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An easy and inexpensive way to estimate the trapping efficiency of a two stroke engine

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Abstract

This paper presents a new analytic model for the estimation of the trapping efficiency of two-stroke engines using an extremely reduced number of measured physical variables. Mainly, the model estimates the trapping efficiency according to the Ostwald diagram, to the molal concentration of carbon dioxide and oxygen at tailpipe and according to the mass flow of air and fuel. In order to provide a measure of effectiveness for the proposed model, a use case has been chosen. The model's effectiveness has been evaluated comparing its outcomes with the results obtained by thermo-fluid dynamic simulation of the use case on a 0D-1D commercial code, whose scavenging model has been previously validated by an extensive experimental activity. The present study shows that, for all the cases considered, the model results differ no more than 11% in absolute value from the simulated ones. In brief, the accuracy of the model allows the estimation of the trapping efficiency for two-stroke engines with reasonable confidence, reduced computational effort and time and costs lower than the currently available techniques.

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Keywords: Two-stroke engines; Trapping efficiency measurement; Ostwald diagram

1. Introduction

Methods for quantifying the scavenging process in two-stroke engines are usually classified into two main categories: measurements in motored engines and measurements in fired engines [1]. While the former postulates that the scavenging characteristics does not depend on the combustion process, the

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latter depicts the process under real operating conditions in full-size engine tests. When operating in lean conditions, the current methods for estimating the trapping and/or scavenging efficiency are based on gas samples at both intake opening and exhaust closing. Although this system allows studying cyclic variability, yet requires to buy and install fast sampling valves close to scavenging and exhaust ports. Moreover, a homogeneous composition of the gaseous mixture into the cylinder must be assumed [1].
The aim of this paper is to describe and test a new method for quantifying the trapping efficiency for a two-stroke engine possibly operating in lean conditions through: the Ostwald diagram related to the fuel used; the measurement of the molal concentration of Carbon Dioxide and Oxygen at tailpipe; the intake air and fuel mass flows.

Nomenclature

E	Air Excess [%]
m_{ar}	Mass flow of residual air from the previous cycle [kg/s]
m_{as}	Supplied air mass flow [kg/s]
m_b	Fuel mass flow [kg/s]
m_{cy}	Mass flow trapped into the cylinder[kg/s]
m_{ex}	Mass flow at tailpipe [kg/s]
m_{gc}	Combustion products mass flow [kg/s]
m_{sc}	Short-circuited air mass flow [kg/s]
m_{sref}	Reference air mass flow rate [kg/s]
m_{ta}	Total trapped air mass flow [kg/s]
m_{tas}	Fraction of the supplied air mass flow trapped into the cylinder [kg/s]
m_{th}	Theoretically required air mass flow for complete combustion [kg/s]
SE	Scavenging efficiency [%]
SR	Scavenge ratio [%]
TE	Trapping Efficiency [%]
V_{gas}	Volumetric flow rate of the gaseous species [m^3/s]
α_{st}	Stoichiometric air-to-fuel ratio [-]
ε_{gas}	Concentration of the gaseous species at tailpipe [-]
ρ_{gas}	Density of the gaseous species [kg/m^3]
ν_{gas}	Molal concentration of the gaseous species referred to combustion products [-]

2. Theory

2.1. Definitions and notations

One of the indicators of the scavenging behavior of two-stroke engines is the Trapping Efficiency (TE) definedas [1]:

$$TE = \frac{m_{tas}}{m_{as}} = \frac{m_{cy}\,SE}{m_{sref}\,SR} \tag{1}$$

where SE is the Scavenging Efficiency and SR is the Scavenge Ratio, defined as $\mathrm{SE} = \mathrm{m}_{\mathrm{tas}}/\mathrm{m}_{\mathrm{cy}}$:, $\mathrm{SR} = \mathrm{m}_{\mathrm{as}}/\mathrm{m}_{\mathrm{sref}}$, respectively. Another important parameter is the air excessE, defined as the percentage difference between the total airmass flow trapped into the cylinder, mta=mtas+mar, and the air mass flow mth theoretically required for the complete combustion of the fuel injected into the cylinder:

