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DESIGNING AN ACOUSTIC TERMINATION WITH A VARIABLE REFLECTION COEFFICIENT TO INVESTIGATE THE PROBABILITY OF INSTABILITY OF THERMO-ACOUSTIC SYSTEMS.

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This paper presents results of the development of an acoustic device to be utilized as a duct termination with variable reflection coefficient. This study is motivated by the idea to experimentally evaluate the probability of instability of a thermo-acoustic system where combustion acts as an active acoustic element, and this termination acts as a passive acoustic element that can be configured to a desired value of the reflection coefficient at the upstream side of the flame and burner for lab-scaled physical modelling of, for instance, domestic boilers. This termination consists of a cylinder containing a stack of truncated hollow cones with narrow gap in between and a telescopic tube. The gap between the adjacent cones, and sound-absorbing fibrous material ("Acotherm") placed in the cavity of these cones produce a low reflection coefficient in the frequency range between 40 and 800 Hz. Longitudinal displacement of these cones inside the cylinder generates a reflection coefficient with magnitude ranging from 0.2 to 0.9. The telescopic tube with an adjustable length (between 0.85 - 1.38 m) allows to achieve a wide range of phases of reflection coefficient. The steps taken to optimize the design and performance of this termination in presence of flame are presented here.
Keywords: variable reflection coefficient, passive termination, stability

1. Introduction

Ensuring acoustic stability of combustion is an integral and indispensable part of R&D work on any new combustion appliance ranging from domestic boilers to industrial gas turbines. Flow perturbations in such appliances can instigate unsteady heat release by the flame which results in pressure and velocity oscillations in the form of acoustic waves which in turn perturb the flow creating a closed feedback loop. These acoustic waves travel two ways through the system and return to the flame after reflecting at the boundaries. Under certain conditions, this loop may become unstable causing autonomous oscillation known as thermo-acoustic instability of combustion systems [1].

Evidently, the instability depends on both the burner with flame (treated as a dependent source) and the acoustic properties of (usually passive) upstream as well as downstream boundaries of the appliance. Therefore stability or instability of operation is a property of a combined system. However, it would be attractive to have some kind of "figure of merit" or quality measure to rank different burners and flames according to their thermo-acoustic stability-instability properties. The idea of such a figure of merit has been proposed earlier [2]. The essence of that approach can be explained as following: one would call a burner “A” thermo-acoustically better than a burner “B” if by placing the burners in different combustion appliances one will encounter instability of combustion less often for burner “A” than for burner “B”. The paper proposed a numerical Monte-Carlo type of test which allowed evaluating a burner’s figure of merit by modeling it as a block in a combustion appliance equipped with variable passive terminations. In the development of this idea in [3] the analytical parameters calculated on the base of the burner acoustic transfer/scattering matrix description were proposed and tested.

To perform an experimental validation of such an idea, one may characterize the acoustic quality of a burner and compare/rank it with other burners. It is therefore necessary to provide a possibility to test the burner by combining it with different acoustical embedding. This task requires the development of a device which can serve as a passive acoustic termination of the system, allows mean flow of combustible mixture and/or burned gases and provides a convenient way to vary its reflection coefficient in a wide range of absolute values and phases.

Therefore, the ultimate goal of our research program is to elaborate a method to characterize burners with flames with respect to their thermo-acoustic quality factor. Within the present contribution, the particular aim is to develop an idea of a flexible device, convenient to operate, which can play the role of a variable acoustic termination at the upstream side of the burner. The principle idea of such a device, its physical implementation, testing of its functionality are subjects of the present work. Finally, the device will be used for first test of two burners aiming to map their stability-instability diagram in the field of parameters of the upstream termination.

The engineered acoustic device has a reflection coefficient which can be varied manually without altering the whole setup, principally operating in the frequency range 40 - 800 Hz and provides the variable reflection coefficient with (frequency averaged) values between 0.2 and 0.9. The network model of the system is explained in section 2. This is followed by a detailed explanation of the experimental setup in section 3. The measurement techniques used are given in section 4 preceding results and conclusions in section 5 and 6, respectively.

