Journal of Cleaner Production 206 (2019) 1–10

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Effect of multiple injection strategies on emissions and performance in the Wärtsilä 6L 46 marine engine. A numerical approach

Maria Isabel Lamas*, Juan de Dios Rodríguez, Laura Castro-Santos, Luis Manuel Carral

Universidade da Coruña, Departamento de Enxeñaría Naval e Oceánica, Escola Politécnica Superior, Esteiro, 15403 Ferrol, Spain

ARTICLE INFO

Article history:
Received 9 September 2017
Received in revised form
18 August 2018
Accepted 19 September 2018
Available online 21 September 2018

Keywords:
Diesel engine
Emissions
Injection
Computational fluid dynamics (CFD)

ABSTRACT

The present paper proposes a Computational Fluid Dynamics model to analyze the operation cycle and exhaust gas composition in a four-stroke marine diesel engine, the Wärtsilä 6L 46. Once validated, the numerical model was employed to study the influence of several pre-injection parameters such as pre-injection rate, duration, starting instant and number of pre-injections. The purpose is to reduce consumption and emissions, especially nitrogen oxides, due to the current increasingly restrictive legislation. It was found that the fuel injection is a critical factor influencing combustion and emission characteristics. Important nitrogen oxides emission reductions were obtained for the parameters analyzed. Particularly, a 31.9% nitrogen oxides reduction was obtained using 20% pilot injection, 65.7% advancing 4° the pre-injection start angle, 20.1% shorting 4° the pre-injection duration and 36.7% using 4 pre-injections. A slight increment of hydrocarbons, carbon monoxide and consumption was obtained, lower than 5% for almost all the cases analyzed, and a negligible effect on carbon dioxide emissions.

1. Introduction

Nowadays, emission reduction in engines is one of the most important challenges that designers are facing, especially nitrogen oxides (NO_x) reduction. Many solutions have been developed in recent years to reduce NO_x emissions. Some methods directly improve combustion such as exhaust gas recirculation, water addition, modification of the injection process, etc. Other methods are based on exhaust gas after treatments, such as selective catalytic reduction systems. Among them, this paper focuses on multiple injection strategies. The first studies about multiple injections in engines appeared in the nineties. One can refer to the work of Nehmer and Reitz (1998), who studied multiple injection strategies in a heavy duty direct injection diesel engine and obtained reductions in particulate and NO_x emissions, especially if multiple injections are combined with EGR (Exhaust Gas Recirculation). The same conclusion using the same engine was obtained by Han et al. (1996) through a numerical model. Using other engines, Ikegami et al. (1997) also obtained reductions in particulate and NO_x. Besides, they indicated that another advantage of pilot injections is the reduction of noise. Carlucci et al. (2006) analyzed the pilot injection timing and duration and found that NO_x emissions levels are mainly influenced by the pilot duration, whereas smoke emission is influenced by both variables. Mohan et al. (2013) reported that post/after injections must be immediately injected after main injection in order to avoid increments in smoke, hydrocarbons (HC) and consumption. Mathivanan et al. (2016) indicated that soot can increase because pilot injections aggravate spray characteristics and particulates can be formed at the rich region. Chen (2000) indicated that a high separation between pilot and main injection reduce NOx but long delays might lead to increment smoke, consumption and HC emissions. Minani et al. (1995) obtained NO_x reductions but recommended to employ a small amount of pilot quantity in order to maintain soot emissions. Awargal et al. (2013) analyzed the time and quantity of the pilot injection, obtaining important NO_x reductions but at expenses of smoke increments. Fang et al. (2008) analyzed the effect of the injection angle when using multiple injections, obtaining NO_x reductions but HC increments. Other authors recommend to combine multiple injections with other systems such as EGR, Chen et al. (2017), or high injection pressures, Cha et al. (2015).

Based on these aforementioned experimental works, it can be concluded that multiple injections are able to reduce emissions but many parameters must be optimized such as injection time, duration of injection, number of pre-injections, dwelling time, etc. In recent years, numerical procedures have become an interesting tool

* Corresponding author.
E-mail addresses: isabellamas@udc.es, isabel.lamas.galdo@udc.es (M.I. Lamas).

https://doi.org/10.1016/j.jclepro.2018.09.165
0959-6526/

to study injection parameters in engines since it is possible to analyze many solutions avoiding complex and expensive experimental setups. Besides, a numerical model provides interesting information which helps to understand the combustion process and emissions formation. In this regard, Petranovic et al. (2015) highlighted the capabilities of CFD (Computational Fluid Dynamics) to decrease the time and cost of experimental researches. Soni et al. (2017) developed a numerical model to analyze the effect of the spray angle using two piston bowl geometries. Fajri et al. (2017) analyzed numerically the effect of start of combustion, combustion duration, and other parameters on the performance and NO_x emissions. In another numerical work, Nazemi and Shahbakhti (2016) studied the effect of the spray angle, SOI timing, injection pressure and pressure rise rate. Imram et al. (2014) analyzed the effect of pilot fuel injection and indicated that an important quantity of NO_x is formed in the region around the pilot spray, where high temperatures exist. Li et al. (2016) studied the effect of split injections coupled with swirl and obtained reductions in both consumption and soot emissions. Another numerical analysis was developed by Yu et al. (2018), who focused on the injection interval and fuel injection proportion.

