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Review on Activities in Active Combustion Control (ACC) at the Technische Universität München (TUM)

Stephan Gleis
Thermodynamik B, Technische Universität München
Boltz mannstrasse 15
85747 Garching, Germany

Abstract

About 30 years ago Professor Dieter Vortmeyer, who has been retired in March 1999, started his research in the field of acoustic instabilities in combustion systems and began the research in active combustion control in 1986. To the honour of Prof. Vortmeyer herewith a review on his work in the field of ACC is given.

Introduction

In the most technical combustion systems the flame is enclosed by combustion chambers and under certain operating conditions the excitation of combustion instabilities occur. These instabilities are characterised by intense pressure oscillations inside the combustion chamber at discrete frequencies. The dimensions of the combustion system, mainly the combustion chamber, determine the acoustic resonant frequencies. Longitudinal as well as radial and tangential acoustic modes may be excited. The occurrence of these oscillations increase with the specific thermal load. So there exist only a few publications reporting about problems with combustion oscillations on small combustion units as gas- or fuel oil fired boilers for heating facilities in residential buildings or transportation systems /1, 2 /. In these cases the oscillations with frequencies of several 100 Hz and pressure amplitudes up to 160 dB mainly are an unacceptable noise.

On industrial combustion systems the combustion instabilities cause much more severe problems. A lot of references can be named reporting the occurrence of combustion instabilities and measures for their elimination on boilers of power plants /3/, blast heaters in steel production /4, 5/, process gas heaters in the chemical industry /6/ as well as on gas turbine combusts /7-9/ and rocket motors /10-12/. Hereby the amplitudes of the pressure oscillations in these practical combustion chambers reach extremely high values, e.g. 0.5 bar in combustors operating under atmospheric conditions /6/ and 5 bar in rocket motors /13/. The consequences of these high pressure amplitudes are damages to the combustion chambers /4-7/, failures in the control units as well as negative effects on subsequent parts of the installation.

These combustion instabilities can be avoided or damped by passive or active means The passive means consist of e.g. geometrical modifications of the combustion chamber or the addition of sound-absorbing devices such as Helmholtz resonators. But at lower frequencies these measure often don't lead to sufficient low amplitudes.

The active methods to control the combustion instabilities use an input signal of the oscillation, e.g. the sound pressure or the fluctuating heat release of the flame, being phase shifted and amplified in an adequate manner and then transmitted to an actuator which obliterates the oscillation in the combustion system. An overview of some approaches in active control of combustion instabilities is given by Candel /14/.

Historic background on the research in ACC at the TUM

In 1968 Professor Vortmeyer became holder of the chair for Thermodynamik B at the TUM. During his preceding research activities he was research assistant at the Imperial College London and worked there together with D.B. Spalding in the field of combustion /15, 16/. Very early after having the chair at the TUM Vortmeyer started the research activities in the field of combustion oscillations /17, 18/ and continued this work perseveringly for about 30 years. At the begin the main goal of this work was the application and refinement of the Rayleigh Criterion /19/ for the prediction and stabilization of combustion oscillations in practical systems /6, 18, 20-24/. During the 21st International Symposium on Combustion in 1986 at the TUM Professor

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Candel and some co-workers visited the lab of Thermodynamik B which has been the trigger off in the research of ACC at the TUM. Outgoing from an experimental set-up for the open loop excitation of a premixed propane-air flame the idea was borne to use this set-up in a closed loop configuration in order to stabilize a self excited flame oscillation similar to the anti noise methods and the experiments of Heckl on a Rijke tube /25/.

Basic Experimental Investigations in Active Control of Combustion Instabilities

The first investigations were performed on a very small laboratory combustor of about 1 kW thermal power with a laminar premixed flame. A very high level of attenuation (66 dB) has been achieved and the results of a theoretical analysis of the stable domains of the phase shift and gain of the closed loop controller show a good agreement with the experimental data /26/. These investigation has been extended to a combustor with a turbulent diffusion flame with a thermal power of about 30 kW /27/. An attenuation of the main unstable mode of about 24 dB in the sound pressure leads also to a elimination of the harmonics. Just in this article it is remarked that the active control of combustion instabilities can be applied in the future for damping of instabilities in full scale combustors as well as a new technique for the investigation of the initiation of a combustion instability, when the controller is switched off after the successful stabilization. That this technique can give very interesting insights in the transient behaviour of a combustion system has been shown in a further investigation.

