International Gas Union Research Conference 2011

OPTIMIZATION OF COMBUSTION IN GAS TURBINES BY APPLYING RESONANT TURBULENCE

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1. ABSTRACT

Is it possible to optimize the turbulent combustion of a low swirl burner by using resonance in turbulence? To answer that question an active grid with periodically opening and closing holes is constructed and placed upstream of a low swirl burner geometry. The presence of this grid introduces large scale turbulent fluctuations to the flow with frequencies related to the driving frequency of the active grid. It is investigated in cold flow condition what the optimum frequency is to enhance the turbulence and also in actual burning situation it is tested what the effect of the modified turbulence is on the flame characteristics. From first measurements it is shown that flame size can be reduced 20% and that the stability is increased marginally.

2. INTRODUCTION

The combustion of various fuels in gas turbines is a popular way of generating heat and power. These installations are responsible for a major part of the global energy conversion and therefore it is even more important that the combustion process inside is as environmentally friendly as possible. Especially the clean combustion of natural gas since this forms an attractive energy source with a number of environmental benefits over other fossil fuels, such as lower CO2, NOx and particulates emissions[1].

A very common method to decrease NOx emissions in gas turbines, as well as in other combustion applications, is to operate in the lean premixed regime. Although this way of combustion is hampered by issues of flame stabilization, the excess of air results in relative low flame temperatures which reduce the NOx emissions dramatically. The flame stabilization issues have traditionally been solved by the high swirl concept, where the premixed fresh gases enter the combustion chamber with a swirling motion. This strong swirling motion results in a toroidal shaped recirculation zone that transports hot products back to the inlet where it continuously ignites the fresh mixture. NOx emissions have been reduces by a factor of ten, compared to older non-premixed flames, when this concept was introducedin the 70's[2]. However it is still possible to reduce NOx emissions further by stepping away from the high swirl concept. The relative high residence time caused by the recirculation in high swirl burners is responsible for the remaining NOx formation. A relative new and promising development is low swirl stabilization, which is based on flow divergence instead of recirculation, resulting in 60% lower NOx emissions[3].

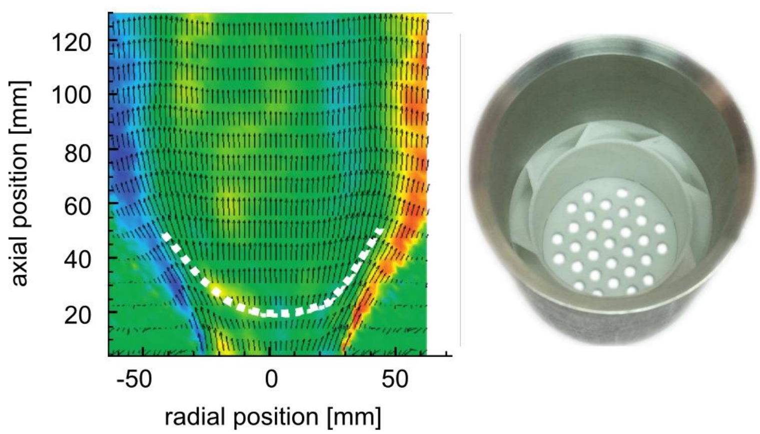

Figure 1: Left: Flow field of low swirl burner. The white dashed line indicates the location of flame. The color indicates the magnitude of the shear stress[4]. Right: Photograph of low swirl burner geometry.

The diverging flow field that is illustrated by the left image of figure 1 is constructed by a vane swirler with a central pass through, like depicted in the right image of figure 1. The swirling annular flow and the central axial flow are balanced by a grid with a certain blocking percentage to choose the amount of swirl of the total flow. When the flow emerges from the burner the swirling motion is creating an outward motion, but the central axial flow is preventing the formation of a recirculation zone. In the diverging flow the velocity is reduced and at a certain point the turbulent flame speed equals the local flow velocity and it is in this point where the flame can stabilize, resulting in a distinct bowl shaped lifted flame (figure 2). The leading edge of the flame is indicated with a white dashed line in figure 1.

