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Research paper

Effects of synergetic and antagonistic additive elements on the thermal performance of engine oils at various bulk temperatures

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HIGHLIGHTS

- Oil additives enhance lubrication properties but may hinder oil thermal performance.
- Sodium, boron, molybdenum, magnesium and barium additives enhance heat transfer.
- Additives containing phosphorous, zinc, calcium and silicon hinder the heat transfer.
- Oil thermal performance is improved by changing some oil additives concentrations.
- Some additives are highly sensitive to interaction with other additives in the oil.

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ABSTRACT

This paper reports effects of additive elements on thermal performance of engine oils during cooling of different engine parts at bulk temperatures from 40 to 150 °C and average wall superheat of 100 °C. The analysis is performed using a back propagation neural network that was trained on experimentally obtained sub-cooled boiling data of engine oils. The results demonstrate that sodium, boron, molybdenum, magnesium and barium additive elements are thermally synergetic while phosphorous, zinc, calcium and silicon elements are thermally antagonistic. Experimental thermal performance of oils could potentially be improved by increasing the concentration of synergetic additive elements or decreasing antagonistic additive elements concentration.

1. Introduction

Internal combustion engine components such as crankshaft, piston under crown, piston ring/liner, cam/follower, valve train, valve stem/guide, bearings, gears, camshaft drive and many other components in the lower part of the engine are dependent on the engine oil for the necessary cooling which represent about 40 percent of required engine cooling [1]. These parts have definite temperature limits which must not be exceeded. Moreover, continuous development of high performance engines poses a continuing challenge to engine lubricant formulators as it means higher operating pressures and temperatures of the engines.

Most previous studies on engine oils focused on the development of additives to accomplish desirable tribological properties of these oils [2]. Considerable attention is given to the development of oil properties such as super alkalinity [3], lower acidity [4], thermal stability and viscosity improvers [5,6], dispersants [7] and anti-friction, antioxidant and antiwear agents [8–10]. Recently, effects of nanofluid additives on the heat transfer, thermal conductivity and flash point have been considered [2,11–14].

However, the effects of tribological additives of engine oil on heat transfer from hot engine surfaces to engine oil have received little attention in the open literature. This is of great interest particularly for high oil or surface temperatures. High oil temperatures develop thermo-oxidative stresses, which leads to deterioration of physical and chemical properties of the oil in the lubrication system of engines and render it ineffective over a period of time. It leads not only to excessive wear and corrosion but may also cause catastrophic failure of lubricated components [15].

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It appears that the first comprehensive experimental program to determine thermal performance of different engine oils was reported by Abou-Ziyan [1] who investigated the relationship between the heat transfer characteristics of lubricating oils and the composition of additives under subcooled boiling conditions. Five commercial engine oils were tested and analyzed. Nine metal and non-metal additive elements, at different degrees of concentration, were identified in the oils using ASTM D4951 and D5185 standards. The author used the experimental oil boiling data together with oil chemical compositions in an attempt to identify the synergetic and antagonistic elements contained in the oil additives. Since there was no way to isolate the effect of each individual element, it was not possible to quantify the effect of any element on the thermal performance of these oils. Therefore, the author was able only to subjectively determine the synergetic and antagonistic elements in the oil additives.

Experimental evaluation of effect of each additive element concentration on the thermal performance of engine oils could be lengthy, expensive and time consuming [16]. The use of effective computational techniques is, therefore, desirable to limit the experimental measurement programs. These techniques should be able to recognize the underlying trends in the experimental data and estimate the oil performance at different conditions. Neural networks offer an attractive option for this purpose since they are known for their ability to analyze highly non linear, complex data trends. Neural network techniques have been used recently in different aspects related to engines or engine oils [16–22].