The initiation of the combustion instability in a laboratory gas combustor burning a near stoichiometric premixed air/propane/hydrogen mixture has been investigated. The experimental set-up is shown in figure 1 and more details are given in /28/. Without active control a combustion oscillation with a frequency of 405 Hz and a pressure amplitude of 130 Pa inside the combustion chamber is present. By the active control system shown in figure 1 the combustion process can be stabilized within a few milliseconds with only 50 dB of noise left. The development of the combustion oscillation is shown in figure 2. After switching off the ACC within about 25 msec at first a transition from the controlled quiet operation to an oscillation with a frequency of 405 Hz and a pressure amplitude of 65 Pa is observed. In figure 2 this state of oscillation is described as "region 1". This oscillation remains for about 100 msec. Only then a transition to the final state of oscillation with the same frequency but a pressure amplitude of 130 Pa takes place. being described in figure 2 as "region 2".

The analysis of the oscillations of the heat release and the sound pressure gives a probably explanation for the stepwise rise in amplitude up to the limit cycle. While the phase shift between the heat release and the sound pressure oscillation is about 20° in "region 1", it becomes 0° in "region 2". Due to the better fulfilment of the Rayleigh-criterion the driving force has become much stronger leading to increased oscillation amplitudes. A view into the behaviour of the flame during the transition from stabilized combustion to the oscillatory state in "region 2" is given in figure 3 by Schlieren photos of the flame having been recorded by means of a high speed camera. The sequence a) of images in figure 3 shows the flame being stabilized by ACC. The sequence b) represents one cycle of oscillation from "region 1" in figure 2 and the frames from sequence c) come from "region 2". While the sequence a) shows a flame of more or less the same shape, the flame in sequence b) performs mainly a change in the flame length during one cycle of oscillation. Only in the images of sequence c) a clear vortex roll up at the flame tip can be observed. By this simple experiment it has been shown, that even if vortices are present during a combustion oscillation they must not be the original cause of the instability.

Even research in the field of combustion enhancement by an active periodic excitation of the flame has been done. This study verifies the possibility to reduce pollutant emissions from a residential hot water boiler heated with fuel oil. Although the investigated combustion system used state of the art technology for a clean combustion a further reduction of the NO emissions of 21 % and of the CO emissions of 46 % could be achieved /29/. But all possible implementations to industrial combustion systems seemed not to be practicable in terms of costs, durability and noise.

Investigations for the Practical Applicability of Active Combustion Instability control (AIC) on Industrial Combustion Systems

The first stimulation for the practical application of the active combustion instability control was given during a project for the calming of combustion oscillations in an industrial process gas heater in 1988 /6/. This process gas heater is a part of a natural gas plant cleaning the crude gas of hydrogen sulphide by a Claus process /30/. The Claus tail gas still contains a residue of sulphur compounds being removed in a subsequent process for which the tail gas has to be heated up in the process gas heater with a thermal power of 28 MW. The frequencies of the observed combustion instabilities were between 30 and 50 Hz at amplitudes up to 0.5 bar. These very strong pulsations led to the destruction of the combustion chambers liner shown in figure 3 and a grinding of catalyst pellets in a subsequent reactor due to the mechanical vibrations caused by the acoustic pressure oscillations.
During the activities in this project also the application of AIC has been discussed, but the lack on suitable actuators led to a passive solution and the decision to develop actuators for the AIC in forthcoming research projects.

Development of actuators for the modulation of liquid fuel

Until 1995 the existing papers on AIC mainly dealt with combustion systems for gaseous fuel where loudspeakers had been used as actuators. Consequently an actuator for liquid fuel has been developed, which is applicable in a broad frequency range /31/. This actuator, shown in figure 4 uses piezo stacks driving pistons which impose pressure fluctuation on the liquid fuel. The performance of the piezo actuator has been demonstrated on a diesel oil burning turbulent laboratory combustor exhibiting strong self excited combustion oscillations at operating conditions of about 50 kW thermal power and a nearly stoichiometric equivalence ratio. The result is shown in figure 5 and it can be seen that the sound pressure, as well as the heat release oscillation, are both attenuated remarkably if the AIC is switched on. The frequency plots in figure 5c present an attenuation of about 40 dB at the controlled oscillation frequency of 360 Hz, while a second oscillation mode at 295 Hz is slightly amplified.
An alternative actuator for liquid fuel has been presented at the International Symposium on Combustion in Naples in 1996 /32/. Here a direct-drive valve for hydraulics was modified to our specifications by Moog Germany to a cut off frequency of 450 Hz. It is shown that an acoustic decoupling and a tuning of the fuel line length is helpful to get a maximum efficiency for the actuator. Even this actuator has been implemented successfully to calm an combustion oscillation in a turbulent diesel oil fired combustor with a thermal power of about 137 kW at a air equivalence ratio Φ=1.2.

