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Thermal-Conductivity Measurements of Aviation Kerosene RP-3 from (285 to 513) K at Sub- and Supercritical Pressures

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Abstract The thermal conductivity of a representative endothermic hydrocarbon aviation kerosene fuel RP-3 was accurately measured using the classical transient hot-wire method at sub- and supercritical pressures. The measured data cover a temperature range of 285 K to 513 K and a pressure range of 0.1 MPa to 5 MPa. The expanded uncertainty of the experiment was less than 3.0 % based on an uncertainty analysis. Furthermore, the measured data were correlated using a polynomial equation to analyze the deviations; 97.6 % of the measured data were within a 2 % error band. The average absolute deviation (*AAD*) and maximum absolute deviation (*MAD*) of the fitted thermal-conductivity data were 0.209 % and 2.31 % for all values, respectively.

Keywords Kerosene · Measurement · RP-3 · Supercritical · Thermal conductivity

1 Introduction

The demand for improved aeroengine performance necessitates higher and higher engine operating temperatures. In particular, as the flight speed increases to the supersonic and hypersonic regime, the temperature of the exit air of a high-pressure compressor becomes too high to cool the hot-end components such as turbine disks and vanes. To achieve this goal, much attention has been devoted to two main aspects:

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improved cooling techniques and increased material temperature capability. However, the progress in both the areas is very limited because of the imbalance between cost and manufacturability. Therefore, some coolants should be used to increase the quality of cooling air. For this purpose, an aviation fuel was introduced to the air heat exchanger of an aeroengine [1,2]. Aviation fuel taken on board is the most promising additional coolant because of its significant heat sink. Moreover, heated fuel is easily atomized, which is beneficial for the combustion of fuel.

The database for thermophysical properties such as density, specific heat capacity, dynamic viscosity, and thermal conductivity are crucial for calculating heat transfer and evaluating the heat exchanger. The thermophysical properties of China kerosene RP-3 including density and heat capacity were measured by Deng et al. [3,4]. Thermal conductivity is an important thermal property parameter for energy and power engineering. The transient hot-wire method is well established as the most accurate method for measuring the conductivity of fluids. Roder [5] developed an apparatus for measuring the thermal conductivity of fluids at temperatures from 70 K to 320 K with an uncertainty of 1.5 %. Perkins et al. [6] used a new apparatus for measuring both the thermal conductivity and thermal diffusivity of fluids at temperatures from 220 K to 775 K at pressures up to 70 MPa based on the step-power-forced transient hot-wire technique. Assael and Karagiannidis [7] measured the thermal conductivity of liquid refrigerants and solids using improved devices based on the transient hot-wire method. The thermal conductivities of pure liquid compounds and mixtures have been investigated by many researchers in different temperature ranges [8–16]. However, the thermal-conductivity measurements of multicomponent hydrocarbon fuels have rarely been reported. In particular, accurate thermal-conductivity data of aviation fuels are indispensable in the calculation of heat transfer in a fuel supply system. In this study, an improved transient double hot-wire apparatus was developed and verified by measuring the thermal conductivity of toluene (290 K to 360 K) and nitrogen (285 K to 485 K). Using this apparatus, the thermal conductivity of a multicomponent hydrocarbon aviation fuel RP-3 was obtained within the temperature range of 285 K to 513 K at sub- and supercritical pressures (0.1 MPa to 5 MPa). The thermal-conductivity database of aviation fuel can also facilitate the design of a fuel supply system.

2 Experimental Setup

2.1 Sample Material

A typical aviation jet fuel RP-3 was used in this study. A composition analysis using GC6890-MS5975 shows that RP-3 consists of 52.44 % alkanes, 7.64 % alkenes, 18.53 % benzenes, 15.54 % cycloalkanes, 4.39 % naphthalene, and 1.46 % other compositions. A detailed composition analysis has been carried out by Deng et al. [3,19]. The critical pressure ($P_c = 2.33$ MPa) of hydrocarbon RP-3 was measured using a critical opalescence phenomenon. Moreover, the toluene and nitrogen used in the validation and repeatability tests were 99.5 % and 99.99 % pure, respectively.