2. Network modelling of acoustic systems

Thermo-acoustic instability in a duct with flame can be represented using the one dimensional network model where each element corresponds to an acoustic element as shown in Fig. 1[4]. The general solution for such a system is:

$$\frac{p'(x,t)}{\rho c} = f(x-ct) + g(x+ct) \tag{1}$$

where f and g are Riemann Invariants and correspond to waves propagating in positive x (forward) and negative x direction (backward) respectively with speed c [4].

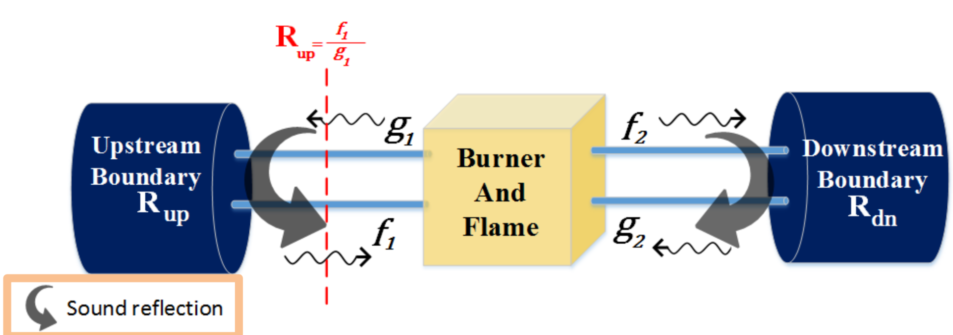


Figure 1: Forward and backward propagating waves in a duct with flame

Reflection Coefficient is then defined as the ratio of outgoing wave to the incoming wave. Therefore for a thermo-acoustic system consisting of two boundaries (upstream and downstream) and a burner with flame as shown in Fig. 1, the reflection coefficient can be written as follows,

$$R_{up} = \frac{f_1}{g_1} \text{ and } R_{dn} = \frac{g_2}{f_2} \tag{2}$$

where *up* refers to upstream properties and *dn* refers to downstream properties.

3. Experimental Setup

To fulfil the requirements of a flexible and easily adjustable acoustic termination at the burner upstream end, the experimental setup shown in Fig. 2 was designed, constructed and tested. This section contains details of the construction of the acoustic device and the burner setup. The general layout of the setup includes 1- a burner; 2- downstream section of the burner which has fixed design and therefore has constant acoustic properties; and 3- upstream sub-system which includes a fixed length duct dedicated for acoustic measurement in future, a telescopic tube to adjust the acoustic length and an innovative acoustic termination which allows smooth variation of the acoustic reflection coefficient in the range 0.2 - 0.9 for frequencies 40 - 800 Hz. In the following sub-sections the details of the setup parts are given.

