Scaling of Stability Limits by Use of Universal Flame Transfer Functions

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Introduction

The enhancement of the efficiency of modern gas turbines and the reduction of the NO_X emissions lead to the application of Lean-Premixed (LP)/Lean-Premixed-Pre-vaporized (LPP), swirl-stabilised combustors. From the implementation of these technology results the problem of combustion-driven instabilities. The consequences of these instabilities, especially observed at high-turbulent, swirl flames with the advantages of ignition stability and wide operation ranges, are mechanical damages, increasing noise emission and limitations of the operating ranges.

The increasing tendency to the formation of self-sustained combustion instabilities is caused by the high volumetric reaction densities of LP/LPP swirl flames with the consequence of reduced delay times and abbreviated times of flame response to disturbances of the mixture mass flow.

The following investigations were focused on the dynamic characteristics of LP flames, dependent from the preheating temperature, the air equivalence ratio, the individual geometries and from the frequency and amplitude of the forced oscillation. The developed and by the measurements validated physical model features the facility to predict and scale the stability limits of LP swirl combustors with given geometry.

Experimental Setup

Self-sustained combustion instabilities with strong periodic fluctuations of the static pressure in the combustion chamber are characterized by a closed feedback loop. Within this feedback loop, the flame is of special importance. It provides the energy for the sustainment of the pressure oscillations and covers the energy losses of the energy dissipation within the pulsating combustion system. The frequency-depending flame characteristics are strongly influenced by the operating conditions, e.g. mean thermal load, air equivalence ratio, air preheating temperature, fuel type and swirl.

The basic design of the generic **double-concentric swirl burner** was derived from a commercial gas turbine burner. For the outer flow of preheated, prevaporized and premixed fuel/air mixture the theoretical swirl number can be varied by exchangeable axial vane swirl generators. In contrast to industrial swirl stabilized burners, the designed generic burner enables to vary independently all relevant operation parameters like mean thermal load, air equivalence ratios of the main and pilot flames inner and outer flow rate ratio and swirl intensities of each swirl generator. The burner can be operated either with lean-premixed natural gas or lean-prevaporized-premixed kerosene.

For the periodical modulation of the mixture mass flow rate of the main flame at the burner exit sinusoidal in time with well-defined frequencies f_{Puls} = 1-240 Hz and amplitudes, a pulsating unit was developed for mixture temperatures up to 500 °C. [1]

To quantify the excitation of the flame in terms of mass flow rate oscillations, hot-wire probes for temperatures up to 700 °C were developed, located between two vanes of the axial vane swirl generator of the main flame. The response of the flame - the time-dependent overall UV radiation (λ = 306.7 nm) from the reaction zone of the flame – was detected with a photomultiplier with narrow-banded UV interference filter.

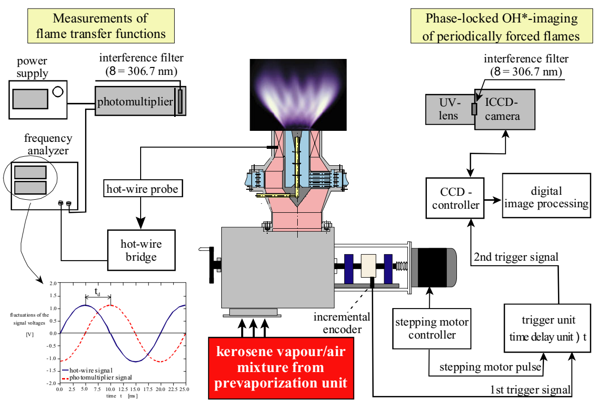

Figure 1: Determination of flame transfer functions and phase-correlated OH-image recording.

In figure 1 the experimental setup and the measurement techniques are illustrated.

Results and Discussion

For systematic investigations of the influence of the preheating temperature, the air equivalence ratio and the fuel type on the flame dynamics, flame transfer functions were measured with variations of preheating temperatures of the fuel/air mixture from 50-300 °C and the equivalence ratio from 1.3 to 1.8. All measured amplitude responses of the LP swirl flames have the same characteristics in common: An increase of the amplitude response up to a so called critical frequency f_{crit}, that characterizes the beginning of a notice-able interaction of the vortex formation, controlled by fluid dynamic effects, with the combustion process, followed by a strong decrease. The typical phase angle functions $\varphi_{fl}(f_{puls})$ of the LP swirl flames are presented in figure 2.

Fluctuations of the mixture mass flow rate have to be transported convectively to the main reaction zone of the flame and the mixture elements have to be heated-up to the ignition temperature before they are burnt.

