HIGH SPEED SHADOWGRAPH VISUALIZATION OF THE UNSTEADY FLOW PHENOMENA IN A VALVELESS PULSEJET ENGINE

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ABSTRACT: A pulsejet is a micro - propulsion device ideally suited for MAV applications because of its low cost, simplicity and scalability. Unsteady flow and complex mixing of fuel, air and residual hot gases in a pulsejet make analysis, modeling and scaling extremely challenging. A general methodology for the design of optimized pulsejet geometry is still not available.

In order to evolve such a design methodology, high speed flow visualization, employing a unique twin-beam shadowgraph technique, has been effectively used to better understand the detailed pulsejet flow physics. An inline - intake, rectangular cross–section, valveless hydrogen-fuelled pulsejet, suitably modified with optical access for flow visualization was used for this experimental study. Visualisation of the unsteady combusting flow phenomena, under sustained pulsation, as well as at starting of the pulsejet has been studied using this high-speed shadowgraph technique. This technique has been shown to be powerful tool to arrive at what need be promising inline-intake valveless pulsejet configurations. A pulsejet starting method, ideally suited for field applications such as in MAVs using only an external flame torch igniter, has also been successfully developed.

INTRODUCTION

The pulsejet is an expendable, micro-propulsion device ideally suited for short duration missions such as for Micro-Air Vehicles (MAVs) because of its low cost, simplicity and scalability. Principally, a pulse combustor consists of an acoustically, carefully sized air inlet, combustion chamber and a tailpipe / resonance tube through which combustion products are exhausted. Ignition and combustion, periodically, of a combustible mixture cause an outflow of the combustion products from the combustion chamber to the ambient, mainly through the tailpipe / resonance tube. Residual flames, from the previous cycle, need to be present in sheltered regions of the combustion chamber, to ignite the fresh charge and thereby sustain the pulsation. A partial vacuum, due to the "Kadenacy effect", is produced in the combustion chamber due to the rapid exhausting of the combustion products. Fresh air is now inducted into the combustion chamber through the valveless intake, and fuelled, in preparation for the next uniform cycle of stabilized wave interactions. A valveless intake has been adopted as it permits scaling down and also avoids the lack of reliability associated with mechanical reed valves. For high performance, according to the Rayleigh criterion, combustion should be arranged to generally occur, when the pressure is rising.

The unsteady, complex mixing of the fuel and air with the residual hot gases, together with the coupled nature of the vortex flow structures and wave dynamics within the pulsejet make analysis, modeling and scaling extremely challenging. A generally accepted methodology for the design of an optimized pulsejet is still not available. Currently, a trial-and-error design approach is being used as there is a lack of complete understanding of the associated basic fluid and combustion phenomena.

This paper reports the results of an experimental investigation of the unsteady flow phenomena in a valveless pulsejet engine by high-speed shadowgraph visualization. The specific aim has been to identify, through detailed flow visualization, valveless pulsejet configurations which allow, Prandtl's "clean aerodynamics", which in turn would naturally lead to good performance. Of these configurations, those which allowed, in addition good starting characteristics, a necessary attribute for field launched MAV models, were further studied. It is anticipated that this work will lead to rules which will permit significant improvement in the current design techniques.

EXPERIMENTAL SETUP AND PROCEDURE

PULSE COMBUSTION

Experiments were performed on a non-premixed, hydrogen-fuelled, rectangular cross-section, valveless pulse combustor (Fig.1). The pulsejet engine was 766 mm long with an intake of 22mm x 17mm x 90/100 mm, combustion chamber 60 mm x 76 mm x 76mm and a resonance tube / tail pipe 25mm x 17 mm x 500 mm. The intake length, which had a significant effect on allowing steady pulsating combustion, was varied from 30 mm to 150 mm. Steady pulsation was not possible outside his range. The tail pipe length was maintained at 500 mm. A taper section, 100 mm, connected the combustion chamber and the tail pipe. The combustion chamber was fitted with a 3 mm thick quartz glass window which offered optical access for high-speed photography. A CAD model and the pulsejet engine construction is shown in Fig. 2.

Hydrogen fuel was injected transversely through a 6 mm diameter tube spanning the combustion chamber. The tube had 0.8 mm x 10 (5x2) choked ports. Trials were also conducted by transverse injection of the hydrogen from a 4mm port flush in the top wall. The hydrogen gas was fed to the injector from a gas cylinder using a SWAGELOCK regulator at an upstream pressure, always maintained at 0.7 MPa. The fuel line had a non-return valve and flame arrester and the fuel flow was controlled using a SWAGELOCK 6 mm diameter needle valve; the fuel mass flow was measured with a MICROMOTION Corolis type mass flow meter. A water-cooled KULITE pressure transducer, flush mounted on the combustion chamber wall, captured the unsteady pressure signals. All the data were recorded using a NATIONAL INSTRUMENTS computer based data acquisition system.