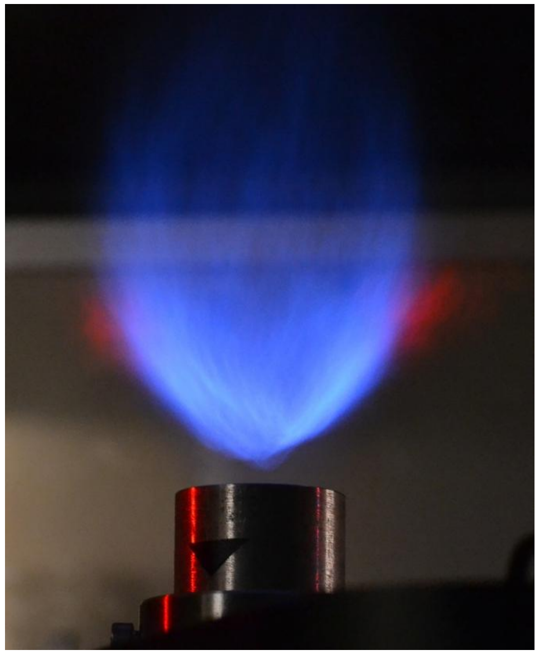

Figure 2: Photograph of a typical Low Swirl flame.

While the low swirl concept provides low NOx emissions, the mixing near the flame is limited resulting in limited flame surface area and therefore limited conversion rates. In this study it is investigated if the mixing can be enhanced by introducing specific scales to the turbulence to cope with this issue. The background of why specific scales should be introduced is described in the next section. The experimental facility that is constructed for the study is described in section 4 as well as the measurement equipment that has been used. In section 5 first results are shown and concluding remarks are written in section 6.

3. ADAPTED TURBULENCE

Several studies have shown that the mixing efficiency of the turbulence can be increased by supplying the 'correct' perturbations. In for example the numerical simulations of Kuczaj et al. [5], it is shown that a time dependent forcing of the flow at the right frequency results in a response maximum for the kinetic energy contained by the turbulence. Experimental observations also confirm this resonant enhancement of the turbulence. Cadot et al.[6] found a response maximum of the turbulent kinetic energy in their counter rotating disk experiment. Cekli et al.[7] observed a response maximum in the eddy dissipation rate when an active grid placed in the wind tunnel is forcing the flow at a specific frequency. In both cases the response maximum is located at the inverse of the large eddy turn over time.

The outcome of all these studies is that the turbulent mixing can be enhanced by applying a time dependent or modulated forcing at the large scales of the turbulence with a frequency close to the internal time scale of the turbulence. Hence this phenomenon is called resonant turbulence or resonant mixing.

It is this phenomenon that might be very helpful in generating more flame surface in the center of the low swirl burner where the turbulent mixing is limited. An optimal balance between introduced turbulent eddies sizes must be found to enhance the total flame surface area. Larger eddies will mainly wrinkle the flame, generating flame surface, while too small eddies are believed to stretch the flame and cause local extinction of the flame.

To construct an apparatus that will apply a forcing at the right scale and frequency, the internal scales of the low swirl burner must be estimated. These follow from Bédat et al.[8] where the integral length scale of the turbulence is about the radius of the central passage independent of the flow rate. The corresponding integral time scale follows from $\tau = L/u'$ where the turbulent fluctuations u' is about 25% of the mean velocity. The apparatus should be able to generate a forcing with these characteristic scales.

