AN ASSESSMENT OF THERMOACOUSTIC VIBRATION POTENTIAL IN A CORNER-FIRED FURNACE OF A UTILITY BOILER- A CASE STUDY

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ABSTRACT

The acoustic waves in a corner-fired furnace of rectangular shape may develop either in the side-to-side or the front-to-rear directions. To assess the thermoacoustic potential of the burner/furnace system, the evaluation shall be based on the development of the acoustic waves in each furnace direction separately. The Rijke and the Sondhauss thermoacoustic models representing the burner/furnace system are utilized and checked for thermoacoustic stability and also for thermoacoustic frequencies of the combined burner/furnace (cold/hot)system. A study case is presented in which thermoacoustic vibration is predicted commensurate with experimental (operational) experience. Modification to the system in the area of the burners is proposed to alleviate or eliminate the vibration. The paper gives an outline of the analysis procedure and provides numerical results for the vibrating original system and for a modified system in which the thermoacoustic vibration is eliminated.

NOMENCLATURE

B	=	furnace depth (front-to-rear), m
c	=	speed of sound, m/s
D	=	burner tube diameter, m
f	=	acoustic frequency, Hz
f_1	=	furnace acoustic frequency in side-to-side direction, Hz
f_2	=	furnace acoustic frequency in front-to-rear direction, Hz
l	=	length, m
l_1	=	length of cold section, m
l_{2R}, l_{2S}	=	length of hot section in Rijke or Sondhauss models, respectively, m
L	=	length giving position of peak acoustic pressure from cold end.
s_1, s_2	=	ratios of acoustic frequencies, dimensionless
T	=	temperature, ºC or ºK (Celsius, Kelvin)
W	=	furnace side-to-side width, m
α	=	T2/T1 = temperature ratio: dimensionless, ºK/,ºK
ξ	=	$(L-l_1)/l_1$ = geometry parameter for Rijke or Sondhauss tube, dimensionless
ω	=	angular frequency, rad/s
Subscripts		
1,2	=	cold, hot
R	=	Rijke
S	=	Sondhauss

1. INTRODUCTION

In the previously published papers by Eisinger (1999) and Eisinger and Sullivan (2002), (2006) and (2007) the thermoacoustic behavior of the burner/furnace system was based on the typical configuration of the furnace being fired either from the front or from the rear furnace wall with burners located at the frontwall and/or rearwall, respectively. Here we are evaluating a burner/furnace configuration with burners located in four corners of a rectangular furnace. While in the frontwall-or rearwall-fired furnace the acoustic waves always develop in the furnace front-to-rear direction, i.e. in the burners' axial direction, in the case of a corner-fired furnace, the acoustic waves are likely to develop either in the front-to-rear or the side-to-side direction, or possibly in both directions, depending on the axial orientation of the burners. In this paper we will utilize the methodology developed for the frontwall-and/or rearwall-fired furnaces, adapted to the corner-fired configuration. It then follows that the developed methodology will be applied in both directions and evaluated separately.

As described in the published papers, the burner/furnace system's thermoacoustic behavior is defined by two criteria:
(1) thermoacoustic stability and (2) frequency separation between the combined burner/furnace acoustic frequency and the acoustic frequency of the furnace. Both of these criteria are checked by the Rijke and Sondhauss thermoacoustic models representing the burner/furnace (cold/hot) thermoacoustic system. In this paper, we will numerically evaluate a specific corner-fired furnace configuration for its susceptibility to thermoacoustic vibration and also devise a method of eliminating thermoacoustic sensitivity or vibration by introducing changes to the geometry of the burners.

2. SONDHAUSS AND RIJKE TUBE PHENOMENA AND STABILITY DIAGRAM

The Sondhauss and Rijke tubes are representative of the thermoacoustic phenomenon which can manifest itself by single frequency pulsation (or sound) if the temperature gradient (hot to cold) between two sections of the tubes exceeds a critical value. The Sondhauss tube is open at the cold end and closed at the hot end. The Rijke tube is open at both ends. The acoustic pressure waves in the fundamental mode are a quarter-wave in the Sondhauss tube and a half-wave in the Rijke tube. The acoustic pressure waves in both, the Sondhauss and the Rijke tubes are of the plane wave type.
The stability diagram defining the onset of large thermoacoustic oscillations for a Sondhauss or a Rijke tube or an equivalent system is given by the equation (Eisinger, 1999).

$$(\log_{10}\xi)^2 = 1.52\,(\log_{10}\alpha - \log_{10}\alpha_{min}) \qquad (1)$$

with $\alpha_{min} = 2.14$

Here $\xi = (L-l_1)/l_1$ is the geometry parameter on the abscissa and $\alpha = T_2/T_1$ is the hot to cold temperature gradient in ºK/ ºK plotted on the ordinate.

