

Large Eddy Simulation of a Motored Single-Cylinder Engine Using System Simulation to Define Boundary Conditions: Methodology and Validation

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ABSTRACT

Large Eddy Simulation (LES) appears today as a prospective tool for engine study. Even if recent works have demonstrated the feasibility of multi-cycle LES, they have also pointed out a lack of detailed experimental data for validation as well as for boundary condition definition. The acquisition of such experimental data would require dedicated experimental set-ups. Nevertheless, in future industrial applications, unconditional dedicated experimental set-ups will not be the main stream. To overcome this difficulty, a methodology is proposed using system simulation to define fluid boundary conditions (crank-resolved intake/exhaust pressures and temperatures) and wall temperatures.

The methodology combines system simulation for the whole experimental set-up and LES for the flow in the combustion chamber as well as a part of the intake and exhaust ducts. System simulation provides the crank-resolved temperature and pressure traces at the LES mesh inlet and outlet. LES results are compared to experimental measurements obtained on the corresponding optical single-cylinder engine under motored operation. For this purpose, statistical analysis over several consecutive LES engine cycles is performed to compare numerical results with Particle Image Velocimetry (PIV). The ability of the developed methodology to capture the in-cylinder cycle-to-cycle flow variations in a motored engine is demonstrated. This result points out the potential of LES to analyse cycle-to-cycle variations observed in spark-ignition engines.

INTRODUCTION

The requirement to further improve the efficiency of gasoline engines while at the same time aiming at near-zero pollutant emissions motivates new technology development such as lean fuelling or highly diluted operation. But leaner or more diluted mixtures increase Cycle-to-Cycle Variations (CCV) limiting their range of operation and becoming one of the main obstacles for the spreading of these new technologies. Therefore, a fundamental understanding of CCV origin and basic physics [1] is crucial.

Up to now, most of the research dedicated to CCV fundamental understanding has been carried out experimentally, mainly using optical diagnostics in single-cylinder research engines [2]. Nevertheless, despite the significant improvements of experimental techniques in the past years [3], experiments offer restricted analyses. They unfortunately only allow *a posteriori* analyses. Moreover, all phenomena are strongly coupled and can depend on the engine geometry and on the operating conditions. Different engine speeds, compression ratios, mixture preparations or flow motion patterns (swirl and tumble) lead to different sensitivity and give sometimes rise to apparently contradictory conclusions as already discussed in the review paper of Ozdor *et al.* [1].

Numerical simulation is complementary to experiment for studying CCV, especially the LES (Large-Eddy Simulation) approach due to its ability to capture large-scale cyclic flow variations. Recent works [4,5,6,7,8] have demonstrated the ability of engine LES to capture cycle-to-cycle combustion variations.

Nevertheless, most of these engine LES have also pointed out a lack of detailed experimental data for initial and boundary conditions. Even if specific experimental engine test-bed for LES setting up can be designed [9], unconditional dedicated database will not be the main stream in future industrial applications. Consequently, it is crucial to define an engine LES methodology adapted to standard experiment lacking of specific LES data.

The aim of the present paper is to develop such a methodology based on the combination of system simulation and LES, taking advantage of a dedicated well-documented experimental set-up [9] for validation. In this paper, only motored operation is considered as a first step of validation before computing fired operation for CCV investigation.

First, the whole test-bed is simulated using system simulation with standard experimental data. Initial conditions as well as solid (wall temperatures) and flow boundary conditions (pressures, temperatures...) can be extracted from the system simulation results and applied to the LES set-up. Then, LES is resolved in the combustion chamber and a part of the intake and the exhaust ducts. The LES results obtained with this complete methodology are finally validated thanks to comparisons with experiment [9].

Simulated engine test-bed as well as the motored operation engine point are first presented. The corresponding system simulation sketch of the whole experimental set-up is validated. Crank-resolved profiles can be extracted from system simulation everywhere in the test-bed for defining LES boundary conditions. According to the system simulation observation, the LES domain is chosen to avoid backflow issues at boundary conditions. Then, the moving tetrahedral meshes that allow simulating 16 consecutive engine cycles are described. Thanks to the initial conditions extracted from system simulation, initial-field-free LES results can be reached from the second engine cycle. Finally, a statistical analysis over the following 15 consecutive LES engine cycles is performed to compare LES results with experimental PIV measurements. Qualitative as well as quantitative comparisons of in-cylinder flow motion allow us to validate LES results issued from the developed methodology.

