How to Solve Abnormal Combustion Noise Problems

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This article discusses abnormal combustion noises in boilers, burners and heating systems. An experimental method is described to provide insight into the causes of such noises. Several techniques are presented for the reduction or elimination of abnormal combustion noises.

During the development of a new boiler, burner or heating system it is always possible that a prototype will emit an unacceptably loud noise that is clearly abnormal. Although the occurrence might be infrequent, its very presence necessitates elimination before the product can go to market. Since the noise is so abnormal, it is tempting to think that a solution will be found quickly by making some small design changes. If one is very lucky, this cut-and-try approach may indeed work. Most likely, however, it will be frustratingly slow and may not succeed at all.

Frustrations often escalate since the occurrence of the abnormal combustion noise can be very elusive. In some cases it may occur only for a few seconds during a cold start, while in others it may occur only when the unit is shut down and restarted while still hot. Others may occur only on days when the gas utility is changing the composition of the supply for peak shaving purposes. I even know of a case when, during the field trials of a new furnace, three units out of 100 in widely scattered locations had an abnormal noise problem, even though the prototype tests had given no such indication. When one of the noisy furnaces was brought back to the lab just a few miles away, it was impossible to reproduce the abnormal noise despite many efforts.

While there is no "magic bullet" that will solve abnormal noise problems in all cases, there are a number of useful tools. The trick is to know what tools are most likely to work in a particular case, which requires a good insight into the causes of abnormal noise and how the different parts of a unit are involved.

Abnormal noise problems have received considerable study in industrial gas turbines,[1] but engineers in the heating industry may find it difficult to apply this information to residential and small commercial equipment. This article will, therefore, use a series of bench-top experiments with the test rig shown in Figure 1 to demonstrate the answers to many of the questions that arise when dealing with abnormal combustion noise problems. The test rig consists of parts that are available in any hardware store, requiring only a few simple modifications. It is recommended that the reader construct such a device for the learning advantages offered by performing the experiments rather than only reading about them. Construction details are available by e-mail from the author.

The burner shown in Figure 1 does not lend itself to the exploration of various burner port geometries nor to the exploration of various lengths of the mixture supply system, both of which are known to offer possible solutions for abnormal combustion noise problems in furnaces or boilers.[2] Experiments for demonstrating these possibilities will be covered in a following article. Since it is often helpful to explore the effect of changing some parts of a system before actually making the change, this separate article will also describe simple computer simulation tools.

Question #1 – What Does Abnormal Combustion Noise Sound Like? The equipment needed for this experiment is shown in Figure 1. Without the transparent window section at the bottom, adjust the sliding extension at the top of the tube so that the total length of the assembly is 610 mm (24 in.). Light

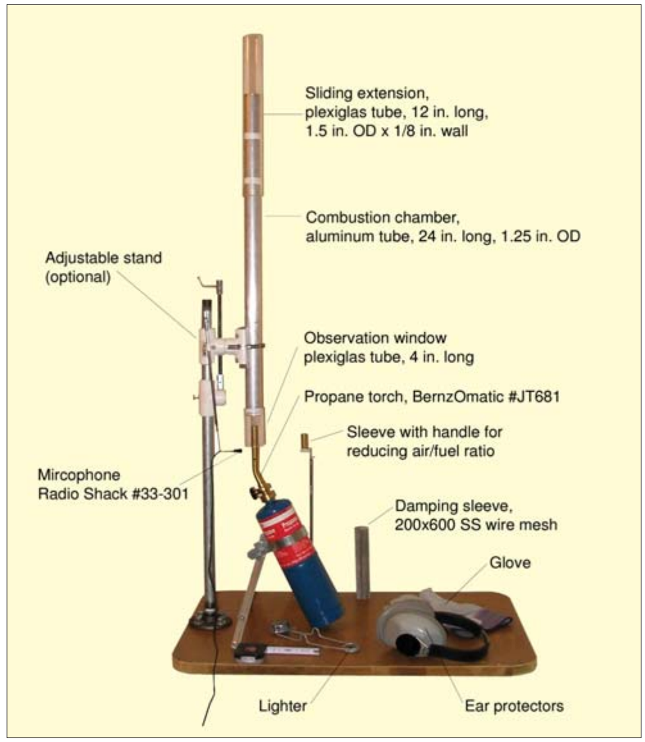

Figure 1. Equipment used for the experiments.

