Valveless Pulsed Detonation Chamber Controlled by Hartmann Oscillators

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ABSTRACT

The paper presents the design of a valveless, high operation frequency pulsed detonation chamber, controlled by means of a system of shock waves generated by two supersonic jets impinging on a Hartmann oscillator. An extended review of the earlier research efforts in the field is included. Theoretical considerations regarding the operation of the pulsed detonation chamber are presented. A diagram of the proposed solution and the CAD model of the design of the experimental model that materializes the concept are also included.

KEYWORDS: *Detonation, valveless, Hartmann oscillator, supersonic propulsion*

NOMENCLATURE

C_i - *Sound - fluid model constant*
β_i - Non-linear damping
μ_i - Energy supply by velocity
ω_{0i} - Individual initial angular frequency
ξ_i - Linear coordinate

Subscripts:
1,2 - Individual pipes
Dot - first time derivative (velocity)
Double dot - second time derivative (acceleration)

1 INTRODUCTION

The paper presents the design of a valveless, high operation frequency pulsed detonation chamber (PDC), controlled by means of a system of shock waves generated by two supersonic jets impinging on a Hartmann type resonator [1, 2]. The Hartmann resonator is an acoustic wave generator driven by shock wave oscillations in an over-expanded air jet [3]. The Mach disk occurring in the supersonic jet downstream of the nozzle is forced to oscillate in the jet axial direction in the presence of a cavity aligned with the jet flow direction and placed in a bluff body placed downstream of the supersonic jet nozzle. Usually, the bluff body is placed near the end of the first cell of the supersonic jet pattern.

Experimental investigations of such systems date back from the mid XX century [3, 4] and numerous studies and review papers have been published to the date.
The early efforts have been focused on understanding the basics of the physical mechanism behind the observed oscillations, and on the effect of various geometrical parameters of the experimental setup on the system acoustics. Morch [3] presented a series of experimental measurements of pressure oscillations and Schlieren visualizations in planar Hartmann resonators investigating the effect of the resonator geometry on the shock wave position and on the acoustic parameters, in an effort to understand the underlying physical mechanism of the observed flow instabilities.
Smith and Powell [4] investigated, by means of optical and acoustic measurements, the amplification of the aero-acoustic oscillations induced by coupling the Hartmann oscillator with a Helmholtz type oscillator, proposing a theoretical mechanism of operation based on the position of the Mach disk with respect to the supersonic jet nozzle and the Hartmann cavity. It was found that the oscillations are driven over a wide range of upstream pressures, jet-to-cavity distances and cavity dimensions, while the maximum amplitude of the shock oscillation is limited by the size of the shock cell.
The frequency and amplitude of the oscillations were determined to be a function of the location of the resonating cavity with respect to the jet nozzle [4], and of resonance cavity geometry (both length [5] and diameter [6]), influencing the emitted sound tone and intensity.
Theoretical and experimental investigations of the acoustic waves generation mechanism in a Hartmann generator were reported by Gravitt [7], highlighting the critical role of the pressure instabilities occurring in the supersonic jet exiting the nozzle which force the oscillations in the resonator channel. A theory of the source of the pulsations registered in a Hartmann - Sprenger resonator tube triggered by the jet issuing from a convergent nozzle and supported by experimental observations, was also advanced by Kawahashi and Suzuki [8].
Experimental data correlating the distance between the jet nozzle and the Hartmann resonator with the frequency of the oscillations is presented in a more recent study by Glaznev and Korobeinikov [9]. In the light of the insights into the structure of a supersonic under-expanded jet [10, 11], a novel oscillation generation mechanism, based on the data, is proposed, showing that the frequency of the oscillations is driven by the resonator length and volume. Davies [12] presented a series of Schlieren flow visualizations in a supersonic axisymmetric turbulent jet, focusing on the effect of preheating the impinging supersonic jet on the density fluctuations in the jet potential core. The interaction between a uniform, supersonic axisymmetric jet impinging on a flat plate has been investigated experimentally and theoretically by Carling and Hunt [13]. The results indicated that jet behaviour in the near wall region jet is controlled by the expansion of the jet boundary and the reflections on the boundaries.
Tam and Block [14] carried out frequency measurements in the subsonic flow over rectangular cavities, proposing a mathematical model correlating the measured tones and the pressure oscillations, based on the coupling between shear layer instabilities and acoustic feedback.
The impingement of a shear layer upon a cavity edge was examined by Rockwell and Knisely [15]. A significant change in the flow structure is observed, extending along the entire length of the shear layer. Vortical structures visualizations indicated that an impinging structure may alternatively undergo either an entire or partial sweeping inside the cavity, or an escape, involving vortex deformation and convection downstream, past the edge.
Savory [16] presented a series of experimental studies aimed at improving the acoustic power output of the oscillator by surrounding the jet with rings of various size and materials. He, along with Hartmann and Trudso [17], also proposed the addition of a stem along the jet axis in order to stabilize the flow and allow the operation of the oscillator even at large subsonic Mach numbers. Cavities of various sizes and shapes were added around the main Hartmann resonator to increase the amplitude of the oscillations and to select the propagation direction of the sound waves [6, 18]. Variable cross - section area resonator cavities were also studied [19].
A review of the self - induced flow oscillations occurring in supersonic flows, and of the underlying physical mechanisms, was published by Jungowski [20], including the case of free jets impinging obstacles. Recordings of the development of the oscillations in this case have been presented by Ostapenko et al. [21] and Petroff and Shipulin [22]. It was observed that, starting from its farthest upstream position, the Mach disk moves towards the bluff body obstacle, generating a compression wave that intensifies and transforms into a shock wave travelling towards the Mach disk. The interference of these two shocks generates a third shock wave travelling upstream, towards the nozzle, affecting the geometrical properties of the jet expansion at the nozzle and its reflection at the

