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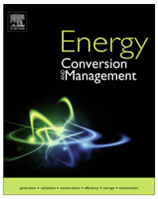

Internal combustion engine cold-start efficiency: A review of the problem, causes and potential solutions

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ABSTRACT

Legislation on vehicle emissions continues to become more stringent in an effort to minimise the impact of internal combustion engines on the environment. One area of significant concern in this respect is that of the cold-start; the thermal efficiency of the internal combustion engine is significantly lower at cold-start than when the vehicle reaches steady state temperatures owing to sub-optimal lubricant and component temperatures. The drive for thermal efficiency (of both the internal combustion engine and of the vehicle as a whole) has led to a variety of solutions being trialled to assess their merits and effects on other vehicle systems during this warm-up phase (and implemented where appropriate). The approaches have a common theme of attempting to reduce energy losses so that systems and components reach their intended operating temperature range as soon as possible after engine start. In the case of the engine, this is primarily focused on the lubricant system. Lubricant viscosity is highly sensitive to temperature and the increased viscosity at low temperatures results in higher frictional and pumping losses than would be observed at the target operating temperature. The approaches used to tackle the problem include the use of phase change materials (to reduce the cool-down rate during a period following engine running) [1,2] and the use of thermal barrier coatings in an attempt to insulate the cylinder bore and prevent heat loss (thus increasing the amount of energy utilised as brake work [3]). A range of system alterations have also been trialled including diversion systems on the lubricant circuit to reduce thermal losses. Presented here is a critical review of the research into vehicle thermal management during the cold-start phase which has been driven by a desire to improve both engine and overall vehicle engine efficiency. The review includes both system developments and material selection issues and the role the two fields have to play in tackling this critical issue.

1. Introduction

The role of the internal combustion engine in a vehicle is to provide power to the driven wheels via the drive train. For this to be achieved efficiently, the engine needs to be served by both a lubricant system and a coolant system. The lubricant system prevents metal on metal contact between moving components (thereby reducing friction and wear), and the coolant system keeps the lubricant and component materials within acceptable service temperatures.

It is largely accepted that the combustion efficiency of a modern internal combustion (I.C.) engine is well optimised, with approximately 98% of the energy contained within the fuel being released on combustion in diesel engines and 95–98% in gasoline engines [4]. However, the useful energy leaving the engine (termed 'brake work') is typically only 40% of the fuel energy [4,5]. The energy that is used to provide drive to the wheels is less than the brake work, since a fraction of this needs to be used to drive ancillaries such as water pumps and the alternator. This inability to convert all the chemical energy into brake work is termed the 'gross indicated thermal efficiency'. The overall efficiency of the engine is termed the 'fuel conversion efficiency' and is defined in Eq. (1):

$$\text{Fuel Conversion Efficiency} = \text{Combustion Efficiency} \times \text{Gross Indicated Thermal Efficiency} \quad (1)$$

Eq. (1): Definition of engine fuel conversion efficiency

As will be outlined in Section 4.1, the properties of lubricants are highly temperature dependent and, without exception, engine lubricants are designed to be at their most efficient at steady state operating temperatures which range between 100 °C and 110 °C [6,7]. High lubricant viscosity at lower temperatures results in

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Nomenclature

I.C.	internal combustion
NEDC	New European Drive Cycle
FTP	Federal Test Procedure
CO	carbon monoxide
HC	hydro carbon
NOx	nitrous oxides
PPM	parts per million
λ	$\frac{AFR}{AFR_{stoichmetric}}$
AFR	air:fuel ratio
So	Sommerfeld number
μ or Z	dynamic viscosity (N s m^{-2})
υ	kinematic viscosity (m^2 s^{-1})
N	relative velocity of the two surfaces (m s^{-1})
P	applied load per unit width of the bearing (N m^{-1})
F	frictional force within the bearing (N)
D	bearing diameter (m)
U	relative bearing speed (m s^{-1})
c	bearing clearance (m)
ε	eccentricity ratio
BMEP	brake mean effective pressure
S.I.	spark ignition
C.I.	compression ignition
TEG	thermoelectric generator
Z	figure of merit
α	Seebeck coefficient (V K^{-1})
ρ	electrical resistivity (Ω m^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
VCHP	variable conductance heat pipe
TBC	thermal barrier coating
FMEP	friction mean effective pressure
PCM	phase change material
C_p	specific heat capacity (J kg^{-1} K^{-1})
m	mass (kg)
AH	auxiliary heater
EGHR	exhaust gas heat recover unit
LHA	latent heat accumulator