Fig. 3 shows a schematic of the test setup and the engine mounted on the test stand; Fig. 4 shows a trace and the FFT of the unsteady combustion chamber wall pressure for a typical fuel flow rate.

TWIN-BEAM SHADOWGRAPH FLOW VISUALISATION TECHNIQUE

Probing a pulsating combusting flow would necessarily require a non-intrusive method. Fig. 5 shows a schematic of a unique Z-type twin beam, focused shadowgraph arrangement (Indian copyright applied for) employed for visualizing the unsteady flow phenomena in a valveless pulsejet engine. Fig. 6 shows a photograph of the test setup. This shadowgraph arrangement allowed simultaneous visualisation of the flow phenomena at entry to the air intake, exit of the tailpipe / resonance tube as well as the combustion chamber interior so as to capture the crucial unsteady flow / combustion coupling. Four Schlieren mirrors of 308 mm diameter and focal length 2.8 m were used as collimators. For high-speed shadowgraph imaging, a PHOTORON FASTCAM SA4 digital camera was used. The camera was capable of recording at frame rates upto 500000 frames per second. The resolution of this camera decreases with increasing frame rates. For the present study, recording was carried out at 8000 frames per second with a resolution of 1024 x 416 pixels. The independently controlled shutter was set at around 3μs. For this high-speed application, two fiber optic illuminators having a 150 W halogen bulb each were used as the light sources.

RESULTS AND DISCUSSION

In order to understand the unsteady combusting flow phenomena and thereby to attempt evolving a general methodology for the design of optimized valveless pulsejet geometry, a unique, specially developed, shadowgraph flow visualization technique was employed.

PULSATING COMBUSTION FLOW PHENOMENA

Fig 7 shows the combusting fluid flow phenomena associated with one cycle of pulsation. (Fig.4 shows the dominant pulsation frequencies were around 250 Hz). The twin-beam, Z-type, shadowgraph arrangement enabled the simultaneous visualization of the coupled flow phenomena at the entry to the intake, tail pipe exit and the combustion chamber interior, under static conditions. Hydrogen fuel was injected from a cross-bar spanning the combustion chamber height. Frame 7.2 shows the expulsion phase of the hot combustion products, following ignition and combustion, through both the intake and the tail pipe. The classic toroidal vortex structures are seen. The importance of minimizing the hot gas outflow through the intake needs to be emphasized, if the thrust has to be maximized. Introducing a sudden expansion at the entry of the intake to the combustion chamber and shaping the intake passage to offer resistance to the backflow are two possible solutions. The backward facing step should also allow residual combustion products to collect at the base to provide an adequate pool of heat and active radicals to ignite the fresh mixture for the next cycle. Accordingly, the height and shape of the backward facing step needs to be optimized. Frame 7.8 show the induced fresh air jet streaming into the combustion chamber following the expulsion phase when the combustion chamber pressure had fallen below atmospheric due to the “Kadenacy effect”. Frame 7.12 show the subsequent ignition / combustion which then led to expulsion of the hot gases to complete the sustained pulsation cycle. Providing good contact area and residence time for the toroidal vortex shaped fresh mixture volume to receive heat and active radicals from the residual gas pool is very important. This becomes even more serious if the pulsejet has a finite flight speed. The air/fuel mixture could then pass over the residual gas pool too quickly to ignite.Ref.1 has suggested introducing an obstruction in the air jet path to allow additional residence time, somewhat akin to bluff body flameholders.

STARTING CHARACTERISTICS

It is a conventional practice to force an adequate packet of starting air from a blower through the intake once the gaseous fuel has been ignited externally with a flame torch. Moreover, the general practice of starting any engine is by igniting the fresh mixture using a spark plug mounted on the combustion chamber wall. If, however, the pulsejet engine has to be deployed in a field application such as in an MAV, it may be difficult to arrange for an air blower with a power source or a spark plug with a high voltage unit and power source. Hence, a method was evolved with inputs from the shadowgraph flow visualization study, to allow sustained pulsating combustion to commence using only an external flame torch (or even a lighter), providing the specific valveless pulsejet geometry chosen allowed it. Fig. 8 shows the typical starting sequence for a valveless pulsejet engine with an external torch ignitor together with starting air jet from a blower. Frame 8.4 shows the toroidal flame jet entering the combustion chamber, followed by ignition, combustion, expulsion and the subsequent fresh air induction (frames 8.8, 8.9) to initiate sustained pulsation. Similarly, Fig. 9 shows a typical starting sequence with only a spark plug mounted on the combustion chamber. Fig 10 shows the starting sequence with only an external flame torch. Successful starting was achieved by careful selection of the initial fuel charge. An explosive shock created (frame 11.7) acted as a key trigger leading to sustained pulsation combustion.

