Title	Nonlinear dynamic measurement of self-sustained thermoacoustic oscillations in a swirling combustor with a heat exchanger
Author(s)	Li, Xinyan; Han, Nuomin; Jin, Xiao; Zhang, Zhiguo; Li, Guoneng
Citation	Li, X., Han, N., Jin, X., Zhang, Z., & Li, G. (2017). Nonlinear Dynamic Measurement of Self-sustained Thermoacoustic Oscillations in a Swirling Combustor with a Heat Exchanger. Energy Procedia, 105, 4872-4877. doi:10.1016/j.egypro.2017.03.965
Date	2017
URL	http://hdl.handle.net/10220/46590
Rights	© 2017 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 105 (2017) 4872 – 4877

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Nonlinear dynamic measurement of self-sustained thermoacoustic oscillations in a swirling combustor with a heat exchanger

Xinyan Li[a], Nuomin Han[a,*], Xiao Jin[b], Zhiguo Zhang[c], Guoneng Li[c]

[a]*School of Mechanical and Aerospace Engineering, College of Engineering, Nanyang Technological Univeristy, Singapore 639798, Republic of Singapore,*

[b]*School of Energy and Power Engineering, Jiangsu Univeristy of Science and Technology, Zhejiang City, Mengxi Road 2, Jiangsu Province 212003, China*

[c]*School of Mechanical and Automotive Engineering, Zhejiang University of Science and Technology, Hangzhou City, Liuhe Road, Zhejiang, 310023, China*

Abstract

Energy transfer from heat to sound is unwanted in many propulsion systems, including gas turbines and rocket motors. However, it is favorable in some practical applications, such as thermoacoustic heat engines or cooling systems. The present work considers an experimental investigation of self-sustained thermoacoustic oscillations in a swirling combustor. Both subcritical and supercritical Hopf bifurcations are found to occur in this swirling combustor. In the presence of the subcritical bifurcation, a small change in the equivalent ratio leads to a sudden/hard jump from steady state to large amplitude limit cycle oscillations. The experimental study sheds lights on the heat-to-sound conversion process. In addition to increase the heat-to-sound energy conversion, an innovative water-involved heat exchanger is designed and experimentally implemented on the swirling combustor. By doing this, self-excited thermoacoustic oscillations are found to be intensified. The present work opens up a new applicable way to amplify thermoacoustic oscillations in swirling combustion systems.

Keywords: *self-sustained thermoaocustic oscillation; nonlinear dynamics; bifurcation; heat exchanger; Swirling combustor.*

1. Introduction

* Corresponding author.
E-mail address: hannmjz@126.com.

doi:10.1016/j.egypro.2017.03.965

The phenomenon of thermoacoustic instability occurs in many propulsion systems [1, 2], such as gas turbines and rocket motors. It is characterized by large-amplitude thermoacoustic oscillations. Due to the fact that the intensified oscillations may result in unacceptable noise, overheating to the combustor wall and structure vibration, they are unwanted in such combustion systems [3, 4]. Generally, thermoacoustic instability is caused by the coupling between the unsteady heat release and acoustic pressure [5-7]. However, the specific transition from the steady state to instability is still unknown. Thus it is important to estimate the operating conditions corresponding to the occurrence of thermoacoustic instabilities.

As the critical system parameter varies, the onset of thermoacoustic instability can take place via a supercritical (soft) or subcritical bifurcation (hard) [8, 9]. Supercritical transition to instability can achieve a consistent growth in the amplitude of the thermoacoustic oscillation as the critical system parameter varies. More importantly, the asymptotic behavior for a given system parameter does not rely on the initial condition. However, in the case of subcritical Hopf bifurcation, there is a hysteresis region for a range of parameter values. In this region, two stable states coexist: one is steady state and the other is stable limit cycle oscillation. The unstable limit cycle serves as a boundary basin to separate the two stable states. At this moment, thermoacoustic system is sensitive to the initial condition and external perturbation. Certain amount of perturbation may incur a transition from the stable operation to large-amplitude oscillations [10]. Furthermore, if the thermoacoustic system is operated near the critical bifurcation point, a trivial perturbation can lead to a jump to large-amplitude oscillation. Stable operation [11, 12] is one of the main requirements for gas turbine combustors. Therefore better understanding of nonlinear dynamics of such complex systems is significantly important and it motivates the present experimental investigation.

