

Generation of Turbulence in a RCEM towards Engine Relevant Conditions for Premixed Combustion Based on CFD and PIV Investigations

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ABSTRACT

The interaction of turbulent premixed methane combustion with the surrounding flow field can be studied using optically accessible test rigs such as a rapid compression expansion machine (RCEM). The high flexibility offered by such a test rig allows its operation at various thermochemical conditions at ignition. However, limitations inherent to such test rigs due to the absence of an intake stroke do not allow turbulence production as found in IC-engines. Hence, means to introduce turbulence need to be implemented and the relevant turbulence quantities have to be identified in order to enable comparability with engine relevant conditions. A dedicated high-pressure direct injection of air at the beginning of the compression phase is considered as a measure to generate adjustable turbulence intensities at spark timing and during the early flame propagation. Based on former engine measurements and corresponding CFD simulations, the regime of relevant operating conditions in terms of velocity and length scale ratios in the Borghi diagram was derived for the RCEM. The main goal of this study is A) to characterize experimentally the flow field evolution for the optically accessible part of the domain in the spark plug vicinity to assess if the target conditions can be reached, and, B) support interpretation of the experimental data by means of CFD calculations which provide insights w.r.t. the flow field evolution also in the non-observable regions. To this end, the underexpanded jet of the angled single-orifice air injector used for the secondary air injection was experimentally and numerically assessed first in a constant volume setup and thereafter under transient conditions (moving piston). Schlieren imaging of the Mach disc location and time-resolved Particle Image Velocimetry (PIV) measurements around the spark plug were conducted to deduce the characteristics of the injection and the resulting tumbling air motion respectively. The numerical findings suggest that the underexpanded jet first impinges on the piston and then interacts also with the cylinder liner leading to the formation of a tumbling motion which is subsequently compressed due to piston motion. Reasonable agreement with the experiment is reported at the end of this process chain for the observable part of the domain. It has been shown that the use of an underexpanded secondary air injection in the RCEM allows for reproduction of the desired velocity and length scale ratios representative of the engine under consideration.

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INTRODUCTION

Optical diagnostics of in-cylinder processes in turbulent premixed combustion is a key element for improved understanding of governing physics occurring and indispensable for further development and validation of numerical models for computational fluid dynamic (CFD) simulations applied to engines. High-speed imaging combined

with heat release analysis [1] has already been employed in the 1930s, demonstrating that engine combustion takes place in a premixed turbulent flame-front regime. Damköhler's pioneering work of turbulent combustion [2] indicated the scaling of the burn rate in proportion to the engine speed due to the increasing turbulent flame area by flame-front wrinkling. Application of planar laser light sheets [3] confirmed the corrugated flame-front regime in an optical square.

piston engine and the increase of the wrinkling with the engine rotational speed. Based on work of Borghi [4], Peters [5] further developed the diagram of premixed combustion regimes in velocity and length scale ratios in order to distinguish laminar flames, wrinkled and corrugated flamelets as well as thin and broken reaction zones.

The evolving in-cylinder flow field leads to the observed turbulent conditions at combustion onset. Particle image velocimetry (PIV) is a well-established technique to capture the instantaneous flow field at high spatial and temporal resolutions to determine, amongst others, turbulent propagation speed and integral length scales. Pioneering work was done by Reuss et al. [6] for in-cylinder flows at low laser repetition rates in two dimensions with two components (2D2C). Temporal resolved PIV (TR-PIV) measurements have been used in internal combustion (IC) engines to characterize turbulence properties [7], analyze spatial flow structures [8], investigate the interaction of the flow with ignition and flame development [9] and the impact of the flow field on cycle-to-cycle variations [8, 10]. Recent developments allowed measuring the third velocity component (2D3C) via a stereoscopic setup with two cameras, but not resolving its spatial derivative. Baum et al. [11] succeeded in measuring the three dimensional velocity field and all corresponding derivatives (3D3C) by applying tomographic PIV (TPIV) to an IC engine by using a four camera setup. This technique requires a high pulse energy laser, good optical accessibility, enough space surrounding the test rig and enough cameras to calculate a volumetric correlation of the in-cylinder particle positions and motions [12]. Recent advances in optical diagnostics include quasi 4-dimensional diagnostics [13] of the early flame propagation by dual plane OH-LIF combined with stereoscopic PIV in an optical single cylinder engine motored at 800 rpm.