CONCLUDING REMARKS

A unique, twin-beam shadowgraph technique has been developed for visualizing the unsteady combusting flow phenomena in a hydrogen-fuelled valveless pulsejet engine. The technique has been shown to be a powerful tool to arrive at promising configurations of pulsejet engines, which in addition have excellent starting characteristics.

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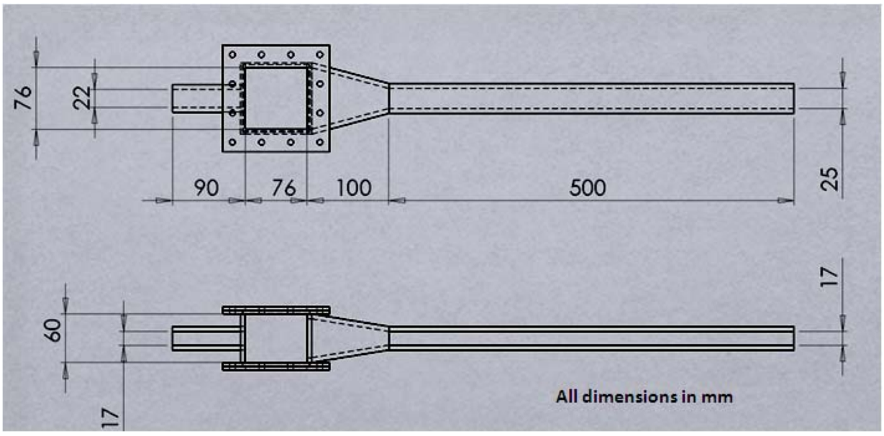

Fig.1 Inline intake valveless pulsejet engine

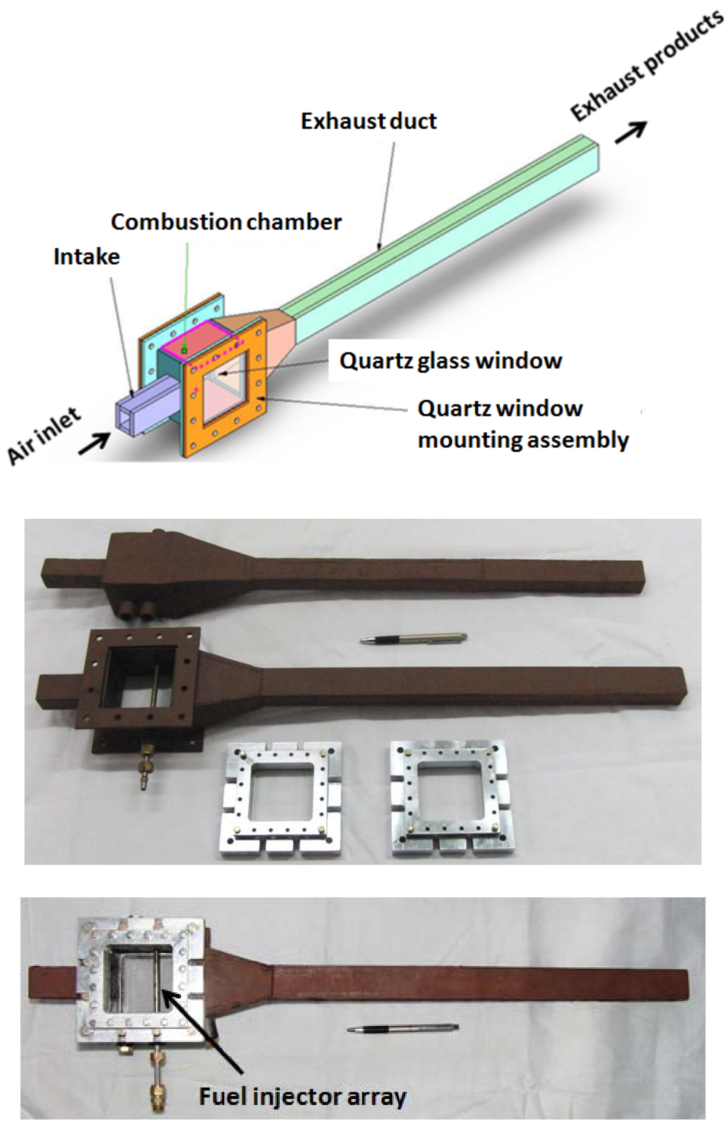

Fig.2 CAD model and construction of the rectangular valveless pulsejet engine with an optical window for flow visualisation.

