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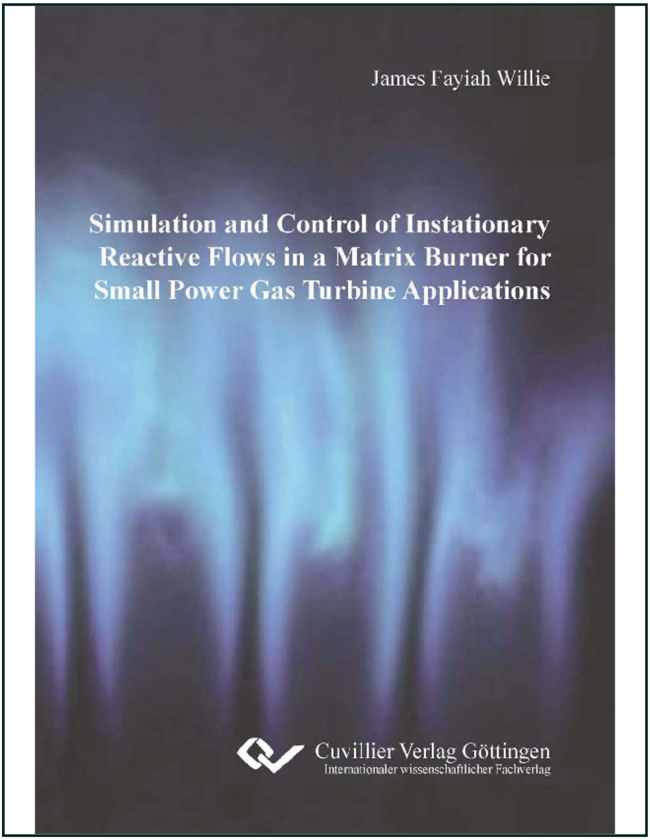
Simulation and Control of Instationary Reactive Flows in Matrix Burner for Small Power Gas Turbine Applications



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Chapter 1

INTRODUCTION

Contents

The subject of thermoacoustic instabilities is very important in power generation and propulsion systems. The world derives most of its energy from the burning of fossil fuels like petroleum, coal, etc. Because of the need to limit NOx and green house gas emissions stringent measures are being imposed by various environmental protection agencies around the world. In the power generation industry, where it is projected that the use of gas turbines will continue to grow due to its high efficiency, attention has shifted from the use of diffusion flames to lean premixed flames. However, running gas turbines lean exposes them to thermoacoustic instabilities. This is because operating gas turbines near their lean blow-out limit or lean flammability limit can result in periodic extinction due to small fluctuation in the equivalence ratio. The potential coupling between the unsteady heat release rate and the pressure can lead to their resonant coupling, thus growth, and is referred to as thermoacoustic instability. These instabilities can result in excessive noise levels that are unacceptable and can lead to component and even engine failures. This phenomenon does not only occur in gas turbines, but also in many other practical systems such as ramjets, afterburners and rocket motors. But it does not only occur in systems that are run lean and close to their lean flammability limits; in ramjets and afterburners, for example, combustion instabilities mostly occur when they are run near stoichiometry. For this reason the attention of many researchers has shifted to understanding the various mechanisms that drive combustion instabilities and to the development of active control techniques that can be used for mitigating their effects. The driving mechanism of combustion instabilities involves many elementary processes and the feedback that relates the downstream to the upstream region is not only acoustic but may also involve convective modes like entropy waves. Flames themselves posses intrinsic instabilities, which do not require acoustic coupling.

In the opening chapter of this thesis a literature review that looks at various approaches that are used for investigating thermoacoustic instabilities will be presented in section 1.1. This will be followed by a brief background on the use of gas turbines in power generation and why this trend is expected to increase is discussed in section 1.2. Some background information on thermoacoustic instabilities will be presented in section 1.3.1. This is followed by a look at the difference between thermodynamics and thermoacoustic instabilities in section 1.3.2. This chapter is concluded by the motivation for this thesis and an overview of what will follow in the remaining chapters (section 1.4).

