Self-excited combustion oscillations of a burner: cause and remedy

Liu, Z. S.; Huang, C.; Qian, W. M.; Liu, Z. G.; Jiang, L. Y.; Campbell, I.; Yimer, I.

Publisher’s version / Version de l'éditeur:

The 10th International Congress on Sound and Vibration [Proceedings], pp. 1-8, 2003-07-01

Self-excited combustion oscillations of a burner: cause and remedy

Liu, Z-S.; Huang, C.; Qian, W-M.; Liu, Z.G.; Jiang, L-Y.; Campbell, I.; Yimer, I.

NRCC-46628

A version of this document is published in / Une version de ce document se trouve dans:
10th International Congress on Sound and Vibration, Stockholm, Sweden, July 7-10, 2003, pp. 1-8

Tenth International Congress
on Sound and Vibration
7-10 July 2003 • Stockholm, Sweden

SELF-EXCITED COMBUSTION OSCILLATIONS OF A BURNER: CAUSE AND REMEDY

Zhong-Sheng Liu[a], Cheng Huang[a], Wei-Min Qian[a]
Zhigang Liu[b], Lei-Yong Jiang[c], Ian Campbell[c], Ibrahim Yimer[c]

National Research Council of Canada
[a] Institute for Fuel Cell Innovation
[b] Institute for Research in Construction
[c] Institute for Aerospace Research
3250 East Mall
Vancouver, BC, Canada, V6T 1W5
Simon.liu@nrc.ca

Abstract

The burner, a piece of "cooking equipment", operates in a wide range of power outputs. Contrary to expectations, it generated a much higher level of noise at lower power outputs than at higher power outputs. At lower power outputs, a fluctuating flame regime existed both inside the combustion chamber and the pre-heating chamber, which did not occur at higher power outputs. Using detailed noise measurements and spectral analysis plus acoustic modeling, the problem was identified as a self-excited combustion oscillations (SECO). Therefore, the remedy was to decouple the acoustic pressure and the unsteady heat release through design modifications. This posed a challenging task. This paper presents our understanding of the SECO in terms of noise spectra, dominant acoustic resonance frequencies and the corresponding acoustic pressure mode shapes by means of this burner. More specially, an effective remedy technique is proposed and its successful application to suppressing the SECO of this burner is demonstrated and analyzed.

INTRODUCTION

A newly designed burner used for cooking was found to exhibit combustion oscillations when operating at low firing rates. The burner operates over a wide range of heat output. At the higher firing rates the burner produced a stable, low noise flame, however at lower firing rates, the combustion process produced a level of noise emission approaching 82dBA. This high level of noise at low firing rates was found to be higher than the customer's specifications and hence prompted an investigation to reduce or eliminate the noise

In an attempt to reduce the noise level, a root cause analysis was conducted covering detailed noise measurements, noise spectral analysis, and acoustic modeling of the chamber. The results suggest that the noise problem was caused by the self-excited combustion oscillations (SECO). Several methods of passively controlling SECO were attempted. These included the use of tubular inserts over burner exhaust holes, flame holders, nozzle wraps and modifications to the pre-heating chamber. Each method provided some changes to the SECO, however the most noticeable change was achieved by simply inserting a thin cylindrical tube inside the pre-heating chamber concentric to the burner axis. This modification proved to be very effective in suppressing the SECO with a noise reduction of approximately 4dBA.

The first objective of this paper is to present an understanding of the SECO by means of demonstrating its major characteristics including noise spectra, acoustic resonance frequencies and the corresponding pressure mode shapes. The second objective is to propose an effective remedy technique, which is to change (1) the distance between a nozzle and a flame zone; (2) to relocate the flame zone where the pressure gradient of the acoustic pressure mode shape in the flow direction of fuel/air mixture is smaller. By doing so, the phase relation between acoustic pressure and unsteady heat release rate is not in favour of causing the SECO.

The SECO, a typical phenomenon in a ducted flame burner, arises from the interaction between unsteady heat release and acoustic pressure. This interaction can lead to higher noise emission, severe vibration and even extinction of flames when the unsteady heat release is in phase with the acoustic pressure [1, 2]. Lord Rayleigh [1] studied this as early as 1897 and proposed a criterion for the SECO. During and after the Second World War, the development of rockets, ramjets, afterburners and gas turbines generated increased interest in this topic. Recently, this topic has received more attention due to the fact that lean-burn combustion, desirable for low NOx emission, is prone to the SECO.

The economic damages the SECO has caused to the thermal energy sector have been reported in the literature. For example, the Wall Street Journal [3] reported that the SECO led to the shut-down of new turbines made by various companies including General Electric Corporation, Europe's GEC- SA, Swiss-Swedish conglomerate Brown-Boveri, and Siemens.