However, such large-amplitude oscillations are desirable in thermoacoustic engines [13] or cooling systems. The efficient heat-to-sound conversion [14, 15] attracts people's attention significantly in some practical energy applications, such as prime mover, refrigerator [16] and mixture separation. When unsteady heat transfers from a high temperature source to a low temperature one, an acoustic sound can be generated. Then the generated acoustic pressure can be utilized to produce electrical power via piezoelectric generator [17, 18], cooling power, and heating in a sustainable ways. Based on such energy conversion mechanism, many heat sources can be utilized or recycled, such as solar energy and industrial waste heat [19]. Compared with the internal combustion engines, thermoacoustic engines have no moving parts and are 'pistonless'. It mainly achieves the conversion of thermal energy to mechanical work by sound waves through compressing and expanding the working inertia gas. Therefore, thermoacoustic engines can achieve high reliability and durability. Such thermoacoustic heat engine with high efficiency is beneficial to fuel saving and environmental protection. In order to increase the efficiency of the heat-to-sound conversion, an innovative configuration is proposed in the present work to enhance the thermoacoustic oscillation.

In this work, the self-sustained thermoacoustic oscillations in a swirling combustor are experimentally investigated. The effect of equivalent ratio at different inlet velocities is conducted with no heat exchanger added. Then at the fixed equivalent ratio, the effect of the proposed heat exchanger in the swirling combustor is evaluated.

2. Experimental setup

Experiments are performed in a swirling combustor. The combustion is operated at atmospheric pressure. Fig. 1 shows the schematic of the test facility employed in the present work. The swirling combustor has one acoustically open end and one closed end. The overall length of the chamber L is 800 mm. The generic swirling burner consists of 8 straight vanes attached to a central bluff body, as shown in Fig. 1(b). The vane angles are of 65^{o} relative to the incoming air stream. The flame is anchored in the bottom swirling burner, as show in Fig. 1(c). Air is supplied by a high-volume rotary-screw compressor while the methane is supplied from a pressured cylinder. The Methane flow rate is controlled and measured by MC Standard Series Mass Flow Controller. Pressure transducer is placed in the middle of the combustor to measure acoustic pressure signals. It is connected to the side branch along the combustor, with semi-infinite line technique used to obtain thermal insulation without distortion from acoustic reflections. The pressure data is acquired by the data acquisition system (NI USB-6343) with a sampling rate of 5 kHz. The heat exchanger consists of a soft mental tube. By wrapping the heat exchanger around the combustor surface and injecting cool water into the tube, the heat transfer can be achieved from the combustor surface to the heat exchanger.

