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Natural Gas Partially Stratified Lean Combustion: Analysis of the Enhancing Mechanisms into a Constant Volume Combustion Chamber

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ABSTRACT

The use of ultra-lean mixture natural gas fueled Internal Combustion Engines has been widely accepted to improve thermal efficiency and reduce exhaust emissions. This is mainly due to the intrinsic features of natural gas such as the wide availability and lower carbon content. Other advantages may occur running the engine under lean operating condition, as for example the lower flame temperature, the higher volumetric efficiency and compression ratios achievable, together with the opportunity of load control by varying the mixture equivalent ratio. Issues related to combustion stability and increase of CoV may however arise at leaner conditions.

A comprehensive analysis of natural gas ultra-lean combustion process has been presented in this work using local charge stratification (Partially Stratified Charge combustion) to stabilize the process and limit the above-mentioned issues. A detailed analysis of the main sub-phases of the Partially Stratified Charge combustion process has been performed using a LES approach to highlight the main driving mechanisms of this combustion strategy. The accuracy of the numerical results has been evaluated by means of statistical and grid independence analysis. The effects of the local conditions around the spark plug on the propagation of the subsequent combustion event have demonstrated to play a key role on the efficiency of ignition and combustion sub-processes. A trade-off between the competing mechanisms of heat losses generated by heat convection of the gaseous jet and decay of the turbulent kinetic energy enhancing the process has been highlighted by the numerical results.

Results show that a one-equation closure model is able to predict accurately the evolution of the injection process, providing a more reliable description of the local distribution of the fuel-oxidizer mixture and turbulent kinetic energy. Very good agreement between numerical results and experimental data has been obtained for the simulation of the combustion process. In particular, the numerical framework here proposed has been able to correctly capture two fundamental aspects of the PSC combustion, such as the interaction between the fuel jet and the flame evolution, which results in an elongated and strongly corrugated flame plumb, and the quenching due to the local high velocity field around the spark plug. These phenomena are crucial to control the combustion stability and the cycle-by-cycle variability in lean burn Internal Combustion Engines.

1. Introduction

Climate changes and the limited fossil fuels resources have been, and are nowadays, the key drivers of the research in the field of energy conversion (power, transportation sectors). Alternative energy sources and a more efficient and clean use of the fossil fuels are the key aspects to address.

In order to promote those strategies financial incentives have been provided by public institutions to sustain the use of the renewable energy sources and strict regulations on efficiency and exhaust emissions from traditional sources have been imposed to use fossil fuels more effectively.

In particular, the increasingly stringent regulations on exhaust emissions and the need for higher conversion efficiency, are pushing research and development activities on Internal Combustion Engines (ICEs).

Lean combustion control strategies combined with natural gas (NG) has a great potential for emission reduction. Methane, the main component of natural gas, is the cleanest and economically available fuel for internal combustion engines, and has also benefit of a recent increase in wide availability [1,2]. Recent papers have demonstrated that engines fueled with natural gas have lower emissions if compared to conventional fueling ones [3,4]. A review by Cho and He [5] showed NG benefits in terms of torque, power [6,7] and exhaust emissions [8].

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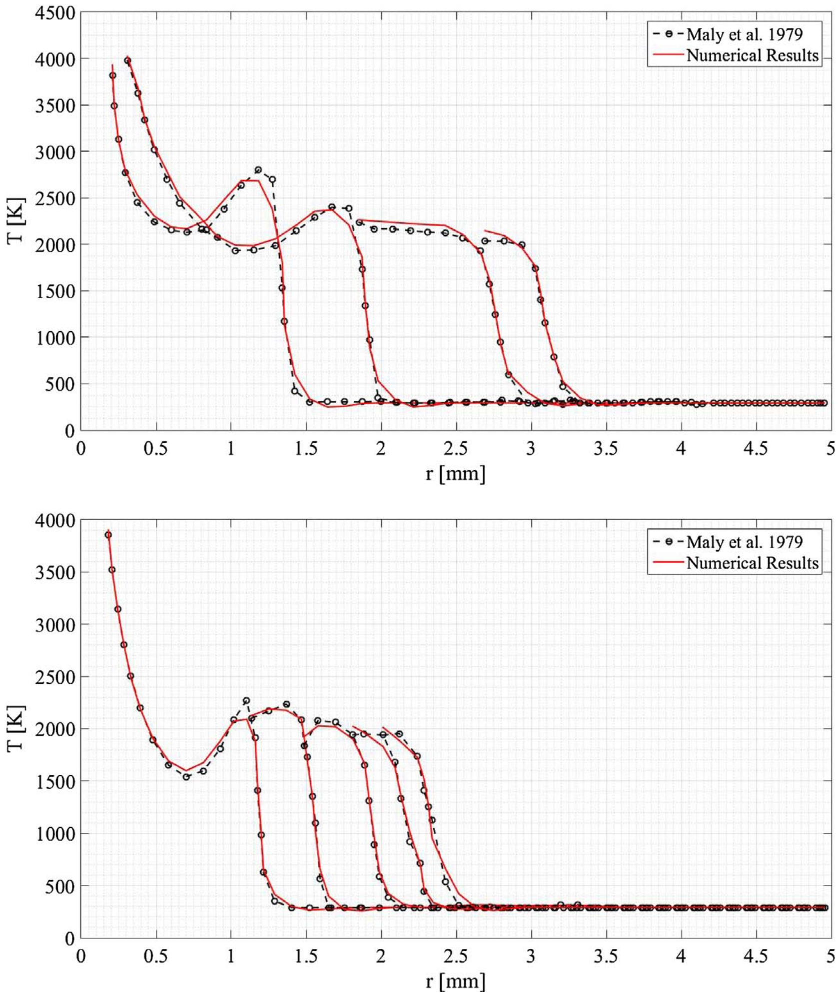