higher frictional losses, reducing the indicated thermal efficiency of the engine further. Will et al. [5,8] estimated that frictional losses in the engine during the early stages of warm-up (when the engine is in the region of 20 °C) can be up to 2.5 times higher than those observed when the lubricant is fully warm. If this temperature is reduced to a cold-start scenario of 0 °C, then Samhaber et al. [9] predicted increases in fuel consumption of up to 13.5%. Such a trend is not only critical over the course of the NEDC but has a significant impact on the vehicle owner. André [10] carried out extensive work investigating the driving habits and trends of vehicles used in real conditions. He found that most trips made by car owners are of a short duration in terms of both time and distance. The work investigated the driving trends of 55 vehicles and characterised 1840 h of vehicle running and found that approximately one third of the trips made did not enable the engine coolant to exceed 70 °C or the engine lubricant to exceed 60 °C.

During the engine warm-up phase, there are effectively three thermal masses interacting with each other, namely the main engine block, the lubricant and coolant. Of the three, the coolant is the fastest to respond owing to its temperature being closely coupled to that of the combustion gases [4,11,12]. In contrast, the lubricant temperature and block temperature are generally much slower to respond owing to the block having a large thermal inertia and the lubricant being much less closely coupled to the combustion process [7,13,14]. During the early phases of warm-up when the cylinder walls are cold, most of the energy from combustion is transferred to the walls owing to the high temperature differential between them and the combustion gases. With this in mind, thermodynamics indicates that insulating the combustion process from the block as much as possible (and thus increasing the gas temperature) will increase the conversion efficiency of combustion energy to mechanical brake work [3,15].

The desired increase in temperature of the lubricant during the warm-up phase results from some direct transfer of heat from the cylinder walls, but primarily results from frictional dissipation in the engine systems such as the main bearings [7,16,17]. During the cold-start phase, a high heating rate of the lubricant to its optimum operational temperature is desirable, which in turn indicates that anything that limits the lubricant heating rate is undesirable. One route to achieve this would be the insulation of the lubricant circuit from the engine block in regions where the engine block is cooler than the lubricant. Alternatively, one could attempt to recover energy from other systems to increase the rate of lubricant warm-up. However, there is a need to ensure that any of these strategies do not prevent the lubricant being maintained at its optimal operational temperature once this has been reached (i.e. lubricant overheating must be avoided).

This work aims to review the approaches taken to improve engine cold-start performance, assess the findings and discuss the likely effectiveness of strategies based on system performance and materials optimisation.

2. Legislation and emissions performance

The New European Drive Cycle (NEDC) is an important performance metric for internal combustion engine efficiency. It is a 1200 s long drive cycle against which all new engines are tested, and aims to simulate a range of driving scenarios from motorway cruising to city centre idling as shown by the speed trace in Fig. 1 [18]. In the European Union, fuel consumption figures for new cars are quantified from the NEDC and thus any methods to improve cold-start efficiency must be effective in reducing fuel consumption over an NEDC test.

As well as concerns with efficiency, the need to improve cold-start performance is also highly influenced by the need to improve emission quality. As pressure increases to minimise the burden that I.C. engines place on the environment, legislation continues to tighten. Examples include the London Emission Zone that imposes financial penalties on commercial vehicles that fail to meet Transport for London particulate matter legislation. European OEMS are required under EU law by 1st January 2015 to ensure

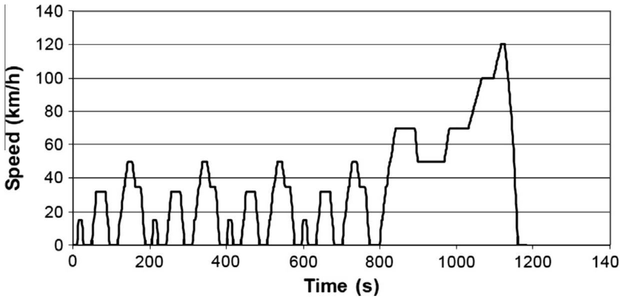

Fig. 1. Speed–time trace for the NEDC [18].