$$E = 100 \cdot \frac{m_{ta} - m_{th}}{m_{th}} \tag{2}$$

2.2. Model theoretical frame

Figure 1(a) shows the schematic model of the real scavenging process used during this work. The model relies on the assumption of *perfect displacement* originally proposed by Hopkinson [2] and later expanded by Benson and Brandham [3]. According to this assumption, neither exhaust gas nor residual air are retained into the cylinder from the previous cycle, i.e. $m_{tas} = m_{ta}$. It results that the air charge completely fills the available volume and, consequently, SE is almost equal to 1. The exceeding air charge m_{sc} is short-circuited in the tailpipe, i.e. $m_{as} = m_{tas} + m_{sc}$. The analytical model proposed in this paper is implemented assuming first a tentative value for *E*. m_{tas} can be then written as:

$$m_{tas} = \frac{E \cdot m_{th}}{100} + m_{th} = \frac{E \cdot \alpha_{st} m_b}{100} + \alpha_{st} m_b \tag{3}$$

where m_b is the experimental measured fuel mass flow. The mass flow at tailpipe, m_{ex},is equal to the mass flow exiting the cylinder, $m_{gc} = m_{ta} + m_b$, plus m_{sc}:

$$m_{ex} = m_{ta} + m_b + m_{sc} = m_{gc} + m_{sc} = m_{as} + m_b \tag{4}$$

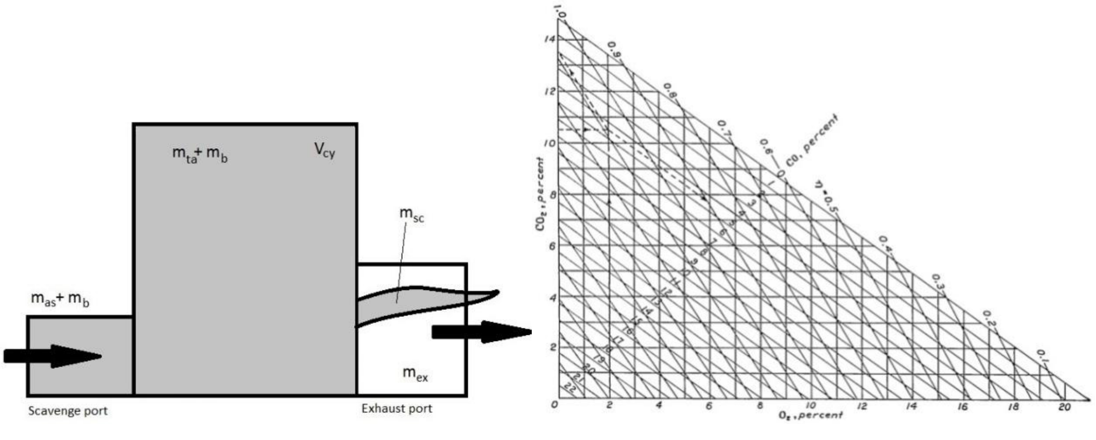
Once m_{tas} has been calculated through eq. (3), m_{sc} is calculated rearranging eq. (4):

$$m_{sc} = m_{as} - m_{tas} \tag{5}$$

Then, always rearranging eq. (4):

$$m_{gc} = m_{ex} - m_{sc} \tag{6}$$

The Ostwald combustion diagram plots the theoretical relationships among the concentration of combustion products ν_{CO_2}, ν_{CO} and ν_{O_2}andthe air-fuel ratio for a given hydrocarbon fuel. Through this diagram it is possible to determine, for example, ν_{CO} and the air-fuel ratio when the values of ν_{CO_2} and ν_{O_2} are known. The Ostwald combustion diagram for Diesel fuel is shown in figure 1(b) [4].



(a) (b)

Figure 1 (a) Schematic model of the two-stroke scavenging process; (b) Ostwald combustion diagram for Diesel fuel. Note: excess of air coefficient is expressed as $\eta = \frac{100}{E+100}$.