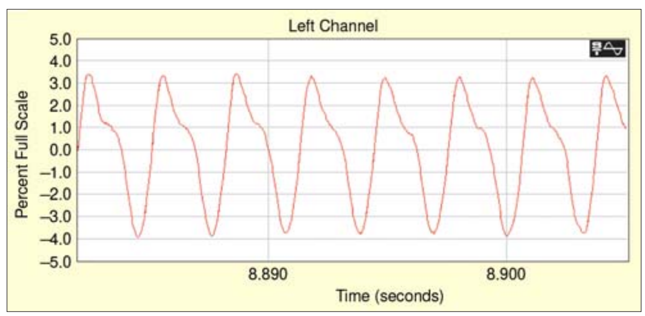

Figure 2. Waveform of the sound pressure at the bottom end of the tube.

the burner outside the tube, adjust the gas flow until the flame is about 10 mm (0.4 in.) high, and let it heat up for at least two minutes. Then lower the tube so that the burner top extends about 50 mm (2 in.) into the tube. A loud noise will be heard. The signal picked up by the small microphone near the bottom of the tube will show the pressure to have the waveform of a somewhat distorted sine wave with a period of about 3.09 milliseconds, which corresponds to a fundamental frequency of about 324 Hz (Figure 2).

The corresponding spectrum in Figure 3 shows the expected spike at 324 Hz. There are also smaller spikes at 648 Hz and 972 Hz. Since the frequencies of these lower amplitude spikes are exact multiples of 324 Hz, these spikes are the second and third harmonics of the fundamental frequency of 324 Hz. Such harmonics are to be expected since the waveform in Figure 2 is a somewhat distorted sine wave. The conclusion to note from this experiment is that the abnormal combustion noise that occurs when the flame is inserted into the confines of the tube has the nature of cyclical pressure oscillations with very little variation from one cycle to the next.

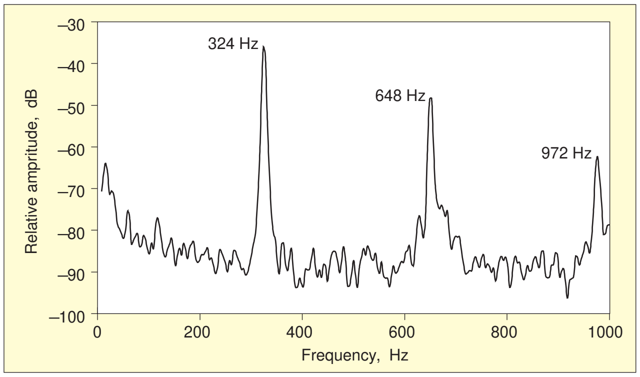

Figure 3. Sound pressure spectrum at the bottom end of the tube.

With this experimental rig, the spikes in the spectrum are more distinct than they typically will be for an actual furnace or boiler. Such units have other noise sources (e.g., fans) that tend to fill in the spectrum between the spikes shown in Figure 3. However, the existence of any discrete frequency spike at a frequency that is unrelated to any of the other noise sources is "smoking gun" evidence of abnormal noise and the first step for solving such problems.

To examine the spectrum requires an FFT analyzer, which also provides a means for recording waveshapes (like Figure 2) and is an indispensable tool for solving abnormal combustion noise problems. Any attempt to solve such problems without such a tool is like shooting blindfolded. Still, while an FFT analyzer is essential, it will not answer all questions by itself. A good insight into the mechanism that causes the pressure oscillations is also required, which is exactly the purpose of the following experiments.

Question #2 – What Determines the Frequency of Oscillation? Listen to the change in the noise while adjusting the sliding extension at the top of the tube to make the assembly longer – the longer the tube, the lower the pitch. Also observe the changes in the spectrum. At a length of 610 mm, the frequency of the fundamental component was 324 Hz, but at 810 mm (32 in.), it is 244 Hz. Since the frequency of oscillation is essentially inversely proportional to the tube length, it appears that the fundamental frequency may be the frequency of the lowest half wavelength resonance of the gas space in the tube (representing the combustion chamber in these experiments).

To check this hypothesis, insert from the top a probe tube with a suitable pressure transducer until the tip extends to about 50 mm (2 in.) below the bottom of the test rig, then withdraw it while recording the pressure-time history. If the probe tube is withdrawn at a uniform rate the record will look like that in Figure 4. The upper envelope should have the shape of half a cycle of a sine wave, confirming that the fundamental frequency of oscillation is indeed that of the lowest half wavelength resonance of the combustion chamber.

The test of Figure 4 is difficult to perform due to the difficulty of withdrawing the probe tube at a uniform rate. Also, it is necessary to pass the transducer signal through a bandpass filter to remove the harmonics since only the map of the fundamental component is of interest. An easier, although somewhat tedious, mapping procedure is to use the probe tube to obtain a series of spectra at fixed points along a traverse through the combustion chamber and then plotting the amplitude values of the fundamental component vs. position. Since the operating conditions of the unit are likely to drift over the mapping duration, the FFT analyzer should be set up to show the decibel difference between the signal from the probe tube and that from a fixed microphone such as the one shown at the bottom of the tube in Figure 1. Such plots of amplitude vs. position are called "mode shape plots."