jet boundary, causing a decrease in the diameter of the Mach disk, and displacing it upstream, back to the initial position, creating a closed loop feedback mechanism [23].
The experimental work of Finley and his team was concerned with the dynamics of supersonic jets impinging on flat plates [24] or bluff bodies [25, 26]. The effect of the distance between the jet nozzle and the obstacle on the jet structure was investigated in detail. It was concluded that the flow oscillation occurs when the terminal shock of the jet is influenced by the transport of pressure fluctuations in the stagnation bubble caused by the jet shocks on the obstacle [27]. If the terminal shock occurs downstream of the first jet cell, a change in pressure will reflect on the shock wave position. Depending upon the distance between nozzle and obstacle, the jet structure variations may occur abruptly or in a fluctuating manner. The mechanism for producing the stagnation bubbles via shock waves was described by Ginzburg [28]. Significant pressure fluctuations accompanied by screech have been also recorded for large distances (over 3 - 8 shock cell lengths) between the supersonic jet nozzle and the obstacle [29]. The coupling, in this case, is achieved through the free shear layer at the jet boundary, which was shown to be very sensitive to periodic disturbances.
Demin [30] expanded the scope of the previous studies by adding small cavities on the flat plate on which the supersonic jet impinges. Oscillations of the jet flowing away from the axis were observed, generating noise frequencies in the range 1 - 50 Hz. Experimental measurements on supersonic jets impinging proper Hartmann resonators were reported by Brocher et al. [31], resulting into a significantly increased oscillations amplitude. The acoustic coupling effect of a secondary resonator has been investigated by Kawahashi et al. [32], while the influence of the resonator tube angle on the temperature was presented by Iwamoto et al. [33]. A cylindrical geometry of a supersonic jet impinging a Hartmann resonator was studied by Wu et al. [34], showing strong pressure oscillations caused by circular shock waves oscillating radially and permitting either inflow, or outflow.
The role of coherent vortices in the generation of self - sustained oscillations in a system containing a supersonic jet impinging on a bluff obstacle, including measurements of the fluctuating force on the bluff body, has been studied by Ziada and Rockwell [35] and Kaykayoglu and Rockwell [36]. Sarohia and Back [37] presented experimental investigations of resonance in a Hartmann resonator and identified several resonation modes (jet instability, jet regurgitant and screech), occurring as a function of the resonator geometry and the dynamic pressure in the device. Sobeiraj and Szumowsky [38] extended the scope of previous studies and, while confirming the significant impact of the cavity shape on the resonator acoustics, determined that the shape of the supersonic nozzle does not affect the switching between the resonation modes.
More recently, the focus of the research efforts in the field of self - sustained oscillations induced by Hartmann resonators shifted more to the application of the effect in various flow control solutions. A fluidic actuator based on the Hartmann effect was developed by Kastner and Samimy [39, 40]. The actuator used the region between the jet nozzle and the resonator for flow control. The critical control parameter for the device was found to be the distance from the jet nozzle to the resonator. Noise sources were identified and located in the actuator flow using a three-dimensional microphone array [41]. Raman et al. [42] measured the resonance frequencies in a similar flow control device and provided detailed unsteady pressure measurements in the flow control region. The shape of the jet wave pattern produced by Hartmann oscillators as a function of their internal geometry was studied by Raghu and Raman [43]. Gregory [44, 45] studied the application of Hartman oscillators as high frequency flow control devices used to improve the performance of an aircraft (enhanced lift, reduced drag, decreased noise levels, delayed stall), proposing a piezo - fluidic actuator solution that allows the oscillation frequency to be specified independent of the upstream pressure.
Savin [46] tackled the design of sound generators for applications in metallurgy and chemistry by proposing a simplified closed model of the self oscillating process triggered by a planar supersonic jet in a resonator, based on Schlieren flow visualizations and pointwise pressure fluctuation measurements. The model is able to predict both the amplitude and the frequency of the oscillations as a function of the jet velocity and on the resonator geometry, and is also useful in aircraft design, as it enables the designer to avoid unwanted resonance regimes on critical aerodynamic surfaces.
A parametric experimental study of cylindrical Hartmann resonators was carried out by Sreejith et al. [47] in order to develop active flow control applications for aerodynamic noise reduction and separation control. Tapered channels were observed to result in higher resonance frequencies than straight channels, while the high frequency oscillations are found to be independent of the resonator geometry. Another parametric study by Sarpotdar et al. [48] focused on the correlations between the nozzle - to - cavity distance and the resonance frequency, finding a reduced influence.