EXPERIMENTAL SET-UP

Table 1. Main engine characteristics. Crank Angle Degrees (CAD) are relative to combustion Top-Dead-Centre (TDC).

Engine Type	Single-cylinder
Number of valves	4
Displacement	441 cm ³
Bore	82 mm
Stroke	83.5 mm
Connecting rod length	144 mm
Compression ratio	9.9 : 1
IVO (at 0.7 mm)	-348 CAD
IVC (at 0.7 mm)	-142 CAD
EVO (at 0.7 mm)	140 CAD
EVC (at 0.7 mm)	348 CAD

The SGEmac (Simulation aux Grandes Echelles dans les moteur à allumage commandé - Large Eddy Simulation for spark-ignition engines) engine test bench [9] has been specifically designed to allow a detailed validation of LES, especially in the context of combustion cyclic variability. The spark-ignition engine is a single-cylinder engine equipped with a 4-valve pentroof combustion chamber and with a flat piston. The main engine specifications are summed up in [Table 1](#).

The whole SGEmac set-up is shown in [Figure 1](#) and its complete geometry is available for LES meshing. In order to perfectly control and to easily define set-up operating conditions, large volumes have been implemented along both intake and exhaust lines. The air mass flow rate is controlled very far from the engine, upstream two volumes, by an independent sonic nozzle to avoid any perturbation.

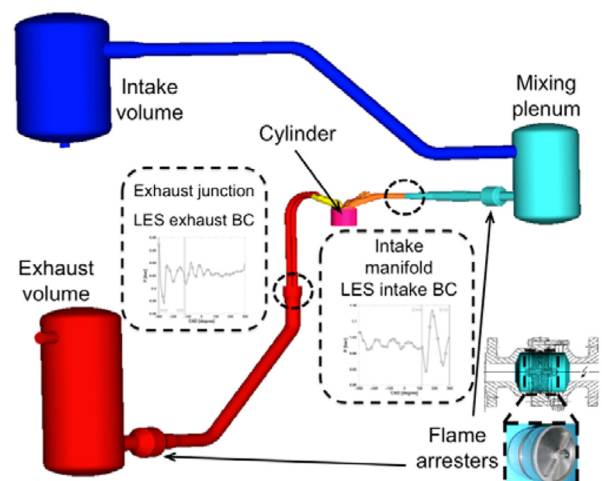


Figure 1. Geometry of the experimental SGEmac engine test bench [9]. Circles locate LES boundary conditions to define with the system simulation.

Dealing with fired operation, the SGEmac test-bed operates as an ideal PFI (Port Fuel Injection) engine and is fuelled by a homogeneous mixture of gaseous propane and air. Gaseous propane is injected inside a dedicated large mixing plenum (Figure 1) and imposes the addition of flame arresters both in the intake and in the exhaust lines (Figure 1) to prevent from accidental flame propagation caused by misfiring cycles. The internal structure of the flame arrester consists of spiral wound corrugated metal sheets resulting in a fine mesh (smaller than 1 mm). Even if this paper only presents motored operation, flame arresters have been conserved in order to assess the global methodology for future fired operation modelling.

SYSTEM SIMULATION OF THE ENGINE TEST-BENCH

The definition of accurate specific boundary conditions (BC) for engine LES is a key point. In future industrial calculations, unconditional dedicated experimental set-ups will not be the main stream. To overcome this difficulty, we propose to develop a methodology combining system simulation and LES and to validate such a methodology with the detailed SGEmac experimental database [9]. In particular, the system simulation can be used to define not only LES boundary conditions but also initial states.

To this aim, the whole test bench is simulated with the system simulation LMS® Imagine.Lab AMESim platform [10] using the IFP-ENGINE library [11]. A variety of sub-models representative of the engine test-bench components are available such as pipes, volumes, cylinder heads, combustion chambers, ...