Application of Active Combustion Instability Control to a Heavy Duty Gas Turbine

All the tools having been developed as well as the experiences having been obtained in the research activities described above were necessary for the successful application of the AIC to an industrial combustion system. The demonstration of the AIC could be performed on a gas turbine at the Siemens testfield in Berlin /33/. A scheme of the AIC installation on the gas turbine annular combustor is shown in figure 6. Only the fuel of the pilot diffusion flame burning about 10 % of the whole fuel is modulated by a Moog direct drive valve. The sound pressure in the air plenum serves as input to the AIC controller. Each of the 24 burners of the annular combustor has been equipped with an actuator, while the number of pressure transducers and controllers could be reduced to six due to the symmetry of the excited azimuthal acoustic mode. With this installation the combustion oscillation in the 170 MW_{el} gas turbine has been reduced up to 17 db at the controlled frequency of 433 Hz. Professor Vortmeyer decided that this demonstration should be the final point in the development of complete AIC installations for his university institute and returned to other interesting questions in combustion instabilities of more basic nature. The AIC activities led to a spin off by two co-workers founding the firm IFTA.

So Vortmeyer's last activities are concerned with the numerical simulation of self excited combustion instabilities. Even the research in this field is successful and the CFD calculations /34, 35/ are in good agreement with experimental results of former publications /36, 37/.

Summary

Although the main field of Professor Vortmeyer's activities is on the research of the thermal and fluid mechanic phenomena in catalytic packed bed reactors, he did some remarkable achievements in the field of combustion instabilities by his continuous and farsighted research. At least partly due to his excellent job the AIC is now recognized as a promising technology for the practical application in future combustion systems which is on the other hand very important to get the necessary fundings for the basic research topics in the field of AIC. We will be glad if Professor Vortmeyer will be at our disposal in the future even if not actively but with his advices. The research in the field of combustion instabilities at the TUM nevertheless will go on in the future, because these activities have been taken over by Professor Thomas Sattelmayer at his chair "Lehrstuhl A für Thermodynamik" (LAT).