Murugappan and Gutmark [49] examined the effect of reduced nozzle - to - resonator distances and reporting the existence of a minimal distance under which the resonation mode switches back from screech to jet regurgitant. The value of this distance is strongly influenced by the diameter ratio between the resonating channel and the nozzle. Resonance parameters of the flow in tapered resonator channel were experimentally analyzed by McAlevy and Pavlak [50]. The channel geometry was not found to have a significant impact upon the initiation and propagation of the oscillations. Conical cavities were also investigated by Neemeh et al. [51] and Rakowsky et al. [52].
The sound generation of jets impinging on flat plates, used in coating control and heat transfer processes, was investigated by Arthurs and Ziada [53, 54, 55]. The reported measurements of pressure fluctuation indicate the generation of intense sound waves for a significant range of jet exit velocities and distances from the nozzle to the obstacle. The influence of the impingement angle and of the jet thickness are also quantified. The studies identify that different physical mechanisms are controlling the flow dynamics, depending on the distance between the nozzle and the obstacle. For small distances, the jet oscillation is controlled by the hydrodynamic flow instability. At large distances, acoustic coupling of this instability and a resonant acoustic modes occurs. In this regime, the impingement distance controls the frequency of the phenomenon. Phase - locked Particle Image Velocimetry measurements are used to measure convection velocity near the plate and a new feedback model to predict the oscillation frequency as a function of flow velocity, impingement distance and nozzle thickness is proposed. Verma and Manisankar [56] presented experimental measurements aimed at analyzing the source of the flow asymmetries occurring in over-expanded planar nozzles, highlighting the critical role played by the jet boundary layer.
More recent applications of the Hartmann effect relate to the intensification of the shock waves travelling through the resonator such as to increase the flow temperature to large enough values to allow fluidic fuel ignition in combustors. Brocher and Ardissone [57] studied the acoustics of a needle Hartmann-Sprenger generator, assessing the influence of the upstream pressure, the incoming stream chemical composition, the geometry of the resonating cavity, and the material properties of the device on the tube's end wall temperature. Kawahashi et al. [58] investigated the effect of conical and stepped resonators on the intensity of the generated shock waves to increase the temperature jump through the shock waves. The influence of the resonator geometry and flow Mach numbers has been determined, and a single step geometry of the resonating cavity has been identified as optimal. An overview of the current research work carried out in this field is presented by Bogdanov [59].
As show by the previously cited work, most of the research efforts carried out in the field have focused on singular, round or planar supersonic jets. Investigations on the coupled effects of supersonic jet systems impinging on Hartmann type resonators are yet scarce [60, 61, 62], even though the interaction effects of closely spaced supersonic jets have been studied both experimentally, for planar [63], round [64, 65], conical [66], or rectangular [67] supersonic jets, and theoretically [68]. Numerical and experimental studies of the vortical structures occurring in the case of two jets impinging at an angle on a flat plate were also reported by Chammem et al. [69].