4. EXPERIMENTAL FACILITY

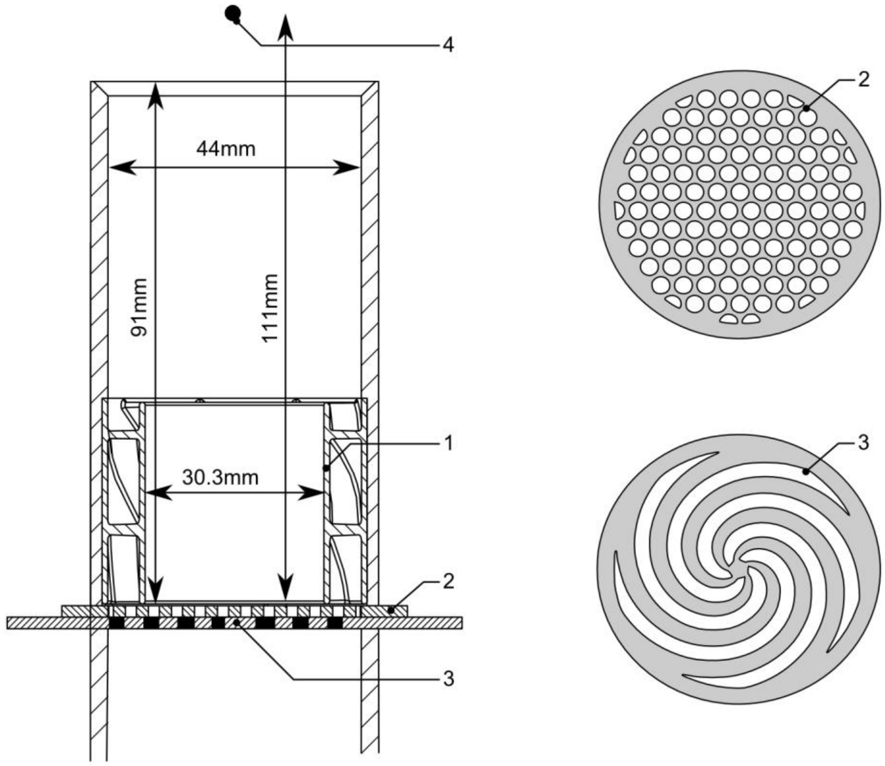

Figure 3: Left: Cross section of the active grid upstream of the swirler geometry with global dimensions. 1: Insertable swirler geometry. 2: Static perforated disk. 3: Rotating disk. 4: Location of the hot-wire probe. Upper right: Static disk with 3mm perforations in a hexagonal pattern. The distance between two adjacent holes is 1 mm. Lower right: Rotating disk with five spiral shaped slots. The width of the slots is 3mm.

Combustion system

The combustion system that has been constructed to study the effect of the modified turbulence on the generation of the flame surface consists of a 44mm diameter low swirl burner, which is shown in figure 3. The vane swirler geometry (1) is made replaceable to easily change parameters like for example the swirl number. For the work presented here, the swirler is equipped with 12 curved vanes with an angle of 42deg. The inner passage diameter is set to 30.3mm with a blockage percentage of 60% to 65%. This realizes a swirl number is about 0.45. All the dimensions are based on the design guidelines described by Cheng et al.[4].

Instead of the single perforated plate in the central passage, an active grid is placed upstream of the swirler, which will be explained in more detail in the next subsection.

In the setup it is possible to burn natural gas with a thermal throughput up to 50kW. The natural gas is entrained by the combustion air flow in a venturi and flows through a static mixer to ensure proper pre-mixing. The combustion air flow is controlled with a mass flow controller and the natural gas flow is set by a proportional control valve. The volume flow together with the actual temperature and pressure of the natural gas are registered to be able to resolve the mass flow rate. This allows one to monitor the current stoichiometry or equivalence ratio.

Before the burner a 1m long straight tube is placed with a restriction at the beginning. This is to eliminate the effect of upstream curvature or swirling motion originating from the static mixer and to have a neat axial and symmetric flow.

Active grid

Based on the active grid experiments of Cekli et al.[7] an active grid is constructed with perforations that are periodically opening and closing. In this way every hole forms a pulsating jet. One way to obtain this is the use of a rotating disk with spiral shaped slots in front of a static perforated plate. In the bottom of figure 3 the two used disks are depicted. The spiral shaped slot will open every perforation one time per revolution, so the five slots will create a pulsating jet at every perforation with a frequency of five times the rotation frequency. The rotation frequency can be set between 1 and 35Hz and is actively controlled with a PID-control loop to ensure a precision better than 0.1Hz, so jet frequencies between 5 and 175Hz can be realized. The total open area of the grid does not change more than 1.3% during a full rotation.