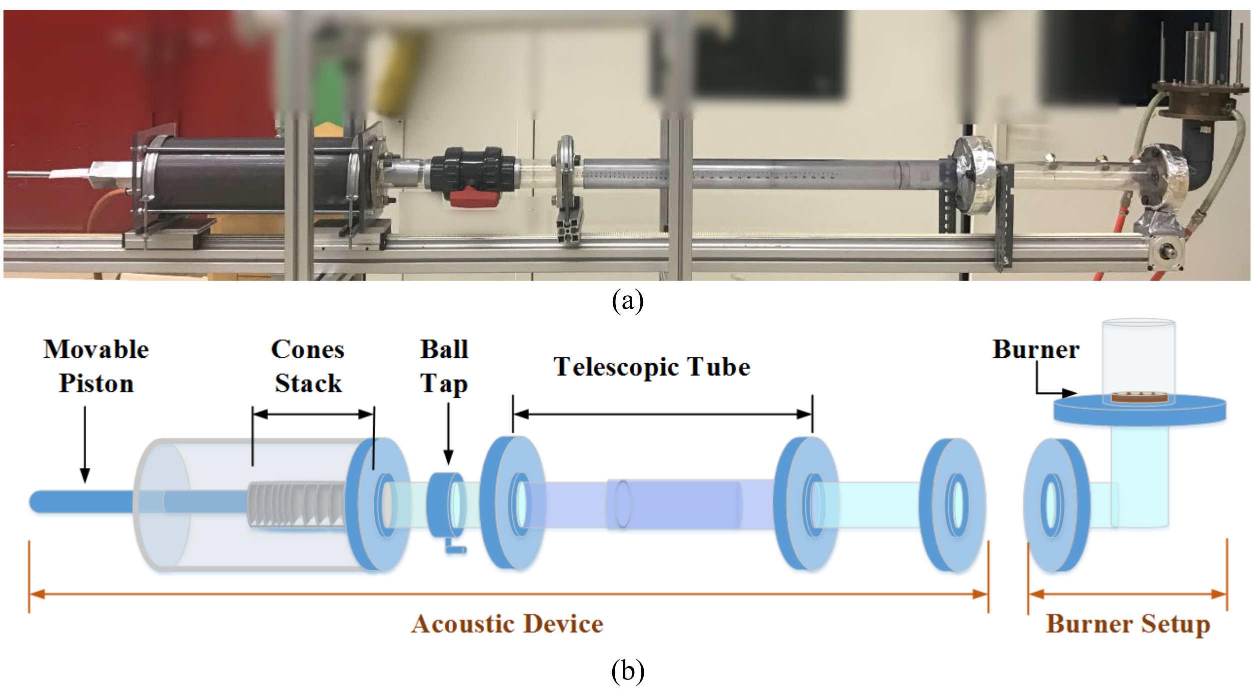


Figure 2: (a) Experimental Setup and (b) Schematic Diagram

3.1 Variable reflection coefficient acoustic device

The low/high-reflection termination device is the core of the whole setup. Its main working part is the stack of 58 plastic truncated hollow cones. The cones have length of 80 mm, interior base diameters are 50 mm and 73 mm and wall thickness is 0.5 mm. The cones were stacked together and separated by spacers made up of metal wires of 0.25 mm diameter as shown in Fig. 3(c). This allowed adjacent cones to be 4-5 mm apart. The number of cones and spacing between cones were determined after a series of optimization experiments aiming to minimize the magnitude of the reflection coefficient in the whole frequency range of 20 - 800 Hz. The optimization was done via an iterative process of measuring the reflection coefficient using conventional impedance tube technique (details in section 4.1 below) and adjusting the cone number and spacing between the cones. A detailed study of the physical mechanisms of absorption in the stacked cones is beyond the scope of this paper and will be presented separately. To improve the anechoic termination performance in the high frequency range, “Acotherm”, a porous polyester fibre was placed in the cavity of the cone stack. The absorption coefficient of Acotherm is 0.36 - 0.45 in the sound frequency range of 550 - 800 Hz respectively [5].

The next principal idea allows the variation of the reflection coefficient magnitude. For this purpose the stack of cones was placed inside a cylinder of length 45 cm and diameter of 14.5 cm and the base of the first cone in the stack was made to coincide with base of cylinder (C_{base}) as shown in the Fig. 3(b(i)). The placement and construction of the stack allows its mechanical displacement inside the cylinder as is visible in Fig. 3(a). This motion can be manually controlled by the movable piston and allows the acoustic device to have variable reflection coefficient ranging from the stack positioned at 0 cm from C_{base} to the stack displaced and positioned at Δ cm from C_{base} as shown in Fig. 3(b(ii)). The maximum possible value of Δ is 7.2 cm.

