# The Dynamic Behaviour of Turbulent, Premixed Swirl Flames

**C. Külsheimer, H. Büchner and H. Bockhorn**
**Combustion Technology, Engler-Bunte-Institute**
University of Karlsruhe (TH), 76128 Karlsruhe, Germany
e-mail: Christian.Kuelsheimer@vbt.uni-karlsruhe.de

**Abstract**

The physical understanding of the frequency-dependent flame dynamics on periodic disturbances is indispensable for the prediction of the formation of combustion-driven oscillations in technical combustion systems (e.g. gas turbines). It is also essential for the development of methods to prevent or to suppress periodic combustion instabilities.

In the present paper the fluid dynamical conditions (Pu/Str) for the first-time formation of ring vortex structures in the burner near region of pulsating isothermal swirl flows are determined. Subsequently the dynamical behaviour of turbulent premixed swirl flames and the influence of the vortical structures on the combustion process is discussed by means of measured flame transfer functions and phase-correlated planar imaging of OH-LIPF (laser-induced predissociative OH-fluorescence) and Rayleigh scattering. The results of the measurements presented in this paper contribute to a basic understanding of the formation and reaction of large-scale coherent vortex structures in turbulent flames, that are realized as drivers of combustion instabilities.

## Introduction

The development of combustion systems to minimize the flue gas emissions ($NO_X$, CO, HC, etc.) and to increase the system efficiency is combined with technical modifications or new combustor design. This also includes modifications of the combustion process using premixed systems and swirl stabilized flames (e.g. gas turbines), which cause high-intensity combustion and enable combustion systems with higher reaction densities. Linked with these improvements, increasing stability problems caused by the appearance of combustion-driven oscillations are observed. The induced pressure oscillations can lead to total damage of the engine and therefore, the combustors can only be run with restrictions on the operation conditions. As the most important mechanism driving these combustion instabilities the in phase formation and combustion of large-scale coherent vortical structures has been identified [1,2].

## Background

The formation of ring-vortex structures is a fundamental fluid dynamical phenomenon, that can always be observed together with the existence of periodic pressure oscillations in highly turbulent combustion systems. The appearance of these ring-vortices was found for non-premixed as well as for premixed combustion systems and is also independent on the applied flame type (jet-, bluff body- or swirl stabilized flames). At a particular combination of amplitude and frequency of the pressure fluctuations these toroidal vortices are formed, rolling-up the outer regions of the separated fuelgas/air mixture flow, together with additional entrained ambient medium [2,3]. Therefore, the mixing and reaction fields of the steady-state flame are changing totally, combined with a modulation of the heat release rate of the flame, which in turn maintains the pressure oscillations in the combustion chamber (Rayleigh-criterion).

Hence, the understanding of the interaction of the periodic flow field, forced by the pressure fluctuations in the combustion chamber, and the flame response is one of the keys to find methods to control self-excited combustion instabilities sustained by this mechanism. The described feedback mechanism for flame/pressure oscillations is schematically shown in figure 1.

Investigations to determine the dynamic behaviour of flames are based on two important points that have direct influence on the appearance of periodic combustion instabilities in a burner-flame-combustion chamber assembly: The flame provides the energy for the amplification of initial small disturbances in the combustion system and for the sustainment of the pressure fluctuations, while cover friction losses of the combustion chamber. Additionally, the effective time delay between the disturbance of the mass flow through the burner nozzle and the fluctuation of the resulting heat release rate of the flame varies in a wide range in dependency on numerous operation parameters of the combustor (e.g. thermal load, air equivalence ratio, air-preheating, etc.). While -in a defined burner and combustion chamber geometry- the time delay between heat release rate and pressure fluctuation and between pressure and mass flow modulation are more or less fixed at a given geometry of the components.