2 PROPOSED CONCEPT DESCRIPTION

The paper presents an application of coupled supersonic jets impinging on a Hartmann type resonator used for the development of an aerodynamic system capable to function as an aerodynamic valve for a PDC. To ensure the correct air flow through the combustor, the classical pulsed detonation combustor design proposes a set of valves that open and close the admission of the air, or air-fuel mixture, in the combustor. The typical detonation frequency in such devices is low. Higher operating frequencies can be expected to increase the specific impulse of the engine, allowing for a more compact combustor, and, due to inertial effects, to smooth out the mechanical vibrations in the combustor. The main problem in using mechanical valves is the high wear they experience, even more so at high frequencies. Also, the valves are subject to very high operating temperatures, and will induce pressure losses in the flow. Therefore, high frequency valveless designs are an obvious goal for the future pulsed detonation combustor development. Furthermore, the use of a Hartmann shock wave generation system to control the flow into the PDC may also serve as a very efficient, reliable and simple ignition system, naturally correlated with the fresh mixture inflow, if the strength of the shock waves is sufficient.
The proposed concept is based on taking advantage of the phenomenon of synchronizing the oscillation of a non-linear self-oscillating system with the frequency of forced oscillations, or with the

frequency of another self-oscillating system when they are coupled [70]. The lock-in and synchronization phenomena can be observed, and successfully used in applications, in hydrodynamic and thermo- gas-dynamic processes for flow control over bodies [71, 72, 73], or for intensification or damping of transfer processes in thermo-acoustic systems [74].
To intensify the processes occurring in shock wave generators (increasing pressure pulsation amplitude and resonator temperature), and to stabilize the self-oscillating operating regime, the concept proposes placing two nearly identical shock wave generators in front of the central detonator chamber. From a practical standpoint, the best suited solution is to use a bi-dimensional, rectangular section, shock wave generator with its exit directed towards the detonation chamber. Conceptualy, the system of resonators in the detonation chamber may be regarded as the interaction of two non-linear, self-oscillating systems of type Van der Pol [75, 76]:

$$\ddot{\xi}_1 - \mu_1(1 - \beta_1\xi_1^2)\dot{\xi}_1 + \omega_{01}^2\xi_1 = C_1\xi_2 \quad (1)$$

$$\ddot{\xi}_2 - \mu_2(1 - \beta_2\xi_2^2)\dot{\xi}_2 + \omega_{02}^2\xi_2 = C_2\xi_1 \quad (2)$$

To adapt the equation system (1) - (2) for the quantitative analysis of the hydrodynamic interaction of two shock wave generators, the value of the coefficients need to be experimentally determined. This is out of the scope of the present work.
The synchronization effect of the shock wave generators placed face to face may be observed in the analysis in Fig. 1. For the case of two interacting generators (Fig. 1 - left), the amplitude of the pressure oscillations at the closed end of the generators, as well as the stability of the self-oscillating regime increases compared to the case of a single resonator (Fig. 1 - right).