Mapping of the pressure field in the combustion chamber can be a very useful tool for diagnosing some abnormal combustion noise problems in actual heating equipment. For either of the test methods, the probe tube must be designed to prevent

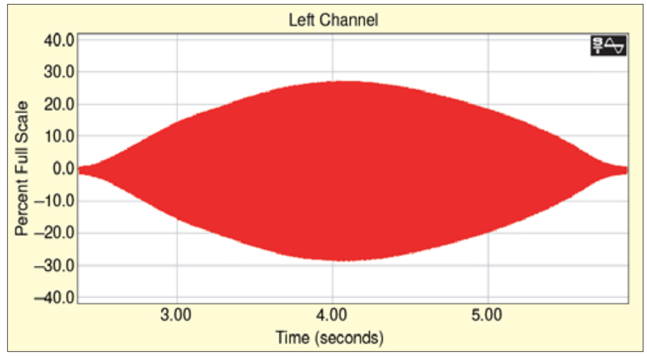

Figure 4. Map of the pressure field in the 610 mm long tube during oscillation. Note – The time scale represents the position in the tube because the pressure was recorded with a moving probe tube microphone. There are about 1000 pressure cycles in the 3.3 sec record shown. Thus, the individual cycles are so crowded that only the peaks can be seen.

overdriving the pressure transducer. Details of probe tube designs can obtained from the author.

Question #3: Is It Possible to Calculate the Resonance Frequency? While it is possible in principle to calculate a resonance frequency, it is often impractical for an actual unit. Such calculations are likely to be very time consuming because the walls of the combustion chamber are often not perfectly rigid. Thus, a rather elaborate mathematical model would be required.

It is instructive, however, to examine the calculation procedure for the rigid walled experimental rig used here. The first step is to set up the equation for the wavelength of sound, which is:

$$\lambda = \frac{c}{f} \quad (1)$$

where:
λ = wavelength in m
c = speed of sound in m/s
f = frequency in Hz.

From the previous experiment, the frequency of oscillation is such that the wavelength of the pressure oscillations is equal to about twice the length of the tube surrounding the flame. Thus the resonance frequency could be found quite simply by substituting $2(L+2\ \Delta L)$ for λ in Equation 1 and solving for f. $\boldsymbol{L}$ is the length of the tube and ΔL is the so called "end correction,"[3] which takes into account the fact that the pressure amplitude does not go to zero at the open end, as shown in Figure 4.

There are several problems with this calculation. The speed of sound increases in direct proportion with the square root of the absolute temperature.[4] The temperature in the test rig of Figure 1 is not constant over the length of the tube, but depends on position. The bottom of the tube is at room temperature (20° C), a maximum exists just above the flame and then the temperature declines depending on heat transfer to the walls of the tube. Further complications arise because of temperature and velocity gradients in the area of the tube outlet.[5]

So even for the simple geometry of the test rig of Figure 1, it would not be easy to calculate the resonance frequency with any degree of accuracy.

Question #4: How Can the Resonance Frequency Be Measured? Under cold conditions, measuring the resonance frequency is not difficult. With a homemade pulse generator (construction details available from the author), one can set off a small explosive charge in the flame area with the cap of a toy pistol. A microphone in the same area will pick up the pressure response. Figure 5 shows the response waveform for a 610 mm long tube at room temperature, taken with a sampling rate of 12,000 samples per second. The first 0.05 seconds show that many modes are excited, although all but the fundamental one die out quickly. In the time interval from 0.1 to 0.2 seconds, Figure 5 shows about 28.5 cycles. Thus the lowest resonance frequency of this system is about 285 Hz at room temperature.

Performing this test in the rig of Figure 1 shows that the peak pressure developed by the explosion exceeds the dynamic range of any ordinary microphone. Figure 5 indicates that the microphone was overdriven for the first 0.04 seconds of the record. Though undesirable from the standpoint of possible damage to the microphone, it did not prevent extracting the resonance frequency information from the test results. When performing this test in an actual heating unit, overdriving is not as likely to occur because the volume of the unit will be much larger than that of the test rig, so that the explosion will be much less confined and thus generate much lower pressures.

Remember that under actual operating conditions, the resonance frequency will be considerably higher because the speed of sound increases with temperature. Still, such measurements can be useful for diagnosing a problem of abnormal combustion noise because they provide more insight into how the unit behaves. By extrapolation, a rough estimate of the resonance frequency of the hot system can be obtained, which is sufficient to determine whether the oscillations do indeed occur at the resonance frequency of the combustion chamber.