EXPERIMENTAL SETUP

The burner consists of an automatic and closed circuit fuelling system, an air compressor, a syphon type fuel nozzle, a pre-heating chamber and a combustion chamber. The combustion chamber, illustrated in Figure 1, is a cylindrical chamber closed at one end and fitted at the other end with a pre-heating chamber. Liquid fuel is atomized by compressed air; the air/fuel mixture passes through the pre-heating chamber entering into the combustion chamber, where combustion occurs. The combustion gases leak out of the chamber through a series of holes arranged on topside of the combustion chamber. Ignition of the fuel/air mixture is done using a glow wire mounted to the side of the nozzle. Due to the working nature of the burner, the burner is arranged in an insulated bowel open at the top. A detailed diagram for the nozzle region is shown in Figure 2, including the insert discussed later.

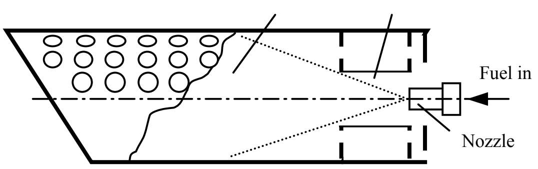

Fig. 1. Schematic of the burner chamber

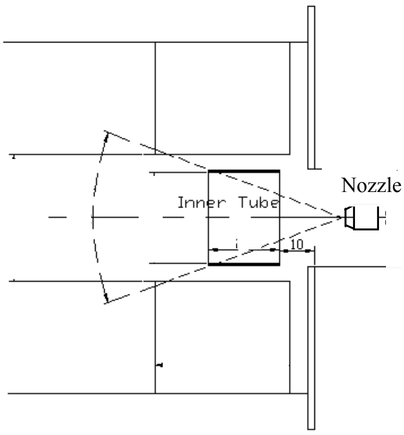

Fig. 2. The pre-heating chamber with the Concentric Inner Tube

The noise was measured using a B&K microphone (type 4133) and a B&K signal analyzer (type 2133) at different firing rates. The burner was placed centrally in an $8.5\times6.5\times3.5m$ semi-anechoic chamber. The walls in the chamber were covered with a 5mm thick fiberglass material to reduce the amount of reflected noise in the room. The microphone was positioned 1.0m away horizontally and 1.55m away vertically from the burner. The sound pressure levels of the noise were collected at eight different directions (at 45 degree intervals) around the burner. In order to reduce any possible effects of the room acoustic resonance frequencies on the spectral analysis, the microphone was positioned close to the nozzle end of the burner, at a distance of 10cm. At this location the noise spectra collected would be due to the combustion noise and burner acoustics.

The temperature distribution on the surface of the chamber was measured using an infrared camera for the purpose of estimating the sonic speed distribution inside the chamber. It was found that the temperature is not uniform along the whole length of the chamber. At the higher firing rates, the downstream side achieved the highest temperature; at the lower firing rates, the upstream side, near the interface between the chamber and the pre-heating chamber, has the highest temperature. This is expected because the locations where the flames reside are different for different firing rates. The higher the firing rates, the farther the flame zone moves downstream.

ACOUSTIC MODELING

The acoustic modeling of the burner chamber was performed using the finite element code ANSYS. Based on the temperature distribution inside the chamber, the chamber volume was divided into several smaller zones so that in each zone, the temperature is close to be uniform and thus a constant sonic speed is assigned to that zone. The temperature distribution was inferred from the infrared measurements. There are two types of boundary conditions, one is wall boundary condition where the normal pressure gradient is zero, and the other is open-to-ambient boundary condition where the pressure takes zero. After the sonic speeds associated to each zone were specified and the boundary conditions were applied, the acoustic resonance frequencies and the associated pressure mode shapes were extracted. The result indicated that the first (lowest) acoustic resonance frequency is 1199Hz. Figure 3 shows the pressure mode shape associated with this resonance frequency. The other resonance frequencies and the associated pressure mode shapes were also calculated, but these frequencies did not have significant presence in the noise spectra.

