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Intake manifold design effect on air fuel mixing and flow for an LPG heavy duty engine

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Abstract
The paper presents an investigation of mixture preparation in the intake manifold of a Diesel converted engine into LPG spark-ignition engine operation. The formation process of air-LPG (liquefied petroleum gas) mixture was studied using computation fluid dynamics (CFD) mode. Two manifold shapes are used in order to test the adequate design in view of flow and air-gas homogenization. The first is designed according the acoustic-wave-filling phenomena, and the second present an unspecified design. The model of simulation is based on solving Navier-Stokes and energy equations in conjunction with the standard k-ε turbulence model, using the 3D CFD code FloWorks. Experiment test are carried out also to test the intake manifold effect on engine performance. Air-fuel ratio and specific fuel consumption are determined. The results indicate the effectiveness of the first manifold.

Keywords: Air-LPG mixture; Intake manifold; CFD; Experiment.

1. Introduction

Increasingly stringent legislation aimed at reducing pollutant emissions from vehicles has intensified efforts to gain better understanding of the various processes involved in internal combustion (IC) engines. In the case of spark-ignition engines (SI), one of the most important processes is the preparation of the air-fuel mixture [1]. This mixture circulates to the intake port through a very complicated path including the air cleaner, intake pipe, and intake manifold. Hence, the design of the intake manifold is an important factor which determines the engine performance. An intake manifold is one of the primary components regarding the performance of an internal combustion engine. An intake manifold is usually made up of a plenum, throttle body connected to the plenum and runners depending on the number of cylinders, which leads to the engine cylinder [2].

In order to understand the flow characteristics inside the intake manifold, many researches has been carried out. Zhao [3] studied the development of a comprehensive engine simulation tool that could predict unsteady flow features in the engine manifold and gas dynamic interaction between the intake system and the engine. Pogorevc [4] has discussed the design procedure of a cheap multipoint injection intake system, adapted to a racing car engine using numerical and experimental ways. The flow and the pressure loss reduction in the engine intake region were investigated. His experimental results confirmed numerical predictions. Ceviz [5] has performed investigates the effects of intake plenum length/volume on the performance characteristics of a spark-ignited engine with electronically controlled fuel injectors. According to his test results, plenum length must be extended for low engine speeds and shortened as the engine speed increases. Sulaiman et al. [6] have studied the flow characteristics of air flowing in various designs of air-intake manifold of a 200-cc four-stroke engine Go- Kart engine. The study is done by three dimensional simulations of the flow. Simulations are validated by an experimental study. From this study, they reveal that the variations in the geometry of the air- intake system can result in a difference of up to 20% in the mass flow rate of air entering the combustion chamber.

Harrison [7] is interested in the description of a linear acoustic model that has proven useful in obtaining a better understanding of the nature of acoustic wave dynamics in the intake system of an internal combustion engine. The model has proved in identifying the role of pipe resonance in the intake process and the importance of acoustic waves in the engine supercharging and filling. Lee [8] has developed a computer program to predict the engine performance characteristics through the analysis of the flow in the intake and exhaust systems and of the cylinder combustion phenomena for the MPI spark ignition engines. The result of simulation has been compared with that of experimental test in order to identify the optimal design of intake manifold.

The motion of fluid and the behavior of air-fuel mixture inside the intake manifold are very complex and very difficult to pinpoint. Nowadays, computational fluid dynamics (CFD) simulation helps in adapting engine part design, saving time and money. CFD is widely used in the design and modeling of the internal combustion engine especially for the intake flow modeling [9-14]. The inlet aerodynamic process was often studied through the experiment, especially with the techniques development of fluid visualization optical methods based on particles images velocimetry [15-17].

However, the analysis of the air-fuel mixture nature through the intake manifold is rarely studied, especially for heavy duty engine. In this paper, a numerical simulation of the flow and air gas mixing fields is achieved through two intake manifold designs, using the CFD code FloWorks. The test engine is an IVECO urban bus engine. This engine has been converted from its Diesel version into a gaseous fueling spark ignition (gasoline-gas bi-fuel) version. The gas using is the LPG alternative fuel, because of its various advantages [18]. Accordingly, the three-dimensional resolution of Navier-Stokes equations in conjunction with the standard k-ε turbulence model is undertaken to provide knowledge of the air gas movement nature and examining the intake manifold optimal geometry. Experiments tests are carried out also to identify the manifold design effect on engine behavior. Air-fuel ratio and specific fuel consumption are determined.

2. Engines manifolds studied models

The studied model is a Diesel engine converted into bi-fuel gasoline-LPG type IVECO. Its main characteristics are presented in Table 1. For this current study, two designs of manifold (Figure 1) were considered to study the flow and air gas mixture behavior. To design an optimal intake manifold, following parameters should be taken into consideration. 1- Uniform distribution of mixture to all cylinders. 2- Minimum possible resistance in runners. 3- To provide as direct a flow as possible to each cylinder, 4- To assist fuel atomization and vaporization. 5- To provide equal aspiration intervals between the branch pipes. Two different manifold geometries were considerate. Geometry 1 consists of a limited volume plenum connecting directly with six runners. The runner's lengths are determined according phenomena of the acoustic waves propagation in intake manifold. It supports the cylinder filling and the engine volumetric efficiency if it is properly exploited [19]. This manifold called 'optimized intake manifold' in the rest on text. The secondary geometry, consist of runners coupled to cylinders through a high volume plenum.