In the rapid compression expansion machine (RCEM) used in this study, optical access is provided via a transparent piston and through two side windows at the cylinder head. The RCEM is a highly flexible, free floating piston test rig. Originally designed for spray combustion experiments, the machine discussed here has undergone extensive redesign in recent years and has been successfully applied in experimental investigations of spark ignited direct injection hydrogen combustion [14], pre-chamber ignited methane combustion [15], micro Diesel pilot ignited premixed natural gas combustion [16] and HCCI combustion [17, 18]. By design, the RCEM lacks adequate turbulence levels due to a comparably slow charge filling process and a slow hydraulic pre-compression phase. Intake turbulence generally dissipates rapidly; delay between end of filling and start of rapid compression is on the order of seconds and therefore turbulent kinetic energy levels are almost completely dissipated when the rapid compression stroke is initiated as shown by Gerke et al. [19]. Therefore, compared to optical engines, different intake port geometries or throttling devices cannot be applied to create different in-cylinder swirl ratios or turbulence levels [20].

In order to investigate turbulent premixed combustion in optically accessible test rigs, known turbulent fluctuation speed levels and length scale ratios are crucial. Shy et al. [21] employed two counter-

rotating fans behind perforated plates in an atmospheric flow reactor to generate isotropic turbulence. Abdel-Gayed et al. [22] and Siebers [23] described a setup with fans in a constant volume vessel to achieve different turbulence levels. Although these methods work flawlessly on the corresponding test rigs, fans are not well suited in an RCEM due to the moving piston and the corresponding space limitations. In order to simulate a tumble flow, as commonly found in SI-engines, an early injection of air at high pressure has been applied at the RCEM described here as a mechanism to generate engine relevant turbulence levels.

Injections above the critical pressure ratio lead to underexpanded jets, which have been widely studied. An extensive overview can be found in the recent review paper by Franquet et al. [24]. Pioneering work in this field was conducted by Mach and Salcher [25]. Already then, comparably small nozzle diameters of 1.2-5.1 mm were of major interest. Later, Scroggs and Settles continued investigating small nozzle diameters and the impact of the nozzle geometry and the pressure ratio on the flow in overexpanded, perfectly expanded and underexpanded conditions [26]. Typically, Schlieren imaging and shadowgraphs were used to visualize the density variations occurring under choked flow conditions [27]. Based on that, empirical correlations for the characteristic position of the Mach disc were proposed [28, 29]. With respect to engine applications, experimental investigations of underexpanded jets are often found for fuel injection, e.g. compressed natural gas (CNG), pure methane, hydrogen, or a combination thereof [30]. In [31] planar laser induced fluorescence (PLIF) has been used to investigate the influence of the injection pressure on the flow structure and turbulent mixing. Considering numerical simulations, the high pressure and velocity gradients and the small structures require a fine mesh and small associated time steps and therefore, come at a very high computational cost. This method was e.g. applied by Kim et al. for CNG [32] and Gerke et al. for hydrogen [19]. Scaling laws based either on an equivalent nozzle diameter [33, 34] or modified inlet conditions [35] or a combination thereof [36] allow to model the far field of the jet without resolving the near field with its shock structures. The so called artificial inlet boundary approach [37] has been used for a multiple cycles LES in a direct injection natural gas engine [38]. Furthermore, using a one-dimensional compressible flow model for the approximation of the barrel shock structure was proposed by Mather and Reitz [39].

This paper presents a method to create engine relevant conditions for premixed turbulent combustion in a RCEM by means of a secondary high-pressure injection of air at the beginning of the rapid compression stroke. The resulting underexpanded jet induces a tumble motion and relevant turbulent fluctuations towards spark timing. In a first step, high speed Schlieren imaging of the jet in a constant volume setup was applied to determine the Mach disc position from the nozzle exit. Based on an empirical correlation, the internal pressure drop in the injector was estimated. Moreover, the pressure rise inside the combustion chamber was measured to derive the total injected mass.

Schlieren images recorded during a compression stroke illustrated the impact of the increasing back pressure and therefore dropping pressure ratio on the Mach disc position.

In a next step, time resolved planar PIV measurements during compression were acquired to resolve flow fields of instantaneous cycles and to identify characteristic flow patterns. Moreover, ensemble averaged flow fields were calculated and turbulent kinetic energy levels derived thereof.