Question #5 – Is the Abnormal Combustion Noise a Resonance Problem? The previous experiments have shown that the frequency of oscillation is determined by a resonance frequency of the tube which, in these experiments, constitutes the combustion chamber. It is therefore understandable that such abnormal noises are often called "combustion resonances," even though the term is misleading since it implies that the noise is a resonance problem. If that was the case, changing the resonance frequency should take the system out of resonance and solve the problem. The experiment for Question #2 has, however, shown that not to be the case, so the abnormal noise is clearly not a resonance problem. The most descriptive term for the abnormal combustion noise explored in these experiments is "combustion-driven oscillations."

These experiments indicate that moderate changes of the resonance frequency of a furnace or boiler will merely change the frequency of the noise without much effect on the amplitude. There are well documented cases, however, in which large changes did eliminate the combustion-driven oscillations. Replacing the 610 mm (24 in.) long combustion tube with one that is only one third as long will eliminate the oscillations. The reason will be explored in a following article.

Question #6: How Does One Solve a Combustion-Driven Oscillation Problem? Putnam has shown that combustion-driven oscillations occur only for certain combinations of the properties of the combustion chamber, flame and mixture supply.[2] This experiment will explore a modification of the combustion chamber that will stop the oscillations quite spectacularly. Some suitable modifications of the flame will be explored later.

To investigate this modification of the combustion chamber, remove the sliding extension at the top of the tube and install a short Plexiglas section at the bottom, about 75 mm long, so that the flame can be observed. Then take an ordinary cloth handkerchief, fold it twice to form a strip about 4 times longer than it is wide. Wrap it around the top part of the tube, leaving about 25 mm (1 in.) uncovered at the top. Now lower the combustion chamber tube over the flame carefully so the Plexiglas will not get damaged. Once the noise has started, slide the cloth sleeve up so it extends about 25 mm (1 in.) beyond the top of the combustion chamber, which will kill the noise instantly.

When doing this experiment for a live audience, I have often used the theatrics of removing the handkerchief, unfolding it, and asking the audience to convince themselves that there is nothing hidden inside it that might have produced the 'magic' of killing the noise.

The sleeve killed the noise by adding damping to the system. I have solved several cases of combustion-driven oscillation problems in actual heating systems by adding damping in a very similar way. In our experimental rig without the damping sleeve, there is hardly any damping other than by acoustic radiation from the inlet and outlet. In most heating units there is also considerable inherent damping due to static pressure drop in various parts of the system. Thus, the desired increase in damping can often be achieved by increasing the pressure drop. For some burner designs, this is best accomplished by increasing the velocity through the burner. Increasing damping by a sufficient amount will always work, although smaller increases will have little effect on the noise.

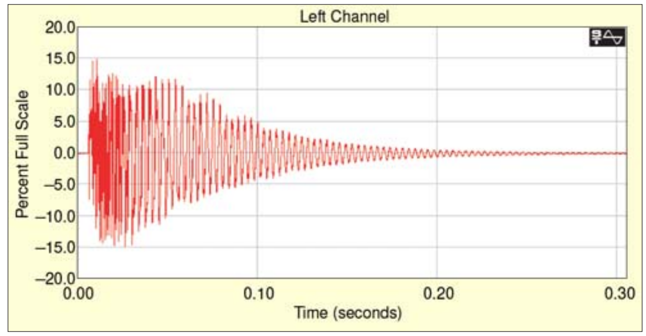

Figure 5. Pressure response of the 610 mm long tube in the test rig of Figure 1 at room temperature when excited by the explosion of a toy pistol cap.

To demonstrate this, slide the damping sleeve up very slowly while listening to the noise. Until the critical position is reached where the oscillations are stopped, there is very little reduction of the total noise. Beyond that position, the reduction is quite sudden.

Question #7 – What Is the Role of the Flame? When performing the above experiment, the flame should be observed closely while sliding the sleeve up and down repeatedly to stop and start the noise. When the noise is off, the light blue inner cone of the flame is sharply defined, but when the noise is on it becomes blurred. The appearance of the flame changes because the flame size grows and shrinks rapidly in a cyclical fashion during the oscillations. Since the flame oscillations occur at the same frequency as the pressure oscillations, the eye cannot follow the rapid size changes, so the cone boundaries simply appear blurred.

A clear view of the cyclic variations of the flame size requires the use of a mechanical stroboscope. A stroboscope is a slotted disc driven at such a speed that the slot passing frequency is about 0.5 Hz below the oscillation frequency. This will produce a slow motion image of the changes in flame size that can also be captured with a film or video camera. Figure 6 shows a sequence of frames from a movie shot through a homemade stroboscope (construction details are available from the author). The significance of the flame size variations is that the burning rate of the flame varies in direct proportion to the surface area of the blue inner cone.