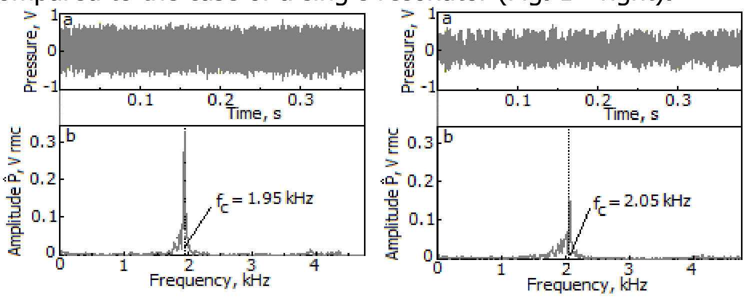

Figure 1: Pressure variation (a) and pulsation spectrum (b) near the closed end of the lateral resonators. Left - 2 resonators in opposition of phase. Right - 1 resonator.

The proposed combustor is of rectangular construction, and includes a shockwave generator with coupled resonators. It consists of the following (notations apply to Fig. 2):

1. Combustor casing;
2. High pressure air chambers;
3. Supersonic nozzle;
4. Lateral resonators;
5. Outer side walls of the lateral resonators;
6. Central detonation chamber;
7. End walls of the lateral resonators;
8. End wall of the central resonator;
9. Separation walls.

More details on the geometry and on the flow can be found in [77] - [80].
The combustor (1) is fed by the high pressure air chambers (2), where the air is delivered by the engine compressors (1 - Fig. 3 [81]) and which feed the air into the supersonic nozzles (3). Two lateral resonators (4), delimited by walls (5), (7) and (9) are placed with their open endings towards the supersonic nozzles (3). Between the lateral resonators (4), the central detonation chamber (6) is placed, delimited by walls (8) and (9). The central detonation chamber (6) and the two lateral resonators (4) are separated by sharp angled walls (9), with the sharp angle edge placed at the open end of the central detonation chamber (6). The supersonic jets are formed by the diverging end supersonic nozzles (3) and provide an increase in temperature at the closed ends of the resonators (4) and of the central detonation chamber (6).
As the supersonic jets impact the sharp edged walls (9) placed at the open ends of the lateral resonators (4), shock waves are formed and travel towards the closed end of the resonators (7). The air entrained by the supersonic jets shear layers is directed into the lateral resonator chambers (4). A

numerical simulation of the flow can be found in [79, 80]. The air stream detaches in the central region of the combustor from the side walls (5) and enters the lateral resonators (5) at a variable angle with respect to the combustor centreline. The travelling shock waves impact the end walls of the resonators (7) and are reflected backwards, towards the lateral resonators (4) open ends, causing an increase in the wall pressure. An earlier model of the proposed resonator tubes and their operation can be found in [82, 83, 84]. When the backwards travelling shockwaves reach the open ends of the lateral resonators (4), they are converted into expansion waves. This moment in time separates the two operation phases of the resonator: the filling phase, before the previously mentioned point in time, and the exhaust phase, which follows.