These experimental results were compared to RANS simulations in order to gain a better insight into the flow processes within the RCEM as well as to validate such flow simulations to cater as a sound basis for future reactive simulations. Multiple LES realisations could be achieved by perturbing the additional injection. While it is expected that phase averaged LES incorporates more detailed flow structures when compared to RANS, the high computational cost and the focus on the mean flow field in order to support the experimental findings make RANS simulations a more viable tool in the context of this paper.

METHODOLOGY

The operating conditions as well as experimental and numerical methods are presented in the following to investigate the suggested turbulence generation mechanism for non-reactive conditions.

Experimental Setup

The RCEM is a flexible tool to emulate the compression and expansion phase of a single engine cycle while granting optical access. The machine basically consists of two main sections, a driving part and an experimental domain, connected by the piston rod. In the driving part, a mass balance piston separates a pneumatic volume from a hydraulic volume, indicated in [Figure 1](#). Pressurized air in the pneumatic volume (driving pressure) presses the mass balance piston on the oil volume. In a first step, oil is bypassed via a throttled starting line to the back of the piston rod, leveraging it hydraulically out of the starting position, resulting in a slow hydraulic compression. As soon as the piston rod is pushed out of the starting aperture, the full area of the rod directly faces the force acting from the pneumatic volume via the mass balance piston. The free floating piston is then accelerated to the cylinder head compressing the fresh mixture before it is slowed down by the increasing pressure in the combustion chamber as top dead center (TDC) is approached. In order to avoid a collision of the free floating piston with the cylinder head and to control the shape of the position trace around TDC, a throttling aperture additionally decelerates the piston by reducing the oil flow and the effective area of the mass balance piston acting on the connecting rod. The retardation can be controlled by adjusting the throttling aperture to approximate the position trace to a crankshaft driven piston in an engine.

After TDC, the oscillating system forces the pistons to move in opposite direction, expanding the gases in the combustion chamber until the pressure rise in the pneumatic driving part decelerates the piston down to halt, the bottom dead center (BDC) position of the

emulated engine cycle, illustrated in [Figure 2](#). After that, the pistons oscillate further back and forth until friction stops the movement completely. At the end, the combustion chamber is scavenged several times in order to flush out all exhaust gases and the pistons are moved back to starting position.

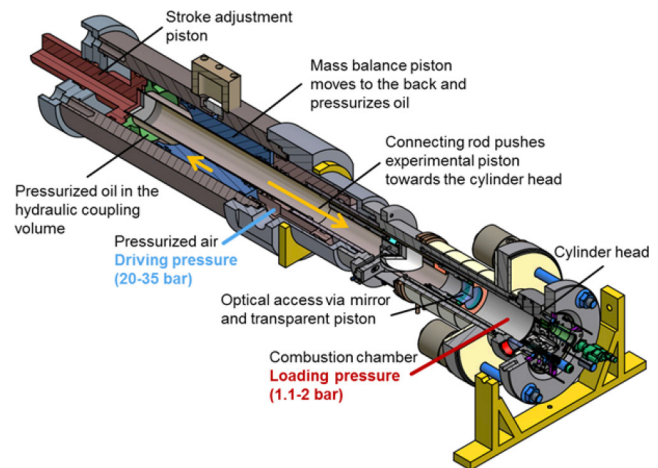


Figure 1. Working principle of the rapid compression expansion machine: Pressurized air moves the mass balance piston towards the stroke adjustment piston, accelerating the working piston towards the cylinder head (orange arrows).

Optical accessibility is granted via a mirror in the slotted piston rod and through the quartz glass window in the piston as indicated in [Figure 1](#). The piston design is a top hat with a depth of 2.2 mm and a bowl diameter of 52 mm, which also defines the field of view via the mirror. Moreover, two sapphire windows of 40 mm diameter in the cylinder head provide lateral access to the combustion chamber. In order to avoid unwanted image distortions, all windows come with a flat design.

The RCEM allows compression ratios ranging from 5 to 25 and piston strokes from 120 to 250 mm. The main bore of the working piston is 84 mm. Within this study, the machine was operated at a stroke setting of 180 mm. The driving pressure was set to 22 bar and the loading pressure of the combustion chamber was fixed to 1.2 bar. Thereof, the clearance distance at TDC is 12.9 mm for a compression stroke as illustrated in [Figure 2](#), resulting in a compression ratio of 11.8.

