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Research paper

# Numerical model and control strategies for the advanced thermal management system of diesel engine

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## HIGHLIGHTS

- Numerical models for the advanced and conventional TMSs of diesel engine are set up.
- Control strategies for the advanced TMS are proposed and evaluated.
- Comparisons are made between the advanced TMS and the conventional one under ETC.
- The proposed control strategies can control the engine working temperature well.
- Above 50% of the conventional TMS power consumption is saved by the advanced TMS.

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## ABSTRACT

The advanced thermal management system (TMS) with electrically-controlled pumps, fan and valves for diesel engine was investigated with the aim of enhancing the engine performance by providing good thermal conditions and reducing its parasitic power consumption. A one-dimension, transient numerical model for the advanced TMS was established. Based on the model, the control strategies for the combined control of the coolant circuit and oil circuit in the advanced TMS were proposed and evaluated. A feedforward and feedback control strategy was proposed for the electrical pumps and fan, and a feedback control strategy was proposed for the electrical valves. In addition, a control strategy for the engine warm-up process was also proposed for the rapid warming up of the engine. Comparisons between the present advanced TMS and the conventional one under the European transient cycle (ETC) show that the advanced TMS with the present control strategies has an excellent ability to control the engine working temperature, and the total power consumption of the advanced TMS during the ETC can reduce 57.0% compared with the conventional system, which is due to the flexible control of the electrical components in the system.



## 1. Introduction

Diesel engines are widely used in various kinds of applications due to their features of high efficiency, good power performance, etc. [1]. As an important subsystem of diesel engines, thermal management system (TMS) contributes greatly to the reliability and efficiency of diesel engines [1,2]. The modern diesel engines are required to develop towards the directions of higher power density, lower fuel consumption and lower emissions, especially under the present background of global energy shortage and environmental pollution [1–6]. Therefore, great challenges are put forward on the design and operation of the modern TMS. An advanced TMS not only needs to guarantee the reliable work of the engine, but also to realize a precise control of the engine working temperature, and to reduce the parasitic power consumption of the accessories in the TMS, such as pumps, fans, etc. [1,2,7].

Generally, the TMS of a diesel engine is mainly composed of a coolant circuit and an oil circuit, and both are very important for the engine [1]. The working condition of the TMS is mainly determined by the operation of the pumps and fan in the system. However, in the conventional TMS, the coolant pump, oil pump and fan are usually driven by the crankshaft of the engine through belts

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or gears mechanically, and the coolant and oil temperatures are maintained through the thermostats which are working based on the thermal expansion and contraction of the wax in them [1]. This kind of systems cannot always provide proper working condition during the running of the engine, since they are designed based on the maximum heat load or worst ambient temperature condition [8,9]. For instance, researches show that the coolant pump in the conventional TMS produces much more coolant flow rate than necessary up to 95% of the working time [9,10] and similar problem happens in the oil pump as well [11], which will not only lead to serious waste of the energy, but also not be beneficial to the temperature control of the engine.

The rapid development of the electronic technology provides a chance for the TMS to deal with the problems of the conventional system in recent decades. Researchers attempt to replace the mechanical pumps, fan and conventional thermostats with electrical ones, which provide an opportunity to apply real time control strategies to enhancing the engine performance. For the electrically-controlled TMS, the proper control strategy is the key for the TMS to make the engine work more reliably and efficiently. Therefore, much attention has been attracted to this field and relevant studies have been done. For instance, Cortona and Onder [12] developed a model for the thermal behavior of the engine and the cooling circuit to reduce the fuel consumption and mechanical wear during cold start and partial load operations by controlling the electrical pump and valve. The results show that the coolant pump energy consumption of the electrically-controlled system can be reduced to 16% of the conventional system, and it is possible to reduce the duration of the engine cold-start phase and to operate the engine under optimal thermal conditions with the electrical cooling pump and the electrical valve. Luptowski et al. [13] developed a fully coupled engine and cooling system model by the linkage of the Vehicle Engine Cooling System Simulation with GT-power, and developed an actively controlled electric cooling system for a 12.7 L diesel engine. The results show that the fuel economy was improved by reducing the accessory power through precisely controlled operation of the coolant pump and fan speed. Liu et al. [14] established a cooling model for the turbocharged diesel engine by using lumped parameter method, and proposed and investigated a control strategy consisting of variable gain PI feedback module and feedforward module. Their results show that the coolant temperature fluctuation could be controlled within ±1 K under the C-WTVC driving cycle test and the power consumption was significantly reduced. Negandhi et al. [15] studied the use of a BorgWarner dual mode coolant pump (DMCP) in the active thermal management, where the DMCP can run both in mechanical and electrical modes. The control algorithm for the pump was developed and the effectiveness of the control strategy was demonstrated by the UDDS cycle. The results show that the fuel economy of the engine was improved by more than 2% due to the effective thermal management with the DMCP. More relevant studies can be found in Refs. [8–11,16–31]. Many results have demonstrated that the electronic control of the TMS is of great benefit to the diesel engine. However, most of the reported studies focus their attention on the control of the electrically-controlled cooling circuit, while the electrically-controlled oil circuit in the engine is less concerned. The later also has large potential for the engine to improve its performance [11]. No report has been found on the control strategies for the advanced TMS where the cooling circuit and the oil circuit are electrically controlled simultaneously.