The stability line given by eq. (1) separates the region of vibration above the line from that of no vibration below the line.

3. EVALUATION PROCEDURE

Figure 1 shows schematically the arrangement of the burner/furnace system in a plan view. Figure 2 shows the burner arrangement schematically, indicating the length l_1, of the cold air burner section. Figure 3 is a composite burner/furnace arrangement with the Rijke and Sondhauss acoustic pressure waves superimposed schematically.

The burner/furnace system is modeled by a channel consisting of the cold air (burner portion) and the hot gas (furnace portion), i.e the thermoacoustic model of the burner/furnace system. For a complete evaluation, two models will be utilized: the Rijke model in which the acoustic wave in the furnace is terminated at zero pressure at the centerline of the furnace and the Sondhauss model in which the acoustic wave in the furnace is terminated with high acoustic pressure at the furnace wall opposite the burner. (These boundary conditions are consistent with the development of acoustic pressure waves in the fundamental modes.) The Rijke model is a channel open at both ends, resulting in a half acoustic wave in the first mode, with zero acoustic pressures at both ends. The Sondhauss model is a channel open at the cold (burner) end and closed at the opposite end at the furnace wall. Because of the expected shape of the acoustic pressure wave in the open-closed Sondhauss model, the second acoustic mode is considered here. Figures 3b and 3c show the superimposed Rijke and Sondhauss acoustic pressure modes, respectively.

3.1 Numerical Data Defining Burner/Furnace System

Table 1 gives the principal parameters defining the geometry of the burners, the furnace and the air and gas temperatures within the system. The length of the cold portion l_1, representing the length of the burner air tube from the inlet to the air swirler is given as are the lengths l_{2R} and l_{2S} defining the hot furnace sections of the Rijke and the Sondhauss models, respectively.
Development of Thermoacoustic Properties (Eisinger and Sullivan, 2007)
Speed of Sound.

$$c = 20.07\sqrt{T} \qquad (2)$$

The speed of sound in the cold and hot sections are respectively c_1, (T_1) and c_2 (T_2).
Furnace Acoustic Frequencies. Of importance are the fundamental acoustic frequencies in large boiler furnaces. The furnace acoustic frequencies of concern are the side to-side frequency given by the expression

$$f_1 = c_2/2W \qquad (3)$$

and the front-to-rear frequency

$$f_2 = c_2/2B \qquad (4)$$

Thermoacoustic Frequencies. Detailed equations for the Rijke and Sondhauss tube acoustic properties, frequencies and acoustic pressure functions are given in the paper by Eisinger and Sullivan (2002). We will repeat here only the essential relationships utilized in the present analysis as follows:

The Rijke acoustic frequency is given by

$$\frac{\tan \frac{\omega_R l_1}{c_1}}{\tan \frac{\omega_R l_{2R}}{c_2}} = - \frac{c_2}{c_1} \qquad (5)$$

and the Sondhauss acoustic frequency is given by

$$\tan \frac{\omega_s l_1}{c_1} \quad \tan \frac{\omega_s l_{2s}}{c_2} = \frac{c_2}{c_1} \qquad (6)$$

The frequencies f_R and f_S in Hz are $f_R = \omega_R/2\pi$ and $f_S = \omega_S/2\pi$ where ω_R and ω_S are the angular frequencies for the Rijke and Sondhauss models, respectively.

Position of Peak Acoustic Pressures.

The position of the peak acoustic pressure in the Rijke model is given by

$$\tan \frac{\omega_R x_{2R}}{c_2} = - \frac{1}{\tan \frac{\omega_R l_{2R}}{c_2}} \qquad (7)$$

and in the Sondhauss model

$$\tan \frac{\omega_s x_{2s}}{c_2} = \tan \frac{\omega_s l_{2s}}{c_2} \qquad (8)$$

where x_{2R} and x_{2S} are the coordinates in the hot section identifying the position of the peak pressure.