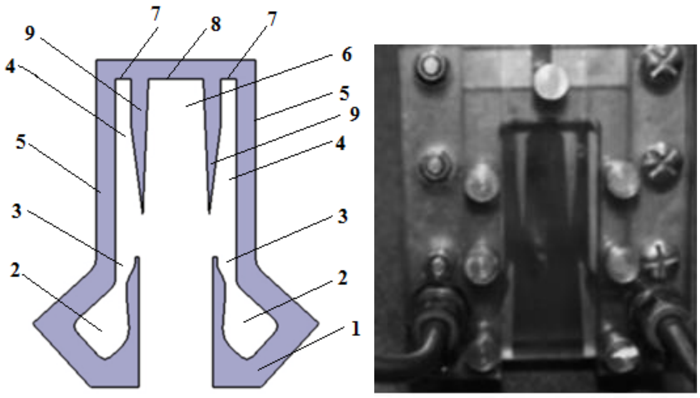

Figure 2: Diagram (left) and experimental model (right) of the PDC

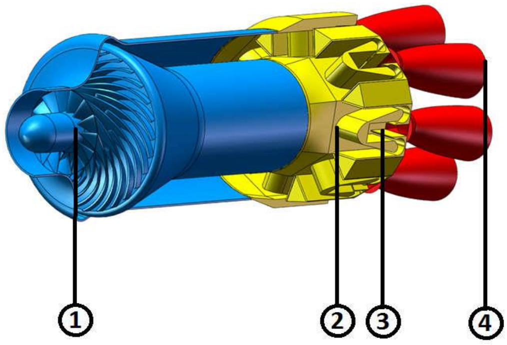

Figure 3: Diagram of the TIDE engine using the proposed PDC

During the filling phase, the air stream velocity in the lateral resonators (4) decreases to zero, and the air mass flow rate deflected around the lateral resonators (4) into the central detonation chamber (6) continuously increases up to the maximum value, which is the inlet mass flow rate. During this process, the velocity of the supersonic jets is basically constant.
The filling phase can be further divided into two sub-phases. In the first, the air mass flow rate entering the central detonation chamber (6) increases slowly, as the velocity of the air stream entering the lateral resonators (4) decreases from the maximum value to zero. In the second sub-phase, both the air mass flow rate entering the central detonation chamber, and its velocity suffer a jump increase due to the sudden opening of the transversal cross-section between the supersonic jets and the side walls (5), allowing the evacuation of the air from the lateral resonators (4). The second sub-phase is significantly shorter than the first sub-phase, creating the conditions for a shock wave to appear in the central detonation region (6), travelling towards its closed end (8). If the proper conditions for creating such a shock wave are not met, then a sonic pressure wave with a ¼ wavelength is formed inside the central detonation chamber (6). In this case, a supplementary increase in the pressure at the central detonation chamber end wall (8) can be achieved through proper profiling of the central detonation chamber [85].
During the exhaust phase, the air from the lateral resonators (4) is exhausted initially due to the pressure difference between the lateral resonators (4) and the central detonation chamber (6), and through supersonic jet entrainment afterwards. This process is very fast and it ends up by creating a maximum pressure deficit inside the lateral resonators (4). At the end of the exhaust phase, the

supersonic jets outside the lateral resonators (4) is directed towards the combustor exit, forming two planar high speed jets.
As a new filling phase starts, the supersonic jet is suddenly deviated towards the lateral resonator wall (5). In the same time, part of the fluid in the central detonation chamber (6) is injected into the lateral resonators (4), under the initial action of the pressure difference, and by jet entrainment afterwards. The deviation of the supersonic jet towards the lateral wall opens up the way for the evacuation of the fluid in the central detonation chamber (6) through the combustor outlet.
The cycle of successively generating shock waves through the impact of the supersonic jet with the lateral resonators (4) and the central combustion chamber (6) has a frequency, *f*, that is a function of the local speed of sound and of the length of the lateral resonators (4) and central detonation chamber (6), chosen to be of equal length.

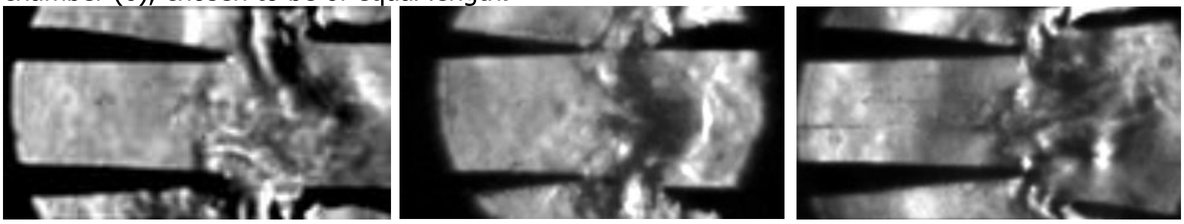
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Figure 4: Interaction between shock wave generators