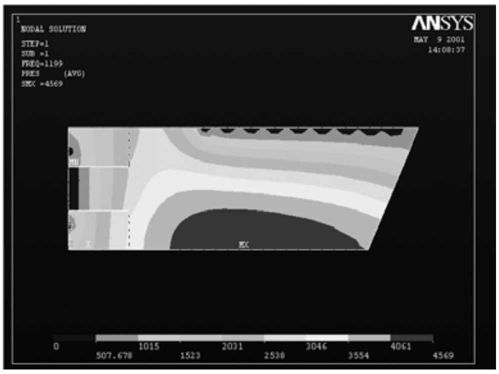

Fig. 3. The First Acoustic Pressure Mode Shape (1199Hz)

RESULTS AND DISCUSSIONS

The results show that the average sound pressure level of the noise is 82dBA at the lowest firing rate, 79dBA at the medium firing rate, and 74dBA at the highest firing rate. It was obvious that the highest noise level is associated with the lowest firing rate or at minimum heat output. In fact, the increase in the noise level was audible when the firing rate gradually decreased. Although contrary to expectations, this has been the case for most burners operating in a premix mode.

It was also observed that the higher level of noise associated with the lower firing rates was always accompanied by a fluctuating flame regime whereby the flame is drawn back into the pre-heating chamber. Increasing the firing rate to the medium range displaced the flame out of the pre-heating chamber into the main chamber, potentially reducing the noise level.

Figure 4 and Figure 5 show the frequency spectra of the noise signal recorded at the lowest firing rate and at the highest firing rate, respectively. In Figure 4, the frequency peak, entered at about 1280Hz, contains a large amount of energy. When the firing rate was increased to the highest firing rate, the 1280Hz peak while still visible is much weaker, as shown in Figure 5. The temperatures and burner geometry precluded the use of internal acoustic measurements to determine the origin of the strong 1280 Hz signal. Modeling of the chamber acoustics under the estimated temperature distribution was used to establish and identify the spectra peak.

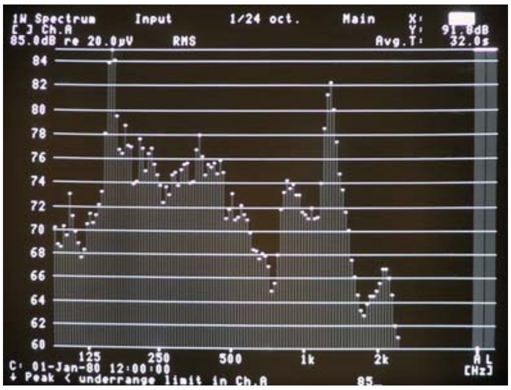

Fig. 4. Noise Spectra Under the Lowest Firing Rate

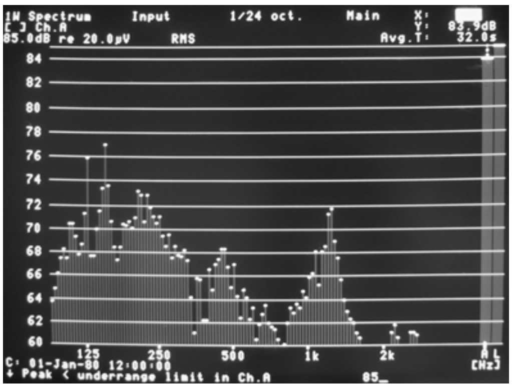

Fig. 5. Noise Spectra Under the Highest Firing Rate

From the frequency spectral analysis of the noise signal associated with the lower firing rates, and the acoustic modeling of the burner chamber, two major characteristics can be drawn: the first is the frequency match, that is, the frequency peak in the noise spectra (in the range of 1200Hz-1300Hz), is corresponding to the lowest acoustic resonance frequency of the chamber because it is so close to the first acoustic resonance frequency, 1199Hz, of the burner chamber; the second is the resonance frequency dominance. As can be seen in Figure 4, the majority of the noise energy centred at about 1200Hz-1300Hz. These two characteristics strongly suggest that the strong coupling between the acoustic pressure and the unsteady heat release rate, or the SECO, exists and causes the higher level of noise.

Although this coupling is believed to be the cause of the noise in the burner as outlined above, it poses a significant challenge to conceive a physical solution. This is mainly because of so many interweaving factors contributing to the phase relation such as:

(1) acoustic resonance frequencies and pressure mode shapes, determined by the chamber geometry and the sonic speeds inside the chamber;
(2) location where the flames reside;
(3) distance between a nozzle and a flame zone;
(4) acoustic wave length of the air/gas mixture confined between the nozzle and the flames;
(5) convective velocity of the air/gas mixture.

Generally, any change in any of the factors listed above will result in a change in the phase relation. For example, an increase in the convective velocity of the air/fuel mixture can lead to a change in the distance between the nozzle and the flames, and therefore cause a change in the phase relation. In the case of our burner, the SECO disappeared almost completely when the convective velocity of the air/fuel mixture was increased by increasing the firing rate. The phase change can also be realized by modifying the chamber geometry whereby the acoustic resonance frequencies and their associated acoustic pressure mode shapes are modified. In this burner case, it was noticed that a higher level of noise and occurrence of fluctuating flame regimes had a dependence on the length of the chimney used for testing purposes.