3. Computational methodology

Intake manifold is designed to provide fresh air or mixture to internal combustion engines. The gas circulation in plenum and runners causes very varied structures of turbulence. As a result; there is creation of unstable mixtures between air and fuel (rich or lean mixture). So far, this research aims at the 3D numerical analysis of flow in two manifold geometries using a CFD code. FloWorks is chosen for its capabilities flow analysis for both in gas and liquid simultaneously.

3.1 3D geometries model of manifolds

In this paper the commonly available CFD tool FloWorks is applied. FloWorks has the advantages of importing geometry directly from a CAD program such as SolidWorks (SW). At the beginning, the 3D geometries construct of intake manifolds are built by the CAD software SW; as shown in Figure 2. The files created by SW are imported into FloWorks to build mesh for final simulation calculation.

Table 1. Characteristics of the IVECO engine

Engine parameters	**Value**
Engine (four cycle)	IVECO
Reference	8210.02
Type	6 Cylinders – Inline
Bore × Stroke (mm)	137 x 156
Displacement (dm^3)	13.8
rod length (mm)	260
Crank radius (mm)	78
Compression ratio	16:1 (Diesel), 12 : 1 (LPG)
Engine speed range (rpm)	700 - 2000
Cooling system	Water cooling
Firing order	1-5-3-6-2-4

3.2 Governing equations

The governing equations of gas dynamics are expressions of the law of conservation and the laws of thermodynamics. The manifolds simulation is based on the 3D unsteady turbulence flow model. In the 3D manifolds model, air-fuel mixture is defined as compressible fluid. The standard k-ε model is utilized to solve the flow problem inside the manifolds. FloWorks solves the Navier-Stokes equations, which are formulations of mass, momentum and energy conservation laws for fluid flows in conjunction with the k-ε model equations:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho u_i\right)+\frac{\partial}{\partial x_i}\left(\rho u_i u_j\right)+\frac{\partial p}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\tau_{ij}+\tau_{ij}^{R}\right)+S_i \ ; \quad i=1,2,3 \tag{2}$$

$$\frac{\partial \rho E}{\partial t}+\frac{\partial \rho u_i\left(E+\dfrac{p}{\rho}\right)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(u_j\left(\tau_{ij}+\tau_{ij}^{R}\right)+q_i\right)-\tau_{ij}^{R}\frac{\partial u_i}{\partial x_j}+\rho\varepsilon+S_i u_i+Q_H \tag{3}$$

$$E=e+\frac{u^2}{2}\,. \tag{4}$$

where 'ρ' is the density, 'u' is the velocity, 'p' is the pressure, 'S_i' is a mass-distributed external force per unit mass, 'e' is the internal energy, 'Q_H' is a heat source or sink per unit volume, 'τ_{ij}' is the viscous shear stress tensor, "q_i" is the diffusive heat flux.

The mixture density is calculated by [20]:

$$\frac{1}{\rho}=\frac{\dfrac{m_{propane}}{m_{air}}\times\dfrac{1}{\rho_{propane}}+\dfrac{1}{\rho_{air}}}{\dfrac{m_{propane}}{m_{air}}+1} \tag{5}$$

The turbulent viscosity is given by:

$$\mu_t=C_\mu\rho\frac{k^2}{\varepsilon} \tag{6}$$

This viscosity is a function of the turbulent kinetic energy 'k' and its dissipation rate 'ε'. The equations of turbulent kinetic energy and its dissipation rate are written as:

$$\frac{\partial \rho k}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i k\right)=\frac{\partial}{\partial x_i}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right)+\tau_{ij}\frac{\partial u_i}{\partial x_j}-\rho\varepsilon+\mu_t P_B \quad (7)$$

$$\frac{\partial \rho \varepsilon}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i \varepsilon\right)=\frac{\partial}{\partial x_i}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right)+C_{\varepsilon 1}\frac{\varepsilon}{k}\left(f_1\tau_{ij}\frac{\partial u_i}{\partial x_j}+\mu_t C_B P_B\right)-C_{\varepsilon 2} f_2 \frac{\rho\varepsilon^2}{k} \quad (8)$$

'P_B' represents the turbulent generation due to buoyancy forces, "C_B" is defined as: $C_B = 1$ when $P_B > 0$, and 0 otherwise.

$$f_1 = 1+\left(\frac{0.05}{f_\mu}\right)^3 \quad , f_2 = 1-e^{\left(-\left(\frac{\rho k^2}{\mu\varepsilon}\right)^2\right)} \quad (9)$$

$C_{\varepsilon 1}=1,44$; $C_{\varepsilon 2}=1,92$; $C_{\varepsilon 3}=-1$; $\mathrm{Pr}_k=1$; $\mathrm{Pr}_\varepsilon=1,3$, and $C_\mu=0,09$, are the constants of the standard model (k, ε).