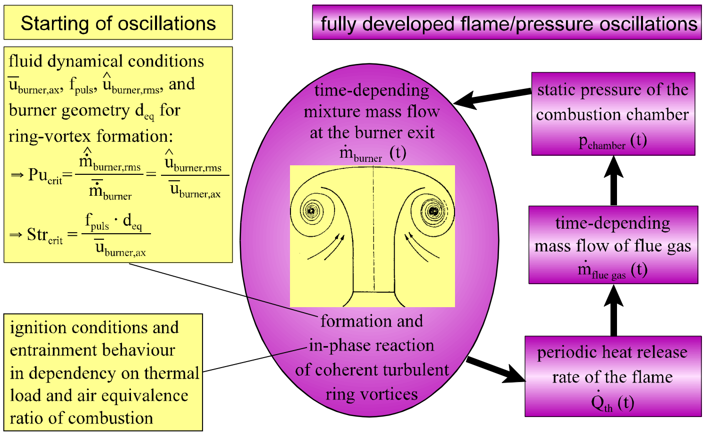

Fig. 1: Feedback mechanism for flame/pressure oscillations

The results of the present investigations of the dynamic behaviour of swirl flames can be used to check and to validate numerical simulations of the flame behaviour for different excitation frequencies and amplitudes. Additionally, the determination of the flame dynamics is essential to improve prediction models for the formation of self-sustained combustion instabilities. Furthermore, the knowledge obtained by the flame response measurements of pulsated flames (formation of large-scale vortices and their influence on combustion process and phase angles of the flame) enabled the development of measures to suppress the reactive ring-vortices and hereby, to control the formation of self-sustained combustion instabilities [2].

## Experimental Setup and Measurement Techniques

The investigations of pulsated isothermal flow fields and natural gas-fired, premixed swirl flames were carried out using swirl burners with variable swirl intensities $S_{0,th}$ (axial vane swirlers with different vane angles). An adjustable part of the total air or fuelgas/air mixture mass flow was modulated sinusoidally in time using a pulsating unit, which generates periodic oscillations of the mass flow rate at the burner nozzle exit within a frequency range between 1 to 350 Hz with continuously adjustable amplitudes up to 70% of the mean mass flow rate. A detailed description of this pulsating unit is given in previous papers [4,5].

The applied measurement techniques were: hot-wire anemometry to determine the periodic mass flow fluctuations at the burner exit ($\hat{\dot{m}}_{b,rms}$, flame excitation), a photomultiplier for the detection of the overall intensity of UV-radiation at a wavelength 8 = 306.7 nm emitted by excited OH*-radicals from the reaction zone of the flame (flame response, no laser excitation) and phase-correlated picture taking of the periodically changing isothermal flow field and flame structures (Rayleigh scattering and OH-LIPF).

## Experimental Results and Discussion

### Fluid dynamical conditions for ring-vortex formation in pulsated isothermal swirl flows

The fluid dynamical conditions (Pu/Str) for the first-time formation of coherent ring-vortex structures were determined in pulsated isothermal swirl flows visualized by the means of a tracer medium and laser light-sheet technique. The results obtained for the periodically excited isothermal flow fields of swirl burners with different swirl intensity and various mass flow rates are shown in figure 2.

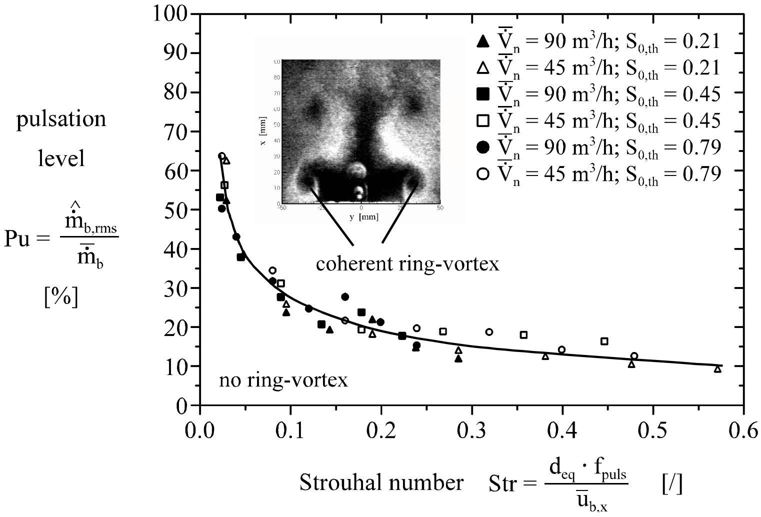


Fig. 2: Dynamical flow conditions (Pu/Str) characterizing the formation of coherent vortex structures in pulsated swirl flows

