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Thermal Conductivity of Some Oxygenated Fuels and Additives in the Saturated Liquid Phase

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The thermal conductivities of ethylene glycol monobutyl ether, dimethyl ether, methyl ethyl ketone, castor oil, and vegetable seed oil in the near-saturated liquid phase have been measured in the temperature range from (229 to 375) K by the transient hot-wire method with a bare platinum wire. The uncertainty of the experimental results was estimated to be within ±2.0%, and the reproducibility of the data was better than ±0.5%. The liquid thermal conductivities obtained have been correlated as a polynomial function of the temperature, with an absolute mean deviation from the experimental data of less than 0.4% and a maximum deviation of less than 0.6%.

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1. Introduction

As petroleum resources are becoming depleted and environmental pollution is more serious, especially in developing countries, it becomes an urgent problem to find and develop new alternative clean fuels. From the research of the past decade, it has been found that alcohols, ethers, esters, and seed oils are potential alternative fuels for their low emission or easy production. More researchers are beginning to carry out research in this field,[1] but there is little experimental data on the thermal conductivity of most oxygenated fuels and additives. This data is indispensable and required for thermal design in the diverse fields mentioned above. In this work, the thermal conductivities of ethylene glycol monobutyl ether, dimethyl ether, methyl ethyl ketone, castor oil, and vegetable seed oil in the temperature range from (229 to 375) K at the near-saturated liquid phase are presented with an estimated accuracy of ±2.0%.

2. Experimental Apparatus

Measurements of the liquid thermal conductivities for oxygenated fuels and additives were performed with an uncertainty of less than ±2.0% in a transient hot-wire instrument with a single bare platinum wire. The fundamental working equation of the transient hot-wire technique takes the form

$$\lambda(T_r, P) = \frac{q/4\pi}{\mathrm{d}\Delta T/\mathrm{d}\ln t} \qquad (1)$$

where q is the power input per unit length of wire, $\lambda(T_r, P)$ is the thermal conductivity of the fluid at a reference temperature T_r and at the working pressure P, and $\mathrm{d}\Delta T/(\mathrm{d}\ln t)$ is the slope of a line fit to the temperature rise under an ideal condition ΔT versus $\ln t$ data, where t represents the time. The principles of the transient hot-wire method have been described in detail with all of the necessary corrections in many other papers.[2−6]

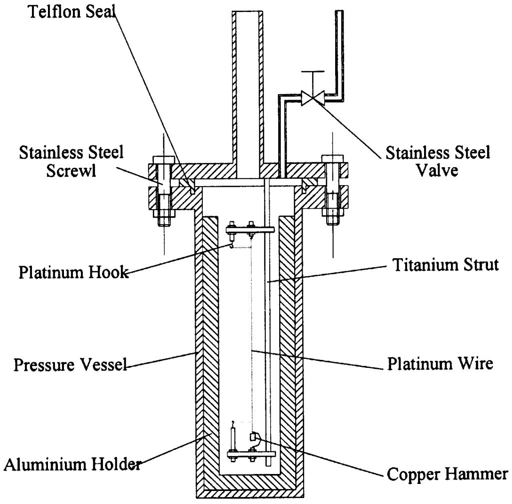

Figure 1. Hot-wire assembly.

Figure 1 shows a cross-sectional diagram of the hot-wire cell with the pressure vessel that is similar to the apparatus reported in refs 7 and 8. The bare platinum wire of 30-μm diameter and 160-mm length is used to decrease effects due to its finite physical properties and its finite length while retaining good tensile strength and uniformity. The wire is welded with the upper and lower platinum hooks with an axial stress of predetermined magnitude by hanging a copper hammer at the bottom of the platinum wire. To compensate for the end effect of the hot wire, two voltage potential leads of the same platinum wire are spot welded at positions nearly 12 mm from each end of the wire. An aluminum-cell holder inserted into the pressure vessel serves to reduce both the vertical nonuniformity in the temperature and the volume of the sample. Between the two potential leads, with the constant current through the platinum wire, the transient voltage rise, which corresponds to the temperature increase in the wire, is measured directly by a high-resolution, 7.5-digit digital voltmeter (Keithley 2010). The calibration of the resistance−temperature relation of the platinum wire was carried out in the temperature range from (230 to 373) K during the experiments. The maximum deviation and the absolute average deviation between the measured values and the correlated equation were 0.22% and 0.06%, respectively.

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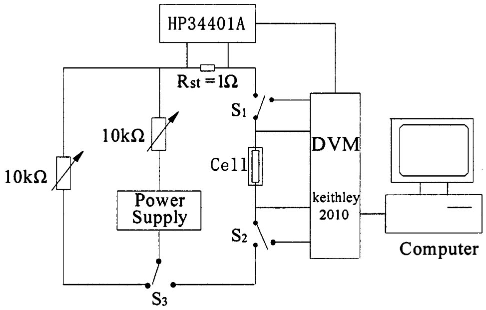

Figure 2. Block diagram of the electrical system.