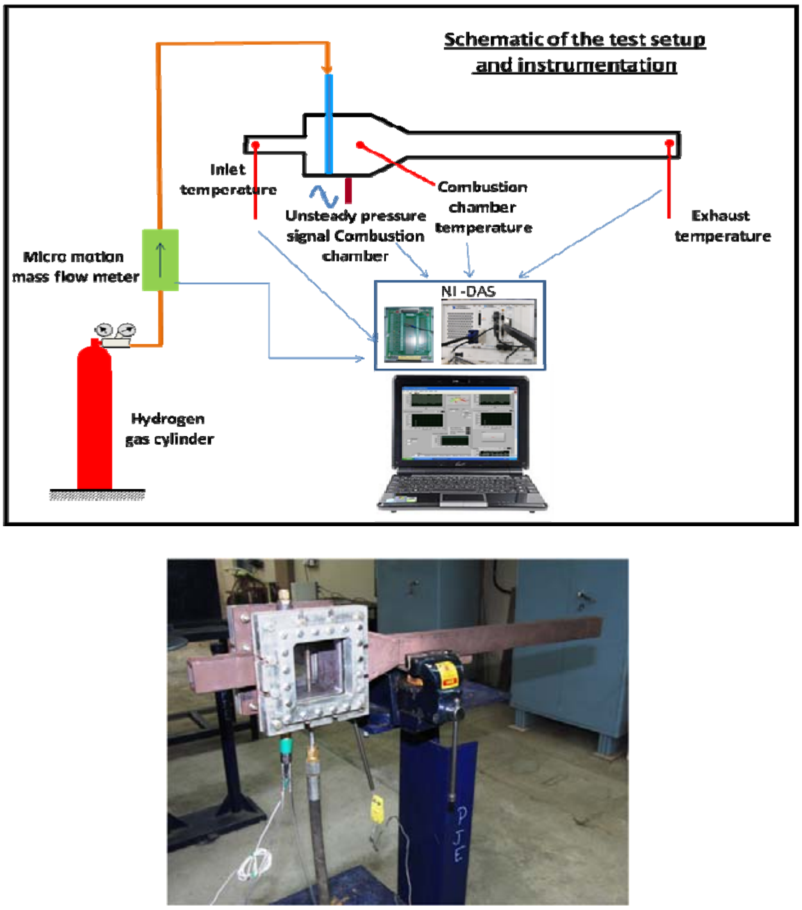

Fig. 3 Schematic of the hydrogen fuelled valveless pulsejet engine test setup and the engine mounted on the test stand.

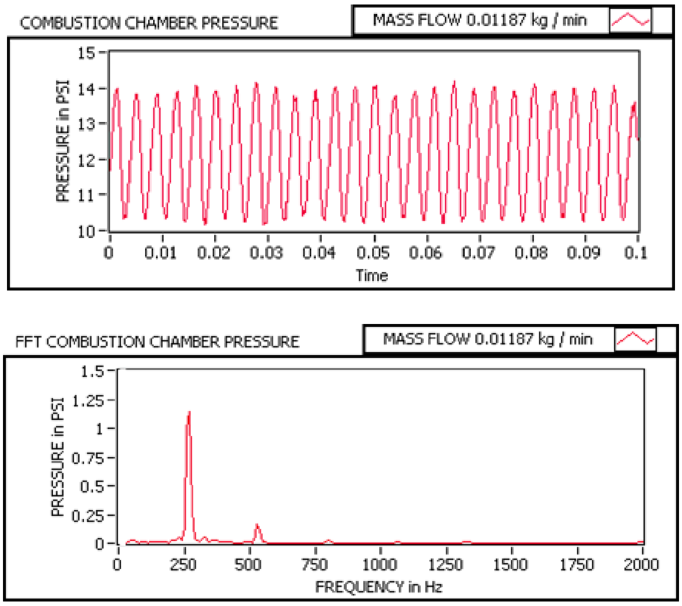

Fig. 4 Unsteady combustion chamber wall pressure signals and the FFT for a typical fuel flow rate