The objective is to get access to pressure and temperature variations along both intake and exhaust pipes during the whole engine cycle. Consequently, physical models and thermodynamics representation are selected to be as accurate as possible without any concerns about the CPU time consumption. In order to capture pressure and temperature oscillations, the intake and exhaust air paths are modelled with inertial pipes which dimensions are exactly those of the engine set-up (Computer-Aided Design data - Figure 1). It considers multi-gas mixture pipe with inertia, friction and compressibility effects. In order to dampen flow perturbations within the air path, the intake manifold has been generated using a stereo-lithography technique for a smooth design of the internal surface. Moreover, pressure drop along the set-up has been measured to be very weak: about 14 mbar for the whole intake line (from main plenum to near cylinder-head) and about 7 mbar in the exhaust line at 5.5 kg/h air flow rate (see Table 2). Consequently, friction effects are weak and wall law issues are not critical in these areas neither for system simulation nor for LES.

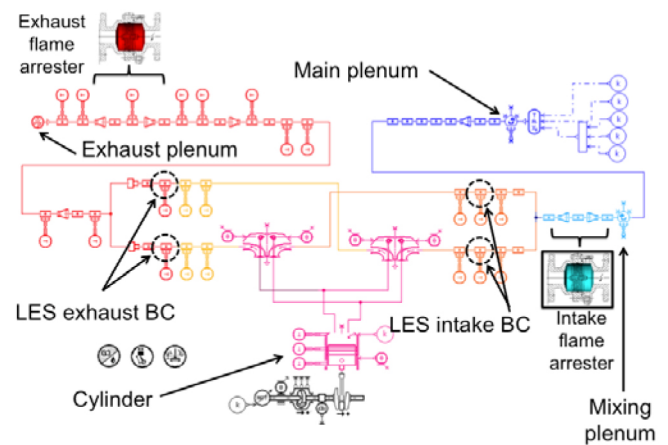


Figure 2. AMESim single-cylinder engine sketch

Concerning flame arrester modelling, only their global shapes can be taken into account in the system simulation since no honeycomb dedicated model is available for engine simulation. Nevertheless, previous experimental studies performed on an acoustic test bench have demonstrated that the internal honeycomb structure is only responsible for a weak sound muffling. Consequently, as a first level modelling, only the global flame arrester inner geometry without honeycomb is used considering sudden expansion and contraction of the inner diameter (Figure 2).

Because 4-valves are involved, intake and exhaust ducts have been disjoined coming out of two parts of the cylinder-head modelised as two items in the system simulation sketch but corresponding, of course, to a single real element. The inertia of the fluid is taken into account by a flow rate state variable. Because only motored engine is considered in this paper, no combustion model is needed.

Figure 2 presents the AMESim sketch describing the single-cylinder engine and its surroundings as implemented in the test bed.

To accurately control the engine volumetric efficiency, air mass flow rate is controlled by independent sonic nozzles feeding the main plenum (Figure 1). Consequently, the inlet system simulation boundary condition corresponds to a constant mass flow rate source yielding air at the same temperature as during the experiment. Air mass flow rate is slightly changed (2%) in order to match cycle-averaged intake pressure (0.44 bar absolute). The outlet boundary conditions are the constant pressure and temperature measured in the experiment.

Table 2. Main characteristics of the motored operation point. Pressures are given in absolute bar.

Data	Unit	Exp	Simulation
Engine speed	[RPM]	1200	1200
P_{intake}	[bar]	0.44	0.44
T_{intake}	[K]	295	295
P_{exhaust}	[bar]	1.01	1.01
T_{exhaust}	[K]	300	300
Air mass flow rate	[kg/h]	5.5	5.4

Various operating points have been acquired in the SGEmac database including motored and fired operations for stable and unstable conditions [9]. As a first step for our methodology, the present paper deals with motored operation which conditions are detailed in Table 2. Engine wall temperatures have been estimated to be close to those of fired operation since motored operation has been purposely acquired on equivalent conditions (cooling water system is warmed to the same temperature in order to near the fired operation). Engine wall temperatures are estimated to be 360 K. In order to take into account the temperature gradient for pipe walls near the cylinder head due to engine proximity, wall temperatures are progressively increasing. In the air path, temperature gradient spreads from the intake manifold (300 K) to the cylinder head inlet (360 K). In the exhaust line, gradient extends from the outlet cylinder head (360 K) to the exhaust junction (300 K).