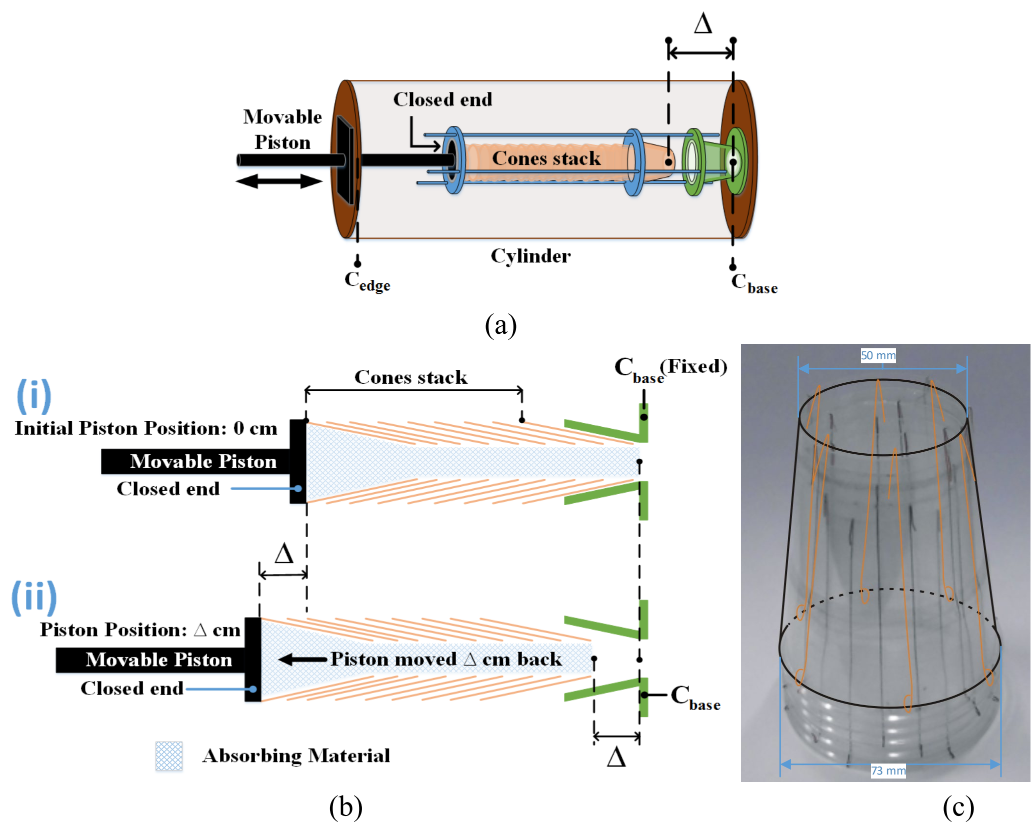


Figure 3: (a) Cylinder with cones stack diagram, (b) 2D representation of initial position of Movable Piston and at Δ cm displacement, and (c) truncated hollow cones stack with spacers (4 cones)

To provide additional possibility of changing the reflection coefficient phase, independent of the variation in the reflection magnitude, a telescopic tube was installed as can be seen in Fig. 2. The objective of placing this tube was to change the phase of the reflection coefficient by changing the length of the tube. The minimum length of the tube is 85 cm and it can be increased up to 138 cm. The increment step can be as low as 0.1 cm. However in this paper we have maintained an increment step of 1 cm, resulting in 54 cases of telescopic tube lengths (85 + [0, 1, 2…, 52, 53] cm). For the ease of presentation, these cases will be mentioned with just the incremented distance i.e. telescopic tube length (TTL): 1 cm would correspond to actual length of 85 + 1 cm. The telescopic tube is connected to another tube of length 42 cm which precedes the burner setup. As a result, the acoustic reflection of the upstream section with respect to the burner can be varied in a wide range of both amplitudes and phases. This property allows to experimentally model different types of acoustic surroundings of a burner in real combustion appliances.

3.2 Burner Setup

The burner was placed at the end of a bend tube of length 22.5 cm. The casing of the burner includes a water channel to maintain a constant temperature of the burner deck holder and thus control the effect of the burner deck holder temperature on the stability of the system. Burner decks used in this study are made from brass, having a thickness of 1 mm. The decks are perforated by circular holes as shown in Fig. 4. The hole diameter was kept constant (2 mm) and two different pitch values (4 and 5.5 mm) were tested. The downstream part of the setup consists of an open ended quarts tube of 12 cm length and 5 cm inner diameter which was placed on top of the perforated burner. The quartz tube prevents lift off of edge flames by creating a surface of high temperature. Thus, the resulting conical flames anchored to the burner decks were uniform.