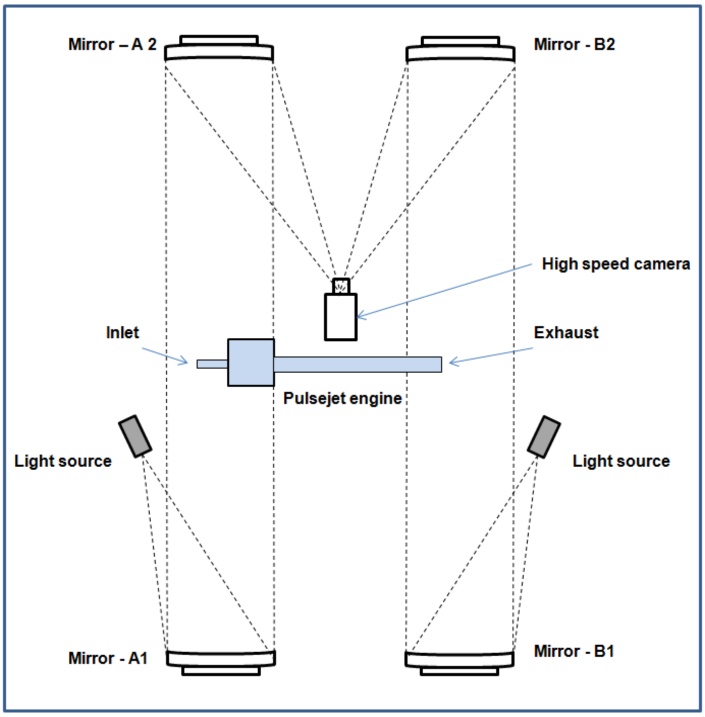

Fig.5 Schematic test setup of the shadowgraph arrangement

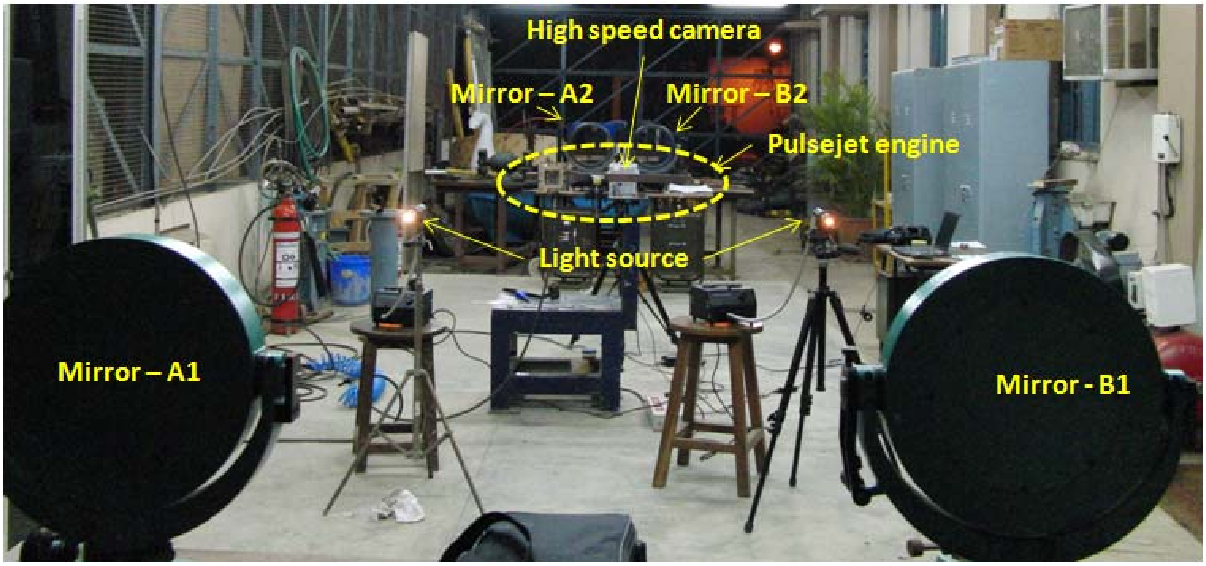

Fig.6 Photograph of the test setup.