3.3 Boundary conditions for the manifolds models

Simulation tests are carried out in the intake stroke for a crank angle equal to 130°. To simplify the calculations, the manifold and the cylinder walls are assumed adiabatic: no transfer of heat with outside. The simulation is performed for the engine speed correspond to the maximum torque (n=1500 rpm) and only the first cylinder in aspiration. Two fluids are used, air and propane (we took a composition of LPG formed almost fully with propane). The inlet intake manifold pressure is taken as an initial condition; it is equal to 1.013 bar for the air inlet and 1.5 bar for the propane inlet. The alternative piston speed along the intake stroke is taken as final condition. The piston speed is taken equal to 3.55 m/s. This value is depends on parameters of the engine crank rod system.

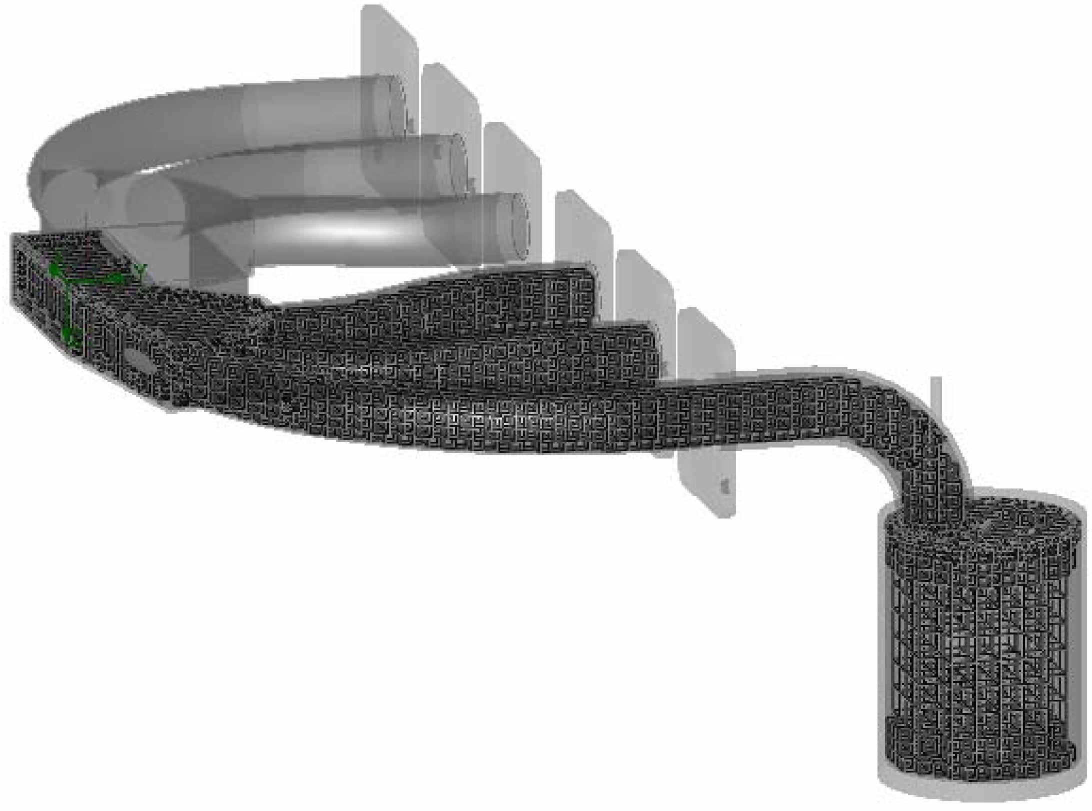
3.4 Computational meshing

Flow Simulation computational mesh is rectangular everywhere in the computational domain, so the mesh cells' sides are orthogonal to the specified axes of the Cartesian coordinate system and aren't fitted to the solid/fluid interface. As a result, the solid/fluid interface cuts the near-wall mesh cells. Nevertheless, due to special measures, the mass is treated properly in these cells named partial. The rectangular computational domain is automatically constructed, so it encloses the solid body and has the boundary planes orthogonal to the specified axes of the Cartesian coordinate system. Then, the computational mesh is constructed in the following several stages; constriction of basic mesh, capture the solid/fluid interface and refinement the solid/fluid interface mesh.

