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Nodal modelling for advanced thermal-management of internal combustion engine

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HIGHLIGHTS

- Coolant and oil temperatures modelling for internal combustion engine.
- Nodal modelling of internal combustion engine in order to reduce warm up phase.
- The nodal modal can be used in order to reduce the engine mass.
- Experimental validation with an engine test bench but also with a vehicle test bench.

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ABSTRACT

The evolution of temperatures in internal combustion engines during cold start is quite important. This greatly affects fuel consumption and vehicle emissions. In this paper, an advanced thermal management model is presented and used on an automotive Diesel engine in order to determine the evolution of the different temperatures during warm-up stage. The paper focuses on the complete description of the engine components, coolant circuit, and lubricant circuit. The objective is to calculate the heat exchanges between the thermal masses of sub-models (cylinder head, engine block, pistons, oil sump...) and the fluids. Experiments on an engine were realized in order to calibrate the model (heat release, friction losses...) but also to obtain the temperature evolutions during transient stage. These last results were used in order to validate the model. This approach gives the possibility to determine the coolant and oil temperature evolution with a minimum of nodes and a relatively short calculation time. The evolution of the coolant temperature in a vehicle during a NEDC cycle with a cold start was studied. A good agreement was obtained. Finally, the model was used in order to study the possibilities to reduce the vehicle mass by a reduction of the engine mass.

1. Introduction

The evolution of the environmental constraints for automotive vehicle leads to new challenges especially for the internal combustion engine. The objective is to reduce pollutant emissions and fuel consumption (and as a consequence CO_2 emissions) [1,2] with the same level of engine performance and thermal comfort. It is important to know that vehicles are often used for small travels [3] and engines run in low loads and low speeds configurations. As a consequence, they are used far from their optimal temperature and in transient thermal conditions [4]. During the warm-up phase, the combustion process is not efficient (due to the low temperatures of the cylinder walls), post-treatment devices are not effective, fuel consumption is important, and the passenger compartment cannot be heated. It is then important to reduce engine warm-up time which increases fuel consumption about 5–30% [5].

It is known that only third of the fuel energy released by the combustion of the fuel mixture is converted to useful work. The remaining part of the fuel energy is evacuated with the exhaust gases or transferred to the coolant or lubricant circuits. The energy distribution between all these circuits varies according to the engine operating point (rotational speed and load) and the engine thermal state. The heat exchanges are convective and radiative types and operate in different parts of the engine. In first place, in the combustion chamber, between combustion gas, walls, and piston, but also within the cylinder head with the intake and exhaust pipes. Hence, all the circuits (air, lubricant and coolant) can be analysed. Previous studies show that during warm-up, the coolant temperature reaches its optimal temperature whereas

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Nomenclature

b	bore (mm)
Bi	Biot number
c	stroke (mm)
Cp	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
Db	bearing diameter (mm)
e	characteristic length (m)
FMEP	friction mean effective pressure (Pa)
K	coefficient
Lb	bearing length (mm)
Lv	maximum valve lift (mm)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
N	rotational engine speed (rpm)
nb	number of bearings
nc	number of cylinders
nv	number of valves
Nu	Nusselt number
Pmax	maximum pressure in cylinder during current cycle (Pa)
Pr	Prandtl number
q	heat flux density ($W\ m^{-2}$)
Re	Reynolds number
S	surface (m^2)
Sp	instantaneous speed of the piston ($mm\ s^{-1}$)
T	temperature (K)
V	volume (m^3)

Greek symbols

ε	emissivity
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
μ	viscosity (Pa s)
ρ	density ($kg\ m^{-3}$)
ϕ	heat flux (W)
σ	Stefan Boltzmann's constant

Subscripts

cool	coolant
cool_Twall	coolant but with the temperature of the wall
i	element i
j	element j
ref	reference

Acronyms

EGR	Exhaust Gas Recirculation
HF	High Frequency
LF	low frequency
NEDC	New European Driving Cycle
TDC	top dead centre
VGT	Variable Geometry Turbine

the lubricant temperature is still in evolution [6–8]. Then, it is important to determine the evolution of the different temperatures in the engine and the interaction between all components. The first objective of the lubricant is to reduce the friction losses and thus the fuel consumption. Indeed, as the lubricant temperature increases, its viscosity decreases leading to a reduction in friction losses. This is why the fuel consumption is directly connected to the lubricant temperature [9–11]. The challenge is to reduce engine warm-up which is equivalent to a quick increase of the coolant and lubricant temperatures.

Many solutions exist in order to run the engine at a higher temperature. For example, it is possible to reduce the engine heat losses (insulation) [12,13] or to introduce electric devices on the coolant system. However, this last solution is not acceptable because the electric devices require energy and increase the fuel consumption. With well suited modifications on the coolant circuit, fuel consumption can be reduced by 2% on NEDC [14–16]. One solution consists to reduce warm-up time with a no flow strategy [17]. The objective is to have zero flow in the engine during warm-up in order to quickly increase the local materials and oil temperatures. It is then possible to reduce around 4% of the fuel consumption (on NEDC) with an active valve with zero flow strategy [18].

Roaud et al. [4] suggest to reduce the engine mass. However, if mass modifications are made, it is necessary to design a new engine and test it in order to define the fuel consumption improvement. Another possibility consists to use a simulation code with a complete description of each engine part. This methodology gives the possibility to study the energy flows in an engine without experiment limitations and reduce the costs and time needed to define the engine behaviour. It is then necessary to calculate the temperatures at different points in the engine (block, cylinder head, piston, sump…). For this reason, a multi-nodes model can be used [19–21] to determine the heat exchange in the different parts on the engine. Unfortunately, it appears that this kind of model is not sufficient due to the low values of nodes and, as a consequence, the calibration parameters. The aim of this paper is to propose a complete model of the engine for thermal analysis of coolant and lubricant temperature and study the influence of engine modifications on reducing the warm-up and the fuel consumption.

2. Engine experimental test bench and instrumentation

In order to establish the new model and study the influence of the different parameters, a four cylinder turbo-Diesel engine is used. The engine specifications are presented in Table 1. It was equipped with a common rail fuel injection system, a high EGR loop, a turbocharger with a VGT and a charge air cooler.

The engine (described in Fig. 1) was installed on a transient dynamometer test bench. The gearbox was removed and replaced with a direct drive to the dynamometer. It is also important to note that engine auxiliary devices were removed like conditioning compressor, alternator… Modifications were made in order to realize tests on this kind of experimental setup (out-vehicle configuration so without air flow due to the vehicle evolution). The intercooler was replaced by an air/water heat exchanger in order to control the exhaust charge air cooler temperature. The car radiator was removed and replaced by a coolant/water heat exchanger which gives the possibility to control the temperature drop around the engine. In another way, EGR cooling was still performed by the main engine coolant.

This experimental setup is used to determine the engine performances and to measure the evolution of different parameters such

Table 1
Engine specifications.

Engine type	Compression ignition
Compression ratio	15.3
Number of cylinders	4 cylinder in line
Number of valves per cylinder	4
Bore	76 mm
Stroke	80,5 mm