The pulsation level $Pu_{crit}$, that is necessary to generate periodically toroidal structures at a given pulsation frequency $f_{puls}$, decreases hyperbolically for all investigated flows with increasing frequency $f_{puls}$. The measured discrepancy of the parameter combination $(Pu/f_{puls})_{crit}$ for different swirl intensities ($S_{0,th}$) and mass flow rates ($\sim \bar{\dot{V}}_n$) can be normalized, transforming the frequency $f_{puls}$ into the dimensionless characteristic Strouhal number defined by $Str = f_{puls} \cdot d_{eq} / \bar{u}_{b,x}$ . The equivalent diameter $d_{eq}$ is calculated from the free flow area of the burner and $\bar{u}_{b,x}$ represents the mean volumetric velocity in axial direction at the burner exit. For the investigated swirl burner types, the limit for the formation of coherent vortex structures is given by nearly constant combinations of Pu and Str (see fig. 2).

These critical parameter combinations $(Pu/Str)_{crit}$ found in the isothermal flow experiments characterize the fluid dynamical conditions for the formation of a first-time ring-vortex structure in the burner near region. These results are very interesting, particularly with regard to periodic disturbances of the mass flow rate created by the burner construction itself (isothermal, self-excited flow instabilities, e.g. vortex shedding, etc.) [6]. If the level of disturbance is sufficiently large enough to generate periodic coherent vortex rings close to the burner exit at a disturbance frequency given by geometry and flow rate, a certain part of the mass flow rate through the burner - under combustion conditions fuelgas/air mixture - will be included in the vortex structure together with ambient medium and - in case of ignition- produce a periodic heat release, which can be seen as the starter of combustion-driven oscillations.

### Investigations of the flame dynamics (flame transfer functions)

In analogy to control theory the flame transfer function describes the dynamic response characteristics of the flame represented by an amplitude response $|F_{fl}(f_{puls})|$ and a phase angle function $\eta_{fl}(f_{puls})$. Therefore, the time functions of the flame excitation and of the system response have to be measured simultaneously. In this paper the time signals of the mixture mass flow rate at the burner exit (flame excitation: hot wire signal) and of the heat release rate of the entire flame (flame response: photomultiplier signal) were recorded simultaneously and analysed to calculate the flame transfer function (see eq.1) [4]. The amplitude response $|F_{fl}(f_{puls})|$ describes the ratio of the rms-value of the total heat release rate and the rms-value of the mixture mass flow rate at the burner exit at a defined frequency of pulsation $f_{puls}$, both normalized by their dedicated rms-values of the corresponding quasi-steady flame. The phase angle function $\eta_{Fl}(f_{puls})$ is related to the overall time delay $\bar{T}_{d,fl}(f_{puls})$ between the outflow of the fuelgas/air mixture at the nozzle exit and their reaction in the main reaction zone of the turbulent flame.

$$|F_{fl}(f_{puls})| = 20 \cdot \log \frac{\dfrac{\hat{U}_{pm,rms}(f_{puls})}{\hat{U}_{pm,rms}(f_{ref})}}{\dfrac{\hat{u}_{b,rms}(f_{puls})}{\hat{u}_{b,rms}(f_{ref})}} \quad ; \quad \varphi_{fl}(f_{puls}) = - T_{d,fl}(f_{puls}) \cdot f_{puls} \cdot 360^{\circ} \qquad (1)$$

The flame behaviour of pulsated non enclosed, premixed swirl flames with different swirl intensities is shown in figure 3. For a better understanding of the flame response the behaviour of an ideal idle-time model - well known in control theory - is plotted additionally in these figures. For the amplitude response $|F_{fl}(f_{puls})|$ in figure 3a the model describes a flame behaviour, that does not show any damping or amplification of the excitation, which means, that the normalized UV-radiation emission (rms-values) of the pulsated flame at every frequency is equal to that of the flame taken at a frequency $f_{ref}$, where the pulsated flame behaves at any time within the period of excitation as a steady-state flame with the same mean thermal load and air equivalence ratio [4].