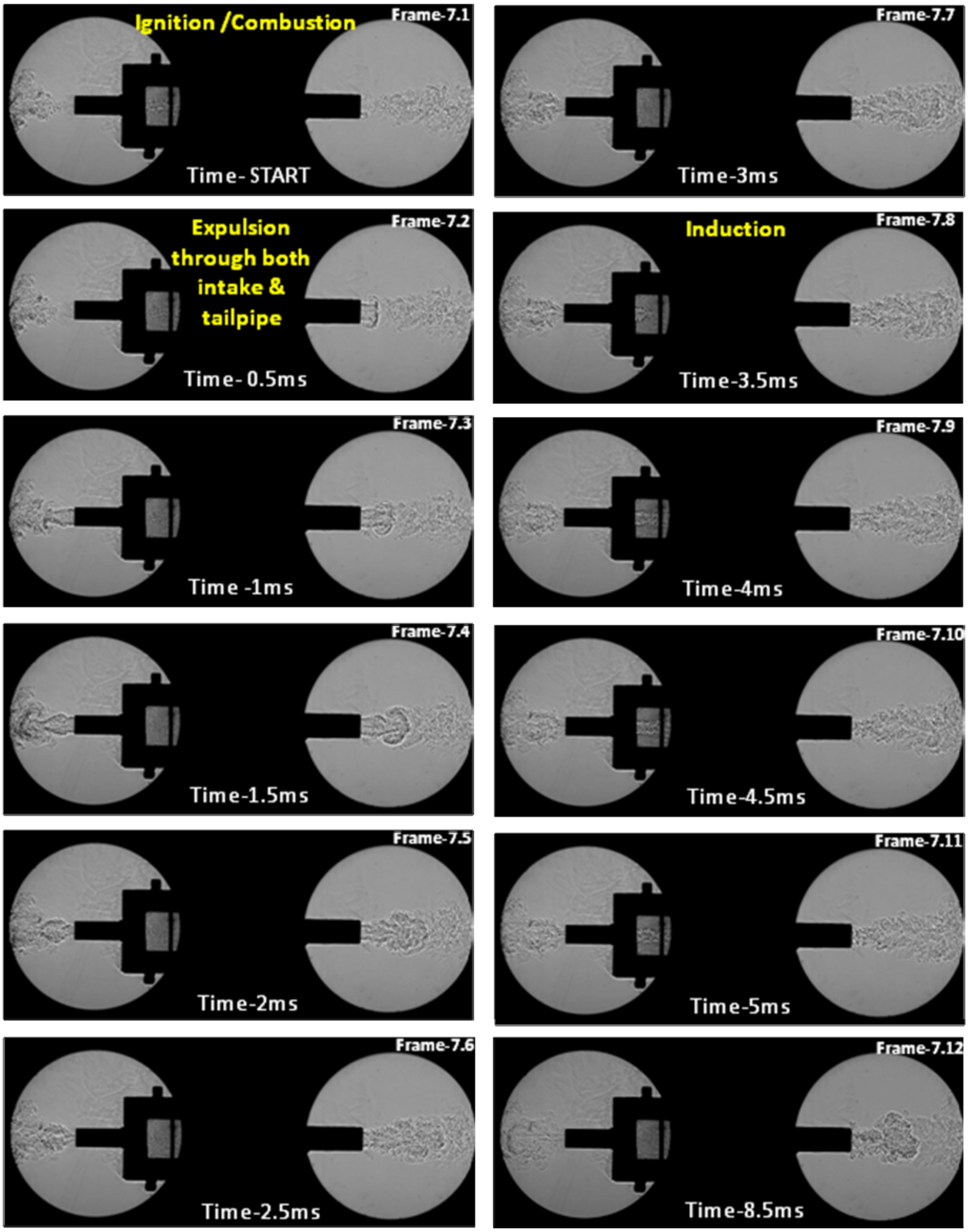

Fig.7 Time resolved frames showing the flow structure of one cycle of sustained pulsation. (Starting of the engine was by igniting using an external flame torch along with air jet assistance)