The cylinder head was equipped with a cooled piezoelectric pressure sensor (Kistler 7061B1) and an absolute reference pressure sensor (Kistler 4075A), mounted in a cooled pressure switching adapter (Kistler 741A) to protect the sensor from high loads during transient operation. The cylinder head and the liner were heated to 110°C, the secondary gas injector water jacket and both pressure transducers were connected to a cooling circuit of 50°C.

General RCEM specifications are given in [Table 1](#). The fuel, in this case methane, was fed directly into the combustion chamber via a piezo-actuated hollow cone injector (Siemens A-Nozzle) immediately after the filling of the combustion chamber to the pre-defined pressure level. Although a non-reactive investigation is presented, an air-to-

fuel ratio λ of 1.34 has been considered. Pre-studies have indicated a latest possible spark timing of 22.5 ms aSOI for the given operating conditions. This limitation is given due to the free floating piston, which would collide with the stroke adjustment piston for a later ST. Hence, throughout the course of this paper, ST is assumed to be set at the latest possible timing of 22.5 ms aSOI.

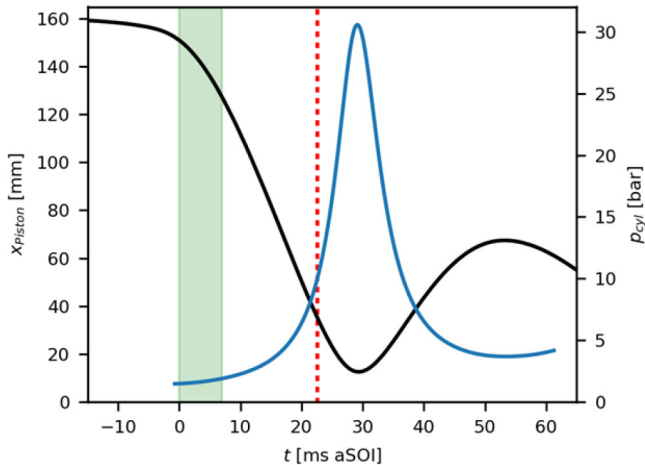


Figure 2. Piston position (black) and in-cylinder pressure (blue) for the considered operating condition. Secondary gas injection indicated by green area, spark timing (red)

Table 1. General specification of the rapid compression expansion machine (RCEM)

Displaced volume	665-1385 cm ³
Stroke	120-250 mm
Bore	84 mm
Compression ratio	5:1-25:1
Number of Valves	2
Cylinder Pressure	Up to 200 bar
Cylinder Head Design	Flat
Cylinder Head Optical Access	2x $\varnothing=36$ mm lateral sapphire windows
Piston Geometry	Top hat
Piston Bowl	$\varnothing=52$ mm, 2.2 mm depth
Piston Optical Access	$\varnothing=52$ mm quartz glass window
Heating	Cylinder head and liner up to 450 K
Fuel Injection	Piezo hollow cone injector
Turbulence Generator	Single hole dual coil injector
Ignition System	Coil-on-Plug

Schlieren

Density gradients in gases result in a change of the refractive index n , they are related by a simple linear relationship:

$$n-1=k \cdot \rho \quad (1)$$

with the Gladstone-Dale coefficient k . Differences in the refractive index are quite small for compressible flows. Considering a barrel shock generated by an underexpanded jet based on the coordinate system given in Figure 3, the refractive index changes along the x-direction result in ray deflections ε in the y-z plane according to:

$$\varepsilon_y = \frac{L}{n_0} \frac{\partial n}{\partial y}, \quad \varepsilon_z = \frac{L}{n_0} \frac{\partial n}{\partial z} \quad (2)$$

if L is the characteristic length of the barrel shock along the x-axis. The principle of the Schlieren technique is well documented and is a commonly employed method to visualize gas injections [27].