Besides the described active grid, also other geometries will be used to generate a modulated forcing. Differences in hole size, number of holes and modulation amplitude in total open area will be studied.

Measurement devices

Turbulent characteristics like turbulent kinetic energy, power spectrum and introduced length and time scales are determined by hot wire anemometry. Locally manufactured 1mm long and 5\mum diameter platinum coated tungsten wires in combination with a Dantec 90C10 CTA module are used to capture velocity fluctuations up to 50kHz. To obtain good converged statistics for the power spectrum and length and time scales integration times of five minutes are used. To measure only the mean velocity and turbulent fluctuations five seconds of integration time is used. A 2D traversing mechanism is used to locate the hot wire probe in the desired position with an accuracy and repeatability better than 0.1mm.

As a first qualitative measurement of the flame surface density, the technique called CH chemiluminescence is used. The idea of this technique is to capture the natural emitted light of the CH-radicals present in the flame. Since these CH molecules are only present at the interface between unburned and burnt gasses, i.e. the flame surface, and emit light at a distinct wavelength range (430nm) it is possible to qualitative observe the changes of flame surface density. Also the flame brush size can be determined by the obtained images. For the detection of the chemiluminescence signal a monochromatic CCD camera (Redlake MotionScope 1000S) is coupled with a high speed intensifier (La Vision HS IRO). The gate width used is 1ms. In front of the intensifier a band pass filter, centered around 430nm with a full width at half maximum of 10nm, is placed to only capture the chemiluminescence and suppress all other light. The area captured has a width of 16cm and a height of 14cm.

Two different methods are used for timing of the camera system. The first method to obtain time averaged images uses a pulse generator that triggers the camera to take images with a frequency of 31.415Hz. By using this irrational capturing frequency all phases of the active grid are captured and averaged when using integer rotation frequencies. If for example the camera is running and 10Hz and the active grid at 5Hz, the response of only two phase angles are captured and this undesired effect is circumvented as described above. The second method that has been used is the phase lock triggering. Here only at a certain phase of the active grid an image is taken. At zero phase an optical sensor provides a triggering signal and with a delay generator any desired phase of the active grid can be captured.

5. RESULTS

Cold flow turbulence

At approximate the location of the flame, which is indicated in figure 3, hot wire measurements are performed with upstream the active grid as shown in the same figure. These disks fill up the entire cross section of the 44mm tube and there is no swirler present. This is to isolate the effect of the active grid.

From these measurements, that are described in more detail by Verbeek et al.[9] it becomes clear that the periodically opening and closing holes introduce large scale perturbations. In the energy spectra, depicted in figure 4, clear and distinct peaks appear in the energy containing range, which represents the large scale turbulent fluctuations. Most of the high peaks correspond to phenomena of the grid. The jet frequency of five times the rotation frequency is present as well as the frequency of 15 times the rotation frequency, which correspond to the modulation of the total open area of the grid. At the rotation frequency itself there is also a peak, which is caused by vibrations of the setup or small errors in alignment of the two disks that also introduces additional frequencies at integer multiples of the rotation frequencies.

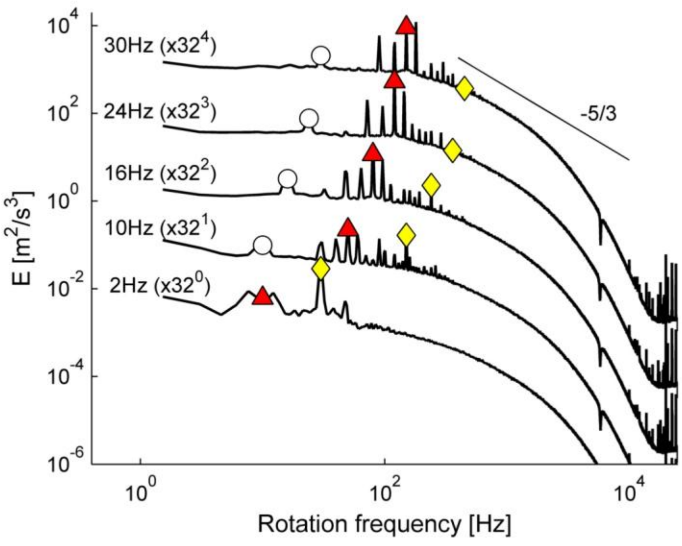

Figure 4: Energy spectra of velocity signal at different rotation frequencies. Peaks originating from the different normalized frequencies are labeled: 1 - circle, 5 - triangle, 15 - diamond. Spectra are shifted vertically with a factor as labeled to enhance the readability.