Recent studies by Abou-Ziyan and co-workers [16,22] focused on the feasibility of using Neural Networks (NNs) to correlate subcooled boiling curves of common base engine oils with the additive elements concentration of these oils. The performance of various types of NNs and their ability to predict heat transfer characteristics of engine oils of different additive elements concentrations under subcooled boiling conditions were assessed. In an attempt to identify the best NN that is capable of accurately predicting oil boiling curves, 57 NNs resulting from 14 NN architectures that belong to three different NN categories were examined; Predictions of these NNs were compared to the experimental subcooled boiling measurements for the 5 engine oils listed in Table 1. A comprehensive statistical analysis was used in the quantitative comparison with the experiments. The studies identified the best NN to be a Back Propagation NN with a single hidden layer that uses a rotation-vanilla technique for pattern selection and weight updates [22]. This NN was capable of accurately predicting the boiling curves and the missing data and smoothing the data with noise levels up to ±5% of experimentally measured values.

The objective of the present work is to identify the thermally synergetic and antagonistic additive elements in engine oils and to quantify their effects on the thermal performance of oils at wall superheat of 100 °C for bulk temperatures in the practical range 40–150 °C. This will provide the oil formulators with valuable information regarding the effect of oil composition on their cooling capabilities of engine parts, i.e., not to adversely affect oil's cooling capability while improving its tribological properties. The benefit of this work is to facilitate evaluating newly formulated oils in terms of their cooling characteristics without the need for extensive thermal experimentation programs since the thermal performance of newly formulated oils may be predicted by the NN under different bulk temperatures provided that the additive elements are known. In addition, the relationship between the thermal performance of oils and their chemical composition can be identified in light of the results of present work.

2. Experimental dataset

Subcooled boiling heat transfer characteristics were determined experimentally for five commercial engine oils at oil bulk temperatures of 40, 60, 80, 100, 125 and 150 °C and for heat flux up to 400 kW/m^2. Details of the experimental setup and procedures were reported by Abou-Ziyan [1]. Three mono-grade oils (SAE 40 with viscosity index of 95) and two multi-grade oils (SAE 20W-50 with high viscosity index) were tested at conditions similar to those found in internal combustion engines. To avoid commercialization, the oils are denoted by letters A, B, C, D and E.

Elemental analysis of engine oils is performed using some standard methods such as inductively coupled plasma atomic emission spectroscopy (ICP–AES) or energy dispersive X-ray fluorescence spectroscopy (EDXRFS) as reported by Sagi et al. [23]. Since there is no standard method to determine the additive compounds in engine oils, the engine oils elemental analysis of the present work was conducted in Kuwait Petroleum Research Center according to ASTM D4951: standard test method for determination of additive elements in lubricating oils by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP–AES) and ASTM D5185-13e1: standard test method for multi-element determination of used and unused lubricating oils and base oils by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP–AES).

The concentrations of barium, boron, calcium, magnesium, molybdenum, phosphorus and zinc in unused lubricating oils are determined according to ASTM D4951 test whereas the concentrations of sodium and silicon are determined according to ASTM D5185-13e1 test.

Many metal and nonmetal elements are present in new engine oils from the additive compounds as listed in Table 1 while viscosity

Table 1
Concentration of metal and non-metal additive elements of the tested engine oils.

Element	Concentration (ppm)					Minimum value	Maximum value
	Oil A	Oil B	Oil C	Oil D	Oil E		
Metal elements							
Sodium (Na)	2.88	2.22	4.2	17.7	2.58	2.22	17.7
Molybdenum (Mo)	11.4	6.6	52.6	6.5	66.0	6.5	66.0
Magnesium (Mg)	2229.4	1291.2	51.6	1216.6	7.4	7.4	2229.4
Barium (Ba)	0.12	0.17	0.12	0.06	0.06	0.06	0.17
Zinc (Zn)	1630	1202.6	323.6	1153.2	762.8	323.6	1630
Calcium (Ca)	101.8	15.4	1950	1081.8	1965.4	15.4	1965.4
Non-metal elements							
Boron (B)	66.0	39.0	6.7	9.0	2.4	2.4	66.0
Phosphorus (P)	1269.2	933.8	233.3	916.2	583.6	233.3	1269.2
Silicon (Si)	9.84	4.74	6.66	8.1	10.14	4.74	10.14