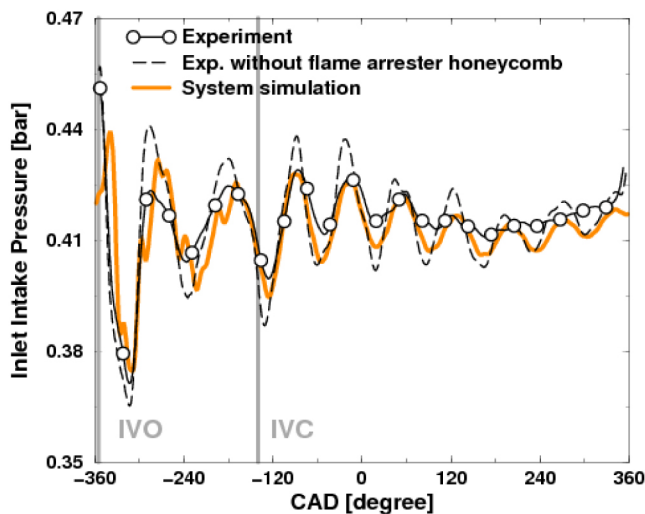


Figure 3. Intake pressure (see circle position in Figure 1 and in Figure 2), comparison between system simulation and mean ensemble-averaged experiment (with and without flame arrester honeycomb)

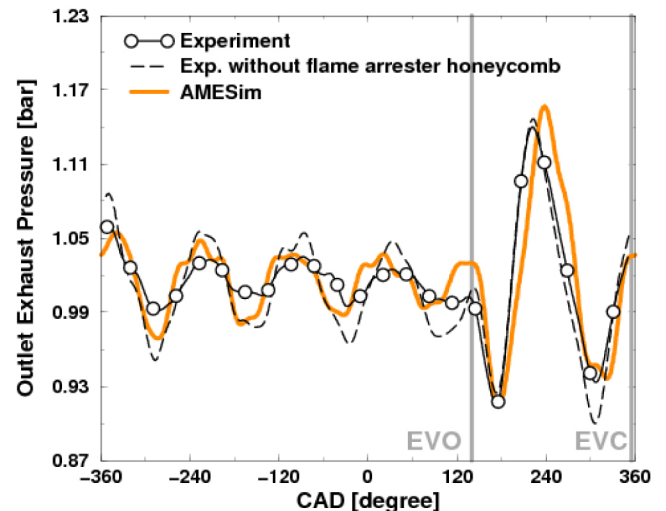


Figure 4. Exhaust pressure (see circle position in Figure 1 and in Figure 2), comparison between system simulation and mean ensemble-averaged experiment (with and without flame arrester honeycomb)

Our goal is to develop a methodology using system simulation information for any LES investigation lacking of experimental data. For this purpose system simulation is expected to define unsteady boundary conditions at the LES inlet and outlet. As a first step for validating our methodology, system simulation prediction and experimental measurements are compared under motored operation. In order to provide engine simulation with accurate data, particular care has been given to crank-resolved measurements in the SGEmac experimental database. Multiple crank-resolved pressure sensors are available in the mixing plenum, in the intake manifold, in the intake pipes and in the exhaust junction (see detailed description in [9]). For each crank-resolved pressure trace, system simulation and experiment are in good agreement. For the sake of clarity only the intake pipe (Figure 3) and the exhaust junction (Figure 4) pressures are presented in this paper since they correspond to the LES BC (indicated by circles in Figure 2).

Because no combustion is involved, measurements without flame arrester honeycomb are available. As previously mentioned, the flame arrester honeycomb structure is only responsible for a weak sound muffling dampening pressure oscillation amplitude but maintaining pressure oscillation frequency and phase.

System simulation is demonstrated to correctly reproduce the unsteady pressure variations in the intake and in the exhaust lines. At IVO, the intake pressure signal (Figure 3) exhibits a strong peak due to the establishment of the pressure balance between the intake pipe and the cylinder. After IVC, the pressure signal oscillates with a characteristic frequency (80 Hz) due to the acoustic resonance between the mixing plenum and the cylinder head inlet.