The measured amplitude frequency responses display a significant difference from this ideal idle-time model. Up to a particular frequency the normalized fluctuations of the OH*- radiation intensities increase in comparison to the normalized fluctuations of the mass flow rate (eq. 1). With further increase of the frequency the measured amplitude frequency response decreases, so that the amplitude response of the flame transfer function for all measured premixed swirl flames is characterized by a maximum ($|F_{fl}(f_{puls})| > 0$ dB) at a particular frequency depending on two contrary effects.

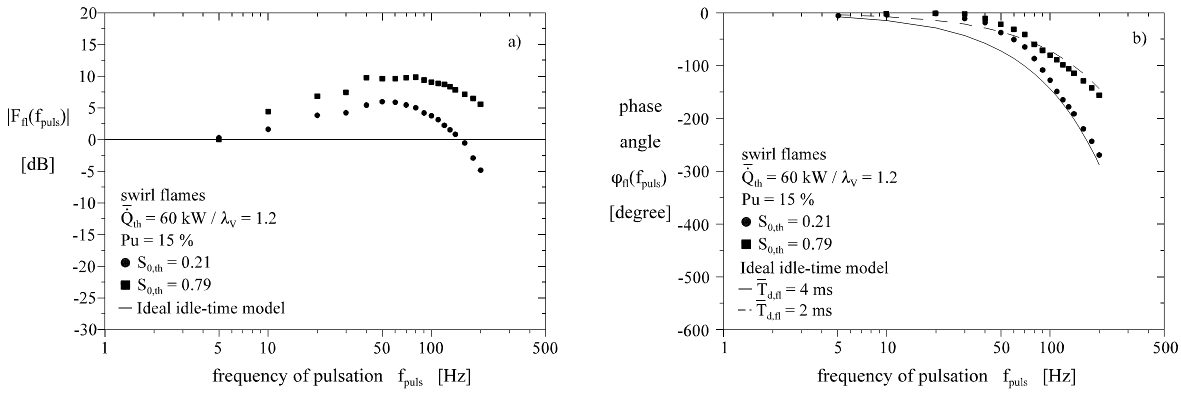


Fig. 3: Amplitude response $|F_{fl}(f_{puls})|$ (a) and phase angle $n_{fl}(f_{puls})$ (b) of swirl flames with different swirl intensities

For moderate pulsation frequencies the detected periodic heat release rate of pulsated, premixed swirl flames is influenced by an effect that inhibits the strong entrainment of ambient medium in comparison with the corresponding steady flames. With increasing frequency this effect will be overlaid by the periodical formation of vortex rings (fig. 2, isothermal flow investigations) entraining additionally and interfering with the combustion process.

The phase angle functions $n_{fl}(f_{puls})$ of pulsated premixed swirl flames, displayed in figure 3b, differ considerably from the phase angles of pulsated premixed axial jet flames, which show a good agreement with the ideal idle-time model, that is characterized by a constant time delay $\bar{T}_{d,fl}$, independent of the excitation frequencies [4]. This means, that the time delay $\bar{T}_{d,fl}(f_{puls})$ (eq. 1) between a change of the mass flow rate at the burner exit and the resulting change in heat release rate is strongly frequency-dependent for pulsated premixed swirl flames. For higher swirl intensities the phase angles decrease with a smaller gradient and as a consequence, the swirl flame reacts on periodic excitation with a shorter time delay than in the case of lower swirl intensities.

**Investigations of the flame dynamics (planar imaging of OH-LIPF and Rayleigh scattering)**
For a detailed description of the observed dynamic behaviour of premixed swirl flames (flame transfer function) phase-correlated planar imaging of the laser-induced predissociative fluorescence of OH-radicals (OH-LIPF) and the temperature distribution (determined from Rayleigh scattering) at certain moments within the period of pulsation of the premixed swirl flame has been carried out. The obtained results allow to explain the frequency dependent reaction behaviour of premixed swirl flames.