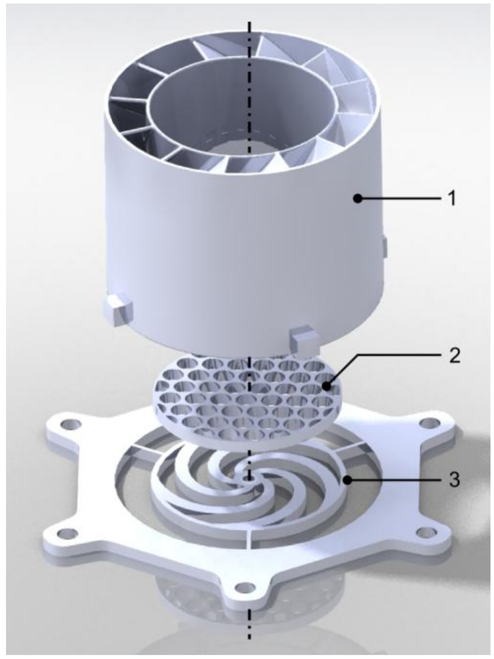

Figure 5: Exploded view of the swirler (1) with static perforated plate (2) and rotating spirals (3) in front for hot flow measurements with adapted turbulence.

The fact that only large scale perturbations can be introduced is most visible for the peaks with a normalized frequency of 15, that are indicated with diamonds in figure 4. When this peak is shifted into the inertial range of turbulence (the part of the spectrum with a slope of approximately -5/3) its magnitude decreases rapidly and this corresponds very well with the experimental observations of Cekli et al.[7] and numerical simulations of Kuczaj et al.[5].

Besides the introduced large scale fluctuations it is also observed that the integral time and length scale are not much influenced. Although a small response maximum is found at a rotation frequency of 4Hz, where the 15 times the rotation frequency peak in the energy spectrum corresponds very well to the 60Hz internal time scale, this maximum is not found in other situations where there is a peak located at the frequency of the internal time scale of the turbulence.

Flame characteristics

To use the active grid, as shown in figure 3, in front of a low swirl burner, the grid is adapted such that the grid is only in front of the central passage of the swirler. The upper perforated plate is connected to the swirler itself, while the rotating disk with spiral shaped slots is connected to the rotor by spoke like joints. (see figure 5)

The first hot wire measurements performed with this grid indicate that the introduced perturbations do not differ much from the experiments where the full cross section was blocked by the active grid. This is expected since at the central axis and approximately 2cm above the burner exit, the flow originates mainly from the grid instead of the annular swirling passage. Although this will be investigated in more detail in the near future, the first results with a burning flame are presented here. For all measurements the thermal power is set to 30kW. The equivalence ratio is set to 0.65 for all measurements except for the lean blow limit study, where the equivalence ratio is varied.

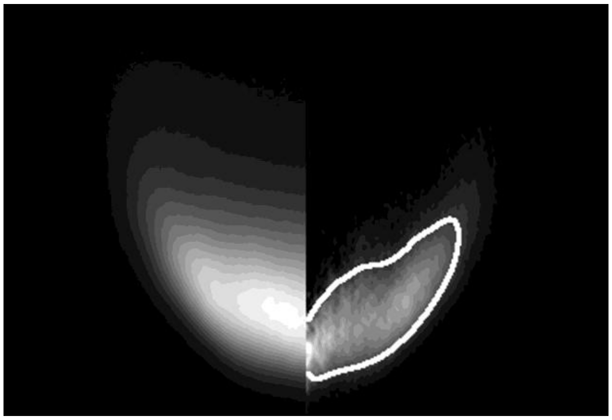

Figure 6: Left: Time averaged picture of the obtained chemiluminescence. Right: Inverse Abel transform of the time averaged picture. The white contour indicates the boundary of the region that is considered to be the flame brush.