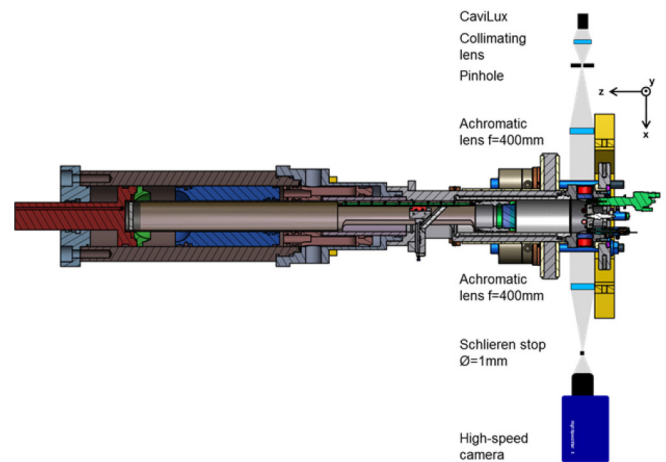


Figure 3. Setup for transient Schlieren measurements at the RCEM using a pulsed laser light source.

A lens-based Schlieren configuration was used as schematically shown in Figure 3. Illumination was done by a 690 nm laser as a pulsed light source (Cavitar CaviLux Smart) with a pulse duration of 50 ns. Image acquisition was synchronized by a LaVision high speed controller connected to a LaVision HSS X camera. The corresponding frame rate was set to 30 kHz, exposure time to 1 μ s with a resolution of 512 x 512 pixels. The laser was guided by optical fibers to the test rig and focused on a 1mm pinhole to generate a point light source. An achromatic lens ($f=400$ mm) of 4 inch diameter was used to create parallel rays with an imaging field of approximately 40 mm diameter, enough to fully illuminate the side windows of the combustion chamber. A Schlieren stop of 1 mm diameter was used to block the deflected light partially, providing dark-field Schlieren images. The advantage of this method is the symmetry in the recorded images, simplifying image processing.

Injection duration was generally adjusted to 7 ms while the secondary gas injector was operated at maximum boost voltage and maximum peak current under all conditions. To ensure that the barrel shock is within the field of view of the camera, the injector had to be moved to the center of the cylinder head, where normally a spark plug is put in place. Doing so, the cylinder liner is closer to the nozzle exit hole compared to its original position. Nevertheless, the distance from the nozzle tip to the wall in direction of the injection is still 84 mm and therefore more than 100 times the nozzle diameter upstream, so that wall effects can be excluded on the near field characteristics.

Two different conditions were examined: (1) a constant volume setup with the piston blocked at 120 mm before TDC; (2) a transient setup with the air injection timed at 150 mm and an effective stroke of 167.8 mm as indicated in Figure 2. The loading pressure of the combustion chamber was set to 12 bar for all experiments. In order

to account for the hydraulic pre-compression and, associated therewith, the increasing back pressure at start of injection (SOI), the rail pressure was elevated to keep the same overall pressure ratios as listed in Table 2.

Table 2. Operating conditions for Schlieren experiments

Constant volume arrangement	
Rail pressures	24, 36, 48 bar
Loading pressure	1.2 bar
Mean in-cylinder pressure during injection	1.2 bar
Pressure ratios	20, 30, 40
Compression stroke	
Rail pressures	30, 45, 60 bar
Loading pressure	1.2 bar
Mean in-cylinder pressure during injection	1.5 bar
Pressure ratios	20, 30, 40

Temporal Resolved Particle Image Velocimetry

The in-cylinder flow field was evaluated by means of high-speed particle image velocimetry. A dual cavity, frequency doubled, high repetition rate Nd:YAG laser (Photonic Industries DM60-532-DH) was used with a maximum pulse energy of 6 mJ per head at a rated repetition rate of 10 kHz. The laser pulse duration was in the order of 200 ns, the pulse-to-pulse separation of the two cavities was set to 25 μ s. The laser beam was focused via a cylindrical concave ($f1 = -15$ mm), a spherical lens ($f2 = 2$ m) and a cylindrical convex lens ($f3 = 300$ mm) to form a non-diverging laser sheet of 1 mm thickness. All lenses and mirrors in use had a highly reflective coating for 532 nm applied. The laser sheet was guided via the mirror and the transparent quartz glass piston into the combustion chamber as illustrated in Figure 4.