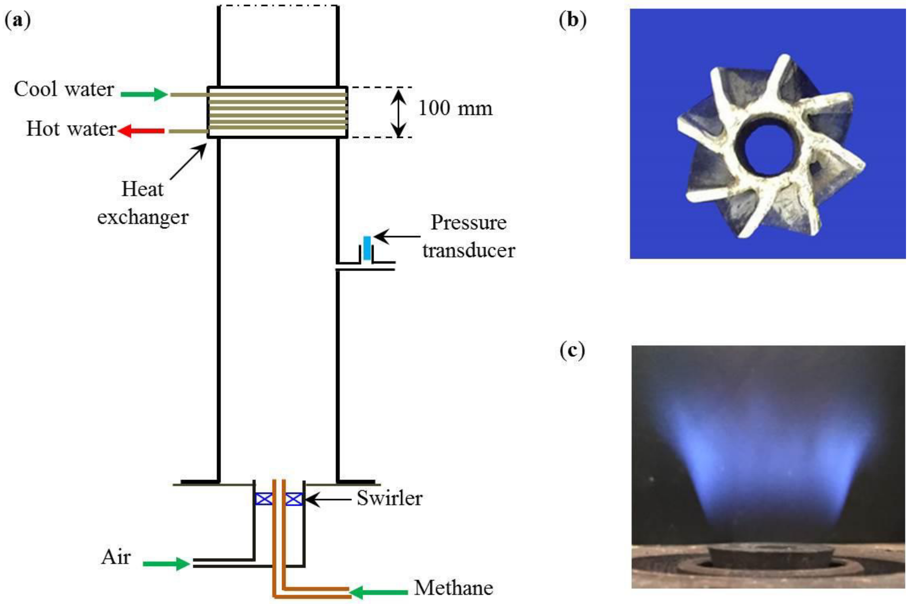

Fig. 1 The schematic of the swirling combustor

3. Experimental results and discussion

Firstly nonlinear dynamic behaviour of the swirling combustor with no heat exchanger is investigated. Fig. 2 shows the exemplary time series of the acoustic pressure in the swirling combustion. Unstable behaviour can be easily recognized by the large-amplitude thermoacoustic oscillations. Fig. 3 plots the dependence of the oscillatory amplitude upon a system parameter (equivalent ratio) at different inlet velocities u. As shown in Fig. 3(a) for small inlet velocity (u=6 l/min), when the supplied equivalent ratio increased to a certain value (around ϕ=1.0), an unambiguous sound is generated. The transition to instability is not abrupt but consistent. In the opposite variation of equivalent ratio, the intensity of sound will be gradually decreased and finally vanishes. While for moderate inlet velocity (u=50 l/min), the transition process shows a significantly different variation from Fig. 3(a). From Fig. 3(b), it can be seen that no intermediate process occurs. The oscillatory amplitude initially remains almost constant at low equivalent ratio, and then grows rapidly once the equivalence ratio exceeds a critical value and finally levels off. On the way back with the decrease of the equivalent ratio, the intensity of the tone is reduced gradually first and then abruptly drop to the silence. Both super- and sub-critical bifurcation are observed in this swirling combustor.

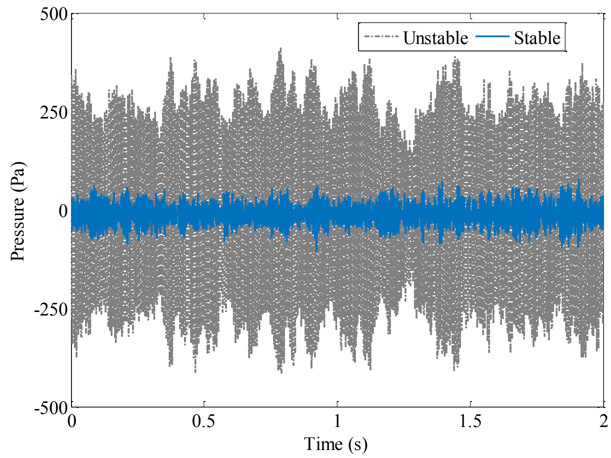

Fig. 2 Exemplary time evolution of acoustic pressure for stable and unstable system response

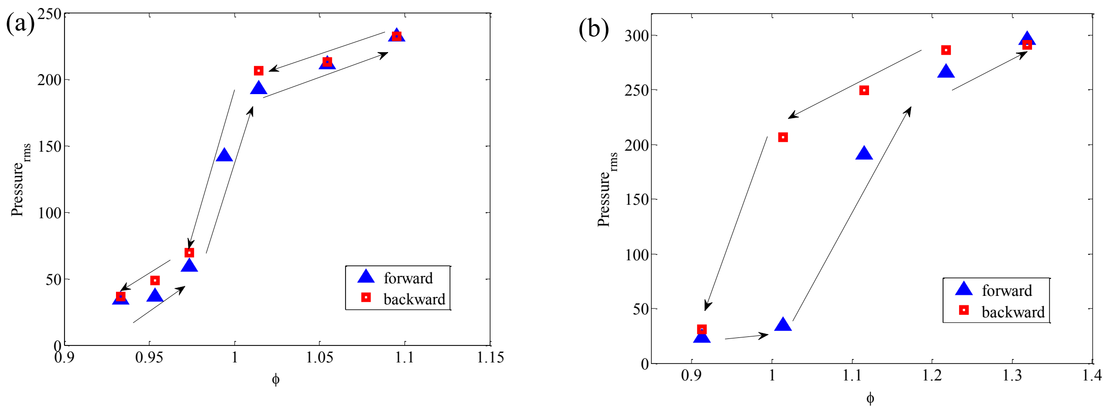

Fig. 3 The bifurcation diagram of the thermoacoustic system in the phase plane of (ϕ, $Pressure_{rms}$) at different operating conditions: (a) inlet velocity u=6 l/min (b) inlet velocity u=50 l/min