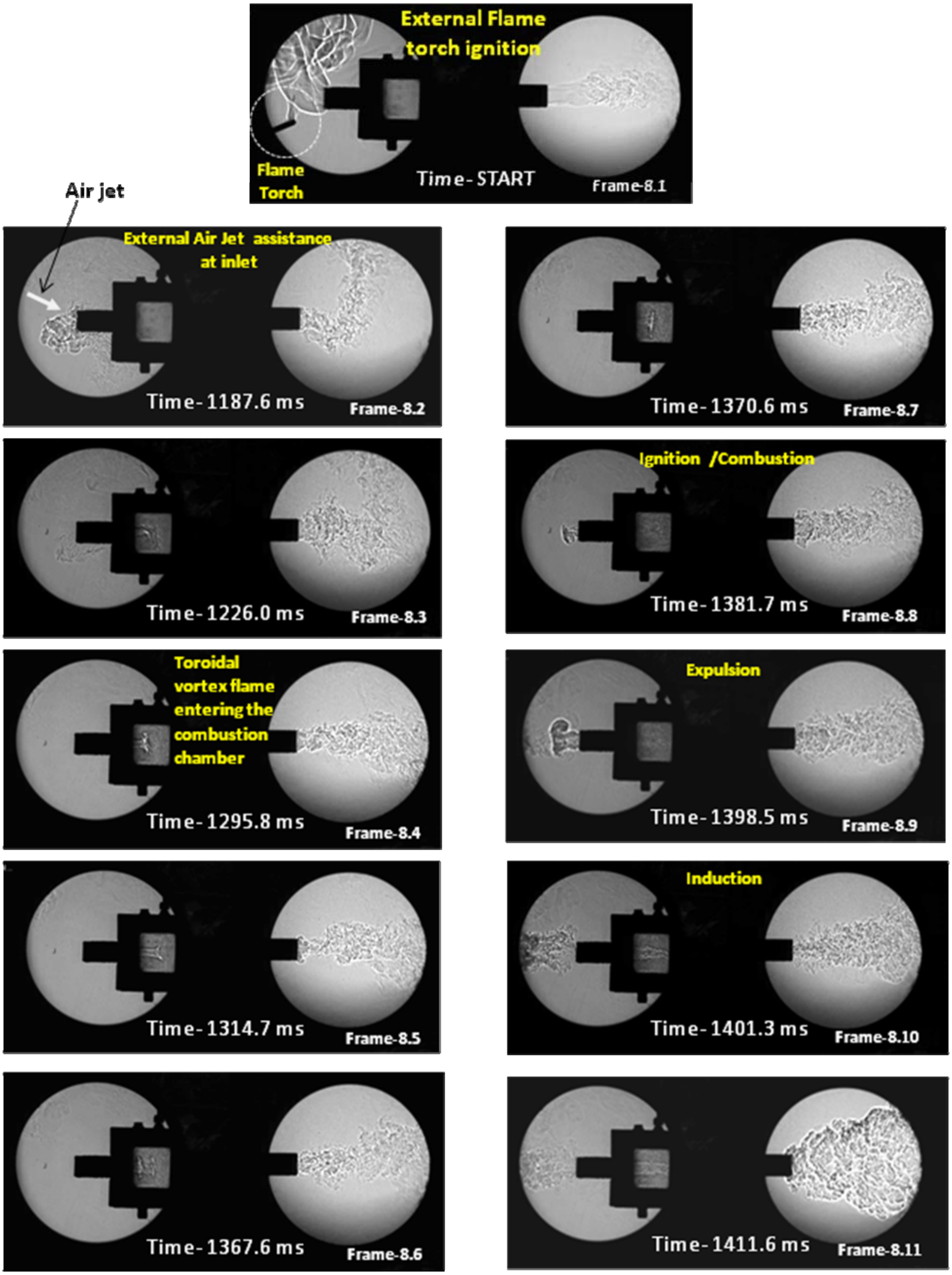

Fig.8 Time resolved frames showing the starting of the engine after the fuel was ignited by an external flame torch followed by air jet assistance.

