# Power spectra measurements for the density fluctuation in a jet flame using dual laser vibrometry

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**Abstract**

Investigation of density fluctuations in a jet-flame were performed using a laser-interferometry. Two laser vibrometer systems together with a signal analyzer were used to obtain frequency spectra of density fluctuations in a methan-air diffusion flame. Laser vibrometers (LVs) are common tools to record surface vibrations up to 200-300 kHz. The capability of LV in recording density fluctuations was published by Mayrhofer and Woisetschläger [1] and Hampel and Woisetschläger [2] for isothermal jets, and Giuliani [8] for premixed air-methane flames. This paper reports on the differences between the spectra obtained in the jet-flame compared to measurements previously done in a non-reactive jet by Hampel and Woisetschläger [2].

## Introduction

For industrial gas turbines and aeroengines the trend is towards optimum use of fuel and reduced emissions. To achieve this goal different combustion chamber concepts are under investigation. For example lean premixed combustion concepts are very promising in reducing emissions. Since these combustors operate near the lean flammability limit they have strong tendency towards combustion instabilities. Unwanted effects like self-sustained pulsed heat release and oscillations of the static pressure caused by these instabilities might result in severe mechanical damage of the machine. Thus the study of turbulent combustion phenomena is of special interest to understand this physics with aim to predict and control these instabilities.

Intensive research is done in the field of turbulent combustion using laser metrology, since optical techniques promise non-intrusive investigations of the flow field and combustion. To gain information on the flow field itself, measurement techniques such as Laser Doppler Velocimetry or Particle-Image-Velocimetry [3, 6] are used. To obtain detailed information on the combustion Raman- or Rayleigh-scattering and planar laser-induced fluorescence (LIF) can be applied [6, 7].

The Institute of Thermal Turbomachinery and Machine Dynamics focuses on flows and combustion in modern turbomachinery. For the investigations of combustion and combustion instabilities laser vibrometers are of special interest. They provide information on the density fluctuations along the laser beam and are used for real-time combustion stability diagnostics by Giuliani et al [8]. To overcome the limitations of integral measurements by the laser vibrometers, a statistical approach to correlate signals in different directions was proposed by Hampel and Woisetschläger [2]. The present work investigates local frequency spectra of density fluctuations in turbulent combustion using the same method.

## Experimental Setup

*Burner design and operating conditions*

The burner used for the experiments was designed and developed by Kawanabe et al [3]. The burner was operated at atmospheric pressure conditions and provided a methane-jet diffusion flame with a nozzle exit velocity of 17.6m/s for a nozzle exit diameter of 4mm. The temperature of the methane jet was 21°C thus yielding a mass flow of 0.15g/s and a Reynolds number of approximately 4300, based on the exit nozzle diameter. An annular air jet (nozzle exit diameter 50mm) surrounded the central methane-jet. The velocity of the air-flow was 0.5m/s and its temperature was 21°C resulting in a mass flow of 1.30g/s and a Reynolds number of approximately 1800.

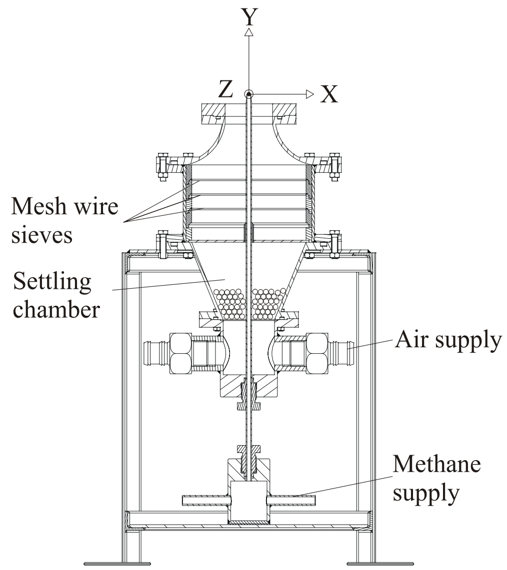


Figure 1: Cross-section of the diffusion burner used for the investigation of the density fluctuations in the methane-jet flame.

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Proceedings of the European Combustion Meeting 2009

The air was supplied by an in-house pneumatic system. Before entering the exit nozzle, the air flow passed a settling chamber filled with steel balls of diameter 3mm. Additionally three wire mesh sieves with a mesh size of 0.16mm were mounted downstream of the settling chamber to condition in the air flow turbulence. The methane supply was ensured by a bottle of methane. Figure 1 shows a drawing of the burner.