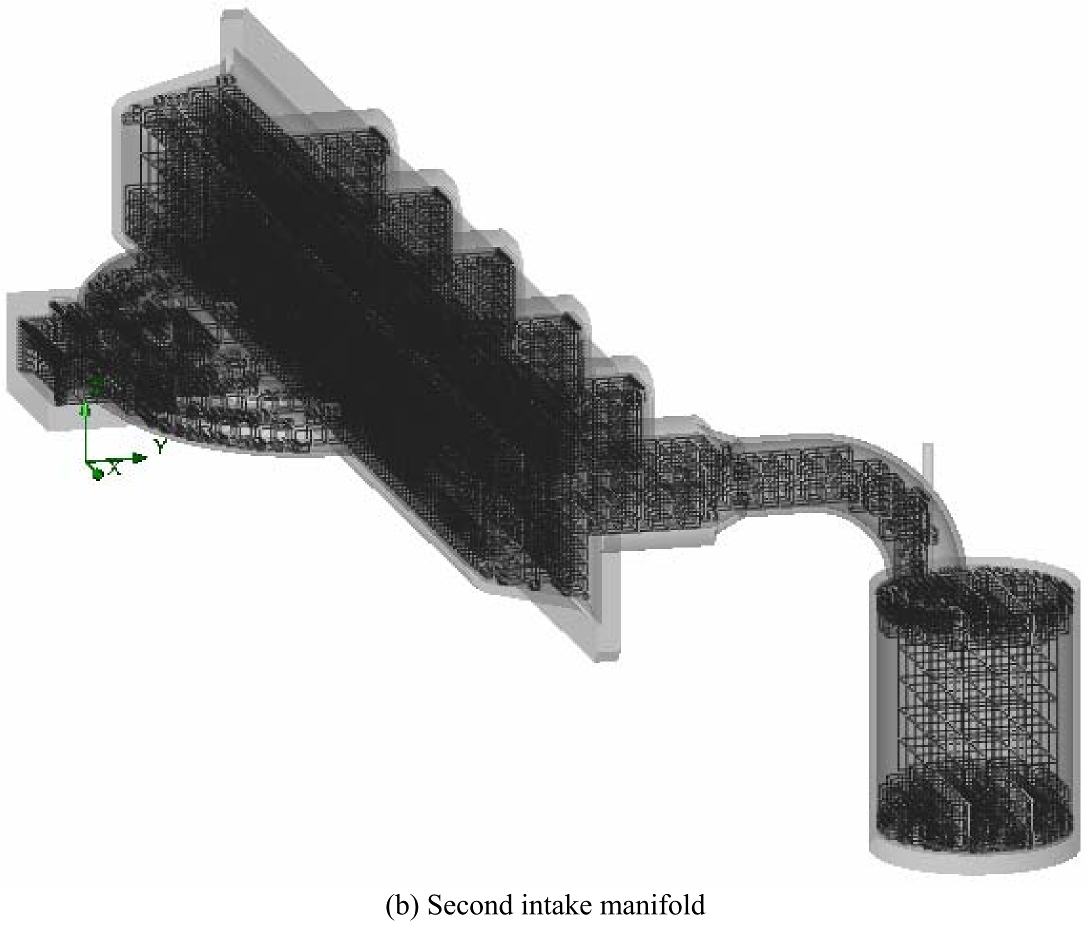
The meshes are defined with the total number of 22632 for the optimized intake manifold (the half of this manifold is meshed view its decomposition into two symmetric parts), and 40684 for the second manifold, see Figure 1.

3.5 CFD results

Velocity field is presented during the intake stroke. The control of velocity distribution in the combustion chamber improves flame quality and returns an economical air-fuel mixture. Figure 2 shows the 3D velocity distribution for the two manifolds. Gas blend is drawn by the downward motion of the piston. The air propane mixture is spreading in the cylinder, interacts with cylinder walls. When the flow reaches the combustion inlet valve, it undergoes an acceleration considering the valve restriction surface. For the optimized manifold the mixture velocity is nearly equal to 81 m/s passing through the valve and decreases less than 25 m/s, such velocity supports filling. Whereas, this isn't the case in the second manifold, 70 m/s and decrease below 16 m/s. This difference shows the manifold geometry influence on mixture velocity. In runners, a velocity discontinuity is noticed in the second manifold. Its origin is the presence of several dead zones in the geometry.