The transient hot-wire cell was immersed completely in the thermostatic bath in all of the experiments. Alcohol was selected as the bath fluid for the temperature range from (193 to 303) K, and silicone oil was used for the temperature range from (303 to 403) K. The temperature stability of thermostat bath was better than ±4 mK·h^{-1}. The total uncertainty in temperature for thermal conductivity was less than ±5 mK on ITS-90. The details about the thermostatic bath and temperature-measuring system have been described in previous publications.[9,10]

Figure 2 describes the electrical system diagram used in the present research. The apparatus consists of several components: an industrial computer, a constant-current power supply, two DVMs (one is an HP34401A for measuring the current though wire and the other is a Keithley 2010 for measuring the voltage applied to the wire), three electron switches, two ballast resistances, a standard resistor, and the hot-wire cell with thermostatic bath system controlled by another industrial computer that is not shown in Figure 2. All data acquisition and instrument control can be performed by the industrial computer via the IEEE-488 interface.

The global uncertainty of the experimental thermal conductivity obtained with the transient hot-wire method was estimated as follows.[11,12] The length of the platinum wire between the potential leads was measured by a cathetometer, and $\delta L/L$ was accurate to 0.02%. The uncertainty in the temperature coefficient of the platinum wire was estimated to be within ±0.2%, the uncertainty in the heat generation of the hot wire was less than ±0.2%, and the uncertainty in the temperature-rise slope $d\Delta T/(d \ln t)$ of the hot wire was less than ±0.8%. Accounting for the uncertainty in the deviations from the mathematical ideal model and the uncertainty in the presence of other modes of heat transfer, which were reduced to a small magnitude for the properly designed instrument and the well-chosen operating conditions, the overall accuracy of the present thermal conductivity measurements was estimated to be better than ±2.0%.

To check the performance of the present transient hot-wire instruments, the thermal conductivity of the liquid toluene that has been recommended as a reference standard for the liquid thermal conductivity by the International Union of Pure and Applied Chemistry (IUPAC)[13,14] was measured in the temperature range from (234 to 373) K at saturated pressure before measuring the thermal conductivity of the oxygenated fuels and additives. In the calibration measurements, the mass purity of the toluene, which was made by TEDIA Company, was better than 99.9%, and no further purification was processed. The sample was taken directly from the bottle and filled in the vessel. Figure 3 shows a typical recording of the temperature rise of the wire. In this run, the natural convection started at 4.5 s. As indicated in the Figure, the start of the natural convection was detected experimentally, so the convective influence on the measurement of the thermal conductivity was eliminated. The experimental results for toluene listed in Table 1 in which each datum was the average of four to six runs agreed very well within ±1.1% with the recommended data.[15] According to ref 12, the maximum expanded uncertainty (k = 2) of toluene is ±0.00213 W·m^{-1}·K^{-1}.

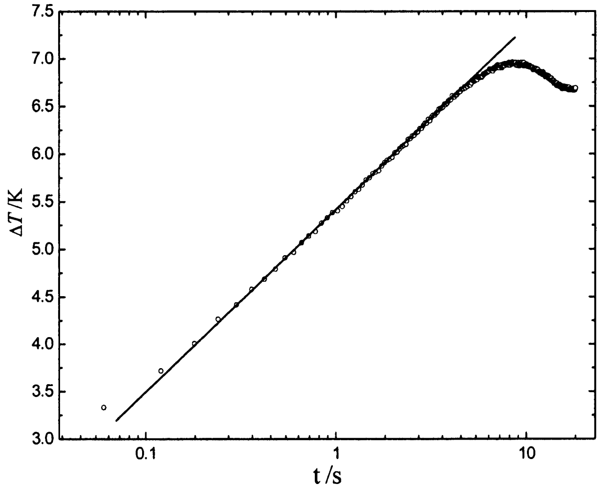

Figure 3. Typical recording of the temperature rise of the wire, toluene (T = 270.15 K, P = 1.465 W·m^{-1}).

Table 1. Thermal Conductivity of Toluene at Saturated Pressure

T/K	λ_{exptl}/(W·m^{-1}·K^{-1})	λ_{ref}/(W·m^{-1}·K^{-1})	$100(\lambda_{exptl} - \lambda_{ref})/\lambda_{ref}$
234.60	0.1477	0.1491	−0.94
254.58	0.1434	0.1439	−0.35
273.17	0.1374	0.1385	−0.83
293.23	0.1334	0.1325	0.64
314.68	0.1264	0.1260	0.25
334.99	0.1211	0.1200	0.84
354.89	0.1136	0.1144	−0.76
373.92	0.1105	0.1094	1.03