Then the heat exchanger is wrapped round the swirling combustor and its effect on the thermoacoustic oscillation is studied. Fig. 4(a) shows the time evolution of system response when the heat exchanger is activated. It can be seen that the system mainly undergoes three stages. In the first stage with no heat exchanger, there is a thermoacoustic oscillation with small amplitude around 200 Pa. Once the heat exchanger is triggered, after a short-time transition process in stage (2), the thermoacoustic system finally generates a louder sound with oscillatory amplitude around 300 Pa. It is clearly shows that by implementing the heat exchanger, the thermoacoustic oscillation in the swirling combustor is enhanced.

The effect of heat exchanger's location x_d/L on the oscillatory amplitude is examined in Fig. 4(b). The red line records the acoustic pressure with no heat exchanger. The blue line shows the acoustic pressure when the heat exchanger is added. The difference between the two cases is obtained by the shaded grey area. It can be seen the enhanced effect is comparatively significant when the heat exchanger is placed closer to end of the combustor chamber

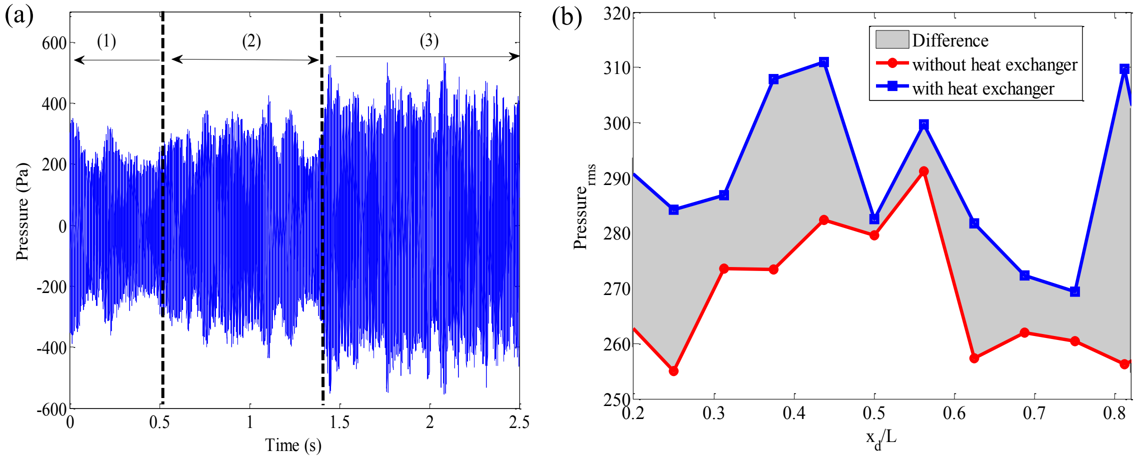

Fig. 4 (a) Time evolution of the thermoacoustic system when the heat exchanger is added, as $x_d/L=0.8$, u=50 l/min, $\phi=1.2$; (b) Dependence of oscillatory amplitude on the location of the heat exchanger x_d/L.

Conclusions

In this work, experimental investigation of thermoacoustic oscillations in a swirling combustor is conducted. Both subcritical and supercritical Hopf bifurcations are found to occur in this swirling combustor as the equivalent ratio changes at different inlet air flow velocities. When the thermoacoustic system undergoes the subcritical bifurcation, a small change in the equivalent ratio leads to a sudden/hard jump from steady state to large amplitude limit cycle oscillations. In addition, an innovative water-involved heat exchanger is developed and implemented on the swirling combustor to change the mean temperature distribution along the axial direction. Experimental results show that the amplitude of self-excited thermoacoustic oscillations is increased by the proposed approach. Finally, it has been found that the amplification of thermoacoustic oscillations becomes more apparent, when the heat exchanger is placed closer to the end of the combustor.