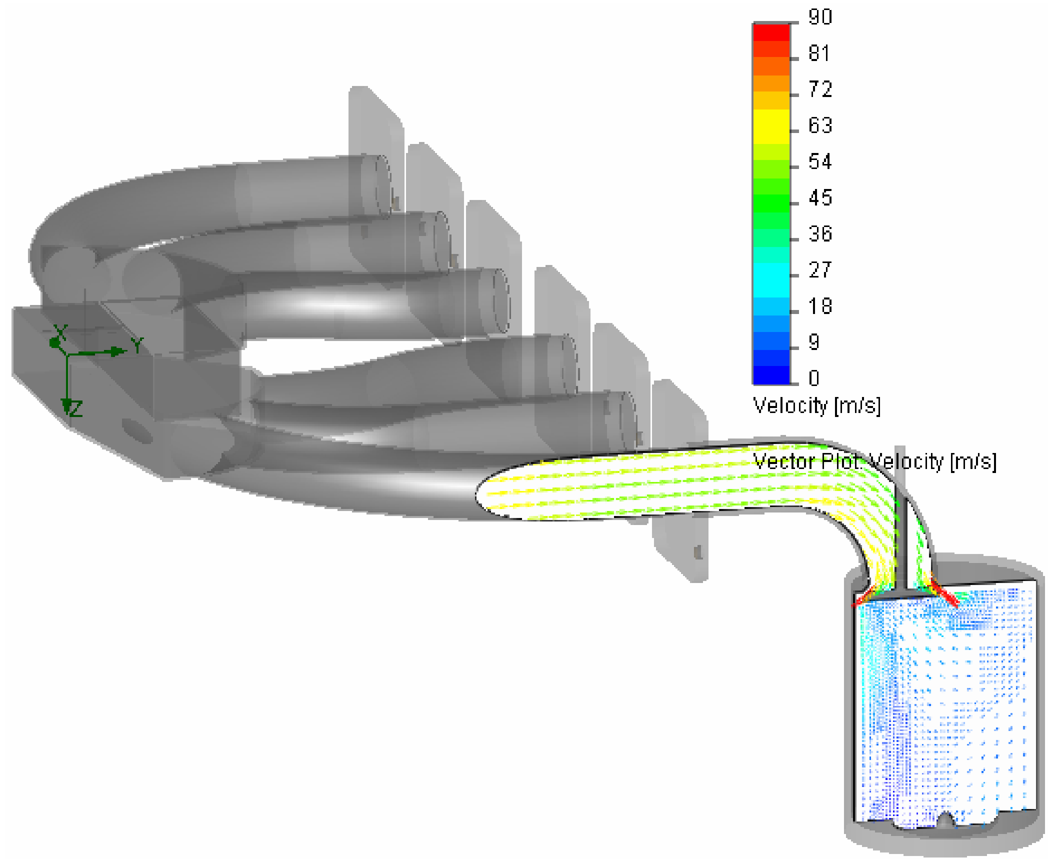


(a) Optimized intake manifold

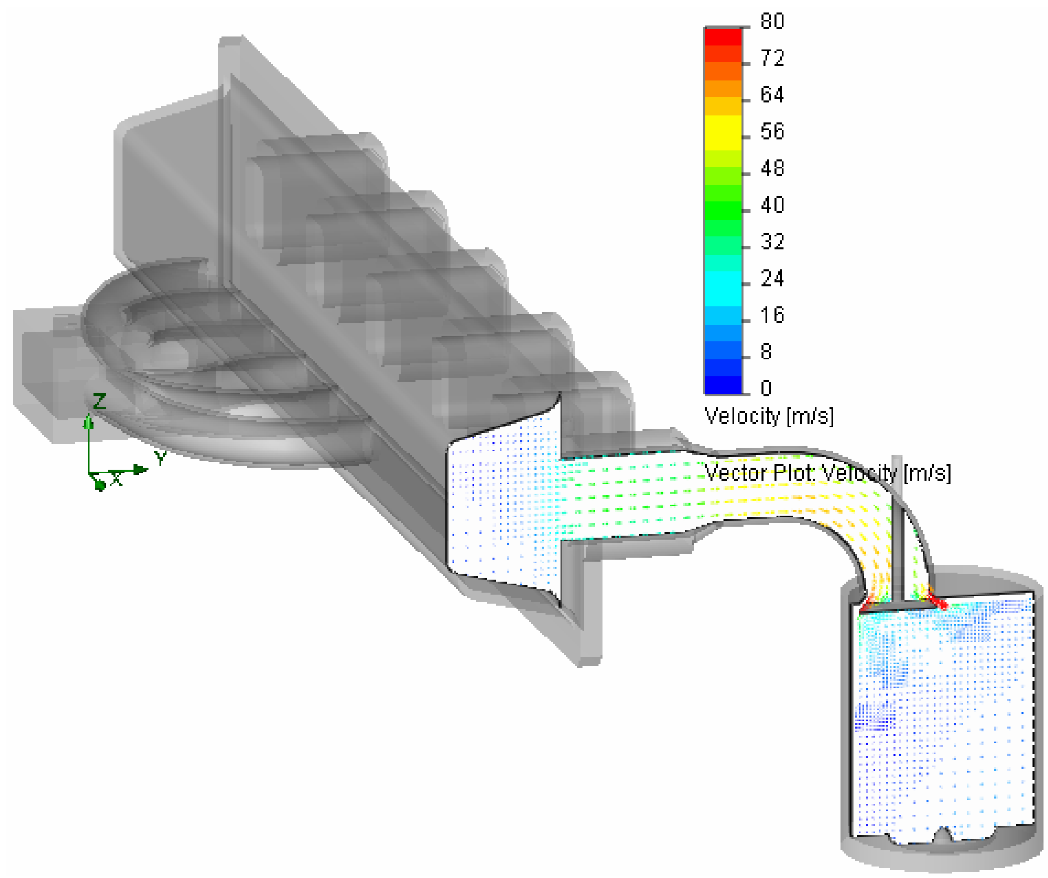


(b) Second intake manifold

Figure 1. 3D Model of intake manifolds



(a) Optimized intake manifold



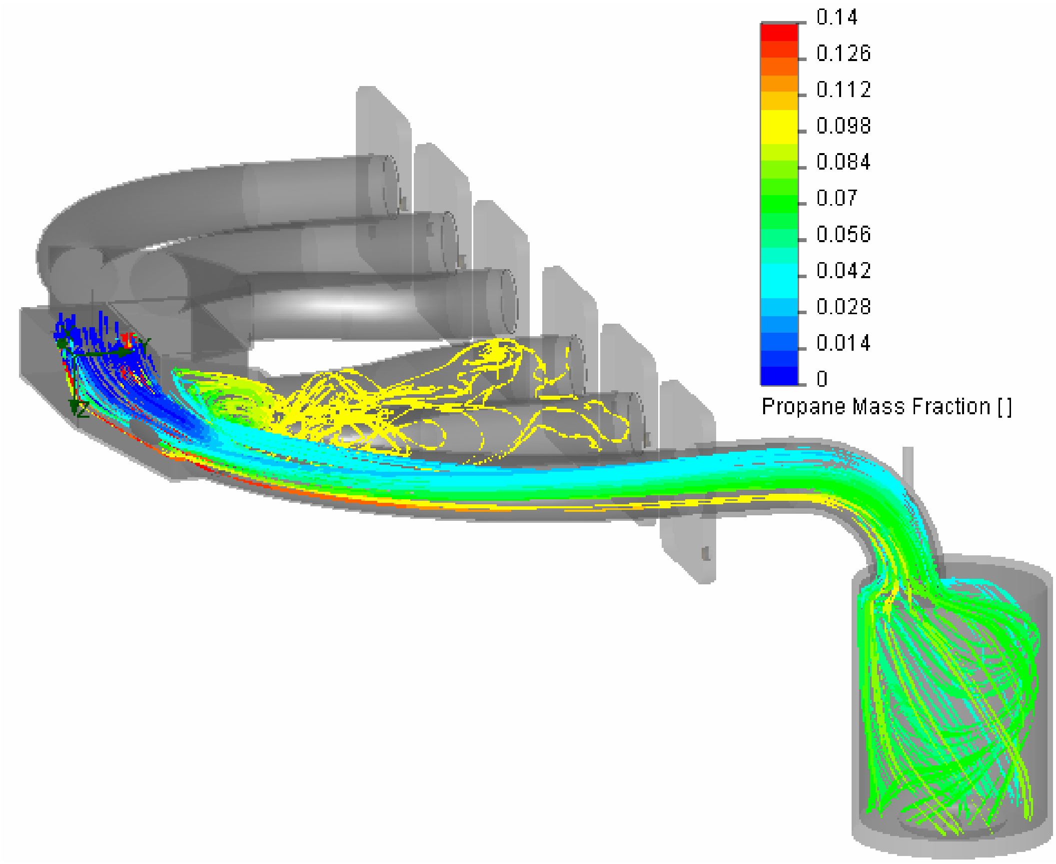
(b) Second intake manifold

Figure 2. Velocity field

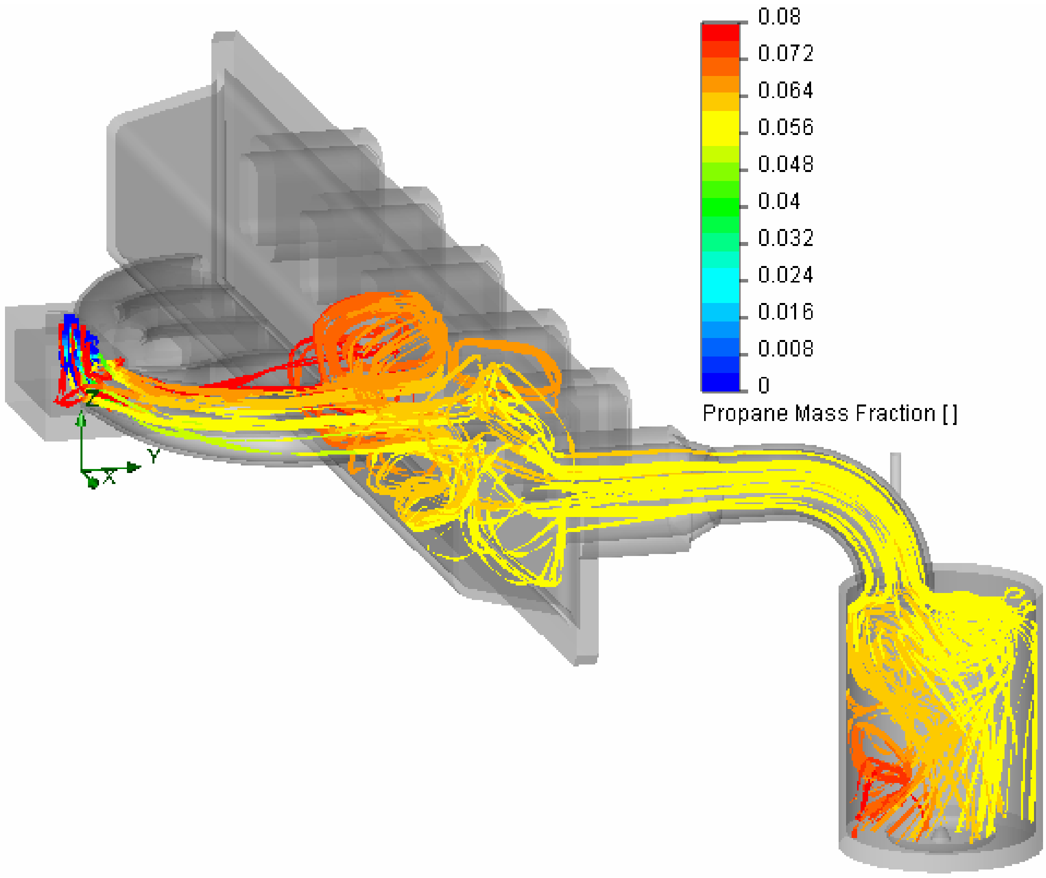
The 3D propane mass fraction is presented in Figure 3 for the two manifolds. As shown in this figure, the mixture is basically lean in the inlet of manifolds on account to the entering air acceleration. Air-gas mixing process in LPG fueled engine can be divided into three continuous areas: manifolds inlet, manifolds runners and inside cylinder. In the first area, the flow is unstable view the incompatibility of air and propane molecules speed. In the second area, the blend was expanded (the flow instability persists in the second manifold especially at the plenum). In the third area, the mixture homogeneity appears clearer. Inside the engine cylinder, for the first manifold design, the means propane-air ratio is 0.07 which is near the equivalent propane-air ratio (0.065); the stoichiometric ratio (SR) is 15.5 for LPG engine [18]. In the second, the ratio is a round of 0.05. Mixing of fuel was more at high speeds in the first manifold; the propane friction shows this mixing. The fluid trajectory lines support the influence of the manifold design configuration on the overall flow in the cylinder. In the non optimized manifold, these lines present stirring motions that hinder the flow and cylinder filling. When entering inside the cylinder, the fluid trajectories, in the optimized manifold, form circulating swirl movements, which further enhances filling and the combustion process.
As a conclusion, the distributions of the velocity fields and the air fuel friction are strongly depending on the intake manifold geometry.

