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BURNER PULSATIONS IN CENTRAL HEATING BOILERS: NUMERICAL SIMULATION OF BURNER-BOILER INTERACTION AND VISUALIZATION OF COMBUSTION INSTABILITY

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INTRODUCTION

Whenever combustion or heat exchange takes place within an acoustic resonator thermoacoustic oscillations may occur. Because unsteady heating generates sound waves, pressure and velocity fluctuations are produced, which in their turn may perturb the heat input. For a suitable phase relationship between the acoustic waves and the heat production of the burner, instability is possible.

State of the art, high-yield, central-heating boilers are often closed systems. In these boilers the burner/heat exchanger combination is placed between a mixture supply duct and an exhaust connected to the flue. Therefore modern central-heating boilers are susceptible to self-sustained burner oscillations.

In practical applications it appears that the stability of these boilers is determined by a large number of parameters such as, the position of the burner in the duct system, the volume of the heat exchanger; the length of the flue, etc... Since some of these parameters may vary from installation to installation, it is difficult to suppress instabilities under all circumstances. As a result manufacturers are forced to spend a considerable amount of time curing the self-sustained thermoacoustic oscillations, often using a trial and error approach. To improve this situation, TNO-TPD and the Nederlandse Gasunie NV, under the authority of the Dutch manufacturers of central-heating boilers (VFK), developed a computer program to simulate the acoustic behavior of central-heating boilers with premix burners.

FREQUENCY-DOMAIN MODELLING OF THERMOACOUSTIC INSTABILITIES

Since the typical cross-flow dimensions of the duct system are small compared to the wavelength of the sound, the acoustics of the duct system can be described in terms of plane-waves. Thus the acoustics of the duct system can be described using a Transfer-Matrix Method (TMM). However, as Dowling [1] indicates, the acoustics of duct system containing a fluctuating source of heat cannot be evaluated correctly without taking the effect of the unsteady heating into account. Therefore the burner must be modelled in terms of a transfer matrix.

The phenomenon of thermoacoustic oscillations was already described by Rayleigh [2]. Acoustic waves gain energy when the rate of heat input is in phase with the pressure perturbations. If this energy gain exceeds the loss on reflection from the boundaries of the resonator and the loss by dissipation in the resonator, linear acoustic waves grow in strength and the system is unstable.

In a TMM description, where the system is excited by an external source, the system will be unstable if the acoustic energy radiated at the boundaries of the resonator is larger than the energy supplied by the external source.

PROPERTIES OF THE BURNER/FLAME COMBINATION AND VISUALIZATION STUDIES

An intensified CCD camera was used to capture the flame shape during the oscillation. With this camera it is possible to observe different parts of the spectrum of the flame separately. According to these visualization studies it appears that the intensity of the ultra-violet part of the spectrum is well correlated with the acoustic velocity immediately upstream of the burner, while the intensity of the infra-red part of the spectrum is unaffected by the acoustic excitation. Since the radiation of ultra-violet light by the flame is related to the presence of OH radicals, and thus a measure for the reaction rate and the heat release, these observations show that the heat release of the flame is well correlated with the acoustic excitation.

Furthermore, the measurements show that for a low-amplitude harmonic excitation, the intensity of the uv radiation varies harmonically as well, indicating a linear response of the flame. However, during self-excited oscillations the harmonic variation of the uv-radiation intensity is destroyed. This suggests that the during self-excited oscillations the amplitude is limited by non-linear behavior of the flame, see Fig. 1.

The linear response of the flame at low acoustic amplitudes opens the possibility to model flame/burner combination as an acoustic two port and to experimentally determine the properties of this two port in the frequency domain.

The measurements of the burner properties show that for frequencies below 200 Hz the burner/flame combination behaves as an amplifier with a complex amplification coefficient. The experiments also show that both the amplitude as the phase of the amplification factor depend on several parameters such as, the air-gas ratio, the specific power of the burner, the temperature of the mixture and whether the burner operates in radiating mode or not.

THE STABILITY OF THE BURNER TEST RIG

Like all resonators containing a heat source, under unfavorable circumstances the burner test rig is unstable against acoustic perturbations. Fig. 2. shows the result of a simulation using the TMM calculation method to predict the stability of this duct system. This figure shows a pseudo-color plot indicating the stability of the system as a function of the frequency and the phase shift of the amplification factor. The dark and light regions denote the unstable and stable regions respectively. Apart from the stability this figure shows the experimentally determined phase of the amplification factor of the flame as a function of the frequency (*). Since this phase shift curve crosses an unstable area in the stability plot, one may expect that for the frequency range between approximately 80 Hz and 95 Hz, the flame produces more energy than supplied by the external source. Indeed, Fig. 3. shows that the amplitude of the reflection coefficient at the burner surface indeed exceeds 1 at approximately the same frequencies, indicating that the flame produces more energy than supplied by the external source.

CONCLUSIONS

This paper presents a calculation method for the prediction of self-excited oscillations in central-heating boilers based on a measured transfer matrix for the flame/burner combination. It appears that, for frequencies below 200 Hz, the flame/burner combination behaves as an amplifier with a complex amplification coefficient. Using this measured transfer matrix instabilities of pipe systems containing a heat source such as boilers are successfully predicted. Hence, this method opens the possibilities to analyze the stability of central-heating boilers in the design stage.

References

[1] Dowling, A.P., 1995, The calculation of thermoacoustic oscillations, J. Sound & Vibration, **180**(4), pp. 557-581

[2] Rayleigh, J.W.S., 1896, The theory of Sound, Macmillan

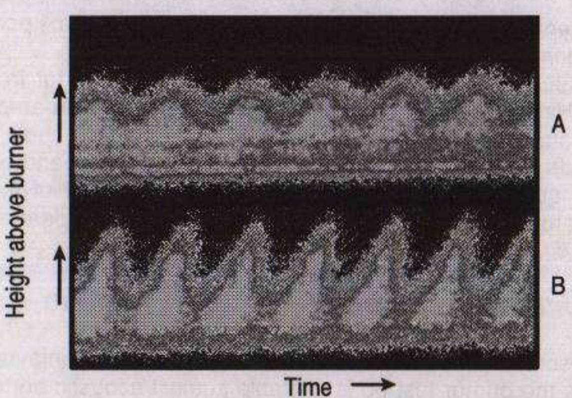

FIGURE 1 A pseudo-color plot of the intensity of the uv radiation as a function of height and time for an acoustically driven flame (A) and a self-induced oscillating flame (B).

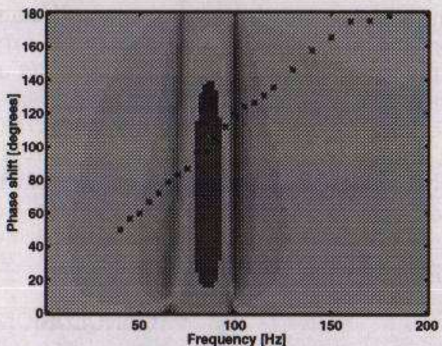

FIGURE 2 The stability plot of the burner test rig

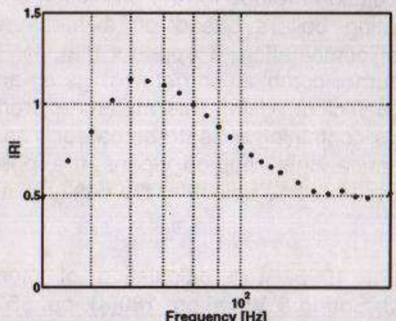

FIGURE 3 The measured reflection coefficient at the burner surface