The molal concentration, for example, of carbon dioxide ε_{CO_2} measured at tail pipe can be written as:

$$\varepsilon_{CO_2} = \frac{V_{CO_2}}{V_{ex}} \cdot 100 = \frac{V_{CO_2}}{\frac{m_{ex}}{\rho_{ex}}} \cdot 100 = \frac{V_{CO_2}}{\frac{m_{gc}+m_{sc}}{\rho_{ex}}} \cdot 100 \tag{7}$$

where V_{CO_2} is the volumetric flow rate of carbon dioxide, V_{ex} and ρ_{ex} are respectively the volumetric flow rate and the density attailpipe. Assuming a reasonable value for the exhaust gas density ($\rho_{ex} = 0.57 kg/m^3$) and rearranging equation (7),V_{CO_2} can be calculated as:

$$V_{CO_2} = \varepsilon_{CO_2} \cdot \frac{m_{gc}+m_{sc}}{100 \cdot \rho_{ex}} \tag{8}$$

The assumed value for the exhaust gas density has a negligible influence on the final outcomes. In fact, for all the analyzed cases reported in the following, an error lower than 0.3% was estimated. In order to obtain the mass concentration of carbon dioxide, ε_{CO_2}, to enter into the Ostwald combustion diagram, m_{sc} can be neglected since it does not derive from the combustion process. Then, the concentration of carbon dioxide, ν_{CO_2}, to enter into the Ostwald diagram, can be calculated as:

$$\nu_{CO_2} = 100 \cdot \frac{V_{CO_2} \cdot \rho_{gc}}{m_{gc}} = \varepsilon_{CO_2} \cdot \frac{\rho_{gc}}{\rho_{ex}} \cdot \frac{m_{ex}}{m_{gc}} \tag{9}$$

where ρ_{gc} is the density of the combustion product gases only, fixed equal to the exhaust gas density. The same procedure can be followed in order to obtain the concentration of oxygen thus obtaining:

$$\nu_{O_2} = 100 \cdot \frac{V_{O_2} \cdot \rho_{gc}}{m_{gc}} = \varepsilon_{O_2} \cdot \frac{\rho_{gc}}{\rho_{ex}} \cdot \frac{m_{ex}}{m_{gc}} \tag{10}$$

The concentrations obtained through equations (9) and (10) are used to enter into the Ostwald combustion diagram and to obtain the related value of air excess E'. Iterating the procedure until E'=E, it is possible to calculate the actual air excess *E*, the actual short-circuited mass flow m_{sc} , the actual exiting gas mass flow m_{eg} and the actual trapped air mass m_{tas}. Consequently, the value of TE can be calculated through equation (1).

2.3. Use case and results

In order to assess the effectiveness of the model proposed in the previous section, a set of simulations has been performed. The term of comparison is provided by a model implemented in AVL BOOST v2011.2,representing a 2-stroke Diesel engine with Uniflow scavenging system. The scavenging model implemented in the software has been previously validated through extensive experimental activity on Uniflow scavenging systems [5].

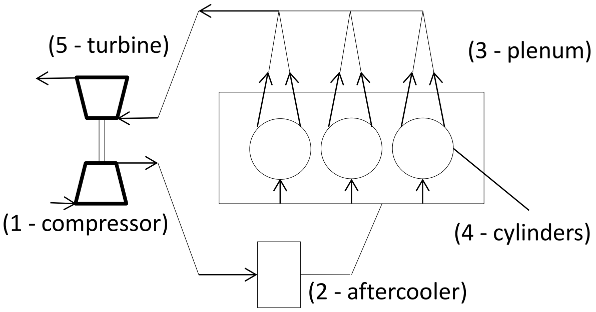


Fig. 2 Engine model developed in AVL BOOST v2011.2 and used as term of comparison

The engine model is shown in figure 2 and refers to a diesel two-stroke turbo-charged engine. The engine is also provided with an intercooler and an intake plenum. The performed simulations comply with a DOE of two variables, engine speed and injected fuel mass per cylinder. The engine speed was varied in the range 1200-2400 rpm with a step of 200 rpm. The injected fuel mass per cylinder was varied in the range 35-60 mg with a step of 5 mg.

