the nozzle.

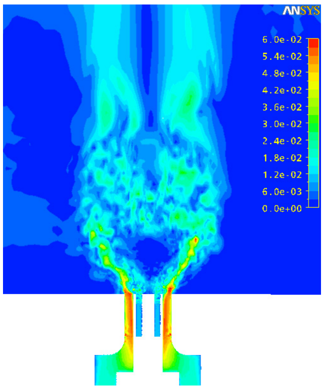

**Figure 2:** Mach number.

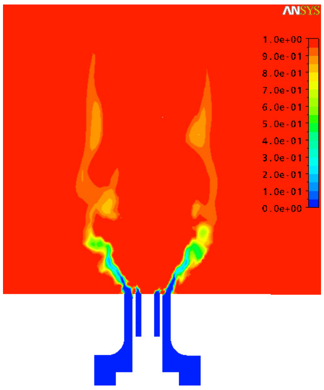

**Figure 3:** Progress variable.

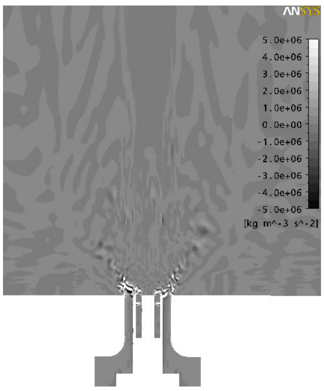

**Figure 4:** $S_{aero}$.

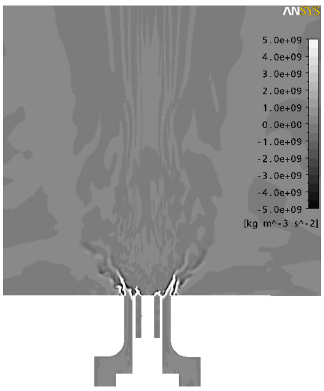

**Figure 5:** $S_{cn}$.

In fig.4 and fig.5, the two main contributions to the Lighthill tensor are compared for the same point in time by a slice view. These are on the one hand the aeroacoustic source $S_{aero} = \frac{\partial^2}{\partial x_i \partial x_j}(\rho v_i v_j)$ and on the other hand the combustion noise source $S_{cn} = \frac{\partial^2}{\partial x_i \partial x_i}(p' - c_0^2 \rho')$, defined in eq.(2) and eq.(3). As can be seen, the main source region occurs close to the nozzle exit of the burner, due to the strong variation of the density and the velocities. The combustion noise source is located exactly at the thin layers, where the reaction takes place. Due to the expansion of the inflows into free domain and the chemical reaction, strong turbulence and acoustic source were generated, which are also evident from fig.4, where one can detect both the reaction zones and vortex structures along the jet flame. Moreover, the magnitude of $S_{cn}$ is about 3 order higher than the magnitude of $S_{aero}$, this holds true since the overall observed Mach numbers are smaller than 0.05 and $S_{aero}/S_{cn} \propto Ma^2$.

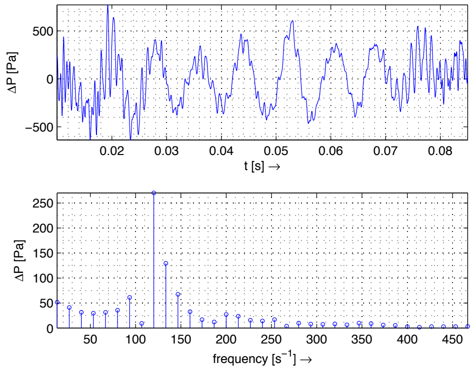


**Figure 6:** Spectrum of the monitor point in the burner.

During the LES several monitor points in the flow domain have been used to follow the temporal progress of the flow variables. Fig.6 shows the spectrum of the monitor point in the main inflow of the burner. A distinct preferential frequency of about 120 Hz can be identified, which is known as the burner eigen frequency. The responsible flow structure is transported downstream to the outside of the burner and can be detected in the main jet. It also caused periodic fluctuation of the local mixture fraction in the reaction zone, and as a result, the reaction rate fluctuates with the same frequency. Other preferential frequencies were also identified in the jet flame, which correspond to the turn over frequency of the swirl flow and the vortex shedding frequency. Because of space limitations, these are not displayed here.

## Conclusion

The Lighthill's acoustic analogy was taken into account to evaluated the noise sources generated by a swirl burner. The contributions of the different components of the Lighthill tensor have been illustrated by visualization of a LES snapshot. Spectral analysis on several monitor points within the flow has been made to analyse the flow/combustion dynamics.

## References

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