As an example, the formation of large-scale coherent vortex structures and their influence on the combustion process is documented in figure 4. The images in figure 4a show different moments within a period of pulsation of a quasi-steady swirl flame ($S_{0,th}$ = 0.21; $\dot{Q}_{th}$ = 60 kW; $8_{premix}$ = 1.2), modulated at a frequency of $f_{puls}$ = $f_{ref}$ = 5 Hz and with a pulsation level Pu = 15 %. In every moment the OH- and temperature distribution corresponds to a steady-state flame geometry with same mean thermal load and air equivalence ratio. By an increase of the pulsation frequency $f_{puls}$, while keeping all the other operation parameters constant, the formation of large-scale vortices occurs, combined with a noticeable influence on the combustion process. This is illustrated in figure 4b for a frequency of pulsation of $f_{puls}$ =100 Hz.

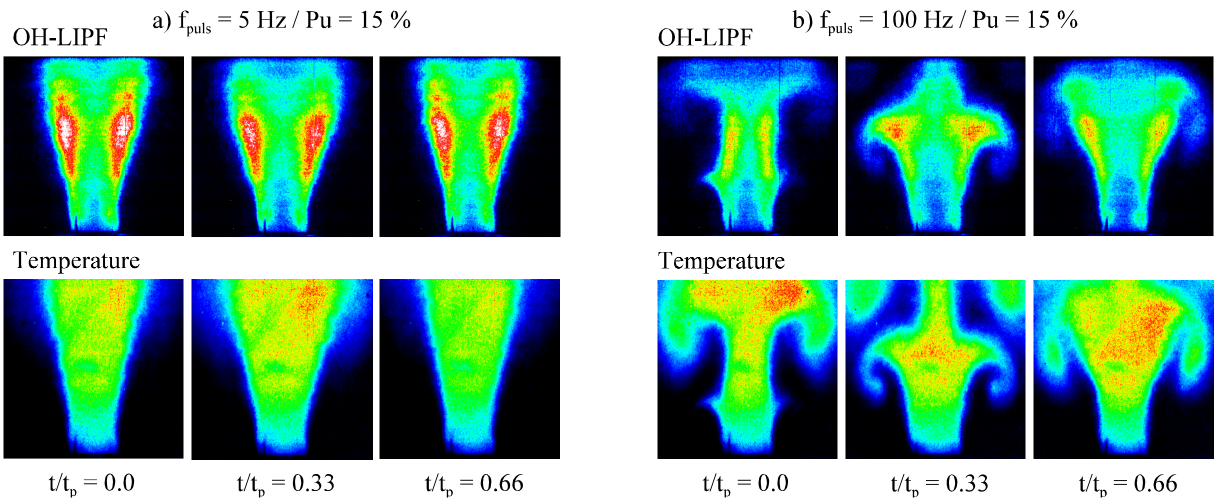

Fig. 4: Phase-correlated planar imaging of OH-LIPF and temperature distribution of pulsated, premixed swirl flames

## References


[1] Schadow, K.C., Gutmark, E., Parr, T.P., Parr, D.M., Wilson, K.J., Crump, J.E., *Combust. Sci. Tech.* 64: 167-186 (1989)

[2] Büchner, H., Bockhorn, H. and Hoffmann, S., *Proceedings of the Symposium on Energy Engineering in the 21st Century (SEE2000)*, The Hong Kong University of Science and Technology, Hong Kong, 2000

[3] Keller, J.O. and Barr, P.K., in: *Unsteady combustion*, Kluwer Academic Publishers, 1996

[4] Büchner, H., Hirsch, C. and Leuckel, W., *Combust. Sci. Tech.* 94: 219-228 (1993)

[5] Büchner, H. and Leuckel, W., in: *Unsteady combustion*, Kluwer Academic Publishers, 1996

[6] Büchner, H.; Leuckel, W., *Proceedings of the 3rd Asian-Pacific Int. Symposium on Combustion and Energy Utilization*, The Hong Kong University of Science and Technology, Hong Kong, 1995