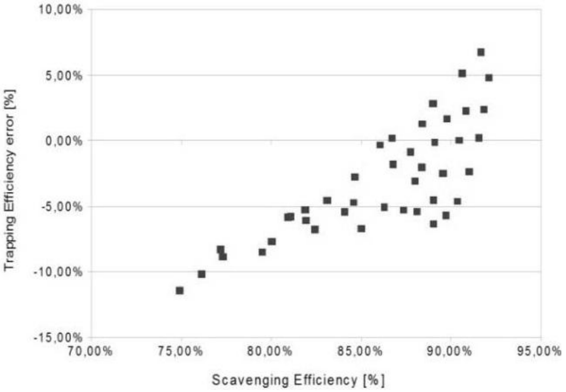


Fig. 3. Scatter plot of trapping efficiency error versus actual scavenging efficiency.

In Figure 3, the error between TE predicted by the proposed model and BOOST software are plotted as a function of SE predicted by the software. As a general remark, the analytic model shows a good predictive capability with a maximum error of 11.6%. The strongest assumption of the model based on Ostwald diagram is that SE = 1. Thus, it is fairly reasonable that when actual SE is far from unity, the model shows greater error. In fact, as SE gets close to unity, the error dispersion has a mean value close to 0.0% and an absolute error almost always lower than 5.5%. Instead, as SE becomes less than 85,0%, the error rises up. Interestingly, the error has linear drift to negative values, meaning that the analytical model tends to underestimate TE.

3. Conclusion

In this paper, a new method for quantifying the trapping efficiency for a two-stroke engine possibly operating in lean conditions is described and tested. The method is based on the measurement of the molal concentration of carbon dioxide and oxygen at the exhaust and of the intake air and fuel mass flows; moreover, the assumption of the validity of the Ostwald diagram related to the fuel used is required. The results obtained implementing this method have been compared with those obtained through the thermo-dynamic simulation of a two-stroke Diesel engine in which a model for the scavenging process suitable for Uniflow systems was applied. The difference between the two values is always lower than 11% and increasing as the scavenging efficiency decreases. This observation suggests an approach for further improvements of the method. On the other hands, its easiness makes it suitable whenever a quick estimation of the average – not cycle-to-cycle – trapping efficiency is required.

References

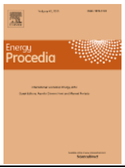
[1] Heywood JB, Sher E. The Two – Stroke Cycle Engine: Its Development, Operation and Design. Taylor and Francis, USA, 1999.

[2] B. Hopkinson. The Charging of Two-Cycle Internal Combustion Engines. Trans. NE Coast Instn. Engrs. Shipbuilders; Vol 30; 1914, p433.

[3] R.S. Benson, P.K. Brandham. A Method for Obtaining a Quantitative Assessment of the Influence of Charge Efficiency on Two-Stroke Engine Performance. Int.J.Mech.Sci.; Vol 11; 1969, p303.

[4] H. C. Gerrish, A. M. Tessmann. Relation of Hydrogen and Methane to Carbon Monoxide in Exhaust Gases from Internal-Combustion Engines. Naca-report-476; 1935, p60.

[5] A.P. Carlucci, A. Ficarella, D. Laforgia, A. Renna. Supercharging system behaviour for high altitude operation of an aircraft 2-stroke Diesel engine. Energy Conversion and Management 101 (2015) 470-480 (DOI:10.1016/j.enconman.2015.06.009) ISSN: 0196-8904



Biography

Paolo Carlucci graduated in 2000 with Honors and received the Ph.D. degree in “Energy Systems and Environment” in 2004. In November 2005 he joined the Engineering Faculty at University of Lecce as Assistant Professor. His research interests are combustion and emissions in diesel and dual-fuel internal combustion engines.