The synchronization of the lateral shock wave generators may occur in different manners, as observed during the concept validation experimentation (Fig. 4). At large distances between the supersonic nozzle and the open ends of the resonators, the synchronization occurs in opposition of phase (Fig. 4a). At smaller distances, a switching - phase opposition regime occurs (Fig. 4b), as the opposition of phase is preserved, but the jets that are partially, or completely, evacuated from the resonators remain coupled throughout the entire oscillation cycle. This jet couple, directed toward the central detonation chamber (6), oscillates both in the transversal direction, form one wall to the other, and longitudinally, maintaining the propagation direction. Finally, in the third self-oscillating regime (Fig. 4c), occurring at even smaller distances, the lateral resonators operate in phase. In this case, horse shoe vortices detach from the region the two jets meet. The results in Fig. 1 refer to this latter regime, which can be predicted from the theoretical analysis of the equation system (1) - (2).
The results presented above where obtained on an reduced height experimental model (Fig. 2 - right), including the central detonation chamber, the nozzles, and the lateral resonators. This may have caused three-dimensional disturbances, such as, for instance, the twisting of the jets in the region where the incoming supersonic jet meets the resonator exhaust jet.
The advantage of the selected constructive solution resides in converting a larger fraction of the supersonic jets kinetic energy to shock wave energy by using the exhaust phase supersonic jet kinetic energy as well. In conventional Hartman generators, this supersonic jet kinetic energy is not used, and is exhausted by the resonator fluid in the ambient air.
The sharp edges of the walls (9) are used in order to reduce the aerodynamic drag imposed on the exhaust jet. Also, an increase in the shock wave amplitude is expected due to the superposition of the oblique shockwave reflected backwards by the central detonation chamber end wall (8), over the normal shock wave. The shape of the diverging channel of the supersonic nozzles (3) was designed to ensure a faster deviation of the supersonic jet towards the lateral wall during the shock wave formation phase. The numerical simulation of the process is available in [80].

3 PDC OPERATION

For ignition, the fuel is injected into the high pressure air chambers (2) placed upstream of the supersonic nozzles (3). Due to the effect of the shock waves and to the Hartman-Sprenger effect they create, the combustible mixture close to the end wall of the lateral resonators (7) is heated up to a temperature that creates ignition. After a short while, the flame front reaches from behind the reflected shock wave and combines with it forming a planar detonation wave. At the open end of the lateral resonators (4), the detonation wave ignites the combustible mixture existing in the central detonation chamber (6), creating there a new detonation wave travelling towards the end wall of the central detonation chamber (8). The admission of the combustible mixture inside the central detonation chamber (6) occurs during the first sub-phase of the filling phase, described in the

previous section, while the detonation wave travels inside the central detonation chamber occurs during the second sub-phase of the filling phase. When reaching the end wall of the central detonation chamber (8), the combustion process stops, and the detonation wave becomes a reflected shock wave that travels, together with the burned gas, towards the combustor outlet.
The detonation waves in the lateral resonators (4) may block the entry of the supersonic jets both in the lateral resonators (4) and in the central detonation chamber. After the exhaust of the burned gas from the lateral resonators (4), the detonation wave may dissipates or transforms into a shock wave, and the supersonic jet may initiate a new lateral resonator shock wave generation cycle, hence a new detonation cycle both in the lateral resonators (4) and in the central detonation chamber (6).

4 CONCLUSION

The PDC constructive solution presented in Fig. 2 was subjected to experimental [77, 78] and numerical studies [79, 80] which resulted in the significant optimization of its operation. The geometry of this initial concept has also been altered, and the final PDC has been proven to operate at frequencies in the range of 350 Hz, under premixed conditions. The results related to the optimized PDC based on the proposed concept are under review for publication.
The proposed PDC design has the advantage of providing a valid solution for the valveless control of the inlet by means of the shockwave system created by the impingement of the supersonic jets onto the Hartmann resonators. The fuel self-ignition, predicted by the numerical simulations, has not been, however, experimentally demonstrated yet, possibly due to heat losses unaccounted for in the simulations. Further experimental and numerical research is planned in two on-going national research programs (MILADEE and ASHCAP).

ACKNOWLEDGEMENT

This work was funded by the European Commission, through the Framework Programme 7European research project no. 335091 – TIDE

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