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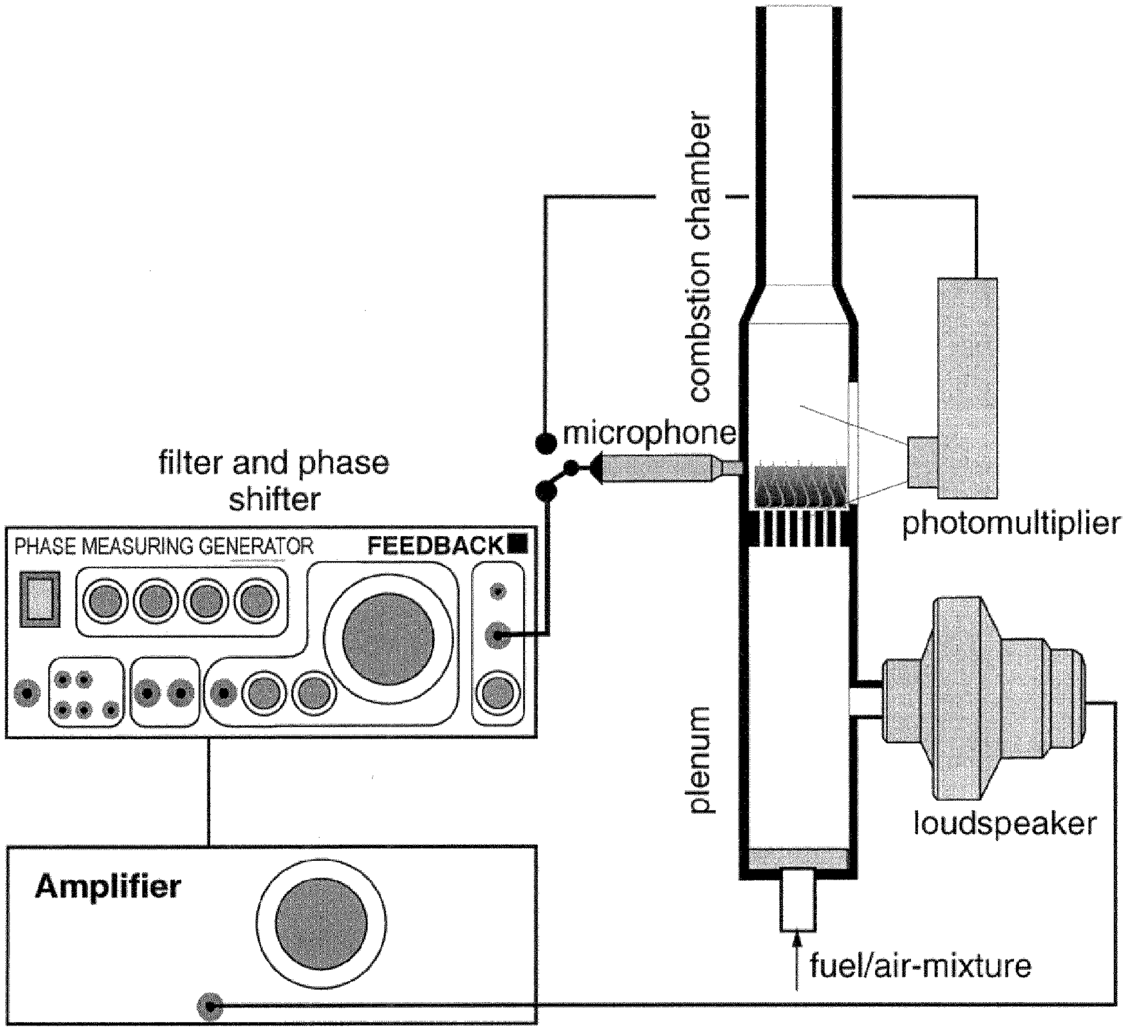