*Arrangement and optical setup*

The complete setup was mounted on a vibration-insulated table. Two laser vibrometer were fixed on a DANTEC traversing system, so that the two laser beams crossed orthogonally. The emerging laser beam of each vibrometer was collimated by a diverging lens (f=-40mm). The beam passed the measurement area and was reflected by a flat mirror, passed the measurement area again and reentered into the aperture of the vibrometer. Each mirror was mounted at a distance of 1m away from the respective LV. To avoid surface vibrations, both mirrors were fixed using vibration insulation. Figure 2 shows the setup for the laser vibrometers and mirrors.

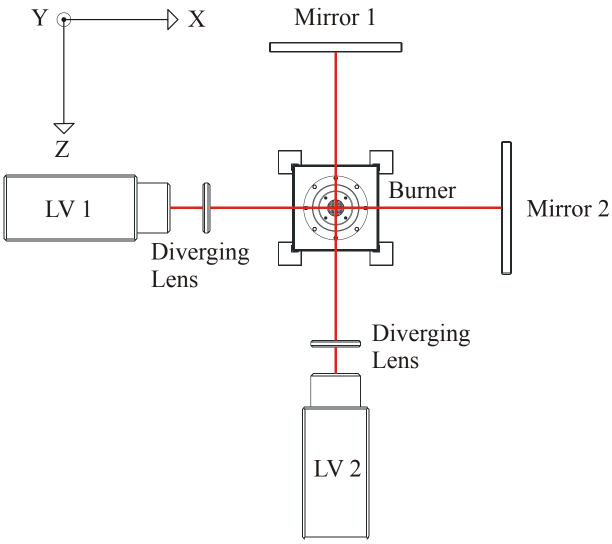


Figure 2: Principal setup of the LV for the investigation of density fluctuations in the methane-jet flame.

The vibrometers employed were both model POLYTEC OFV-353 each with an OFV 3001 controller unit. In our experiments the calibration factor k was set to 5 mm $s^{-1}$ $V^{-1}$ and a low-pass filter of 20 kHz was chosen. The measurement planes were placed at four different heights 70, 90, 120 and 150mm (see Figure 3) above the methane nozzle exit, perpendicular to the methane flow direction.

The burner was pivot-mounted on the vibration-insulated table to allow measurements from different viewing angles. The necessity of several measurements is due to artifacts, which could be caused by large coherent structures in the flow, as previously described in [2].

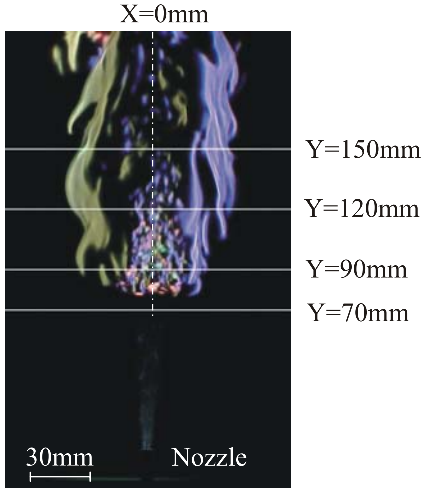


Figure 3: Color-Schlieren-visualization of the methane-jet flame. Layers for LV measurements are marked according to the coordinate-system in Figure 1.

*Data acquisition and signal processing*

The analogue voltage signals of both vibrometers were digitalized by a National Instruments PXI-1033 chassis and a NI 4452 A/D converter board. The NI 4452 A/D converter board was mounted in a standard PC, which displayed the FFT of both signals for observation purpose only. The PXI-1033 chassis was connected to another PC for data acquisition. Both vibrometer signals were recorded simultaneously by software developed using National Instruments' LABVIEW 8.0. A sample rate of 40.96kHz and a recording duration of 100s were chosen per measurement point. FFT transformation of pieces of the time signal with 4096 values resulted in 1000 spectra with a frequency resolution of 10Hz. The FFT, the calculation and the averaging of the cross spectra was done in MATLAB vR2007b. The data acquisition software created in LABVIEW 8.0 was also used to automate the LV measurements. After a given measurement point was reached the software waited 4 seconds for the vibrations, caused by the traversing, to damp down before starting the data acquisition.