The solution finally implemented was to insert a concentric tube into the pre-chamber, as shown in Figure 2. With the presence of the inner tube, some significant changes were observed in the flame at the low firing rate. First, the flame zone had moved downstream by about 4cm, that is, the length between the nozzle and the flame zone, when the inner tube is present, is about 4cm longer than the original one. The change in this length leads to a change in the phase relation between the acoustic pressure and the unsteady heat release [2]. Another contributing factor to the suppression of the SECO comes from the fact that the inner tube relocated the flame zone downstream by about 4cm where the pressure gradient of the acoustic mode shape in the flow direction of fuel/air is smaller, as shown in Figure 3, and thus the fluctuating flow rate of fuel/air mixture is getting smaller.

The other effect of the inner tube was the flow regime and the combustion zone was much more stable and no visible flame migration inside the pre-heating chamber. Most importantly, the sound pressure level associated with the lowest firing rate was reduced by about 4dBA and there was a significant change in the noise spectra, as shown in Figure 6. In comparing Figure 6 with Figure 4, a noticeable reductions in all the frequency bands is observed, in particular, there is about 7dBA reduction in the frequency band of 1280Hz. Obviously, the inner tube, despite its simplicity, has significantly suppressed the SECO. Other measurements have also shown that the CO emission was reduced when the inner tube was present. This is also expected since combustion oscillations, especially at higher amplitude promote local quenching of the flame thereby increasing the CO levels. However, the inner tube caused nearly no effect on the combustion at the highest firing rate. Figure 7 and Figure 5 give the noise spectra associated with the highest firing rate when the inner tube was present and not present, respectively. It is obvious that they are almost the same. An explanation to this could be that the SECO did not exist at the highest firing rate.

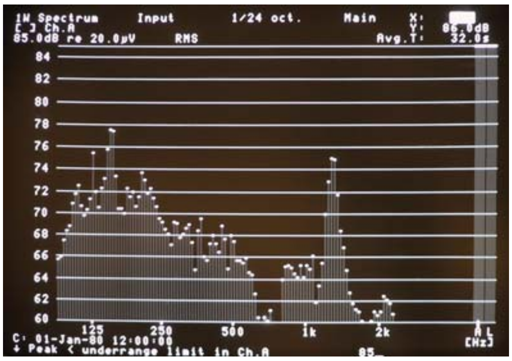

Fig. 6. Noise Spectra under the Lowest Firing Rate with the Inner Tube

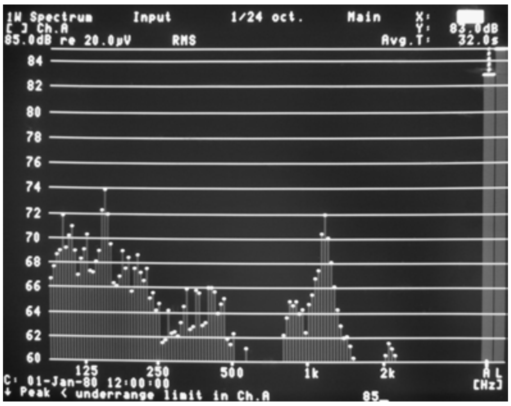

Fig. 7. Noise Spectra under the Highest Firing Rate with the Inner Tube

CONCLUSIONS

When the firing rate was lower, the burner generated a higher level of noise than it operated at the higher firing rates. The high noise emission caused by the SECO, was significantly reduced by the introduction of the concentric inner tube into the heating/mixing chamber. The effect of the inner tube insertion in the pre-heating chamber appears to be (1) the change in the distance between the nozzle and the flame zone and (2) the change in the relative position of the flame zone with respect to the acoustic pressure mode shape. The overall effect of them is to decouple the acoustic pressure and the unsteady heat release rate.

REFERENCES

[1] J.W.S. Rayleigh, The Theory of Sound, Vol. 2 (Dover Publications, New York, 1945), 224-234.
[2] A.A. Putnam, Combustion Driven Oscillations in Industry (American Elsevier Publishing Company, New York, 1971).
[3] Turbine Makers Are Caught in Innovation Trap, Wall Street Journal, 02/13/1998.

ACKNOWLEDGEMENT

The authors want to thank Mr. Jonathan Young, Mr. Brad Couch, Mr. Jun Zhang, Mr. Craig Fisher, Mr. Alex Schwartzman, Dr. Foued Ben Amara and Dr. Krish Krishnappa for their participation in this noise reduction project.