2.2 Transient Method

The transient double hot-wire method is well established as the most accurate method for measuring the thermal conductivity of fluids. Many researchers contributed to the development of the transient hot-wire method [16–18]. This method is based on several assumptions as follows: (1) the diameter of the wire is infinitesimal, (2) the thermophysical properties of the fluids and wire are constant during an experimental run, (3) the effects of thermal radiation and convection are negligible, and (4) the boundaries of fluid space around the hot wire are infinite. In this study, an improved transient hot-wire apparatus was developed.

The equation for one-dimensional transient hot-wire energy in a cylindrical coordinate system can be expressed as follows:

$$\frac{\partial \theta}{\partial \tau} = a\left(\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r}\frac{\partial \theta}{\partial r}\right), \tag{1}$$

where $\theta = \theta\,(r, \tau) = T\,(r, \tau) - T_0$, and a is the thermal diffusion coefficient.

The measured thermal conductivity can be expressed by the following equation:

$$\lambda(T_\mathrm{r}) = \frac{q}{4\pi} \Big/ \frac{\mathrm{d}\Delta T}{\mathrm{d}(\ln \tau)}, \tag{2}$$

where $\lambda\,(T_\mathrm{r})$ is the thermal conductivity of the fluid at a reference temperature T_r, q is the heat generated per unit length of the line source, and $\mathrm{d}\Delta T/\mathrm{d}(\ln\tau)$ is the experimental gradient of temperature rise versus the natural logarithm of elapsed time τ. The reference temperature of the thermal conductivity of a fluid can be defined as follows:

$$T_\mathrm{r} = T_0 + (\Delta T_1 + \Delta T_2)/2, \tag{3}$$

where ΔT_1 and ΔT_2 are the temperature rise at the start and end of an experimental run, and T_0 is the initial temperature of the platinum wire. The relationship between temperature and electrical resistance can be described as follows:

$$R_T = R_0 + \mu(T - 273.15) \tag{4}$$

where $\mu = aR_0$ is the temperature coefficient of the platinum wire electrical resistance, R_0 is the electrical resistance of one section of the platinum wire with a given length at 0 °C. It should be made clear that the relationship between the resistance and temperature of the platinum wire was calibrated from 283 K to 540 K.

2.3 Experimental Apparatus

The experimental system is shown in Fig. 1 and consists of a heating system, data acquisition system, and measurement system. The system pressure was achieved using