Based on the above consideration, the numerical model for the advanced TMS with cooling circuit and oil circuit was established, and control strategies for the combined electrical control of the cooling circuit and oil circuit were proposed and evaluated in the present paper. Comparisons were also made between the advanced TMS and the conventional one.

## 2. Configuration of the advanced TMS

Fig. 1 shows the configuration of the advanced TMS, which is mainly composed of a coolant circuit and an oil circuit. In the coolant circuit, the coolant is divided into two branches after it flows out from the coolant pump. A small part flows into the oil cooler and then returns to the inlet of the coolant pump. The major part flows into the engine and absorbs heat from the cylinder wall and engine block, then flows into the coolant valve. The valve distributes the coolant flow rates between the bypass pipe and the radiator to control the heat flow rate released to the environment. Finally, all the coolant branches merge together at the inlet of the coolant pump and start a new cycle again. A fan is used to enhance the heat transfer of the radiator. In the oil circuit, the oil pump drives the oil from the oil sump to the oil filter and oil valve. The oil valve distributes the oil flow rates between the bypass pipe and the oil cooler, and then all the oil branches joint together at the inlet of the engine. The operations of the cooling circuit and the oil circuit are electrically-controlled jointly. The operations of the electrical coolant pump, oil pump, fan and valves are controlled by the electronic control unit (ECU) of the engine based on the working condition and the prescribed control strategies. The two basic input parameters that need to be measured for ECU are the coolant temperature at the outlet of the engine, $T_{c\text{-}out}$, and the oil temperature at the outlet of the engine oil sump, $T_{o\text{-}out}$, which are exactly the objects that we want to control in the advanced TMS.

In order to develop the control strategies for the advanced TMS, we should know the thermal behaviors of the TMS. Therefore, the numerical model of the TMS was established and is described in the next part.

## 3. Numerical model for the advanced TMS

A one-dimension, transient numerical model for the advanced TMS was established based on the lumped parameter method [8,14,22–25] according to the practical configuration of the engine. The model was developed on the platform of MATLAB/Simulink and solved by the ode45 solver. The energy conservation analysis was used for the verification of the numerical results. The

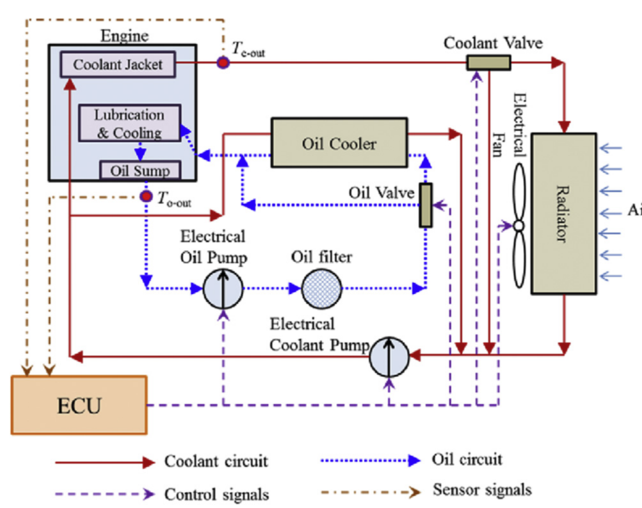


Fig. 1. Configuration of the advanced TMS.