*Measurement technique*

Laser vibrometers are commonly used for vibration analysis on surfaces. The laser vibrometer therefore detects the changes in the geometrical path length of a laser beam reflected by a vibrating surface. By keeping the geometrical path constant, it is possible to detect density fluctuations in flows, as these fluctuations alter the optical path, delaying or advancing the phase front of light. This method was used by Mayrhofer and Woisetschläger to investigate density fluctuations in an isothermal jet [1]. They showed that the output voltage signal of the laser vibrometer is proportional to the time derivation of the density ρ' as follows:

$$u'_f = \frac{G}{k} \int_z \frac{\partial \rho'_f}{\partial t} dz \qquad (1)$$

In this equation G is the Gladstone-Dale constant, k the calibration factor of the vibrometer and z the penetration length of the laser beam through the medium. Obtained data are of integral nature, so that all changes in density are integrated along the optical path of the laser beam.

Spatially resolved data can be received by applying mathematical algorithms like the Abel transformation or Algebraic Reconstruction to the raw data but the use of these algorithms is restricted. Investigated geometries have to be simple and density or density changes must be close to zero at the boundaries of the flow field. To obtain spatially resolved data for arbitrary geometries and density changes unequal to zero at flow field boundaries Hampel and Woisetschläger [2] developed a measurement technique crossing two laser beams. The beams intersect at a certain position and the signal of both vibrometers contains information on the density changes at this position. As the measurement volume is small compared to the total beam length, the signal of interest is only a minor part of the total integral signal strength of each vibrometer. Mathematical processing has to be applied to the raw data to determine the correct strength of the fraction of the integral signal. As turbulent density fluctuations should be measured, the use of statistical methods is necessary. The main tool for this method is the application of frequency resolved correlation in the form of averaged cross spectra. Hampel and Woisetschläger successfully employed this method to investigate local density fluctuations and power spectra in a turbulent isothermal jet. A detailed description of the method and the underlying mathematical considerations can be found in [2]. The same method was used in the experiments described in this paper to evaluate raw data obtained in the flame.

Local power spectra of density fluctuations are calculated using frequency-resolved correlation in the form of averaged cross spectra. Therefore both vibrometer time signals are divided into sets of 4096 measurement values and FFT is done for each set. Subsequently cross spectra are built consisting of the product of one spectrum and the complex conjugate of the other spectrum. Afterwards a frequency-wise averaging of cross spectra is done over a number of spectra. The cross spectrum is a degree for the coupling strength of both spectra. Its magnitude is the power spectrum of the fraction included in both signals. The complex angle of the cross spectrum is the phase difference of both signals according to the frequency-dependent and averaged time delay of the equal parts within the two signals [2].