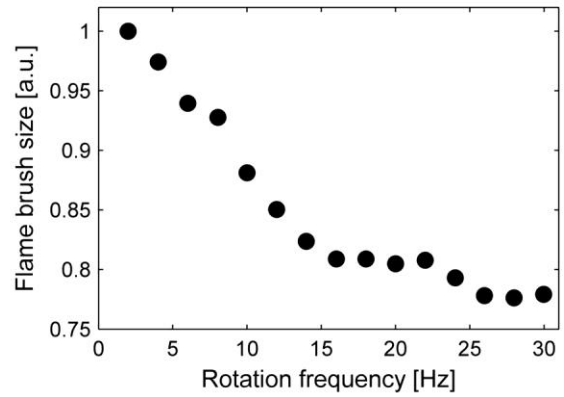

Figure 7: Flame brush area versus the rotation frequency.

In figure 6 the result of the time averaging for one specific rotation frequency, 10Hz, is shown. In the left part the raw chemiluminescence is shown. The typical bowl shape is clearly visible. Since this image contains the signal integrated over the line of sight, an inverse Abel transform[10] is needed to obtain a single cross section of the chemiluminescence signal. By applying this technique the right part of figure 6 is obtained. From this picture it is clear that the combustion only takes place at the upstream outer edge and not as much in the center as might have been suggested by the line of sight projection.

To quantify the flame brush area, the inverse Abel transform image is converted to a black and white image using a threshold and subsequently the area of the white region that represents the flame is determined. The edge of this area is also depicted in figure 6. This area is different for the different rotation frequencies. In the graph of figure 7 it is shown how this area changes with grid rotation frequency. The flame gets more confined at higher frequencies. There is almost a linear decrease of the flame brush area until 15Hz. For higher rotation frequency the flame size is not reduced anymore and the reduction stagnates at approximately 80% of the largest area.

By obtaining the phase averaged instead of the time averaged images the effect of the rotation frequency is again clear, but now also the effect of the grid phase can be seen. In figure 8 the phase lock averaged images are shown for 6 and 14Hz. At six equally spaced phase angles the average is taken

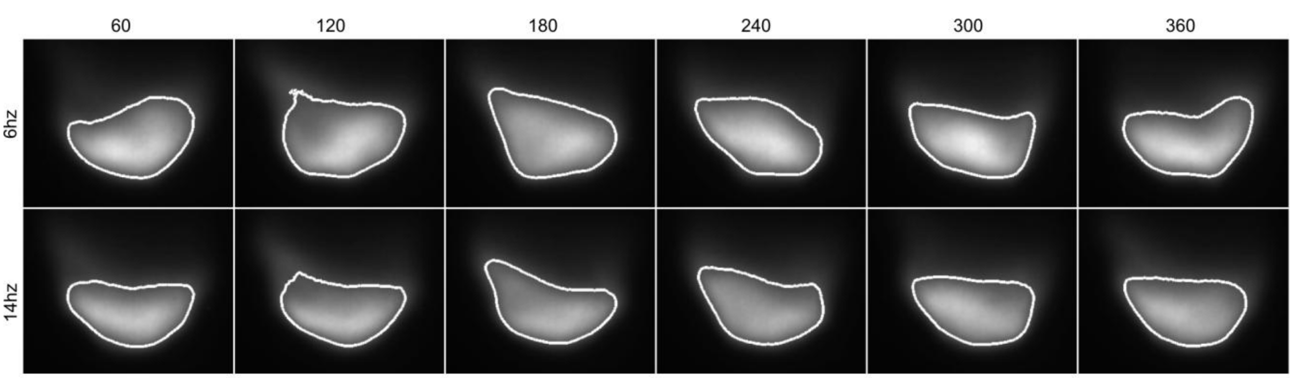

Figure 8: Phase lock averaged chemiluminescence at different phase angles and different rotation frequency. The upper series of images is obtained at 6Hz, the lower series at 14Hz. The phase different between two consecutive images is 60 degrees. The white contour is the gray isocontour of 0.29 and is draw to emphasize the difference in flame shape between 6 and 14Hz.