The lengths L_R and L_S to the peak acoustic pressures in the Rijke and the Sondhauss models are then given by

$L_R = l_1 + x_{2R}$ (9)

and

$L_S = l_1 + x_{2S}$ (10)

Evaluation of Acoustic Frequency Differences (Ratios) and Stability. Of interest are also the frequency differences between the Rijke and the Sondhuass frequencies and the furnace frequency. The corresponding frequency ratios are for the Rijke model

$s_{1R} = f_R/f_1$ (11)

$s_{2R} = f_R/f_2$ (12)

and for the Sondhauss model

$s_{1S} = f_s/f_1$ (13)

$s_{2s} = f_s/f_2$ (14)

For assessing the stability of the Rijke or Sondhauss models in the stability diagram α versus ξ, we evaluate the geometry parameters ξ_R and ξ_S, which enter the stability diagram, respectively

$$\xi_R = \frac{L_{R-}l_1}{l_1} \qquad (15)$$

$$\xi_S = \frac{L_{s-}l_1}{l_1} \qquad (16)$$

Along with the geometry parameters ξ we enter the absolute temperature ratios

$\alpha = T_2/T_1$ (17)

into the stability diagram.

Table 2 gives the numerical results obtained for the evaluated burner/furnace system utilizing the procedure described. Two cases were evaluated: The original case defined by the length of the cold air section l_1 = 1.69 m, and the modified case with a substantially reduced cold air section of l_1' = 0.61m

Figure 4 shows the data superimposed on the stability diagram of Eisinger and Sullivan (2002). It can be seen that in the original system, the derived parameters fall all into the unstable range above the stability line, indicating vibration (Fig. 4a). In the modified case, Figure 4b, the derived parameters all fall into the stable range below the stability line, indicating no vibration.

The derived frequency ratios are shown in Table 3. It can be seen that in the original case, there is sufficient frequency separation in all of the front-to-rear cases and small separations in the side-to-side cases. In the modified condition, only the side-to-side evaluation shows no frequency separation. Although the frequency differences are important for defining potential resonances, as was shown in (Eisinger and Sullivan, 2007), they play only a secondary role in predicting vibration as the governing condition remains the condition of stability.

4. DESCRIPTION OF MODIFICATION

As shown in the analysis results, the length of the burner's cold section plays a significant role in the thermoacoustic behavior of the burner/furnace system. A substantially reduced length of the cold air section from 1.69m to 0.61m makes the system thermoacoustically stable, both, based on the Rijke and on the Sondhauss models (Fig. 4b).

The reduction of the acoustic length of the cold air section can be achieved by providing openings (Eisinger, 1994) in the cold air burner channel at the desired location at l_1' = 0.61m upstream of the centerline of the swirler which represents the transition between the hot furnace gases and the cold combustion air. The size of the opening provided is typically in the range of 10% to 15% of the flow area of the air channel. Figure 5 shows schematically the arrangement of the openings made in the cold air sections air channel.

5. SUMMARY AND CONCLUSIONS

The burner/furnace system's thermoacoustic vibration potential in a corner-fired furnace can be evaluated by adapting the methodology developed for the frontwall-and rearwall-fired systems, and applying the analysis in both furnace directions.

In this respect, the stability diagram provides a reliable answer about the thermoacoustic vibration potential of the corner-fired furnace. It was shown that the lengths of the burners' cold air sections play a significant role in making the system vulnerable to vibration and thus by making these sections acoustically shorter, the vibration can be eliminated.

6. REFERENCES:

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Eisinger, F.L., and Sullivan, R.E., 2007, "Prediction of Thermoacoustic Vibration of Burner/Furnace Systems in Utility Boilers", ASME PVP Conference Proceedings, July 22-26, 2007, San Antonio, Texas, Paper No. PVP 2007-26090, also in ASME Journal of Pressure Vessel Technology, Vol. 130, February 2008.