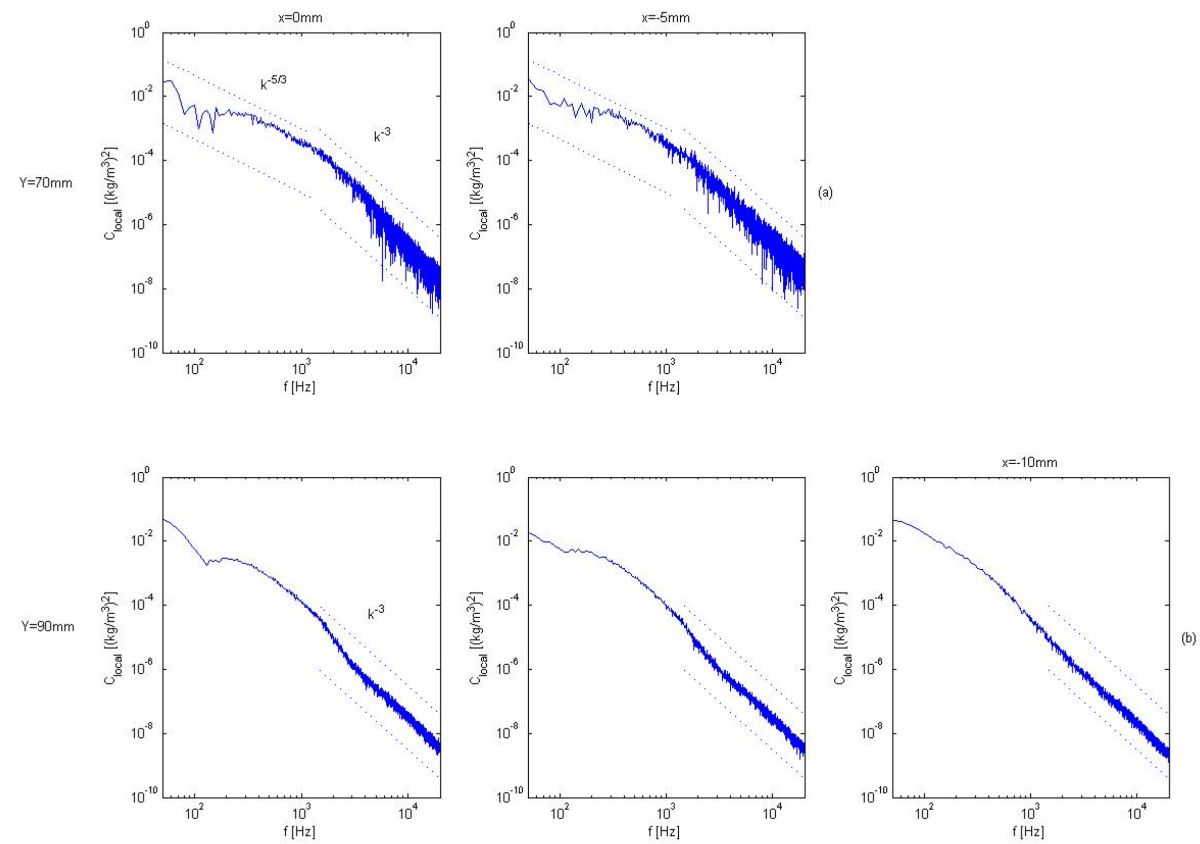


Figure 4(a), (b): Spectra of local density fluctuations at Y=70mm and Y=90mm. (a) Local spectra of the non-reactive methane-jet at x=0mm and x=-5mm. Position x=-10mm is outside the methane-jet and therefore not plotted. Dashed lines represent the power law exponent -5/3 or -3. (b) Local spectra of density fluctuations in the flame. Dashed lines show a decline with exponent -3.

**Results and Discussion**

In figure 4(a) spectra of local density fluctuations of the non-reactive methane-jet are plotted at x=0mm and at x=-5mm for Y=70mm. At this height combustion has not started yet. Dashed lines represent a decline with an exponent of -5/3 and -3. The -5/3 power law describes the Kolmogorov decay in the so called inertial-convective region, the -3 power law is a special feature of buoyant jets and belongs to the inertial-diffusive sub range. According to Papanicolaou and List [4] the jet behaves like a non-buoyant pure jet in the region close to the jet exit, followed by an intermediate region, where inertial and buoyancy forces have the same order of magnitude. After the intermediate region the jet behaves like a pure plume.

The position for the transitions from non buoyant region to intermediate region can be estimated according to Wang et al [5]. For our experimental conditions this estimation leads to a transition position at approximately 70 to 80mm above the nozzle.

Figure 4(b), (c) and (d) show spectra of local density fluctuations at different heights and positions in the flame. At higher frequencies a decline with exponent -3 can be seen in all pictures in the flame. Compared to figure 4(a) no -5/3 decay can be found. Buoyancy-generated forces seem to dominate over the inertial forces within the flame.

At frequencies higher than 2-3 kHz the noise in some of the spectra reaches a high level and interpretation has to be done carefully. The noise is due to the finite number of spectra averaged in the measurement process, as the deterministic signal has to be calculated from chaotic signals. According to Hampel and Woisetschläger [2], the signal quality can be checked by observing the correlation factor. In dependence on the number of averaged spectra a limiting relative correlation can be defined. If the relative correlation of a cross spectra is below this value, the real spectrum can not calculated as the noisy background is too strong. Increasing the recording duration per measurement point, thus leading to a higher number of spectra, offers an opportunity to improve results.