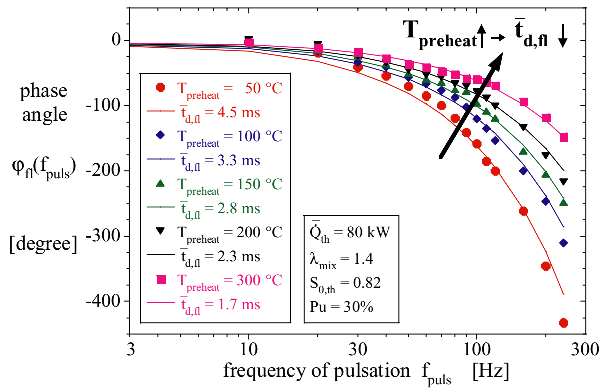

Figure 2: Phase angles functions $\varphi_{fl}(f_{puls})$ of LP swirl flames with variation of the preheating temperature $T_{preheat}$ of the mixture.

The response of the flame (UV-radiation measured with phase-correlated OH-imaging technique) must occur after a characteristic delay time $t_{d,fl}(f_{puls})$ with respect of the excitation (mixture mass flow modulation), expressed in terms of negative phase angles (eq.1).

$$\varphi_{fl}(f_{puls}) = -t_{d,fl,total}(f_{puls}) \cdot f_{puls} \cdot 360° \qquad (1)$$

By theoretical considerations of the flame geometry of steady-state turbulent premixed flames, a physical model was derived and validated with measurements of the flame transfer function under well-defined forced, pulsating conditions.

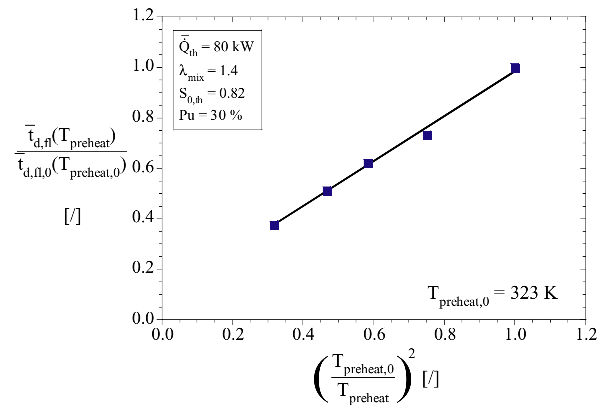

Figure 3: Scaling of delay times $\bar{t}_{d,fl}$ of LP flames as a function of the preheating temperature $T_{preheat}$ of the mixture.

In figure 3 the delay times $\bar{t}_{d,fl}$ of the flames calculated from the measurements of the phase angle functions (fig. 2) are plotted over the $(T_{preheat,0}/T_{preheat})^2$ scaling law.

Based on the same theoretical considerations of the flame geometry of steady-state turbulent premixed flames and the described dependency of the delay time $\bar{t}_{d,fl}$ of the flame on the axial position of the main reaction zone the physical model was extended and proved again with regard to the air equivalence ratio λ_{mix}.

Conclusions

The use of natural gas LP-and kerosene LPP-flames with high swirl intensities for gas turbine applications to reduce the NO_X emissions often suffers from combustion-driven instabilities, limiting the applicability of the technology.

With a generic, double-concentric swirl burner systematic investigations of the preheating temperature $T_{preheat}$ of the mixture and the air equivalence ratio λ_{mix} for two fuel types on the frequency-dependent flame characteristics were carried out.

Two dominant effects were identified: For pulsating frequencies higher than the critical frequency f_{crit} the formation and reaction of coherent vortex structures were visualized and the strong effects of the turbulent ring-vortices on the amplitude response of the swirl flame was described. For moderate frequencies, the increase of the amplitude response is caused by different entrainment characteristics of periodically pulsating swirl flow in comparison to steady-state flows. With increasing preheating temperatures the determined maximum of the amplitude response is shifted to higher pulsating frequencies.

The measured shift to significantly reduced phase angles $\varphi_{fl}(f_{puls})$ and reduced delay times $t_{d,fl}(f_{puls})$ of the flame with increasing preheating temperature or decreasing air equivalence ratio was explained with the increased turbulent burning velocity and a shift of the main reaction zone of the flame relatively closer towards the burner exit.

Based on the discussed basic understanding of the frequency-dependent dynamics of natural gas LP and kerosene LPP swirl flames and on theoretical considerations of the flame geometry of steady-state turbulent premixed flames, a physical model was derived and validated. The model enables to scale and predict the delay times of the flames and - accordingly - the entire phase angle function $\varphi(f_{puls})$ of the turbulent swirl flames in dependence on the relevant operating parameters preheating temperature, equivalence ratio, fuel type and thermal load.

Starting from only one fully-documented unstable operation point, the whole stability map of the combustor - for all critical combinations of operating parameters, which lead to the same critical phase angel $\varphi_{fl,crit}(f_{osc})$ - can be calculated by use of the universal flame transfer function and the derived scaling laws.

References

[1] Büchner, H., Hirsch, C., Leuckel, W., 1993, „Experimental Investigations on the Dynamics of Pulsated Premixed Axial Jet Flames“, Comb. Sci. and Tech. 94:219.

[2] Lohrmann, M., Büchner, H., Zarzalis, N., Krebs, W., 2003, „Flame Transfer Function Characteristics of Swirl Flames for Gas Turbine Applications“, GT2003-38113, ASME Turbo Expo 2003, Atlanta, USA.