Similarly, in the exhaust junction (Figure 4), a high-pressure oscillation is initialised at EVO due to the establishment of the pressure balance between the exhaust path and the cylinder. After EVC, the pressure signal oscillates with a characteristic frequency (60 Hz) due to acoustic resonance of the exhaust line.

Even if system simulation predictions miss oscillation muffling due to the flame-arrester honeycomb, these results are considered as adequate for developing our coupling methodology between system simulation and LES.

Unsteady pressure oscillations have been successfully reproduced by system simulation for all fired operating points involved in the SGEmac database [9] but are not discussed here.

As a first step of our methodology, pressure and temperature profiles extracted from system simulation can be used to define inlet and outlet LES boundary conditions. Consequently, LES mesh can be chosen free from experimental sensor positions.

Intake (Figure 3) and exhaust (Figure 4) pressures oscillate on either sides of mean (cycle-averaged) pressure value. It means that BCs at these places are alternatively inward and outward requiring a specific treatment (see next section).

Eventually, strong oscillations due to the valve opening may cause backflow phenomena in the intake pipes. Even if there is no consequence dealing with motored operation (only air is injected in the combustion chamber), backflow is a main issue for the choice of the LES mesh domain for fired operation (in-cylinder combustion products ejected toward the intake must not leave the mesh). Because present LES work on motored operation is planned to be used for future fired operating point modelling, particular care must be taken when LES domain is selected.

LES STRATEGIES

NUMERICAL APPROACH

LES is performed with the fully compressible and explicit code AVBP on unstructured meshes with a cell-vertex finite-volume formulation [12]. Centered 2nd order Lax-Wendroff scheme [13] with explicit time-advancement limited by the acoustic CFL number is used to control numerical dissipation. Subgrid stresses are described by a standard Smagorinsky model [14]. Choked flows created at valve openings are controlled by introducing a hyper-viscosity in the viscous stress tensor [15]. Thermodynamic properties are tabulated depending on temperature and composition mixture. Solid walls are handled using a logarithmic law-of-the-wall formulation [16] with local isothermal wall conditions.

At the intake and exhaust boundaries, mixed inflow/outflow conditions based on a multi-species extension [12] of the Navier-Stokes Characteristic Boundary Conditions (NSCBC) [17] are imposed. In order to impose time-varying signals at the intake and exhaust BC, quasi-nonreflective NSCBC are used via a Linear Relaxation Method (LRM) [18]. This method allows to separate waves leaving the domain and the reflecting ones. The cut-off frequency of this low-pass filter is directly proportional to a relaxation coefficient imposed on the target pressure signal. Because most common experimental data are pressure traces, the set of pressure, temperature and mass fraction profiles have been imposed as BC instead of the triplet mass flow rate, temperature and mass fraction. Intake (Figure 3) and exhaust (Figure 4) pressure variations exhibit strong oscillations that may impose the use of high relaxation times if the time-varying BC profiles have to be reproduced. But high relaxation times induce more reflective waves. Consequently, intermediate values have been chosen as the best compromise between BC variations and a satisfactory reflection coefficient. The consequence on the BC profiles will be pointed out later in this paper (see Figure 12 and Figure 13).

Because of the inward and outward fluid motion induced both at intake and exhaust by acoustic oscillations (see Figure 3 and Figure 4), simple inflow or outflow conditions are not suitable. Mixed inflow/outflow conditions allow to switch from an inlet formulation to an outlet one according to the instantaneous direction of the flow.

Previous experimental [9] and numerical [19] works have suggested that duct flow is mainly axial. Nevertheless, 3D structures have been pointed out in the present set-up [9] leading to both positive and negative velocities at a given section of the duct. 3D-structures are a real challenge for LES BC definition. To tackle this issue, extended 3D-NSCBC approach [20] could be introduced in order to deal with 3D-structures on BC. But this would require additional information on non-homogeneous space velocity and would lead to a very complex BC treatment. Moreover, with a view to the coupling of engine LES with 1D approach at BC, “classical NSCBC” approach [17] has been retained in the present work. Consequently, in order to ensure nearly 1D flow structure at BC, LES domain has been extended far from the cylinder head on both the intake and exhaust side (see Figure 5).