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Engine oil warm-up through heat recovery on exhaust gases – Emissions reduction assessment during homologation cycles

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ABSTRACT

Fuel saving is currently the most important technology driver in the development of low-emissions internal combustion engines. As known, friction is responsible for losses during engine operation, leading to an increased fuel consumption and ultimately increased emissions. Among all options for friction reduction, the oil thermal management has not yet received the attention it deserves, despite the fact that its potential compares to the one of other more consolidated techniques. Such a lack of interest appears even worse, when the impact of an accelerated oil warm up on the emissions reduction during reference homologation cycles is considered: in standard NEDC cycles, the oil viscosity reaches its design value only during the final part of the cycle, i.e. once the most part of harmful emissions has already occurred. This is due to a delayed thermal stabilization of the lubricant oil and poor friction reduction performances during the NEDC early phases.

In this paper, the Authors investigate the effectiveness of the waste heat recovery on the exhaust gases, to speed up the lubricant oil warm up, effective immediate after engine ignition and thus, with little or no delay on the start of NEDC homologation cycle. The experimental activity, performed on a turbocharged engine (F1C 3L IVECO), starts with the setting up of a proper oil circuit and exhaust line layout, to allow the exhaust tailpipe to include a shell and tube heat exchanger for heat recovery. The unsteady heat availability on the exhaust gases, along with the variability the mass flowrate experiences during the NEDC cycle represents a major variable to account for in the heat exchanger selection and design. All interactions between the modified oil circuit, engine, coolant circuit and the exhaust line needed to be evaluated as well. Significant reduction of fuel consumption and pollutant emissions have been experimentally demonstrated.

1. Introduction

The growing awareness of the issue represented by present Carbon concentration into the atmosphere has drawn attention to the transportation sector as one of the biggest contributors to greenhouse gases emissions on a global scale. Dependently on each specific context, Governments worldwide agreed on setting limitations to harmful emissions. Among them, EU set 95 gCO_2/km by 2021 target for passenger vehicle and 170 gCO_2/km for light duty vehicles, for new registrations [1], with an eye on primary pollutant emissions (HC, CO, NOx and PM) as well [2].

As known, internal combustion engines for vehicle applications – markedly, passenger and light duty applications – suffer the intrinsic unsteady operation, particularly in urban cycles, during which the design operating conditions are far from being reached. A main reason for this, the fact that the engine hardly reaches its thermal regime. The cold engine operation in early phases of any driving cycle [3–5] is characterized by higher frictional losses [6], ineffective combustion and off-design operation for after-treatment devices [7] and an emissions-related behavior not at all similar to the one in steady operation [8,9]. Hence, the research interest has shifted toward transient engine operation, recognizing in the faster engine warm-up the best option to reduce emissions [10,11]. The need to assess both novel layouts for lubricant circuit [12,13] and upgrades in the combustion technology also came out, since any disturbance on the combustion process reflects on a worse engine performance in terms of friction, in both naturally aspirated and turbocharged engines [14]. The datum on diesel engines is impressive: cold operation can lead to particulate matter emissions up to 7 times those occurring in warm conditions [15]. A great contribution to this datum comes from friction losses, as the contact between parts in relative motion – namely the ring pack and cylinder liner [16–19] and crankshaft main bearings [20,21] – is mediated by a lubricant operating far from its design conditions [22–24]. During normal operation, low temperatures on the lubricant can lead to a friction mean effective pressure increased by 400% [25,26]. The availability of lubricant oil in conditions close to the design ones already in the early

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stages of any driving cycle is allowed by several interventions, on which an extensive literature has been developed. Nonetheless, the possibility to implement these interventions on engines, beyond pilot plants on a lab scale, is questioned by different concerns: any intervention on the oil physical (e.g. low viscosity grade [27]), chemical and thermal properties (e.g. low thermal mass [28]) affects oil lifetime and O&M costs for the engine in standard applications. The oil sump insulation is promising, but lower benefits must be expected [29].

The pursuit of a less invasive option to reduce friction losses suggests the need to move toward faster oil warm ups, by either preheating it [31,32] or by providing it with additional thermal energy during normal trips, directly fed by on-board dedicated storage devices [33]. In both cases, though, the additional energy demand to cover the extra oil thermal needs would result in an increased fuel consumption, with obvious detrimental effects on the engine emissions. An interesting and yet relatively unexplored option is the heat recovery from the exhaust gases: a first assessment of its effect on fuel consumption and emissions performance can be retrieved from [34–36]. Nonetheless, a comprehensive analysis of the technology needed and of all plant-related issues is not yet available.