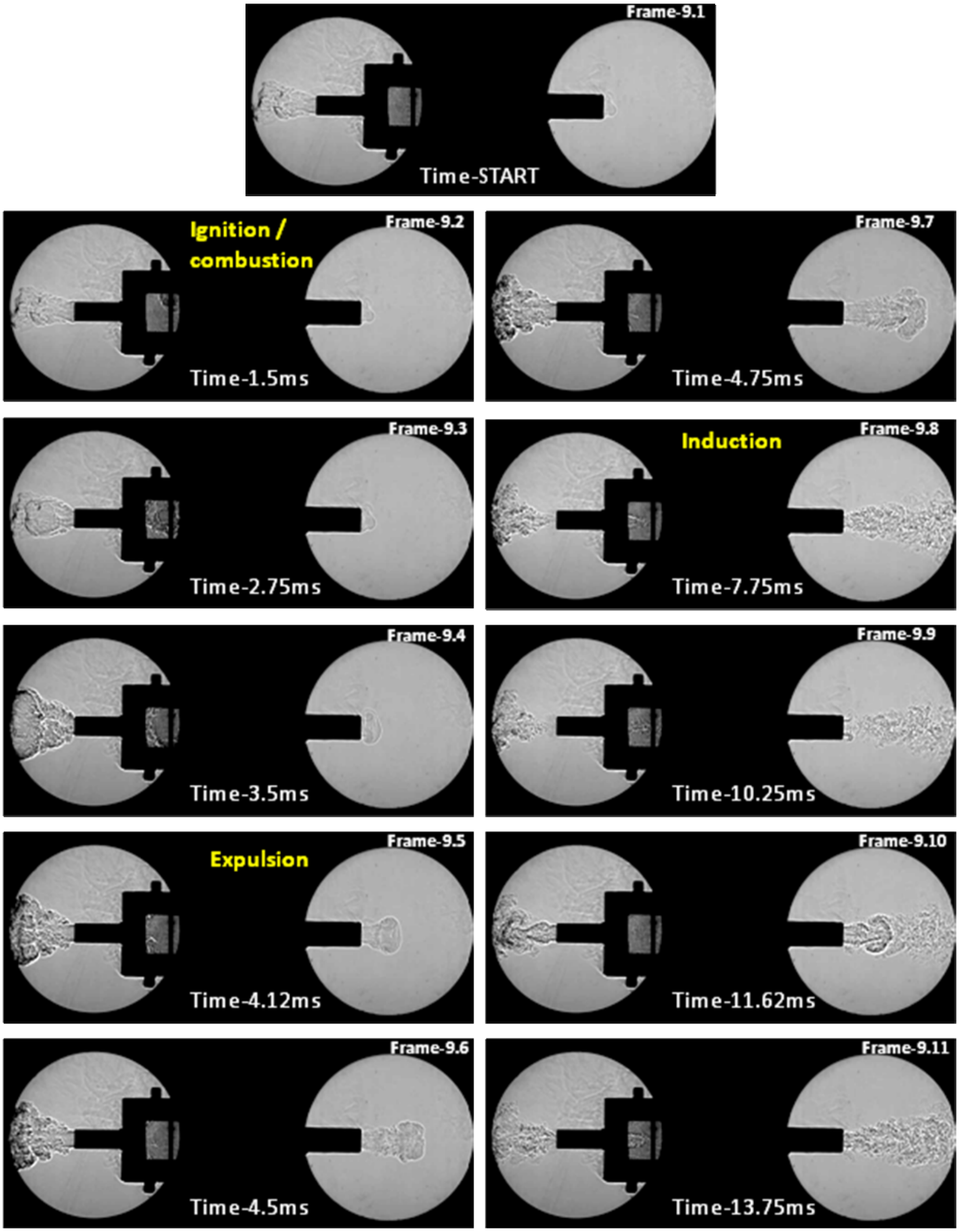

Fig.9 Time resolved frames showing the starting of the engine only by using a spark plug mounted on the combustion chamber of the engine.

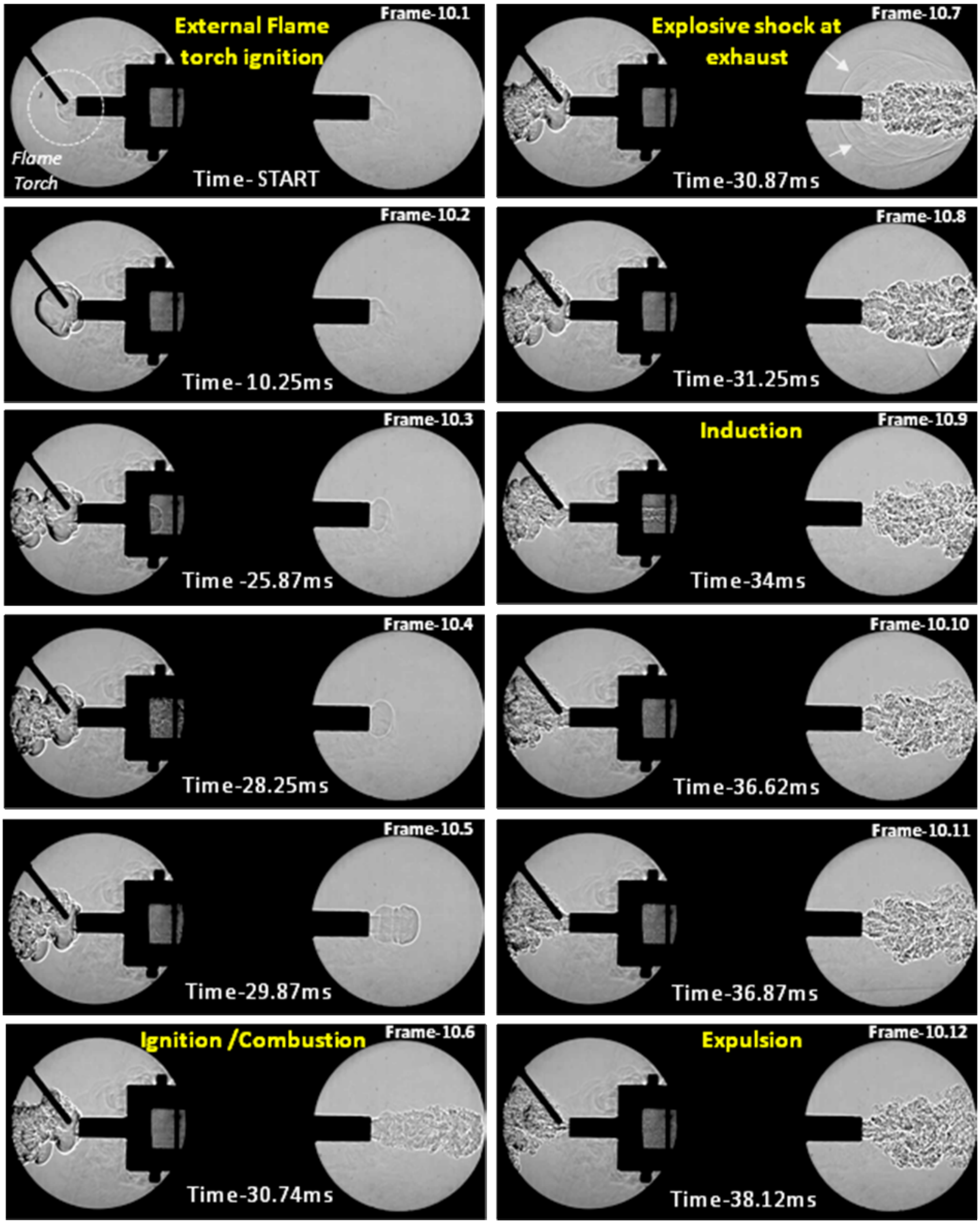

Fig.10 Time resolved frames showing the starting of the engine only by flame torch ignition.