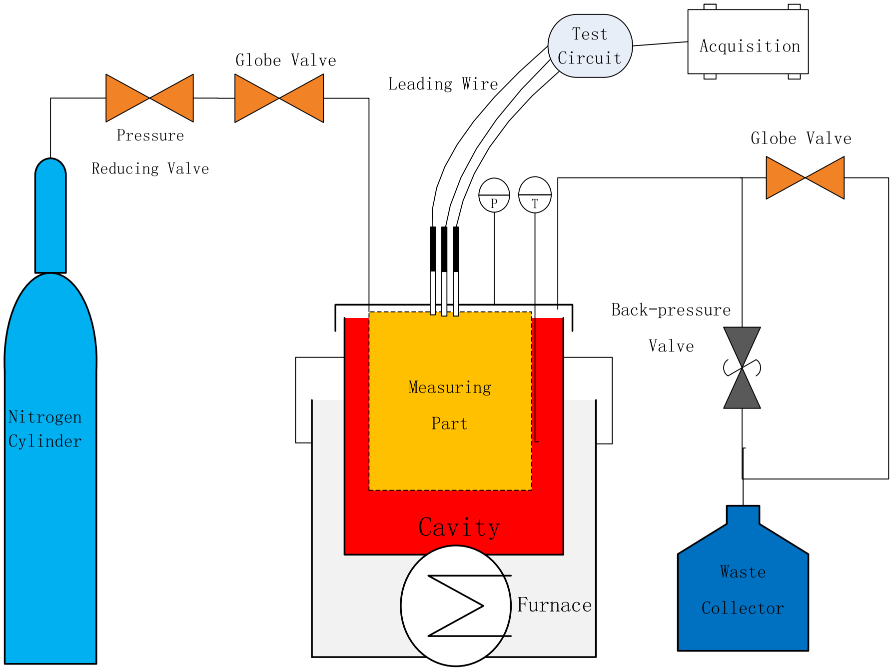

Fig. 1 Experimental apparatus

a high-pressure nitrogen tank. A self-feedback thermostat furnace was introduced for measurements.

To eliminate the end effects of the platinum wire, the transient double hot-wire method was used. A fixed constant electric current was passed through two serial platinum wires with different lengths. To convert the temperature rise to a measurable electrical signal, an unbalanced Wheatstone bridge was introduced, the most common electric circuit to transform small signals. The circuit diagram of this transient double hot-wire method is shown in Fig. 2. At the initial moment, resistances R_3 and R_4 were altered to balance the Wheatstone bridge, and then a constant step current was passed through the long and short platinum wires. During the experiment, the hot wires were used as both electrical resistance thermometers and heat sources. R_1, R_2, and R_{st} are high-precision resistances with a relative error of 0.01 %. The voltage of R_{st} was measured to obtain the current passing through the platinum wires. R_3 and R_4 are variable resistance boxes with a relative error of 0.01 %. R_5 stabilizes the power supply output. A constant-current circuit was introduced for its smaller nonlinear error. One multifunction card (PCI-1710HGU, Advantech) with eight differential analog inputs and 100 kHz sampling rate was used as the data acquisition system.

The voltages of R_l, R_s, R_{st}, and the bridge were measured with a 1000 Hz sampling rate. The bridge voltage is deduced as follows:

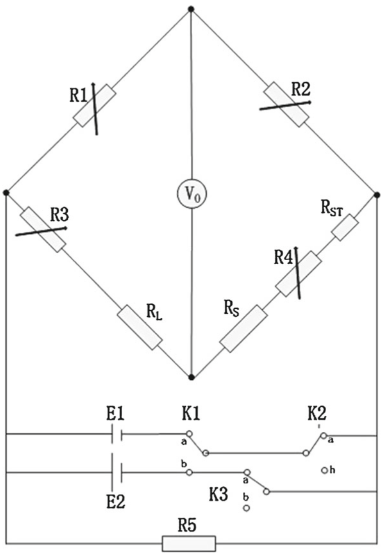

Fig. 2 Electrical circuit of transient hot-double-wire method

$$\Delta U = \frac{(R_3 + R_\mathrm{L} + \mathrm{d}R_\mathrm{L})\,E}{R_3 + R_\mathrm{L} + R_4 + R_\mathrm{S} + R_\mathrm{ST} + \mathrm{d}R_\mathrm{L} + \mathrm{d}R_\mathrm{S}} - \frac{E}{2}$$
$$\lambda = \frac{\mu I^3 R_x}{8\pi L_x} \Big/ \frac{\mathrm{d}U}{\mathrm{d}(ln\tau)}. \tag{5}$$

At the beginning of the experiment, a small direct current of 1 mA to 2 mA was applied to the circuit for adjusting the electrical resistance of the two bridge arms to make sure that the bridge is balanced. Then, an experimental direct current of 25 mA was introduced as the heating current after quickly switching to the measuring circuit. Because of environmental interference to the electric signals, an electric filter was used to eliminate the disturbance.