Question #8 – Which Came First, the Flame Oscillations or the Pressure Oscillations? The old "chicken-or-egg" scenario – small oscillations of the flame size and burning rate cause pressure oscillations that cause larger oscillations of the burning rate that cause larger pressure oscillations, and so on. It is a vicious circle (see Figure 7) that results in high amplitude combustion oscillations, limited only when the amplitude surpasses the limits of linear behavior.

Question #9 – How Does the Vicious Circle Get Started? Comparing the first few seconds of pressure oscillation under various conditions can provide quite a bit of insight about self-excited combustion oscillations. The following three experiments explore the effect of how far the tip of the burner extends into the combustion tube (adjusted to a total length of 610 mm).

Before starting the burner, adjust the stand so that the burner tip extends exactly 50 mm into the tube. Rough adjustment is made by loosening the band clamp and sliding the combustion chamber tube up or down with the vertical adjustment screw in a position leaving about 13 mm between the two T-fittings of the stand. Then use the vertical screw for fine adjustment, making sure that coupling at the lower end of the screw remains in contact with the fixed (bottom) T-fitting and that the burner

Figure 6. Sequence of frames from a slow motion movie of the oscillating flame. Note – The frames show the flame size at instances 1/4 of a cycle apart. The last frame shown is a repeat of the first.

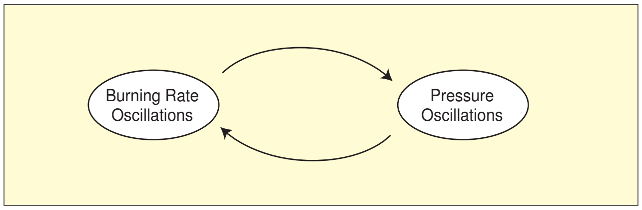

Figure 7. The vicious circle that gives rise to combustion oscillations.

is centered in the tube.

Lifting the top T-fitting and swinging the combustion tube out of the way exposes the burner for lighting. Adjust the flame to be 10 mm high, swing the top T-fitting to bring the tube into position and lower it until the coupling in the adjustment screw contacts the top of the bottom T-fitting. Note that it will take about a minute for the oscillations to start and that the amplitude will slowly grow for about another minute as the burner continues to heat. This delay in the start of the oscillations is of little practical concern, so long as the oscillations start once the system has heated.

In order for these tests to provide valid comparisons, the entire test rig must be at a constant temperature since any temperature drifts would introduce an additional variable. Let the apparatus stabilize for another 2 minutes. During this time, apply the damping sleeve used in the experiment for Question #6, then start recording the pressure signal as the sleeve is quickly pulled off the top of the tube. A typical record is shown in Figure 8a, which indicates that the oscillations do not start instantly but take about half a second to build.

An expanded view of part of the oscillation build-up is shown in Figure 8b, which shows that the amplitude of each cycle is about 3% larger than that of the previous cycle. Mathematically, this is known as an exponential build-up, and the growth per cycle is called the build-up rate. This building up of the pressure amplitude shows that acoustic energy is generated by the oscillating flame faster than it is dissipated by damping and by radiation from the ends of the combustion tube. In the experiment for Question #6 we have seen that the oscillations can be stopped by increasing damping to the point where the acoustic energy is dissipated faster than it is generated by the oscillating flame.

After obtaining this record, obtain a spectrum and note that the fundamental frequency of the fully built-up oscillation is 324 Hz. Next, re-apply the damping sleeve and use the vertical adjustment screw to raise the combustion tube by 10 mm, which will take 6.3 turns clockwise. Record the pressure signal again as the sleeve is quickly pulled off the top of the tube. A typical record is shown in Figure 9. Note that the oscillations build up much more slowly than those in Figure 8. Check the spectrum of the fully built-up oscillation and note that the fundamental frequency has shifted to 331 Hz.

Finally, re-apply the damping sleeve once more and use the vertical adjustment screw to raise the combustion tube by another 10 mm. Again record the pressure signal as the sleeve is quickly pulled off the top of the tube. With the insertion depth of the burner reduced to 30 mm, oscillations do not build up at all. The build-up rate has been reduced to zero.