4. Experimental validation

To validate the numerical simulation work, an engine test, presented in Figure 4 is plugged with the two intake manifold geometries. This engine is converted from its original Diesel version into LPG gaseous fueling. Its features are summarized in table 1. The air gas ratio and the specific fuel consumption of the engine are measured for the two manifolds versions. These engine performances are determined using LPG.
The engine was mounted on a test bench and connected with a hydraulic dynamometer brake type "H3 BIS" in order to measure power and torque. The quantity of consumed fuel is measured using a mass flow meter type “Kroohne Optimass MFC 050. The air flow is measured by Differential pressure flow meter. Engine speed is measured by an optical tachometer type “Chauvinistic Arnoux CA 27”.
The air-fuel ratio (AFR) is showed in Figure 5. The evolution of air-gas ratio shows an increase if the engine speed is increased for both manifolds. The highest of the ratio is 15.1 for the optimized manifold on engine speed 1400 rpm and its lowest is 11.8 on 600 rpm, however, it is in the range of (11, 14.8) for the second manifold. It is notable that the engine runs rich mixtures, especially in the starting speeds. The ratio average difference between the two manifolds is equal to 7.1 %. At 1400 rpm, the mixture nature is almost near of the air LPG stoichiometric ratio (15.5 for LPG engines) for the optimized intake manifold operation. This advantage is due to the homogenization optimize of the mixture in this manifold especially with the loss reduction due to its design.
Figure 5 presents also the evolution of the specific fuel consumption (SFC) for the two manifolds. It can be seen that the SFC for both manifolds decrease gradually when the engine speed is increased. The fuel consumption for the optimized manifold is greater than the second. On an average basis, the first intake manifold operation reduces the specific fuel consumption by 28 % for all the engine speeds tested. This reducing is explained by the in-cylinder filling growth and the proper mixture homogenization, which is attached to reduced charge losses.