1.1 Literature review

This portion of the thesis reviews the existing work and methodology in the literature that are used for investigating thermoacoustic instabilities. There are many approaches, in the literature, for investigating thermoacoustics. These include phenomenological approach, analytical approach, modeling using CFD and Matlab/Simulink and experiments. Over the last 50 years, however, the study of combustion instabilities has shifted from phenomenology to a situation where it is amenable to modeling and simulation.

The development of analytical and theoretical models of combustion instabilities is being done, even though such models are low order models that neglect most of the physics involved in real combustion instabilities problems. Most researchers use modal expansion, but the accuracy of such models, to a large extent, depends on the number of modes that are accurately accounted for [1, 2]. In this technique, the physical system is characterized in terms of its resonant modes. In industry it finds application in determining parametric frequency responses from measured vibration data. Each mode is typically described in terms of its resonant frequency, band-width (or damping), and gain (and perhaps phase). Given any order n transfer function H(s) describing the input-output behavior of a physical system, a modal description can be obtained immediately from the partial fraction expansion $H(s) = \frac{A(s)}{B(s)} = \frac{b_m}{a_n}\frac{\prod_{i=1}^{m}(s-\varepsilon_i)}{\prod_{i=1}^{n}(s-p_i)}$, where p_i denotes the i^{th} pole, and ε_i is the i^{th} zero and b_m and a_n are polynomial coefficients. Since such systems are real, complex poles will occur in complex conjugate pairs. Thus for each complex term $\frac{r_i}{s-p_i}$, there is also the term $\frac{\bar{r}_i}{s-\bar{p}_i}$, where $\bar{z}$ denote the complex conjugate of z. It must be noted that a modal expansion can also be obtained from a network model. The continuous time model can then be converted to a discrete-time, and finally expressed in state-space formulation [3].

Physics based models are also being developed but mostly this is not possible without making a lot of assumptions [4, 5, 6, 7, 8]. The complexities of thermoacoustics, for the most part, makes the equations that are involved intractable. Apart from the additional time scale that is introduced by combustion, turbulence and other very complex flow phenomena like vortex breakdown, the interaction between turbulence and chemistry have to be taken into consideration. The flame or combustion introduces the source term in the Lighthill analogy [9, 10, 11]. For this reason, the source term is modeled either through the use of the $n - \tau$ model to account for the scaling between the acoustic velocity near the burner mouth and the heat release inside the combustion chamber [12, 13]. For more complex geometries, the above approach does not function satisfactorily and the flame transfer function, that is obtained by doing system identification using CFD or measurements, is employed [3, 14, 15, 16]. For system identification purposes using CFD, non-reflecting boundaries are used to prevent artificial excitation of the flame by waves that impinge on the boundaries. Self exciting simulations using CFD with fully reflecting boundaries is also commonplace in thermoacoustic analysis using large eddy simulations (LES) and unsteady Reynolds Averaged Navier-Stokes (URANS) simulations [12, 17, 18]. The finite element method (FEM) is also used extensively in the investigation and analysis of thermoacoustic instabilities. Apart from the structural modal analysis and its use in finding the structural modes in gas turbines, fluid structure interaction (FSI) is also used to determine if there is an interaction between the fluid and the structure and vice versa. Such information is vital in the design of the liner of gas turbines [10, 19, 20, 21]. Another approach of importance is the use of a 1D acoustic network. In this approach, each element that constitutes the test rig is treated as a four pole element and the elements are connected in a 1D network. The appropriate acoustic boundaries at the inlet and outlet are imposed and the resulting eigenvalue problem that is obtained is solved for the longitudinal eigenmodes and damping coefficient of the system [12, 22].

Measurements have been the most popular means by which thermoacoustic instabilities, occurring in gas turbines, are investigated. Apart from the invaluable contribution it offers in model validation, the complexities of some of the phenomena associated with thermoacoustics means that it is tractable only through measurements. For example, active control of combustion instabilities by numerical means is very rare in literature. Mostly, this has been done by measurements [18, 23, 24]. One of the few exceptions is in the work by [17], but in this case the control was for aeroacoustic instabilities occurring in a rocket motor.