Figure 1: Experimental setup for basic AIC experiments

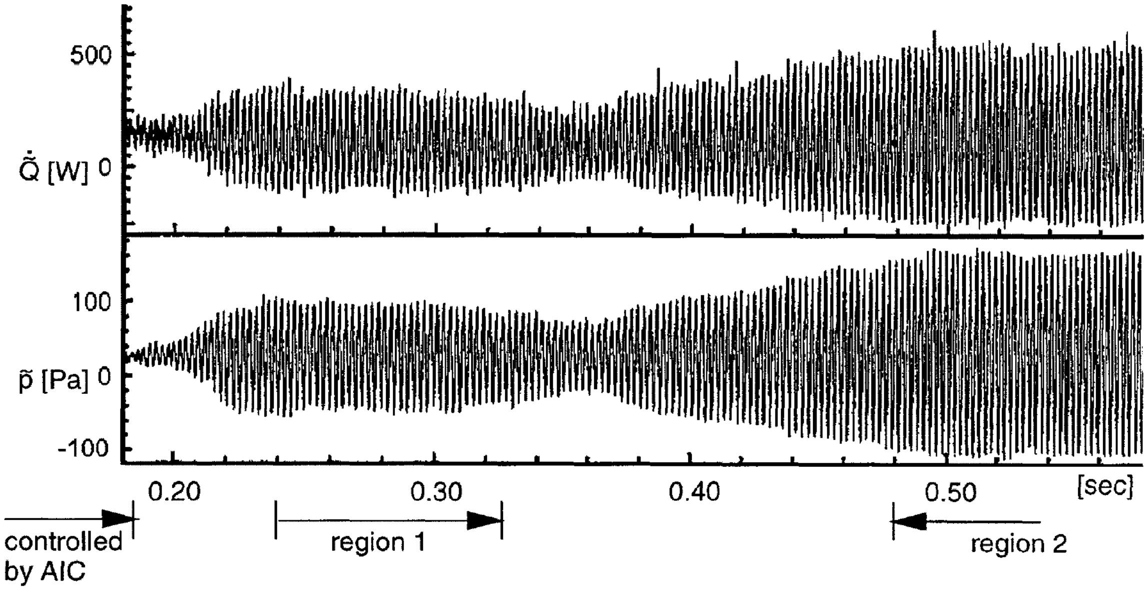

Figure 2: Transition from stable to unstable combustion

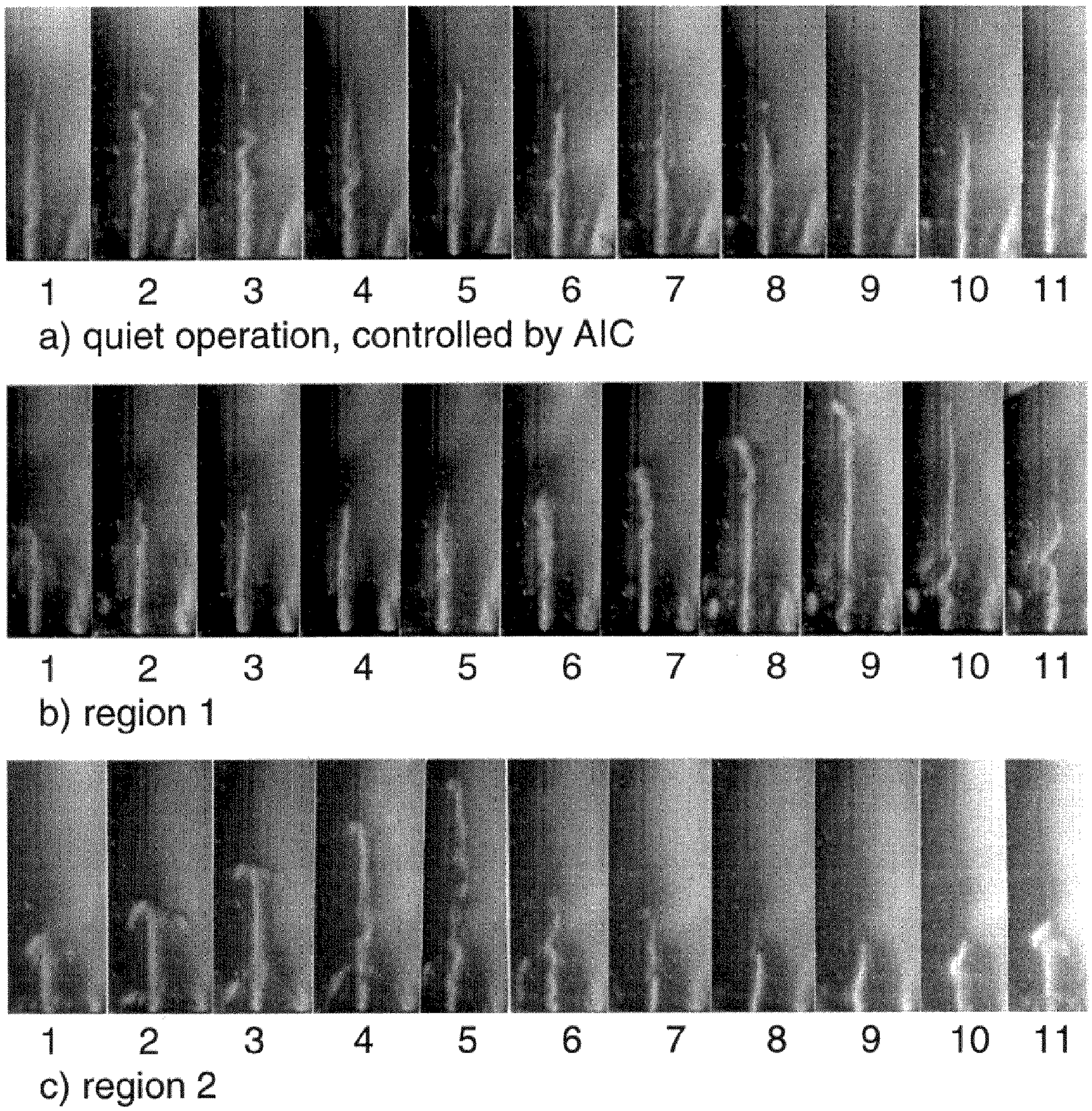

Figure 3: Schlierenphotos from a high speed movie showing the initation of the combustion oscillation from figure 2 (frame rate 5000 frames/sec)