Fig. 1. Comparison between simulated and experimental flame temperature radial profile for two different air-to-fuel ratio (λ = 1.0 top and λ = 1.4 bottom).

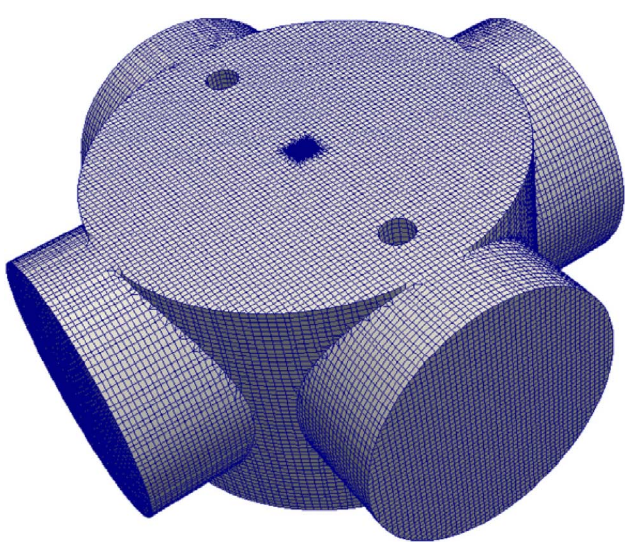

Fig. 2. Constant Volume Combustion Chamber (CVCC) representation of the computational domain used in the simulations.

Other studies have highlighted how running the engine under lean conditions might improve the emissions and efficiency even though there is still room for improvement toward the minimization of the Cycle by Cycle Variability (CCV) [9,10] and related emissions of Unburned Hydro-Carbons (UHC) [11] or misfiring [12]. These issues may be mitigated optimizing the mixing and the combustion processes. For example, in [7], [13–15] the influence of the evolution of turbulent parameters on the combustion process has been studied, showing how the combustion process can be significantly speeded-up [7], limiting cyclic variability [14] and compensating for the lower temperature obtained under lean operating conditions [15].

Ignition and injection strategies also play an important role to this aim. In fact, the use of a pre-chamber may support the ignition of ultra-lean natural gas mixtures while producing highly turbulent flow through the jet [16–18], giving a more stable kernel development.

Other groups have focused their attention on ignition technologies, and namely Joshi et al. in a collaborative effort of Colorado State and University of Alabama [19], as well as, Srivastava and Agarwal [20] have carried out a comparative experimental evaluation of performance and emission of laser ignition with respect to conventional spark plug in a compressed natural gas fueled engine. They showed marginally higher maximum cylinder pressure and Rate of Heat Release (RoHR) and lower cycle to cycle variation, attributed to the more efficient process of charge release given through the laser ignition process if compared to the traditional spark ignition one.

Another way to stabilize the combustion process for lean and ultra-lean mixtures is based on the stratification or partial stratification of the charge: Arcoumanis et al. have demonstrated in [21,22] the extension of the lean limit by a stratification of the mixture in the combustion chamber. Chung et al. [23,24] have shown how additional fuel injection may give a richer mixture close to the spark plug improving the combustion efficiency and stability, as well as extending the lean limit. In 2004 Reynolds et al. developed a Partially Stratified Charge (PSC) system to improve the lean burn combustion process [25]. The Partially