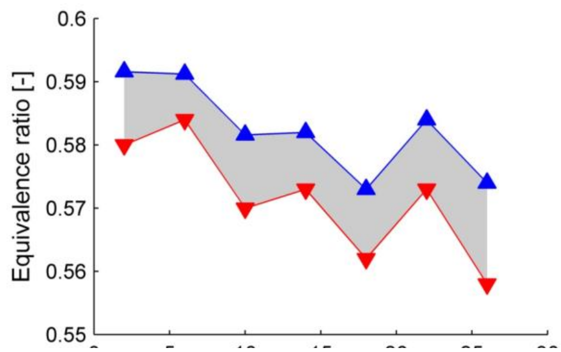

Figure 9: The lean blow-off limit as function of the rotation frequency. Upper operating point resulted in stable flame, while the lower operating points resulted in a unstable flame and blow off.

over one thousand individual images. The top row shows the result for a rotation frequency of 6Hz and the bottom row for 14Hz. As function of the phase angle the flame is not symmetric anymore and the shape alters significantly. It seems like the flame undergoes a precessing motion which is induced by the grid. At 6Hz this effect is much more pronounced then at 14Hz, where the flame is much more fixed in the bottom, without strong "blobs". This corresponds very well with the observation of a small and more compact flame in the time averaged result. Since only for two frequencies the phase averages images are obtained it cannot be said how this trend will develop further. But most likely also for this case a cross over frequency can be expected around 15Hz where the effect of an even faster rotating grid is minimal. Perturbations with a higher frequency cannot be followed by the flame anymore as they are damped too quickly.

Another also interesting quantity to study is the lean blow-off limit, the equivalence ratio which marks the border between a stable and an unstable flame. This is investigated by reducing the equivalence ratio and keeping the power constant, 30kW in this case. An operating point in the equivalence ratio vs. rotation frequency map of figure 9 is called stable if the flame did not experienced a blow-off for at least one minute. So the upper operating points were the lowest stable points and at the lower points the flame extinguished within one minute. The effect of rotation frequency on the lean blow-off limit is limited, but there is a small decreasing trend visible. At higher rotation frequency the flame is better stabilized, since lean blow-off limit is lowered with 3.5%. The resolution in equivalence ratio is too low to again observe a cross-over frequency of 15Hz.

6. CONCLUSION

From the first measurement performed with an active grid especially designed to create optimized turbulence for combustion, one can conclude that it is possible to introduce large scale fluctuations by means of an active grid consisting of holes that are periodically opening and closing. These fluctuations show up as clear and distinct peaks in the energy spectrum and this corresponds very well with the work of other researchers in the field of resonant turbulence. However there is no real response maximum observed when the introduced perturbations have the same frequency as the turbulence itself.

At low rotation frequencies the flame is following large scale fluctuations applied by the grid, but at higher rotation frequencies this diminishes and the flame is more fixed and compact in space. According to the flame brush area measurements this effect is present up to 15Hz and for higher frequencies no strong dependence is observed anymore. The reduction of the flame size is about 20%. The active grid has, although limited, effect on flame stability. Higher rotation speed stretches the stability limit and it becomes possible to stabilize a leaner flame, but only with a reduction of 3.5%, so the question remains how significant this is.

Although the first result look promising, since the flame is more confined and marginally more stable when the proper frequency is applied, actual flame surface measurements by means of Planar - Laser Induced Fluorescence (PLIF) will be performed to validate the generation of more flame surface. Also additional experiments with different geometries of the active grid disks will be carried out to explore more of the possibilities of the phenomenon of resonant turbulence in combination with combustion.

7. ACKNOWLEDGEMENT

This project is sponsored by Technology Foundation STW, The Netherlands. Grant nr. CCC 10425.

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