Acknowledgements

This work is supported by Singapore Ministry of Education AcRF-Tier 1 Grant RG91/13-M4011228. This financial support is gratefully acknowledged. Ms. Li Xinyan would like to acknowledge Nanyang PhD research scholarship.

References

[1] Fichera A, Losenno C, Pagano A. Experimental analysis of thermo-acoustic combustion instability. *Appl Energy*. 2001;**70**:179-91.

[2] Zhao D, Chow ZH. Thermoacoustic instability of a laminar premixed flame in Rijke tube with a hydrodynamic region. *J Sound Vib*. 2013;**332**:3419-37.
[3] Li X, Zhao D. Transient growth of acoustical energy associated with mitigating thermoacoustic oscillations. *Appl Energy*. 2016;**169**:481-90.
[4] Lieuwen TC. Experimental investigation of limit-cycle oscillations in an unstable gas turbine combustor. *J Propul Power*. 2002;**18**:61-7.
[5] Li X, Zhao D, Li S, Ji C. Effect of heat source on transient energy growth analysis of a thermoacoustic system. *Energy Convers Manage*. 2015;**89**:309-17.
[6] Singh A, Yu M, Gupta A, Bryden K. Thermo-acoustic behavior of a swirl stabilized diffusion flame with heterogeneous sensors. *Appl Energy*. 2013;**106**:1-16.
[7] Ji C, Zhao D, Li X, Li S, Li J. Nonorthogonality analysis of a thermoacoustic system with a premixed V-shaped flame. *Energy Convers Manage*. 2014;**85**:102-11.
[8] Matveev KI. Energy consideration of the nonlinear effects in a Rijke tube. *J Fluids Struct*. 2003;**18**:783-94.
[9] Li S, Zhao D, Ji C, Li J. Combustion instabilities in a bifurcating tube: open-and closed-loop measurements. *AIAA Journal*. 2014;**52**:2513-23.
[10] Li L, Zhao D, Yang X. Effect of entropy waves on transient energy growth of flow disturbances in triggering thermoacoustic instability. *Int J Heat Mass Transfer*. 2016;**99**:219-33.
[11] Zhao D, Li XY. Minimizing transient energy growth of nonlinear thermoacoustic oscillations. *Int J Heat Mass Transfer*. 2015;**81**:188-97.
[12] Li X, Zhao D. Unity maximum transient energy growth of heat-driven acoustic oscillations. *Energy Convers Manage*. 2016;**116**:1-10.
[13] Zhao D, Ega E. Energy harvesting from self-sustained aeroelastic limit cycle oscillations of rectangular wings. *Appl Phys Lett*. 2014;**105**:103903.
[14] Wu Z, Chen Y, Dai W, Luo E, Li D. Investigation on the thermoacoustic conversion characteristic of regenerator. *Appl Energy*. 2015;**152**:156-61.
[15] Zhao D, Li S, Zhao H. Entropy-involved energy measure study of intrinsic thermoacoustic oscillations. *Appl Energy*. 2016;**177**:570-8.
[16] Luo E, Dai W, Zhang Y, Ling H. Thermoacoustically driven refrigerator with double thermoacoustic-Stirling cycles. *Appl Phys Lett*. 2006;**88**:074102.
[17] Bi T, Wu Z, Zhang L, Yu G, Luo E, Dai W. Development of a 5kW traveling-wave thermoacoustic electric generator. *Appl Energy*. 2015.
[18] Yu Z, Jaworski AJ, Backhaus S. Travelling-wave thermoacoustic electricity generator using an ultra-compliant alternator for utilization of low-grade thermal energy. *Appl Energy*. 2012;**99**:135-45.
[19] Zhao D. Waste thermal energy harvesting from a convection-driven Rijke–Zhao thermo-acoustic-piezo system. *Energy Convers Manage*. 2013;**66**:87-97.

Biography

Ms. Nuomin Han is currently pursuing PhD degree under supervision of As. Prof. Dan Zhao in the School of Mechanical and Aerospace Engineering, College of Engineering, Nanyang Technological University (NTU), Singapore. Before joining NTU, she obtained her Bachelor degree from National University of Singapore in 2014. Her research interests include renewable energy, energy conversion and energy harvesting technologies.