Table 1: Principal Initial Parameters Defining Burner/Furnace System In the original (l_1 = 1.69m) and the modified (l_1' = 0.61m) cases

								Rijke		Sondhauss	
								Side-side	Front-rear	Side-side	Front-rear
W	B	D	l_1/l_1'	T_1	T_2	c_1	c_2	l_{2R}	l_{2R}	l_{2S}	l_{2S}
M	m	m	m	ºC	ºC	m/s	m/s	m	m	m	M
13.4	9.165	0.48	1.69/0.61	291	1,426.7	477.1	828	6.7	4.58	13.4	9.165

Table 2: Principal Derived Acoustic Parameters and Thermoacoustic Parameters of Burner/Furnace System In the Original (l1 = 1.69m) and the Modified (l1' = 0.61m) cases

				Rijke						Sondhauss					
				Side-Side			Front-Rear			Side-Side			Front-Rear		
l_1/l_1'	f_1 Hz	f_2 Hz	α -	f_R Hz	L m	ξ -	f_R Hz	L m	ξ -	f_s Hz	L M	ξ -	f_s Hz	L n	ξ -
1.69	30.9	45.2	3.01	46.6	3.95	1.33	58.3	2.72	0.608	40.2	4.8	1.84	53.8	3.14	0.868
0.61	30.9	45.2	3.01	56.5	3.64	4.97	78.9	2.57	3.21	44.3	4.7	6.6	63.3	3.2	4.3

Table 3: Thermoacoustic Frequency Ratios in the Original (l_1 = 1.69m) and in the Modified l_1' = 0.61m) System

l_1/l_1' m	Rijke				Sondhauss			
	front-rear		side-side		front-rear		side-side	
	s_1	s_2	s_1	s_2	s_1	s_2	s_1	s_2
1.69	1.89	1.29	1.51	1.03	1.74	1.19	1.3	0.89
0.61	2.55	1.74	1.83	1.25	2.05	1.40	1.43	0.98

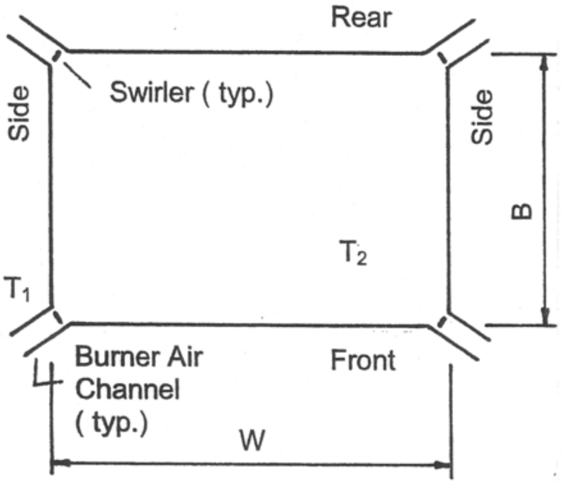

Fig. 1 Plan view of furnace with burners located in furnace corners (schematic)

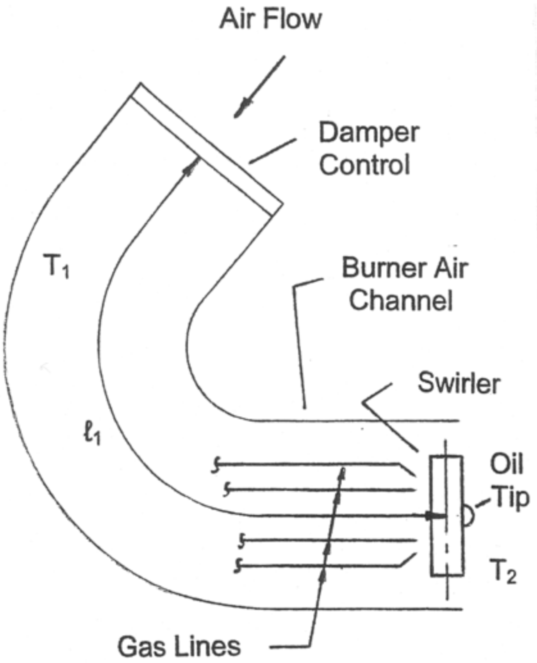

Fig. 2 Burner Arrangement (schematic)