To obtain the thermal-conductivity data of RP-3 at higher temperatures, several measures were taken to reduce the effects of natural convection. First, small power heating was introduced to reduce the radial and temperature nonuniformity significantly. A symmetrical temperature field is the most important factor to reduce natural convection. Second, a multilayer structure was used in the device to reduce any fluid motion due to convection as much as possible. Figure 3 shows the inner layer that was designed elaborately to change the lengths of the two platinum wires, thus facilitating the installation of the platinum wires. A quartz casing was positioned in the middle layer. Finally, a smaller temperature difference between the device and surroundings is beneficial for a uniform temperature field in the cavity. For this purpose, a heating band was located outside the cavity. With the heating band, the environmental temperature could be increased to 450 K evenly. The calibration experiment proved that the repeatability and stability of the experimental data were improved dramatically. The experiment was carried out ten times in succession at each particular temperature. The platinum wire system is the core part of the entire device. The difficulty in designing the platinum wire system lies in the fact that it functioned as not only the heating

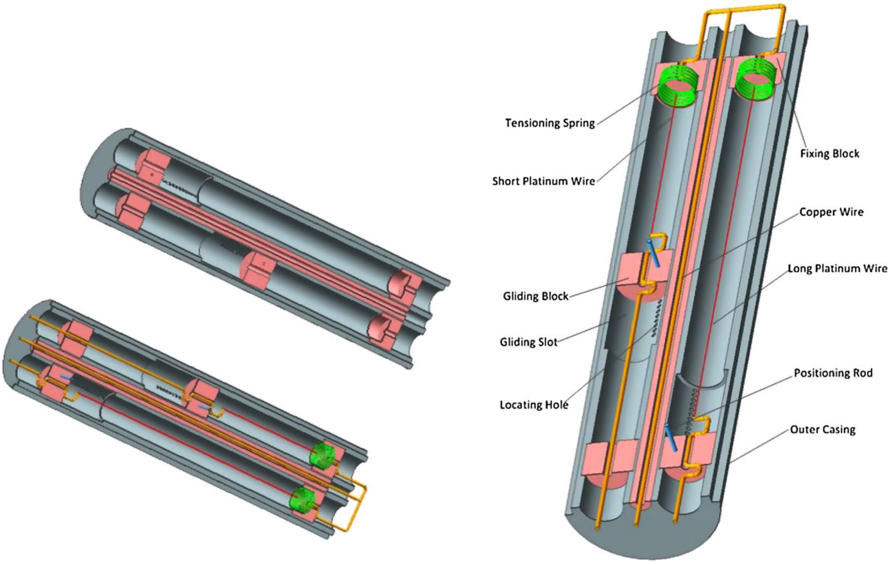

Fig. 3 Experimental device of the test rig

component, but also the temperature measuring units as mentioned above. One part of the platinum wire system was sealed in a high-pressure-bearing cavity, and the other part functioned as the peripheral electric circuits. Therefore, it is crucial to insulate the platinum wire from the steel case electrically. A new leading wire was developed to sustain a higher pressure and insulated electrically. Magnesium oxide padding was used to insulate the copper wire from a steel drive pipe of 3 mm in diameter. To endure high pressures and temperatures, a copper oxide sealant was daubed at the two ends of the drive pipe.

The test device was placed in a pressure-bearing steel cavity, immersed in the hydrocarbon fuel RP-3. Moreover, the gliding block can facilitate the fine adjustment for strengthening the platinum wire. Because a higher sensitivity to temperature variations and lower model error results from a thinner platinum wire, a platinum line of 15 μm in diameter was introduced. Based on the requirements of the transient experiment, the frequency of the analog signal acquisition board was selected as 1000 Hz. The time of experiment must be limited to 0.8 s to eliminate the effect of free convection, which is 800 points taken in one experimental run. The experimental pressure was measured using a pressure gage transducer (Model 3051CA4, Rosemount) with an uncertainty of $>$0.025 %. The vessel is capable of sustaining a temperature range from 290 K to 520 K and pressures up to 7 MPa. The total uncertainty of the temperature measurement system was less than 0.01 K.