Combustion processes involve time-lags. Reactants are introduced into the system at one time and converted into products at a later time. Systems with delays are more susceptible to instability [12, 25]. Another reason why combustion is readily unstable is because, in confined systems that work with combustion of gaseous or liquid fuels, resonant coupling may readily occur in the confined and weakly damped geometries used in most practical combustors. Among the most common coupling modes, acoustics is dominant. Resonance is sharp, because damping is limited. Energy losses in such systems can be due to viscous dissipation at the walls, radiation from inflow and outflow, various relaxation processes in flows with particles or droplet spray. For the most part, the attenuation obtained in such systems is weak and if the growth exceeds the losses, it may lead to resonance. If the resonance is in the low frequency range (typically f<1kHz), the wavelength exceeds the typical transverse dimension and wave propagation is essentially longitudinal and involves the whole system resulting in "system instabilities". If resonance is at a higher frequency (f>1kHz), the wavelength is of the order or less than the transverse dimension and the coupling usually involves a transverse mode of the chamber [19]. These "chamber instabilities" are found in systems where the combustor is well decoupled from the upstream and downstream systems (reactant supply lines, turbomachinery). There are numerous mechanisms which may feed energy in the perturbed motion. Growth is obtained if, according to the Rayleigh criterion, the heat release fluctuation is in phase with the pressure oscillation [26]. The flow perturbations which may initiate the process involve vortex rollup, shear instabilities, flame acceleration, collective interactions between reactant streams and collisions with boundaries. If the feed lines are not well decoupled from the chamber, instabilities can also be driven by the differential response of the injection system when it is submitted to incident perturbations, giving rise to inhomogeneities in reactant content.

Some of the elementary processes that have been found to drive combustion instabilities are discussed here. This is of importance because combustion instabilities are mostly driven by these elementary processes. On the most fundamental level, researchers try to analyze the flame response to perturbations and whether a coupling exist or not. Some of these coupling processes include but are not limited to unsteady strain effects on diffusion or premixed flame elements; flame/vortex interactions, vortex-enhanced mixing, and subsequent combustion; acoustic flame coupling; interaction of perturbed flames with boundaries; flame response to incident composition inhomogeneities. Other processes, such as flame acceleration by shocks or weak pressure fronts is also important, especially when flames travel in ducts. The interaction between acoustic waves or shocks and droplet or spray has profound effects by inducing a breakup of the liquid phase, thus helping the rate of vaporization. A detailed survey of this can be found in [27].

1.2 Historical background of gas turbines use in power generation

Since the invention of the gas turbine in 1939, a lot has changed. Engineers and technical professionals are constantly pushing the limit of gas turbine technology. One reason why the gas turbine has become indispensable is because of its power and efficiency. For example, combined-cycle power plants are able to achieve efficiencies of up to 65% [28]. Power plants that are run on coal, on the other hand can achieve efficiencies around 45% [29]. Another advantage gas turbines have is that they can run on natural gas which is cleaner when compared to other fossil fuels. Their design also allows them to run on other fuels like syngas and diesel.

Figures 1.1 and 1.2 shows respectively the gas turbine production by sectors and the worldwide gas turbine production [28]. The trend shows that from 2005 on there has been an increase in the number of gas turbines being produced in all the sectors, with the commercial aviation section growing the most.

Great steps have been made in the development of gas turbines for electrical power generation. General Electric's first 9H gas turbine combined-cycle plant went into operation at Balgan Bay, Wales, in 2003. It is the world's largest gas turbine with a combined-cycle output of 520 MW and a thermal efficiency of just under 60%. In 2005, Siemens announced it is developing an H-type gas turbine with an output of 340 MW and a combined-cycle output of more than 530 MW and a thermal efficiency of over 60%. As new materials are being developed, cooling is being improved, inlet temperatures of gas turbines being increased the overall efficiency is being improved. Today, typical jet engines operate at turbine inlet temperature of 1650° C while turbines for non-military application are able to reach a temperatures up to 1480°C or lower. With improved film cooling design, for example, it is possible to operate the F135 engines in the Joint Strike Fighter Lighting II at a temperature of 1982°C [28].