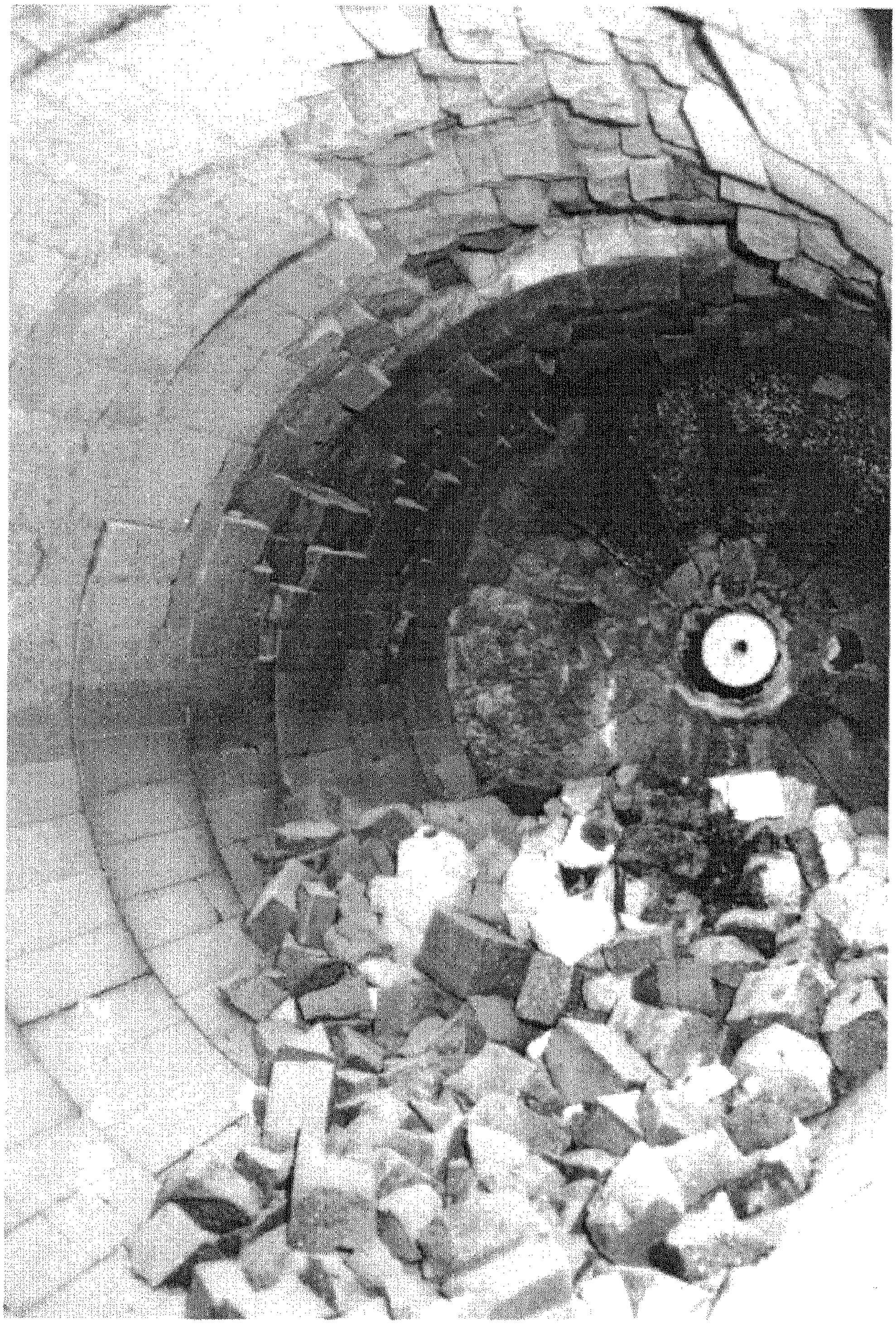

Figure 4: Combustion chamber of the process gas heater with 14 MW thermal power and a diameter of about 1 m, the brick lining is destroyed due to combustion oscillations