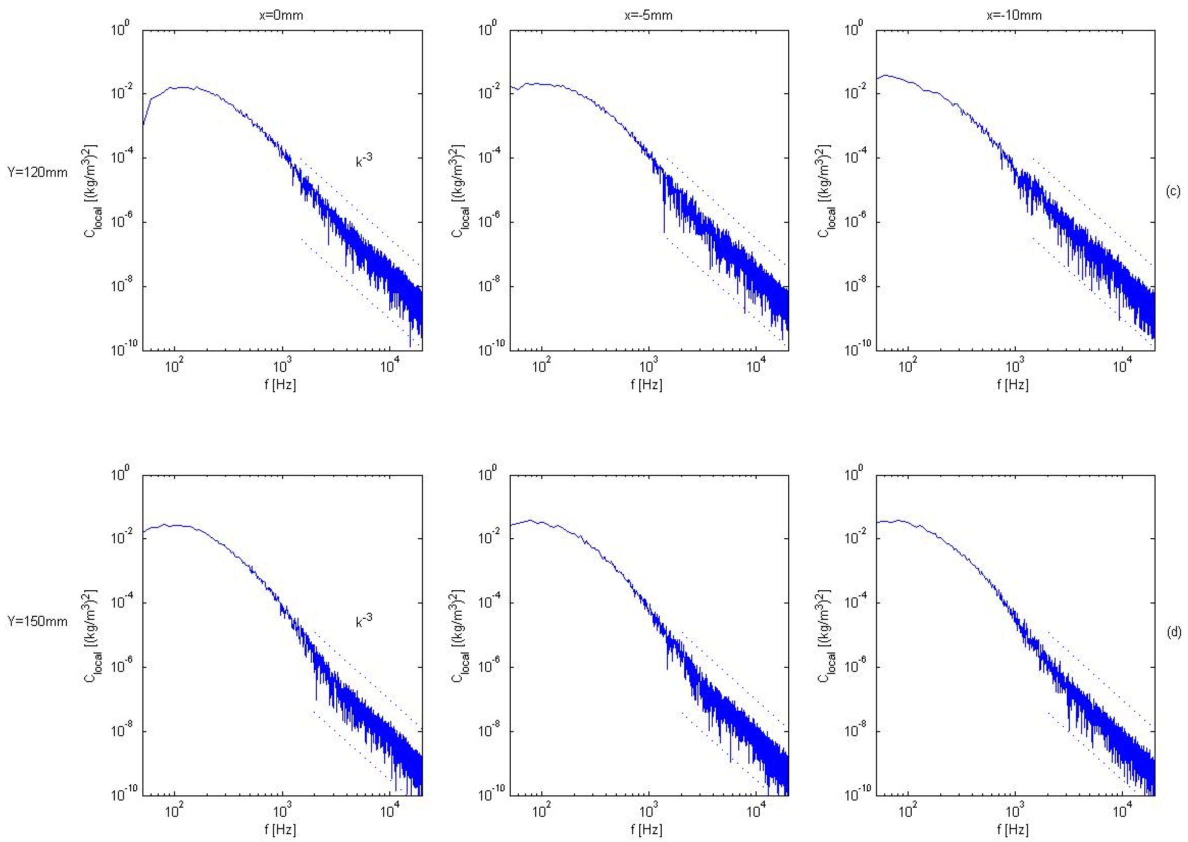


Figure 4(b), (c): Spectra of local density fluctuations at Y=120mm and Y=150mm. Dashed lines represent an exponent of -3.

## Conclusion

In this paper, two laser vibrometers were used to record the local magnitude of density-fluctuations in a methane-jet diffusion-flame. This measurement technique has been used at the Institute of Thermal Turbomachinery and Machine Dynamics previously, but was applied to investigate local density fluctuations in combustion for the first time in our experiments.

Several measurements were performed at different heights in the flame and one was performed in the methane-jet. The obtained power spectra showed different decay compared to the isothermal jet investigated in [2]. Instead of the expected -5/3 decay according to the Kolmogorov law a decline with an exponent of -3 was observed at higher frequencies, indicating a domination of buoyancy-generated forces over inertial forces.

In a further step we plan to employ this measurement technique for investigations of density-fluctuations in a gas turbine model combustor in a multiple flame configuration.

## Acknowledgements

This work was funded by the Austrian Science Fund (FWF) in grant P19955-N19 (Experimental Investigation of Flame-Flame Interaction in a Gas-turbine Model Combustor with Forced Flow Instabilities). We want to thank Mr. T. Leitgeb for his help with the automation of the traversing system. Furthermore the authors wish to thank Mr. Ch. Walchshofer and Prof. H. Steiner from the Institute of Fluid Mechanics and Heat Transfer for their support with theoretical background. In the end we would like to thank the Erasmus Exchange Program supporting F. Fontaneto for the academic year 2008/2009.

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