Although institutions like the European Union and the International Energy Agency (IEA) are encouraging the development of alternative sources of energy, the use of fossil fuels will continue to increase. One reason is because of the increase in the worldwide consumption of energy. Renewable sources of energy will not be able to meet this demand. It is estimated that this consumption will double in the next 25 years [29].

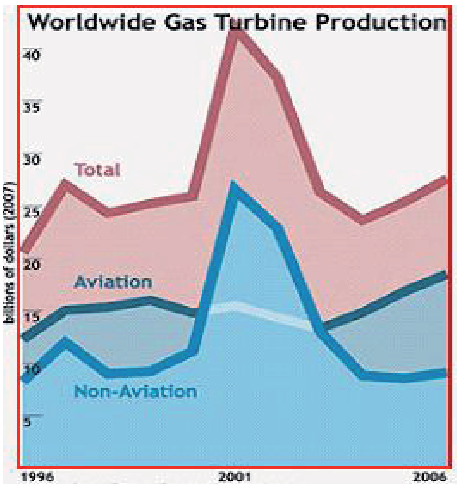

Figure 1.1: Worldwide gas turbine production [28].

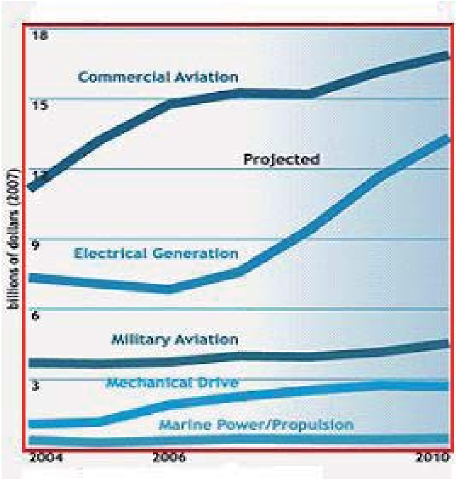

Figure 1.2: Gas Turbine production by sector [28].

Figure 1.3 shows the contribution of various fuels in power generation [30]. It can be seen that the contribution made by natural gas is about 25% of the total while coal contributes 40%. But due to stringent restrictions on NOx and other exhaust emissions, the use of natural gas is expected to increase over the years.

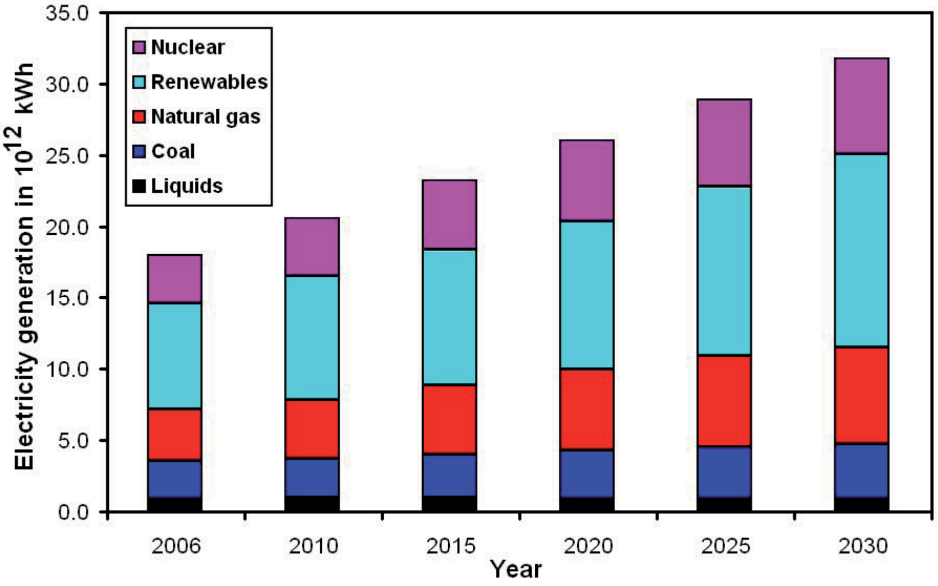

Figure 1.3: World energy output by fuel and reproduced by data taken from [30].