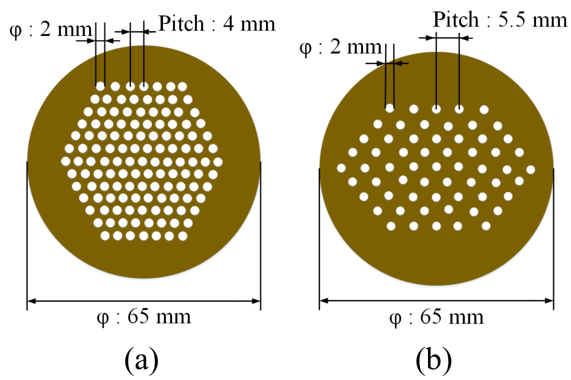


Figure 4: (a) Burner P_4 with Pitch 4 mm and area 398.9 mm^2, and (b) Burner $P_{5.5}$ with Pitch 5.5 mm and area 191.6 mm^2

4. Measurement techniques and operating conditions

4.1 Reflection coefficient measurement

To characterise the termination's acoustic properties, the reflection coefficient was measured using the standard multi-microphone method [6] [7]. The measurement setup includes an impedance tube of 1 m length, equipped with 6 calibrated microphones (BSWA MPA416) equally spaced from each other. A loudspeaker is positioned at one end of the tube and the object whose reflection coefficient is to be determined is placed at other end of the tube.

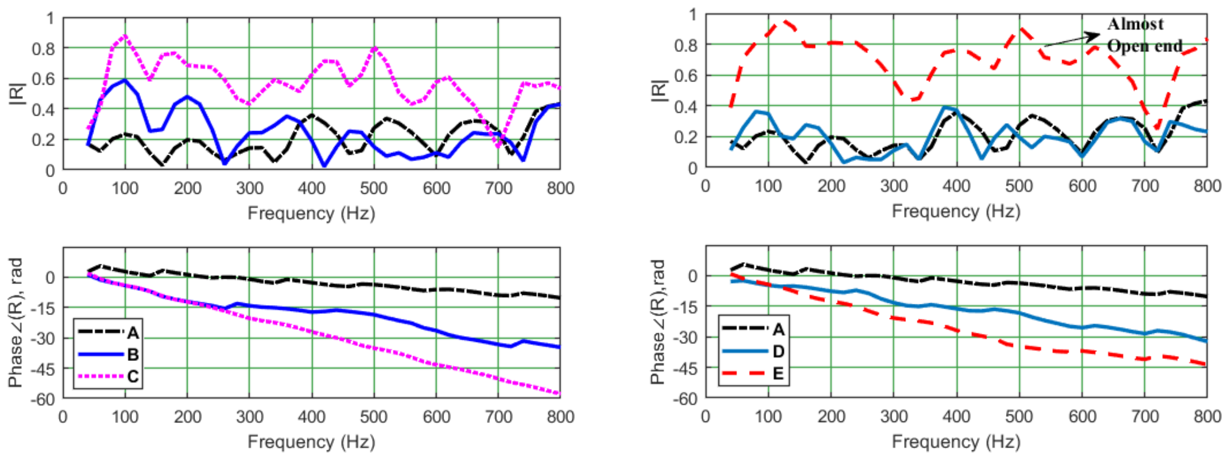
Plane waves of increasing pure tone frequencies starting from 40 Hz and ending at 800 Hz with increment ($\Delta f = 20$ Hz) were produced by the loudspeaker, transmitted to/from the measured object via the impedance tube. The microphones measure the distribution of resulting pressure wave amplitudes; signals to the loudspeaker and from the microphones are recorded using NI data acquisition card. The procedure of measurement is automated via LabVIEW code. Pressure signals are post processed using the Matlab code and pressure waves (forward and backward moving waves) in the impedance tube are reconstructed. The ratio of outgoing to incoming wave gives the reflection coefficient at incident plane wave frequency [8].

The reflection coefficient for all cases (by varying the movable piston position and telescopic tube length) was obtained, but for ease of presentation and lack of space only 5 locations (A, B, C, D and E case) are selected and presented in this paper as shown in Fig. 5. These measurements were performed in the presence of a mean air flow of 170 cm/sec ($M < 0.005$) as well as without mean flow. As expected for low Mach number (M) flows, reflection coefficient values for both these cases were identical.