Question #10 – How Can the Effect of Burner Insertion Depth Be Explained? The previous experiments have shown that the

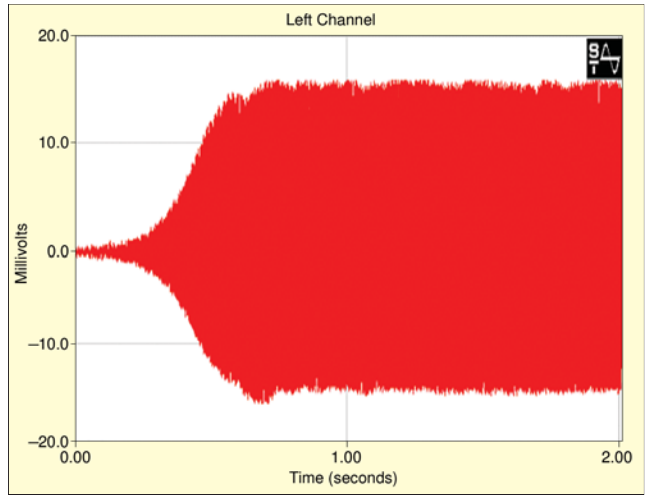

Figure 8a. Onset of the oscillations during a hot start with the burner inserted to a depth of 50 mm.

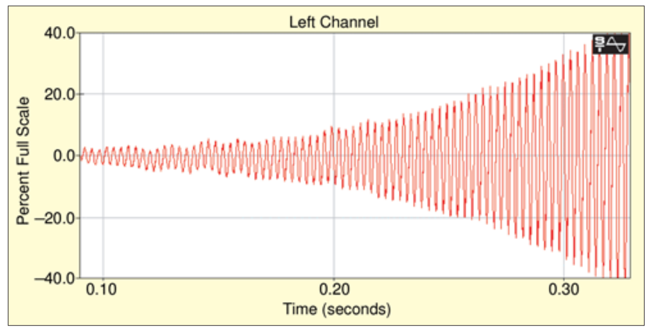

Figure 8b. Expanded view of the oscillation build-up during a hot start with the burner inserted to a depth of 50 mm.

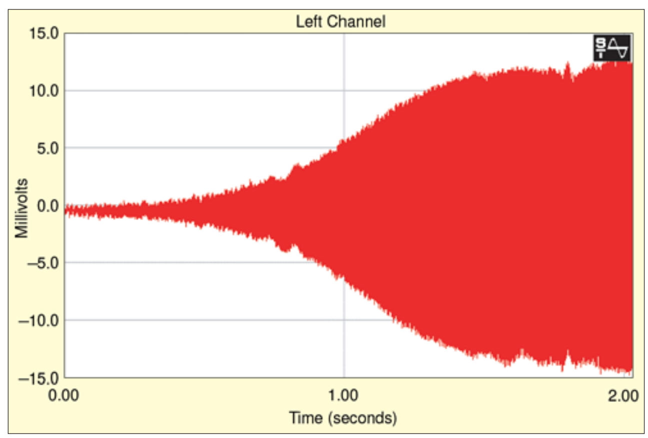

Figure 9. Onset of the oscillations during a hot start with the burner inserted to a depth of 40 mm.

build-up rate of oscillations depends on the degree of confinement of the flame. This may seem only of academic interest because in most furnaces and boilers flame confinement is impossible to change. I do, however, remember a furnace with an oscillation problem that was solved simply by increasing the clearance around the burners at the entrance to the heat exchanger. Aside from that, the relation of oscillation build-up to flame confinement is the key for gaining a deeper understanding of what causes combustion oscillations.

The first step is to quantify the rather vague term "degree of confinement" used above. For this, we need to replace the diagram of Figure 7 with the one shown in Figure 10. In this schematic, the interactions of the flame and the pressure are arranged as a feedback loop that can be analyzed mathematically. Under certain conditions, such loops become unstable, giving rise to self excited oscillations, such as the generation of musical sounds by flutes or organ pipes. These equations for the onset of instability are derived in reference 6.

The blocks labeled Z, H and G in Figure 10 represent the acoustic properties of the combustion chamber, the mixture supply system, and the flame, respectively. These properties can be formulated as equations that define the response of each of these system components to an acoustic input. The response of any one of the components becomes the input to the next one, and so on around the loop. The loop becomes unstable when pressure oscillations are sustained even if there is no external input, i.e. when $q_{external} = 0$. This condition for instability is that the magnitude of the product Z × H × G must be greater than 1.0 at any frequency at which the sum of the phase angles of Z, H and G is zero or 360°.[6]

The block labeled Z in Figure 10 represents the confinement of the flame in the combustion chamber. The symbol Z is used because this confinement amounts to an acoustic impedance.[3] For the test rig used in these experiments, the acoustic impedance seen by the flame can be calculated, subject to some simplifying assumptions. The resulting plots of the magnitude and phase of Z are shown in Figure 11A and B for burner insertion depths of 50 mm and 30 mm, and a total length of the combustion tube of 610 mm.

Figure 11 shows that the magnitude of the acoustic impedance seen by the flame has a peak at any resonance frequency of the combustion chamber and that the phase angle goes though a 180° change at such a frequency. This jump in the phase means that there is at least a 50/50 chance that, at these frequencies, the above phase condition for self excited oscillations will be satisfied.