1.3 Thermoacoustic instabilities

The flow chart shown in figure 1.4 shows the various mechanisms that give rise to thermoacoustic instabilities. The chart looks at the case where the primary fuel supply is either gaseous in which case atomization and vaporization are not included in the process and for the case where the primary fuel is liquid, which will then include atomization and vaporization in the process. The coupling of the combustor dynamics with feedline impedance either through the air side or fuel side or both is also included.

Combustion processes ('flame dynamics'), including flame stabilization, are more sensitive to fluctuations at lower equivalence ratios than under operation at higher mixture (F/O) ratios. Sensitive flame dynamics include the dynamics of flame fronts and zones as well as the stabilization processes. The coupling between combustion and fluctuations may occur due to the sensitivity of the reaction rates to pressure, as well as due to fluctuations of the total flame surface area. Recirculation zones associated with injection and stabilization respond to perturbations and may possess multiple dynamical states (bifurcations and hysteresis). The dynamics of the injector devices may contribute to instabilities. Fluctuations of F/O ratio and hence energy release may produce coupling between combustion and combustor dynamics. Problems may arise because of coupling between individual premixers and injectors in an array. All of the above elementary processes lead to combustion instabilities if coupling exists between combustion dynamics and combustor dynamics.

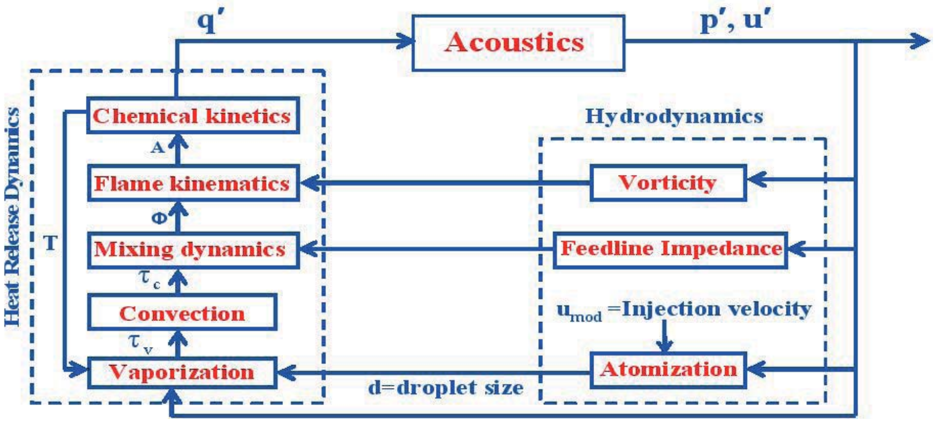

Figure 1.4: Flow chart illustrating various processes that give rise to thermoacoustic instabilities.

1.3.1 Historical background of thermoacoustic instabilities

Flames, which are essentially surfaces across which reactants are converted into products, not only possess their own inherent instabilities, but are also known to respond readily to imposed fluctuations. Historically, the first observation of combustion oscillation was the "singing flame" which was discovered by Higgins in 1777. Several other researchers' interest was caught, as for example Faraday in 1918 and Le Conte in 1958, and they described that high levels of sound can be produced by placing a flame, anchored on a small diameter fuel supply tube in a larger diameter tube. The tube was found to excite the fundamental modes or one of the harmonics of the larger tube. Rijke showed in 1959 that sound can be generated in a vertical tube open at both ends by placing a heated metal gauze inside the tube. Rayleigh [26] was the first to hypothesize the onset of instability and defined a criterion for positive coupling based on a phenomenological, heuristic, description of the instability. According to him, if the heat release oscillations are in phase with the pressure oscillations inside the combustor, the instability is encouraged and if they are out of phase, the process is discouraged. This can be written as:

$$\int p'(x,t)\dot{q}'(x,t)dt > 0. \tag{1.1}$$

Clearly, this condition is a necessary, but not a sufficient condition for combustion instabilities to occur. For instabilities to occur, the acoustic energy of the system must exceed the dissipative effect in the system. The Rayleigh criterion was, therefore, extended by [31] to take this into account; it can be expressed as:

$$\frac{\gamma-1}{\bar{\rho}\cdot\bar{c}^2}\int_V \overline{p'(t)\dot{q}'(t)}dV > \int_S \overline{p'(t)u'(t)}dS. \tag{1.2}$$