4.2 Thermo-acoustic instability frequency measurement

The procedure of mapping the combustion instability in the range of upstream reflection coefficients magnitude and phase goes as follows: A mixture of air and methane at equivalence ratio (φ) of 0.75 and mean flow velocity of 170 cm/sec was provided through the acoustic device to the burner. Keeping the telescopic tube length constant at 85 cm, the piston of stacked cones was slowly moved from initial position (0 cm) to final position (7.2 cm). On the occurrence of instability, an external microphone was used to measure this instability frequency. The piston was then returned to initial position and the TTL was increased by 1 cm (85 + 1 cm). Again, keeping TTL fixed at this new location, the piston was displaced from initial position to final position and the instability frequency was noted. Again these series of steps were repeated till the TTL reached 53 cm (85 + 53 cm).

The total number of operating conditions with respect to varied R_{up} values were 44 (movable piston positions) times 54 (TTL positions) = 2376.



(a) (b)

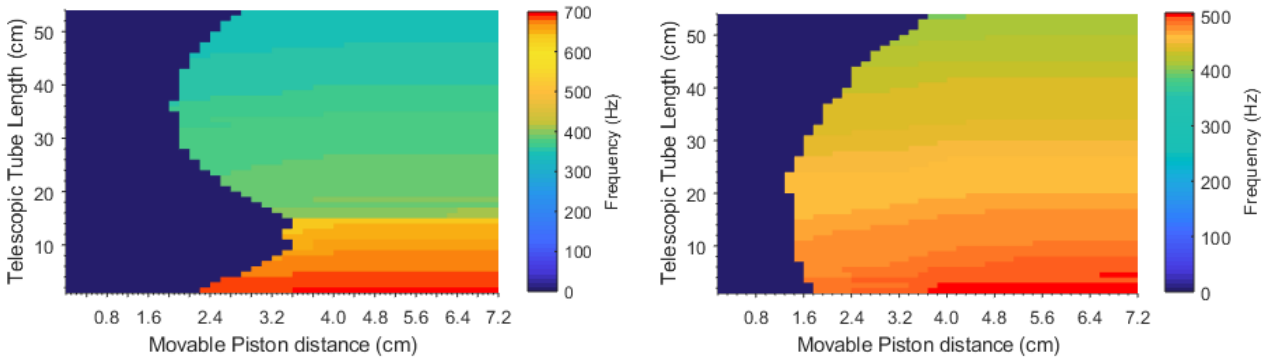
Figure 5: (a) Reflection Coefficient for A (Movable piston position: 0 cm, TTL: 0 cm), B (Movable piston position: 0.5 cm, TTL: 18 cm) and C (Movable piston position: 3 cm, TTL: 32 cm) and (b) Reflection Coefficient for A (Movable piston position: 0 cm, TTL: 0 cm), D (Movable piston position: 0 cm, TTL: 53 cm) and E (Movable piston position: 7.2 cm, TTL: 53 cm)

5. Results and Discussion

5.1 Reflection coefficient

As the reflection coefficient of the acoustic device was measured, it was observed that the lowest reflection occurred when the stack of cones was positioned at C_{base} (Movable piston position: 0 cm; case A in Fig. 5(a)). The explanation for this is that the maximum sound energy is absorbed for this configuration. As the sound waves travel through the cavity between adjacent cones and the absorbing material, flexible surface of cones and absorbing material layers begin to vibrate. This vibration results in conversion of sound energy to thermal energy by virtue of viscous damping. Thermal dissipation of this energy prevents reflection of sound. However, as the piston is moved away from the C_{base}, a gap is created between the stack and cylinder base. This gap allows propagation of the sound wave in the cylinder cavity without forcing it to pass solely through the cones as for case A. Thus, the reflection coefficient magnitude slowly increases as the gap increases and sound waves escape into the cavity of the cylinder before getting reflected at C_{edge}. By this logic, the highest reflection should be obtained for the case where the movable piston is at maximum distance from C_{base} as is visible in the experimental results for case E (Movable piston position: 7.2 cm, TTL: 53 cm) in Fig. 5(b). Substantial amount of experiments concluded that sound frequencies from 40 to 300 Hz were predominantly affected by the inter cone spacing as well as the movable piston distance. The reflection coefficient magnitude in this range of frequencies steadily increased as the movable piston distance increased (case A and B) whereas waves of frequency above 500 Hz still show relatively low reflection.