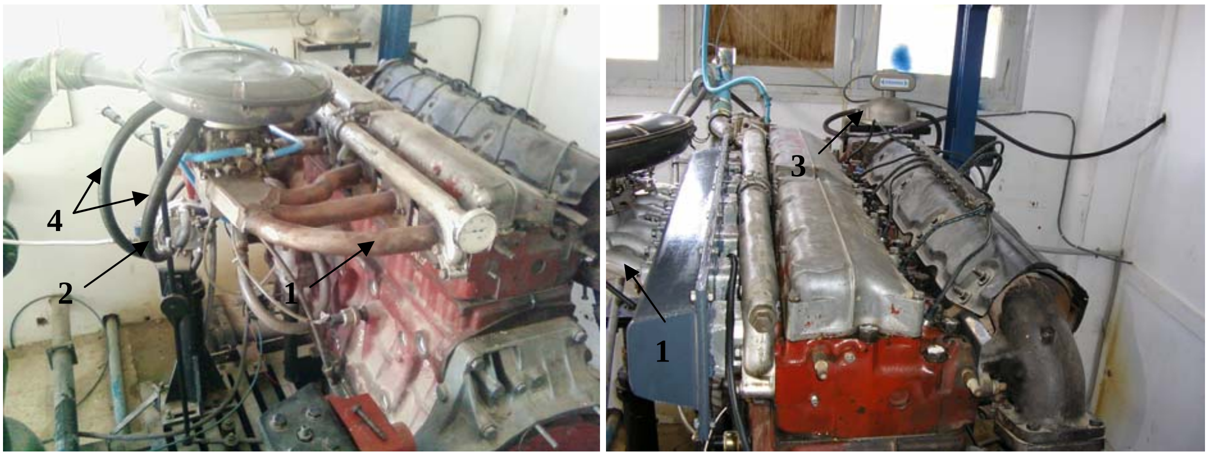


(a) Optimized intake manifold



(b) Second intake manifold

Figure 3. Propane mass fraction field



(a) Optimized intake manifold (b) Second intake manifold

Figure 4. Manifolds disposition on the engine test
1-Intake manifolds, 2-LPG vapo-regulator, 3-Fuel flow meter, 4-LPG pipes

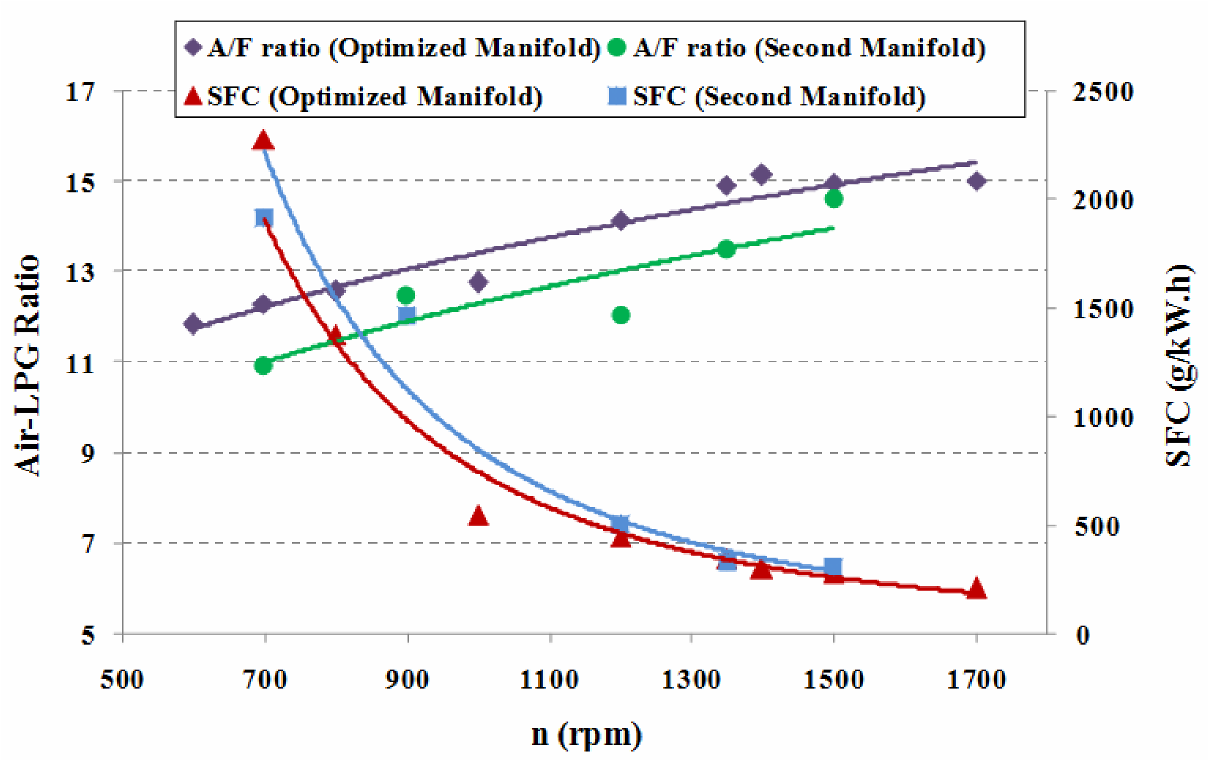


Figure 5. Intake manifold effect on air-LPG ratio and SFC

5. Conclusion

The main conclusions we can draw from this paper are the following:

1- The analysis of the flow and mixture motion features, during the intake stroke, is numerically made by a CFD code. The numerical study made it possible to select the optimized intake system geometry.

2- Velocity field and propane mass concentration are investigated in this simulation. Results affirm the effectiveness of the manifold which designed according the acoustic-wave-filling phenomena.

3- Experiment tests were performed in order to study the intake manifold influence on the engine performance. The air-fuel ratio and the specific fuel consumption are measured and determined. With the optimized manifold, both AFR and SFC are improved by 7 % and 28 % respectively.

4- Numerical and experiments results show the great impact of the intake manifold on the fuel mixture formation.

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