1.3.2 Comparison between thermodynamics and thermoacoustic instabilities

Thermoacoustics is about the interaction between thermodynamic and acoustic phenomena. It refers to the thermal origins of sound produced by pressure oscillations. The foundation of the Rayleigh criterion is thermodynamic; it is not just mechanical, but it is more general. In the work by [32], for example, the Rayleigh criterion was reformulated using thermodynamic principles and variational calculus. Sound finds application in many areas that benefit society. For example, ultrasonic surgery, noise-cancelation system, and sonar are in common use in society. Replacing harmful sound with their less harmful counterparts is an attractive option to society. Refrigeration, electricity and mechanical energy are all examples of applications that sound is well-suited for, and they also introduce the notion of a tie between acoustics and thermodynamics.

A good example of this analogy will be explained in the following. Consider a vertical tube that has one or both ends closed, and heat is applied to the closed end of the tube. As the temperature increases, heat is converted to kinetic energy in the gas molecules at the closed end of the tube. The gas molecules accelerate towards the cooler end of the tube, thereby creating an area of relative low pressure in the heated end. As the molecules cool off, other gas molecules accelerate towards the hot end to fill in the area of low pressure. These molecules are then heated, and the process is repeated again. This completes one cycle of the thermal oscillation, and is analogous to the Stirling cycle, which is a thermodynamic cycle. The acceleration and deceleration of the gas molecules with respect to time maps to a sinusoid. Essentially, the result is a self-sustained series of longitudinal sinusoidal air pressure oscillations. Within the tube, the pressure wave fronts are approximately planar, whereas minimal toroidal behavior occurs in the vicinity of the mouth of the tube. The predominant waveform outside of the tube's mouth is spherical. It comes as no surprise that these traits are equivalent to those of sound waves, and in most cases audible sound is a direct byproduct of the entire process.

1.3.3 Self-excited acoustic oscillations and resonance in mechanical systems

Comparison between self-excited acoustic oscillations and resonance in mechanical systems is discussed in this section. In the former, two distinct possibilities exist and it is important to distinguish between them. Firstly, we have flow amplificators (or convectively unstable flows) and flow resonators (or absolutely unstable) as depicted in figure 1.5 [12]. Note that the perturbation is evacuated at a later time in an amplificator but it leads to resonance in a resonator. In the resonator, the perturbation is not dissipated and if boundary conditions do not damp these perturbation, a mechanism for self-sustained oscillation is created. Combustors subjected to combustion instabilities are obviously resonators because of the strong feedback created by acoustic waves. However, in certain cases, resonators may be transformed into amplificators if part of the feedback loop is dissipated.

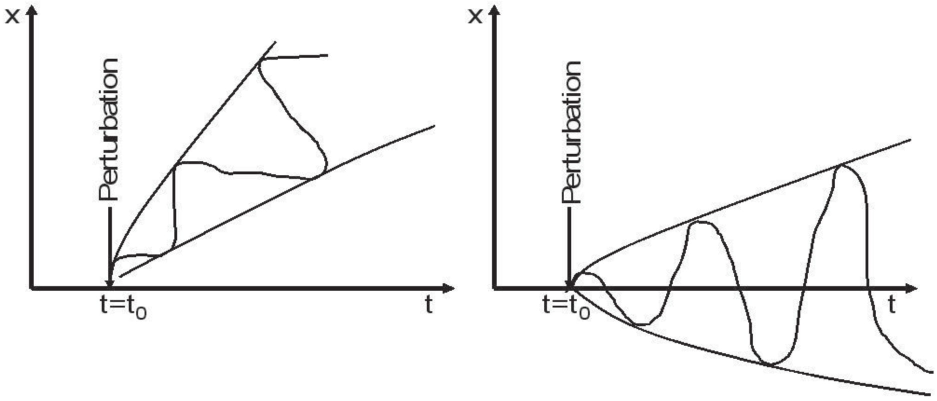

Figure 1.5: Schematic of amplificator (left) and resonator (right) in acoustic systems [12].