This paper presents a thorough experimental activity to evaluate the benefits of a shorter time for oil warm up, allowed by the waste heat recovery on the exhaust gases [37,38], in a turbodiesel IVECO F1C (3L) engine for both light and heavy duty applications. The engine is run on a dynamometric test bench that allows to implement transient NEDC homologation cycle. The paper goes deep inside all of the required upgrades on the oil and gas circuits, coolant circuit (i.e. the role of the thermostatic valve) and the assessment of the impact on engine performance, associated with the backpressure the heat exchanger induces [39,40]. The major constraint in the heat exchanger selection and sizing, i.e. the need to maximize the thermal transfer to the oil in the preliminary phases of the homologation cycle and to exclude it once the oil thermal regime is reached is also discussed. The fuel consumption reduction, as well as the CO_2 emissions reduction, obtained with a warmer oil is in the 2–3% range. The lower fuel consumption and the change in both in-cylinder temperature and air-to-fuel ratio at once, assure great reduction on primary pollutants (CO, HC, NOx and particulate matter) emissions, as well.

2. Novel oil lubrication circuit design

Fig. 1 shows the lubricant oil circuit layout, integrating the WHR section: in its standard configuration, a crankshaft-driven gear pump is in charge for oil circulation in the turbocharged IVECO F1C 3.0L diesel engine, and serves two main purposes: lubrication of crankshaft bearings, pistons, camshaft and turbocharger shaft and feeding of hydraulic tappets and tensioners for valves control. A relief valve on the gear pump prevents overpressures in the circuit, by continuously adapting the circulating oil mass flowrate: normal values the gear pump provides are in the 15–55 l/min range, in the 800–4000 RPM speed range for the engine. The coolant heat exchanger in Fig. 1 allows a proper temperature control on the oil, once the engine reaches its thermal regime.

The system conceived to allow oil heating through waste heat recovery (WHR) from the exhaust gases features a shell and tube heat exchanger on the exhaust line of the engine with the exhaust gases flowing in the tubes. The oil is fed to the shell-side of the heat exchanger by a derivate branch: the selected layout allows to bypass the WHR/oil heat exchanger once the oil reaches its thermal stability, in order to avoid overheating of the oil and to keep its thermo-mechanical properties to normal design values. Furthermore, the fact that the WHR/oil heat exchanger is in parallel with the cooler leads to reduced pressure drops on the exhaust line and to a more effective flow control through thermostatic three-way valves. The need to compromise between high thermal transfer efficiency under off-design conditions (i.e. variability of exhaust flowrate and enthalpy content) and on-board applicability (e.g. shell diameter suitability with exhaust pipe size, tubes geometry and number to minimize engine backpressure) leaves very little margin on both heat exchanger selection and sizing.

An AVL APA 100 dynamometer drives the engine through the NEDC cycle, i.e. four ECE urban cycles (780 s, 4 km) and an EUDC extra-urban cycle (400 s, 7 km), performed in different seasons and under different environmental conditions.

The mass flowrate of exhaust gases is calculated, based on the values of air mass flowrate and fuel consumption, both directly measured. Same goes for CO_2 and other primary pollutants, whose values are measured upstream the after-treatment section. Pressure losses associated with the additional heat exchanger on the exhaust line, the available thermal power to the WHR/oil heat exchanger and the fluid-dynamics in the lubricant circuit are all reconstructed through sensors, according to Fig. 1 and Table 1. Table 2 reports the values of main quantities used in vehicle parametrization and allowing a proper modeling of power profiles associated with the NEDC cycle. Fig. 2 shows the aerodynamic and friction losses and the inertia contribution the engine needs to overcome during both standard urban and extra-urban cycles.

Aerodynamic and inertia-related losses seem to rearrange during the

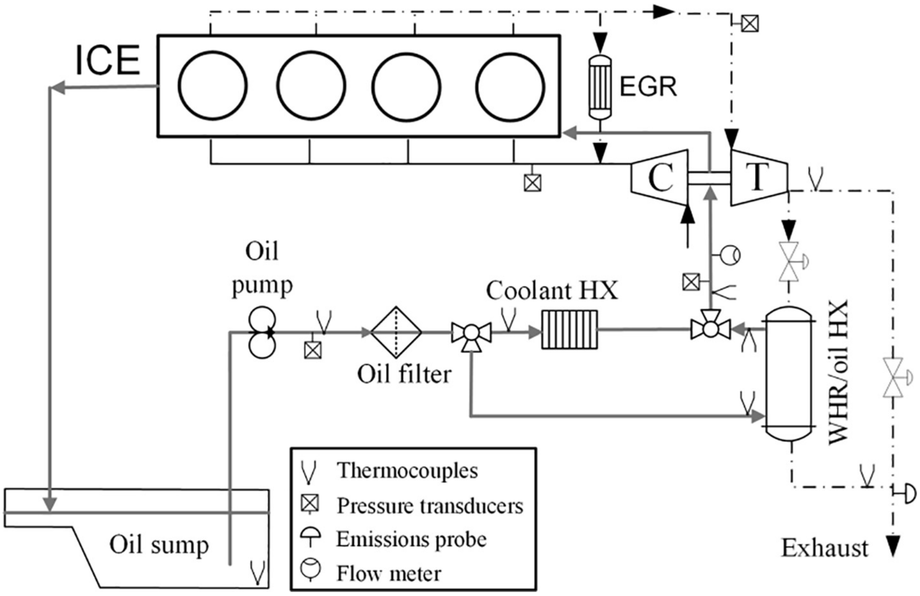

Fig. 1. Engine oil circuit layout with WHR.