This study aims to offer a validated CFD model to provide information about the injection system. Several injection parameters were analyzed such as pre-injection rate, duration, starting instant and number of pre-injections in the marine diesel engine Wärtsilä 6L 46. The goal is to reduce consumption and emissions and provide a cheap and fast tool for studying engines and developing new designs. This work provides a model than can be employed to reduce consumption and emissions in future engines.

2. Development of the model

2.1. Case studied

The engine studied in the present paper, the Wärtsilä 6L 46, is a four-stroke, medium-speed, marine diesel engine with 6 cylinders in line. Each cylinder has two intake and two exhaust valves in the cylinder head. This is a direct injection engine, *i.e.*, the fuel is injected directly into the combustion chamber. A fuel injector is located near the outer edge of the combustion chamber. The nozzle has 10 holes of 0.65 mm diameter and 144° spray angle. Other data of the engine are indicated in Table 1.

In the present work, an extensive analysis was performed in a Wärtsilä 6L 46 installed on a tuna fishing vessel. Many parameters were characterized at different loads such as in-cylinder pressure, consumption, power, scavenging air pressure and temperature, exhaust gas pressure and temperature, lubricating oil pressure and temperature, cooling water temperature, etc. Although this engine is designed to operate under heavy fuel oil, marine diesel oil operation is also possible. Since these data were taken on board and near the coast, marine diesel oil was employed. The viscosity and density of this fuel are 12.5 mm^2/s and 885 kg/m^3 at 15 °C and its sulfur content 0.89%. The engine operated 2 h at 25% load, 2 h at 35%, 2 h at 50%, 2 h at 75% and 2 h at 100% load. 8 tests were taken at each analyzed load and the average was taken. As the engine has 6 cylinders, one test per cylinder was carried out. The engine performance analyzer MALIN 6000 was employed, which is a portable instrument commonly used for preventive maintenance. The pressure transducer included in MALIN 6000 is piezoelectric with 1% accuracy. This is connected to the bleed valve, located at the engine head. The signal from the pressure transducer is processed by a computer. Concentrations of NO_x, CO (carbon monoxide), HC and CO_2 (carbon dioxide) were also analyzed at different loads using the Gasboard-3000 series (Wuhan Cubic) gas analyzers. The accuracy and measurement range of these composition analysis instruments are indicated in Table 2.

Some experimental data at different loads are indicated in Table 3. Particularly, the velocity (RPM, revolutions per minute), power, IMEP (indicated mean effective pressure), maximum pressure, SFC (specific fuel consumption) and fractions of NO_x, HC, CO and CO_2.

2.2. Numerical procedure

The performance cycle of this engine was modeled and validated with experimental results in previous papers (Lamas et al., 2012, 2013; Lamas and Rodriguez, 2013). The software SolidEdge was employed for the CAD 3D design and Gambit 2.4.6 for the generation of the mesh. The computational mesh is indicated in Fig. 1. As can be seen, the cylinder and valves were meshed. In order to implement the piston movement, a deforming mesh was used and the movement was imposed to the valves and piston surfaces. Particularly, Fig. 1 (a) represents the tridimensional mesh, Fig. 1 (b) a cross-section at BDC (bottom dead center), *i.e.*, 180 or 540° and Fig. 1 (c) a cross-section at TDC (top dead center), *i.e.*, 0° or 360°. The number of elements varied from 50,125 at TDC to 802,527 at BDC. In order to minimize the number of cells and obtain good convergence, hexahedral elements were used to mesh the cylinder. On the other hand, the cylinder head and ducts were meshed using tetrahedrons. In this region the mesh was refined in order to adapt properly to the opening and closing of the valves. Several meshes with different elements were tested in order to verify that the results are independent of the mesh size. Table 4 indicates the error obtained between experimental and numerical results of pressure and fractions using a mesh with 501,769 elements at BDC (mesh 1), as well as 802,527 elements (mesh 2) and 1,264,873 (mesh 3). As can be seen, there is no difference between the meshes 2 and 3, for

Table 1
Specifications of the engine.

Parameter	Value
Output (kW)	5430
Mean effective pressure (kPa)	2250
Speed (rpm)	500
Cylinder displacement volume (cm^3/cyl)	96400
Bore (mm)	460
Stroke (mm)	580

Table 2
Accuracy and measurement range of the composition analysis instruments.

Gas	Accuracy	Range
NO_x	3%	0–2000 ppm
CO	3%	0–5000 ppm
HC	2%	0–1000 ppm
CO_2	2%	0–25%

Table 3
Experimental data.

Load (%)		25	35	50	75	100
RPM		500	500	500	500	500
Power (kW)		2047.6	2367.8	2923.6	4051.1	5430.1
IMEP (kPa)		810	1390	1760	2000	2250
p_{max} (kPa)		10270	13800	16040	17580	18630
SFC (g/kWh)		173.2	171.9	169.8	169.5	172.1
Fractions	NO_x (ppm)	1048	1092	1149	1167	1128
	HC (ppm)	510	485	448	466	515
	CO (ppm)	261	255	247	268	292
	CO_2 (%)	3.5	4.6	6.9	7.9	8.3