Similarly, examples of resonance occurs in mechanical systems and it occurs when a system is driven at a frequency that is equal to the system's natural frequency. For example, the Tacoma Narrows Bridge [33] and the London Millenium Bridge [34] were built without considering the effect of resonance. In the case of the former, the resonance caused by the vibration of the structure from the wind in 1940 had a severe effect and it led to the destruction of the bridge. The structure integrity of the bridge did not take the effect of the wind into consideration. Other examples of mechanical resonance include the production of musical tones from wind instruments, the shattering of a goblet by an opera singer, and an off-balance washing machine. Mechanical resonance is typically introduced by a spring-mass system. The natural frequency of this system can be written as

$$f_0 = \frac{1}{2\pi}\sqrt{k/m} \tag{1.3}$$

where f_0 is the resonance frequency, k is the spring constant and m is the mass. The system can be driven below, above or at its resonance frequency. In the latter case the amplitude of the spring-mass vibrations get increasingly large. This amplitude is affected by mechanical resistance in the system, for example, the air resistance to the moving mass. Similarly, in self-sustained acoustic systems losses are encountered through say viscous dissipation, acoustic radiation, etc. and the system amplitude will only grow in both cases if the growth rate in the system's amplitude exceeds the losses occurring in the system.

1.4 Motivation and overview of the thesis

The drive behind the new design of gas turbine burners, using lean premixed and prevaporized combustion, is low NOx emissions. Unfortunately, running gas turbines lean makes them exceptionally prone to combustion instabilities. The Matrix burner investigated in this thesis is no exception. Combustion instabilities leads to periodic extinction of the flame when the equivalence ratio fluctuates close to the lean flammability limit. The induced instability of the flame causes the equivalence ratio to further oscillate, which then drives the fluctuation of the heat release and, when this couples with the pressure inside the combustion chamber, it leads to growth and, if the acoustic energy exceeds the damping in the system to instability.

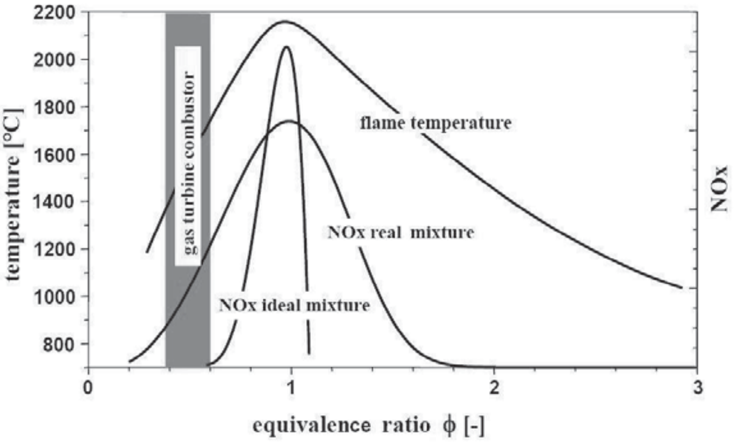

Figure 1.6: Plot showing the effect of temperature, equivalence ratio and mixing on NOx [29].

The sketch in figure 1.6 shows the variation of NOx with temperature and equivalence ratio. The curve in figure 1.7 also shows how NOx varies with pulsations in conventional gas turbines and in the matrix burner, investigated in this thesis. In the case of conventional gas turbines NOx decreases with increasing pulsations because the instabilities lead to movement of the real mixing curve towards the ideal mixing curve, whereas for the matrix burner under investigation, the opposite is true. This is so because for the matrix burner, NOx production is driven by chemical kinetics as well as by the mixing of the fuel and the oxidizer upstream. In the case of strong pulsations, chemical kinetics plays a more dominant role, which leads to a high reaction rate and hence to an increase in the flame temperature. The increase in flame temperature leads to high NOx production. When the pulsation levels are weak, mixing plays a more dominant role and the improved mixing upstream leads to a uniform burning rate at the flame and therefor to lower NOx levels.