These cones were functionally translucent for all acoustic waves irrespective of frequency after the movable piston displaces more than 4.2 cm away from C_{base}. The reason for calling them translucent is that the peaks and minima in the reflection coefficient magnitude still occur at almost the same frequencies with slight deviations. It is also observed that a certain range of TTL decreased the magnitude of reflection coefficient for frequencies in range of 400 – 550 Hz. This decrease maybe due to a change in TTL which results in change of location where the sound wave encounters the absorbing material but more study needs to be conducted to determine the exact cause of this absorption.



(a) (b)

Figure 6: (a) Stability Plot for Burner P_4 and (b) Burner $P_{5.5}$ colours indicate frequencies (blue i.e. 0 Hz frequency represents stable regime)

5.2 Burner grade results

Diagrams of burner stability (dark blue region: 0 Hz frequency) and instability can be seen in Fig. 6(a) and Fig. 6(b). Even though the hole diameter of both burners was the same, there is a significant difference in their stability plots. The availability of this kind of data opens vast perspectives to be used to derive conclusions about stability margins of a particular burner, range of frequencies where the burner instabilities are the most probable, etc. Also the data provides an input for designing acoustic properties of the burner's upstream part which would improve the appliance stability. All these and other directions of future analysis/research can be approached.

Furthermore, different burners and their working regimes (the mixture flow rate and equivalence ratio) can be compared and ranked according to their probability of instability. The present data presented in Fig. 6(a) and Fig. 6(b) can be used to illustrate this possibility. The figure of merit for Burner P_4 can be calculated by taking a ratio of the region where the burner flame was stable divided by the total area of the diagram and it turns out to be 0.35 while for Burner $P_{5.5}$ it is 0.26. This shows that under the same operating conditions (the mixture flow rate and equivalence ratio), Burner P_4 is more stable than the flame of Burner $P_{5.5}$ with respect to thermo-acoustic instability. Also, one may expect that it is quite probable that the frequency of sound produced by Burner P_4 is considerably higher than Burner $P_{5.5}$. It might be interesting to view this result in light of Burner P_4 having almost twice the flow area (due to perforation) compared to Burner $P_{5.5}$. Certainly, it is too optimistic to conclude that increasing the pitch increases the probability of a burner to become unstable from just two burner tests. Nevertheless, this example demonstrates a way in which the developed experimental approach can be used to determine the effect of different physical properties (burner diameter, pitch, thickness, mean flow rate, equivalence ratio etc.) of the combustor on the burner's probability of instability. This method opens possibilities to validate different approaches based on measuring and processing the flame transfer function and the scattering matrix [3]. Also the methods which use Monte Carlo based modelling strategies [2] can be checked experimentally.

6. Conclusion

Within the work presented in this paper a new acoustic device has been proposed, constructed, tested and successfully utilized as an upstream duct termination. The device is a single duct termination whose acoustic reflection coefficient can be changed on the course of, e.g., combustion tests. Due to its flexibility the device provides a range of new possibilities and enables a wide variety of experiments which can be done at laboratory scale combustion setups.

The research based on a particular application of this setup, namely the characterization of a burner with respect to its thermo-acoustic quality was initiated. It is shown that the device can be extremely useful to observe the behaviour of various burners and determine their quality/figure of merit based on their stability under different boundary conditions. From the point of view of practical applications this is a promising new approach as the inlet reflection coefficient of different domestic boilers varies depending on material of pipes, geometry etc. and accordingly, such properties can be easily mimicked using this acoustic device. Thus, this device can help in determining the best burner to be used for variety of applications.

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