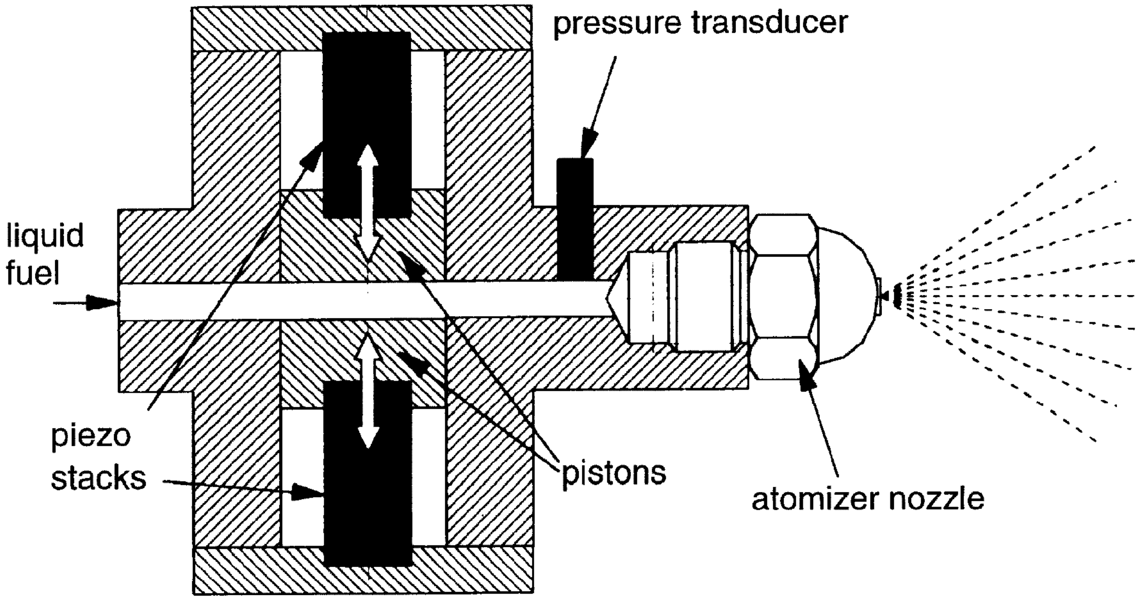

Figure 5: Piezo actuator with injection nozzle /37/

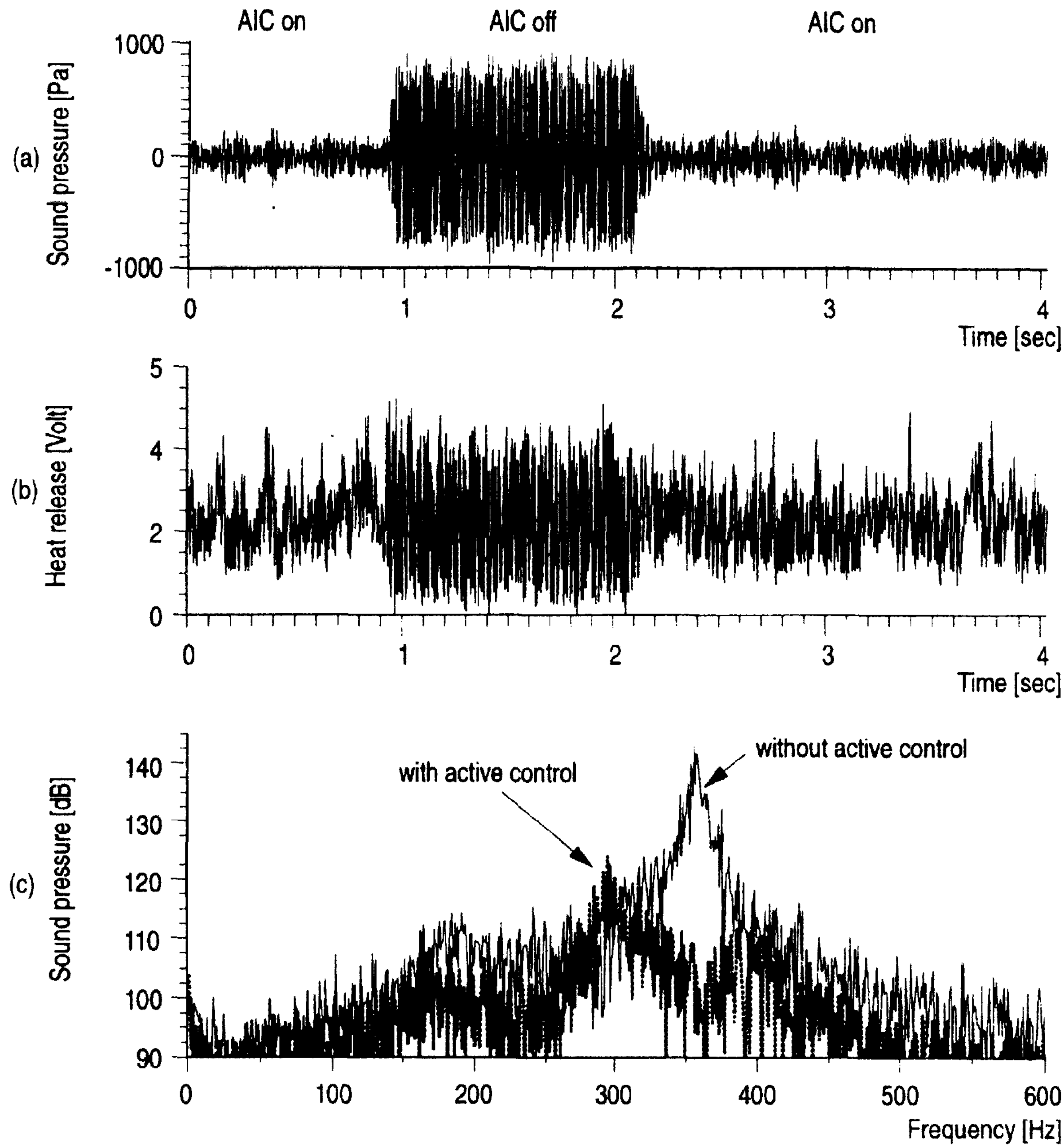

Figure 6: Sound pressure (a) and heat release oscillation (b) with AIC system switched