The main objective of this work is to understand the main mechanisms that drives instabilities inside the matrix burner. In general, two mechanisms have been identified, namely equivalence ratio fluctuation and velocity perturbation. A third mechanism, which is due to flame-vortex interaction that leads to the interaction of the flame fronts, which in turn drives the sound emission inside the matrix burner is discussed. Various modeling approaches, namely, CFD and the use of system identification, fluid-structure interaction using a combination of finite element method and CFD, and a 1D acoustic network are explored. Also investigated is the use of

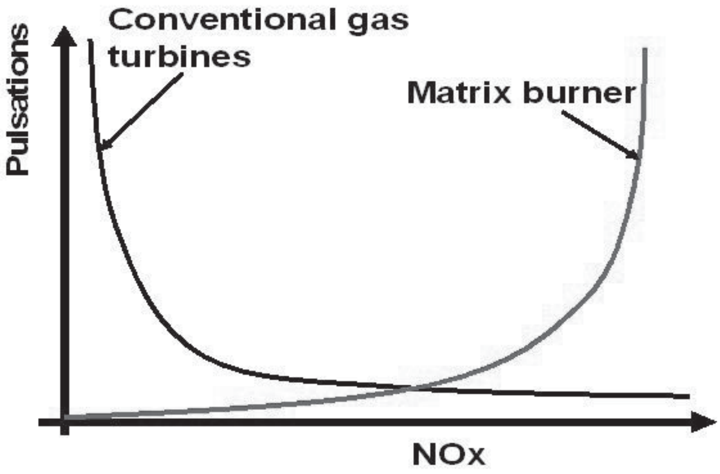

Figure 1.7: Schematic showing effects of pulsations on NOx in conventional gas turbines and the matrix burner.

active control in suppressing combustion instabilities inside the matrix burner. The effect combustion instabilities on NOx emissions is reported. The matrix burner investigated in this work is similar to the one investigated by Deuker and Krüger [35, 36]. This burner is suitable for reproducing the conditions prevailing in stationary gas turbines. It can also be used for additional firing in combined-cycle power plants [37].

In the following, the theory and equations of acoustics are presented in chapter two followed by the description of the experimental setup in chapter three. The CFD model setup is presented in chapter four, which is followed by the discussion of the 1D acoustic network and FEM in chapter five. In chapter six, control of combustion instabilities is treated and in chapter seven the results and discussions are presented. Finally, in chapter eight, the summary, conclusions and future work are presented. The thesis is closed with appendix A and appendix B. In appendix A, the derivation of the duct impedance at the outlet of the test rig is presented and in appendix B, the analytical derivation of the acoustic transfer matrix for a 1D duct and an area change are presented.

1.5 Summary

Chapter one gives an introduction and a general overview of thermoacoustics. It begins with the literature review in section 1.1 and this is followed by a brief historical background of gas turbines use in power generation in section 1.2. In section 1.3.1, the historical background of thermoacoustic instabilities is discussed. The chapter is concluded by giving the motivation and the overview of the thesis in section 1.4.

After giving the general introduction, the literature review surveys the existing literature in order to explain the various approaches that are being used to study thermoacoustic instabilities today. The various coupling mechanisms that are responsible for thermoacoustic instabilities are also discussed. The chapter then tries to answer some of the basic questions about why gas turbines play such an important role in our everyday life. It also explains why the increase in the worldwide production of gas turbines is expected to remain so in the near future. The chapter continues with the historical background of thermoacoustics, beginning with the observation of the first combustion oscillation by Higgins in 1777. The Rijke tube is mentioned, followed by the Rayleigh criterion. It is shown that thermoacoustics is driven by an interaction between thermodynamics and acoustic phenomena. After this a comparison is made between self-excited acoustic oscillations and resonance occurring in mechanical systems. Finally, the motivation of the thesis is given. Here, a look at why lower NOx requirements in the gas turbine industry is fueling research in lean-premixed combustion and thermoacoustic instabilities, is discussed. The role played by mixing in the emissions of NOx is highlighted followed by the effects of pulsations levels on NOx generation in conventional gas turbines. This is compared with the effects of mixing on NOx generation in the matrix burner. The chapter is concluded by giving the main objective of the thesis, which is to understand the mechanisms that drive instabilities and how active control can be used to lower pressure levels inside the matrix burner. The approaches used in fulfilling the objective stated above include CFD, FEM, 1D acoustic networks and measurements.