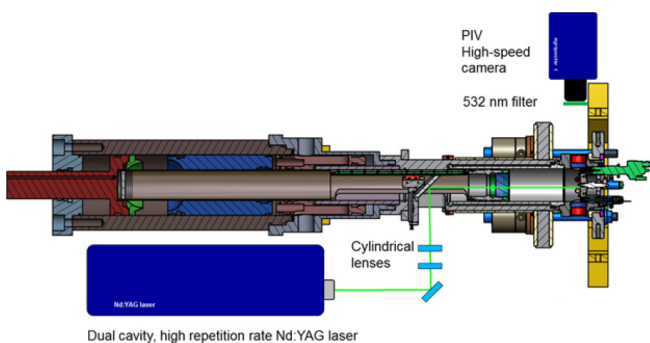


Figure 4. Setup for temporal resolved PIV with the laser sheet coupled via the piston rod trough the quartz piston to the cylinder head, parallel to the side windows and 8 mm off-center.

The laser sheet was set 8 mm off centered from the spark plug, parallel to the side windows in order to minimize reflections towards the PIV camera (Photron FASTCAM SA-X2). Camera and laser were synchronized by a LaVision high speed controller and operated at 10 kHz in double-frame, single exposure mode with a constant pulse separation timing of 25 μ s. In doing so, the camera could be operated with a resolution of 640x1008 pixels, covering an area of 30x47 mm². Seeding was done by monodisperse TiO₂ particles of 800 nm size, added via the exhaust valve to the combustion chamber during the loading process. Fuel injection was timed to the end of loading and

start of the slow hydraulic pre-compression, approximately four seconds before the initiation of the fast pneumatic compression stroke. Thereby, good mixing of air, fuel and particles was granted for all turbulent operating conditions.

The secondary gas injector was placed in the y-z plane at the top with the exit hole pointing downwards as illustrated in Figure 5 (left). Camera recording was initiated simultaneously to the secondary gas injection at a fixed piston position, at 150 mm distance to the cylinder head as depicted Figure 2.

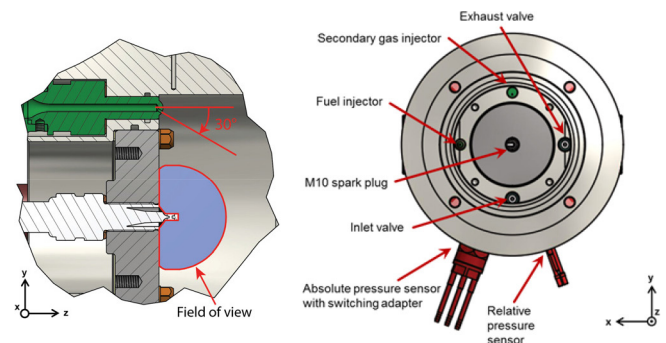


Figure 5. Side window with field of view for PIV (left) and fully instrumented RCEM cylinder head (right)

PIV images have been processed by a commercially available algorithm (LaVision, DaVis 8.3). A multi-pass cross-correlation algorithm has been applied with a final interrogation window size of 32 x 32 pixels with a 75% overlap. In order to account for the low velocity magnitudes in the field of view at the beginning of the compression stroke, processing was also done on a temporal basis including only one cavity corresponding to the repetition rate of the Nd:YAG laser. Therefore, pulse separation Δt could be elongated to 100 μ s in the early phase, and the shorter Δt of 25 μ s was used when the turbulent jet entered the field of view. By that, a significantly higher quality factor could be achieved on the correlations in the early phase. Additionally, spurious vectors have been removed if the median substantially differed from the neighboring vectors and iteratively replaced, if the next higher correlation peak suggested better agreement. Finally, a velocity field with a size of 25 x 36 mm was obtained with a vector spacing of 0.37 mm. PIV data has been acquired from 44 individual compression cycles. Phase-averaged flow fields $\bar{u}$ and turbulent kinetic energies have been calculated thereof. Turbulence intensities u' have been calculated assuming isotropic turbulence. Spatially averaged velocity magnitudes $|\bar{u}|_{av}$ and turbulence intensities u'_{av} have been derived around the spark plug vicinity (15 x 15 mm) and in the entire visible domain.

Turbulence Generation

In order to study the interaction of ignition and subsequent flame formation with the flow field for spark ignited concepts, it is crucial to provide a flow pattern similar to engine conditions at the point of ignition and the time thereafter. While turbulence levels in engines are mainly driven by their intake port geometries, the flow around the intake valves and the rotational speed, the RCEM lacks of an adequate intake process.