off and on. Frequency spectrum of the sound pressure with an without active control (c) /31/.

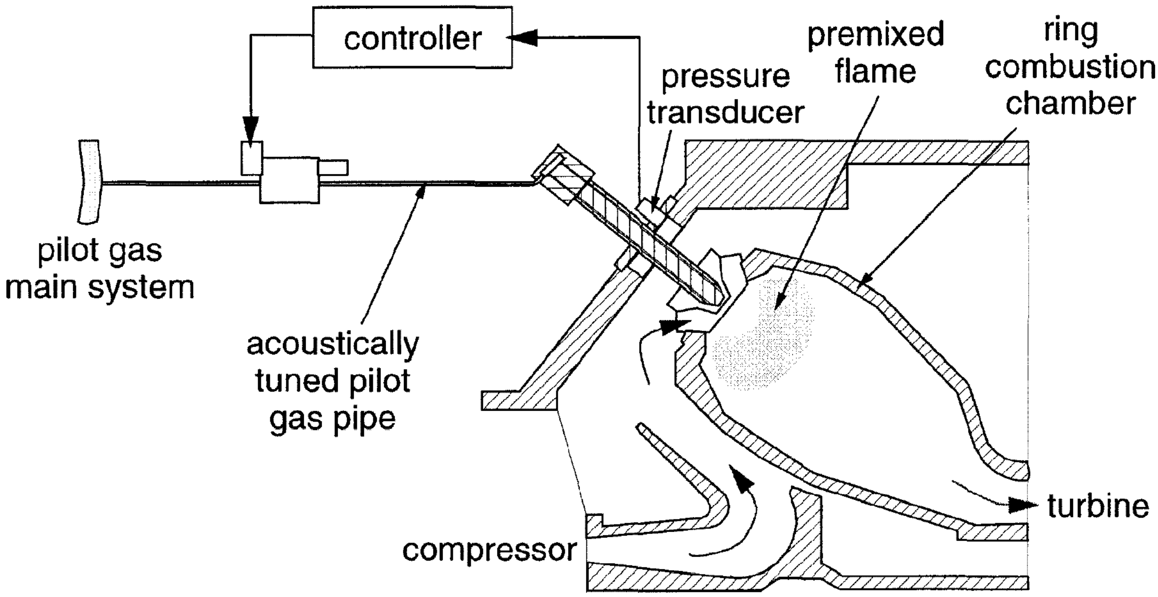

Figure 7: Schematic of the AIC applied to the Siemens Model V84.3A gas turbine /33/