While the phase condition must be satisfied for self excited oscillations to build up, it alone is not sufficient for build-up to occur. It is also necessary that the magnitude of the product of Z × H × G must be larger than 1.0 at the frequency at which the phase condition is satisfied. Putting it another way, it is necessary that the magnitude of Z exceed the magnitude of 1/(H × G).

Figure 11a shows that reducing the depth of insertion of the burner reduces the peak magnitude of the acoustic impedance by about 50%. For this reason, oscillations built up with a burner insertion depth of 50 mm in the experiments described above, but did not build up with a burner insertion depth of 30 mm.

Figure 11 also shows that reducing the insertion depth of the burner moved both the calculated phase and the peak magnitude of Z to a somewhat higher frequency. In the above experiment with a 40 mm insertion, an even larger shift of the oscillation frequency was also observed. From the experiment in Question #2, we know that such frequency shifts do not stop the oscillation. Thus, reducing the height of the impedance magnitude peak must be the reason there are no oscillations at a burner insertion depth of 30 mm.

Question # 11: What Are the Practical Uses of the Feedback Loop Model? Figure 11 has shown that the mathematical model of Figure 10 can be used for explaining the effect of the flame confinement on the occurrence of self excited oscillations. Similar curves could also have been generated to show that the effect of additional damping is simply to reduce the height of the impedance peak at the resonance frequency.

In principle, this model could be used to predict whether a proposed boiler or furnace design will have an oscillation problem. That such predictions are possible has been demonstrated for a gas turbine combustor[7] as well as for typical heating products.[8] The amount of effort required is rather substantial, however, and is not likely to be justifiable since these problems do not occur very often in heating products and the stakes are not nearly as high as in the case of gas turbines.

Thus, the primary use of the feedback loop model in typical heating products is to provide guidance for solving oscillation problems if and when they occur. For this purpose it is not necessary to know the equations for Z, H and G with any degree of precision – approximating the trends involved is adequate. In many cases, there is no need to be concerned with the phase angles either since they are needed primarily for predicting the already known frequency of oscillation.

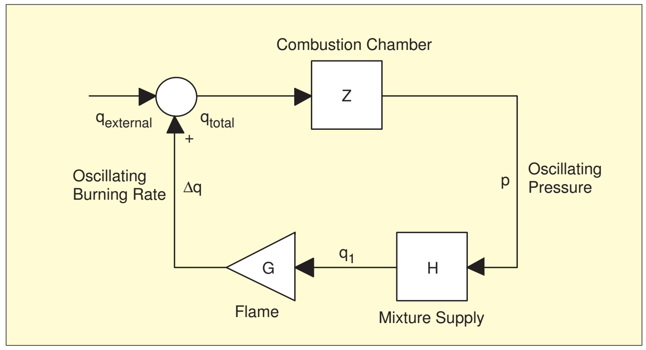

Figure 10. Schematic representation of the feedback loop (from Baade, 1978).

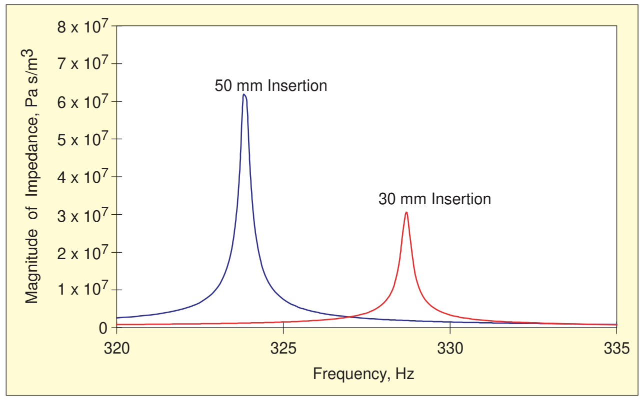

Figure 11a. Magnitude of the acoustic impedance seen by the flame in the test rig for insertion depths of 50 mm and 30 mm.

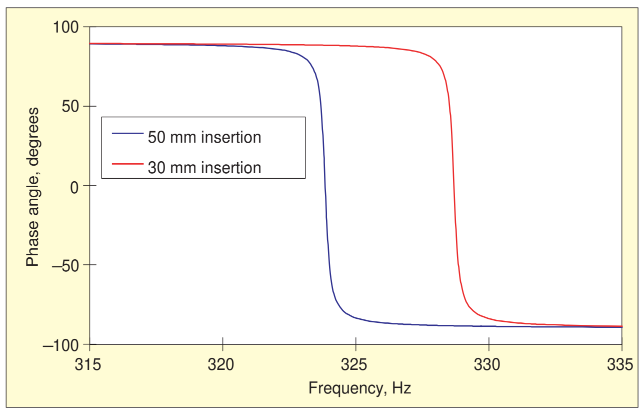

Figure 11b. Phase angle of the acoustic impedance seen by the flame in the test rig for insertion depths of 50 mm and 30 mm.