3. Results and Discussion

The thermal conductivities of oxygenated fuels and additives in the liquid phase were measured in the temperature range from (229 to 375) K at saturated pressure with the transient hot-wire apparatus. The mass purity of ethylene glycol monobutyl ether, methyl ethyl ketone, and castor oil (glyceryl monoricinoleate) was more than 99.0% for each. The mass purity of dimethyl ether was better than 99.95%, and the vegetable seed oil was a mixture (C, 77.1%; H, 12.1%; O, 10.4%; others, 0.4%). In this work, no further purification was necessary. The thermal conductivity of oxygenated fuels and additives is listed in Table 2. The values represented here are the averages of four to seven runs, whose repeatability was less than ±0.5% at the same temperature and the same pressure. In all measurements, the temperature rise of the platinum wire was about (2.0 to 5.0) K, and the measurement time was (0.3 to 6.0) s after the initiation of heating by adjusting the current through the wire. The initial time of each measurement is mainly determined by the thermal properties of oxygenated fuels and additives and ends when convection starts. A period of about 15 min was allowed between experiments. The temperature fluctuation of the thermostatic bath was controlled to be within ±4 mK·h^{-1} during all measurements at the same temperature point.

Table 2. Thermal Conductivity of Some Oxygenated Fuels and Additives at Saturated Pressure

T/K	λ/(W·m^{-1}·K^{-1})	$u(\lambda)$ (k = 2)/(W·m^{-1}·K^{-1})
Ethylene glycol Monobutyl Ether		
283.96	0.1381	0.0024
293.67	0.1365	0.0026
303.56	0.1350	0.0026
314.25	0.1333	0.0024
323.88	0.1319	0.0020
333.98	0.1305	0.0024
344.05	0.1290	0.0023
354.63	0.1272	0.0018
363.59	0.1258	0.0023
373.84	0.1241	0.0021
Dimethyl Ether		
229.67	0.1832	0.0032
244.98	0.1762	0.0034
254.60	0.1701	0.0028
271.55	0.1605	0.0027
281.76	0.1537	0.0030
291.33	0.1485	0.0026
Methyl Ethyl Ketone		
284.48	0.1501	0.0028
294.42	0.1481	0.0022
305.02	0.1459	0.0028
314.26	0.1435	0.0023
323.96	0.1414	0.0026
334.71	0.1390	0.0026
344.54	0.1362	0.0020
354.33	0.1334	0.0022
364.46	0.1308	0.0022
374.56	0.1284	0.0024
Castor Oil		
285.22	0.1752	0.0018
295.14	0.1741	0.0024
305.23	0.1729	0.0013
315.10	0.1716	0.0027
325.18	0.1710	0.0017
335.05	0.1702	0.0017
345.31	0.1690	0.0021
355.25	0.1678	0.0013
365.09	0.1671	0.0015
375.20	0.1661	0.0020
Vegetable Seed Oil		
283.38	0.1587	0.0028
292.78	0.1573	0.0023
303.25	0.1558	0.0018
313.43	0.1544	0.0026
324.08	0.1534	0.0024
333.25	0.1522	0.0018
343.34	0.1508	0.0025
353.76	0.1495	0.0023
363.09	0.1483	0.0020
373.53	0.1470	0.0025

Table 3. Values of A and B of Equation 2 for Some Fuels and Additives

material	formula	A/ (W·m^{-1}·K^{-1})	B/ (W·m^{-1})
ethylene glycol monobutyl ether	$C_6H_{14}O_2$	0.13972	-1.538×10^{-4}
dimethyl ether	C_2H_6O	0.15195	-5.740×10^{-4}
methyl ethyl ketone	C_4H_8O	0.15345	-2.445×10^{-4}
castor oil	$C_{18}H_{34}O_3$	0.17620	-9.990×10^{-5}
vegetable seed oil	mixture	0.15981	-1.280×10^{-4}

For engineering applications, the measured thermal conductivity data were correlated by a linear equation in each temperature range as follows:

$$\lambda/\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}} = A + B(T/\mathrm{K} - 273.15) \qquad (2)$$

T represents the temperature at the saturated pressure. Table 3 lists values of A and B of each correlated equation. The departure of the experimental data from those calculated by eq 2 was less than 0.4% with the mean deviation and less than 0.6% with the maximum deviation. Both were consistent with the estimated accuracy. Because there were no previous measurements of liquid thermal conductivity for oxygenated fuels and additives found, no comparison is presented here. The second series was carried out so as to confirm the accuracy of the results after the first series of experiments finished several days later. Data from the two series of experiments agreed well with each other within an accuracy of ±2.0%.

4. Conclusions

In the present work, the thermal conductivities of some liquid oxygenated fuels and additives, such as ethylene glycol monobutyl ether, dimethyl ether, methyl ethyl ketone, castor oil, and vegetable seed oil, were measured in the temperature range from (229 to 375) K by the transient hot-wire method with a bare platinum wire. The uncertainty of the results is ±2.0%, and the repeatability is ±0.5%. The experiment data of each liquid were correlated as a function of temperature with a mean deviation of less than 0.4% and a maximum deviation of less than 0.6%.

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