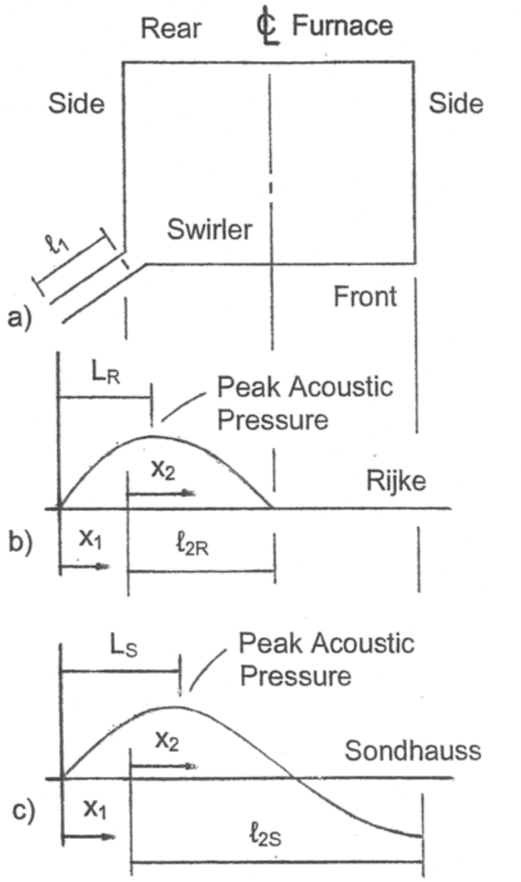

Fig. 3 Composite sketch of burner / furnace system with superimposed Rijke or Sondhauss acoustic pressure waves (shown acoustic waves in furnace side-to-side direction)

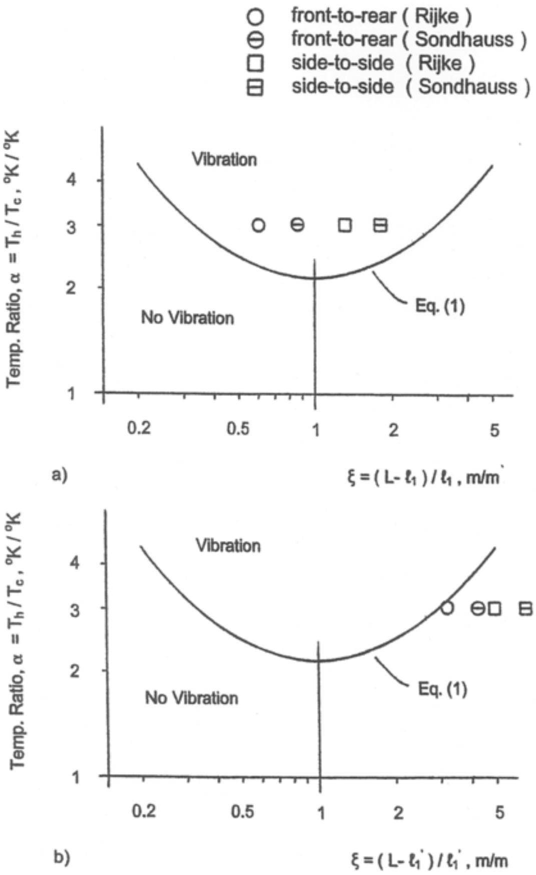

Fig. 4 Thermoacoustic stability diagram with superimposed evaluated data based on Rijke and Sondhauss thermoacoustic models a) original system with ℓ_1 = 1.69m and b) modified system with ℓ_1' = 0.61m

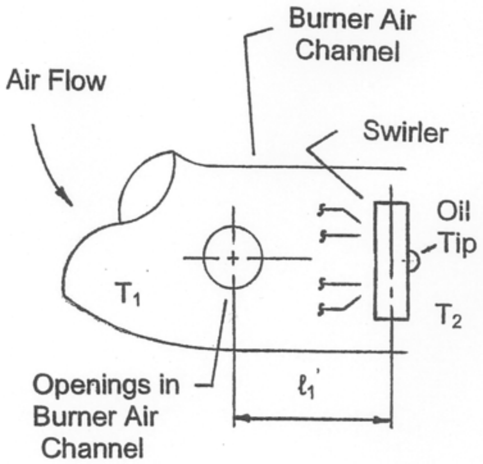

Fig. 5 Modified burner air channel showing openings to reduce original acoustic length ℓ_1 to new acoustic length ℓ_1'