The magnitude of Z × H × G can be reduced by reducing the magnitude of *any one* of these properties at the known frequency of oscillation. This was demonstrated in the experiments with the damping sleeve and insertion depth. Both of these experiments have shown that the oscillations can be avoided by reducing the magnitude of only the combustion chamber impedance. The changes made did not involve either the mixture supply or the flame. Thus, the key to solving oscillation problems in heating equipment is to determine which part of the particular unit best lends itself to modifications that can reduce its response magnitude at the frequency of oscillation. Most often, this is more easly said than done. To help with this task, one needs to understand the trends of the behavior of the various components of the system. These trends can be seen in the frequency response functions of the system components in Figure 10.

Question #12: How Do the Pressure Oscillations Cause Flame Oscillations? So far, we have examined the frequency response of the combustion chamber that governs the way in

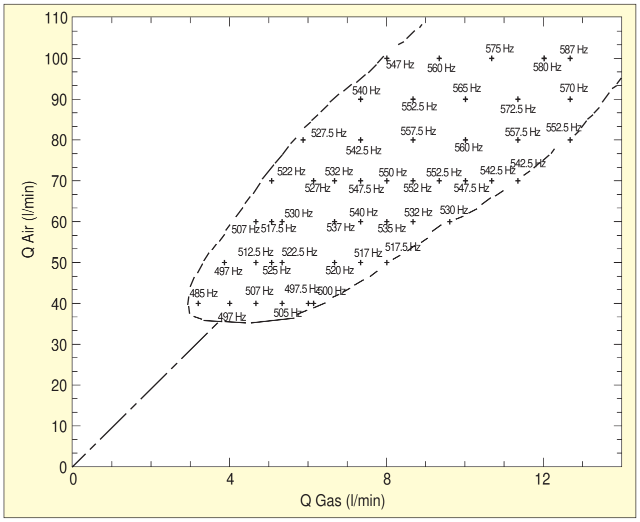

Figure 12. Instability plot for the experimental system used by Elsari and Cummings (2003).

which pressure oscillations are caused by flame oscillations. We have seen that, in some cases, this can be exploited to solve a problem. In the majority of cases, however, the solution will require changing the way in which flame oscillations are caused by pressure oscillations, which depend on the type of burner. Flames of some burners are prone to vortex shedding.[2] Swirl type burners are also subject to similar fluid dynamic instabilities.[9]

For the majority of burners used in residential and small commercial heating units, however, such flow instabilities are not likely to be important. With these types of burners the oscillating pressure acting on the burner ports will modulate the flow of the air/fuel mixture into the flame. This modulated input results in modulating the burning rate of the flame. This process involves both the properties of the mixture supply and those of the flame, as depicted in the bottom part of the feedback loop in Figure 10. To reduce these modulations, either the mixture supply system or the flame have to be modified.

In many heating units, the mixture supply system may be the easiest to modify. Suitable modifications are to lengthen or shorten the mixture supply conduit. Unfortunately, such modifications cannot be explored with the burner shown in Figure 1. Experiments with other burners will be documented in a subsequent article. The mixture supply is also the only part of a heating unit that lends itself well to modeling. Thus, the subsequent article will include methods for predicting the effect of proposed changes to avoid costly trial and error efforts.

Meanwhile, the reader can find some relevant information in Chapter 3 of Putnam.[2]

Question #13: How Can the Flame Be Modified to Solve an Oscillation Problem? The air/fuel ratio is a significant variable for the the "driving potential" of a flame.[2] In Figure 10, the driving potential is represented by the amplifier G. Figure 12[10] shows that, in systems operating on the lean side, the air has to be increased to stop the oscillations; while for systems with Bunsen-type flames, the primary air has to be reduced. Years ago, many Bunsen-type systems had a spoiler in the burner mixing tube for reducing the primary air.

The torch used in these experiments can be easily modified for exploring the effect of changing the air/fuel ratio further away from the stochiometric ratio. All that is needed is to add a sliding sleeve that will partly block the air inlet holes (construction details are available from the author). By doing so, the abnormal noise can be stopped quite easily.

While any substantial changes in air/fuel ratio may not be acceptable as a permanent solution, it is useful to explore this in a real unit if permitted by the burner design. Doing so will make it quite clear that the flame drives the oscillations even though practical solutions can often be found without changing the flame.

One very informative flame model for conical flames shows not only the effect of the fuel/air ratio but also other factors involved in the driving potential of such flames.[11] These factors will be addressed in a subsequent article.

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