2.4 Uncertainty Analysis

According to Eq. 1, the total uncertainty of the measured thermal conductivity using the transient double hot wire is estimated as follows. The uncertainty of I is 0.06 %; the

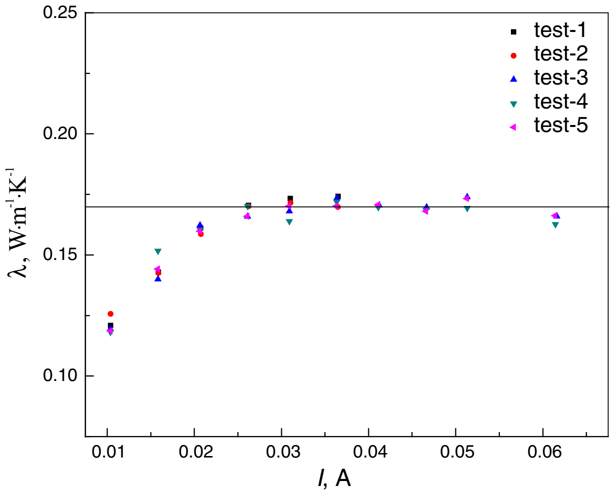

Fig. 4 Validation test with different heating powers

length of the platinum wire was measured using a micrometer caliper with an uncertainty of 0.2 %. The uncertainty of the electrical resistance versus the temperature coefficient of the platinum line was within 0.1 %; the uncertainty of the voltage rise slope $\mathrm{d}U/\mathrm{d}(ln\tau)$ was 0.6 %. Accounting for the uncertainty in the presence of other types of heat transfer and uncertainty in the deviations from an ideal mathematical model, the errors were reduced significantly by an elaborately designed experimental apparatus and appropriate operating conditions. Therefore, the combined standard uncertainty of these thermal-conductivity measurements was estimated to be 1.5 %. The relative expanded uncertainty of the thermal-conductivity measurement was determined as 3.0 % (coverage factor $k = 2$).

3 Results and Discussion

3.1 Accuracy and Repeatability

To evaluate the effects of the heating power on the measurements, absolute ethyl alcohol was used for the repeatability test. This validation test was conducted at room temperature five times, which also is a way to validate the repeatability of this method and the apparatus shown in Fig. 4. Moreover, the measurements at different applied powers, resulting in different temperature rises, are the tests to verify that the convection effects are insignificant in the tests.

The measurement deviation from the standard data (the horizontal line in Fig. 4) is relatively large for a small heating power. This can be explained by the fact that the bridge voltage deviates from the range of the acquisition module. Moreover, the test results show good repeatability in these five measurements at each heating power. Toluene was used as the calibration fluid because of its hydrocarbon characteristics and vast experimental data reported in the literature. The validation experiment was

Table 1 Relative errors (ξ_{exp}, ξ_{fit}) of the measured λ_{exp} and fitted values λ_{fit} of toluene compared to the published data λ_{pub} at 0.1 MPa

T (K)	λ_{pub} (W·m^{-1}·K^{-1})	λ_{exp} (W·m^{-1}·K^{-1})	λ_{fit} (W·m^{-1}·K^{-1})	100 × ξ_{exp} (%)	100 × ξ_{fit} (%)
290.21	0.1332	0.1335	0.1333	0.19	0.05
396.74	0.1312	0.1312	0.1312	−0.01	0.01
303.35	0.1292	0.1287	0.1292	−0.37	−0.02
308.22	0.1277	0.1277	0.1277	0.01	−0.02
312.17	0.1265	0.1266	0.1265	0.05	−0.01
319.51	0.1243	0.1244	0.1244	0.07	0.03
325.12	0.1227	0.1226	0.1228	−0.07	0.09
328.86	0.1216	0.1221	0.1218	0.39	0.13
330.91	0.1210	0.1214	0.1212	0.31	0.16
348.81	0.1160	0.1164	0.1167	0.31	0.27
354.37	0.1146	0.1153	0.1151	0.64	0.47
360.95	0.1128	0.1135	0.1133	0.60	0.43

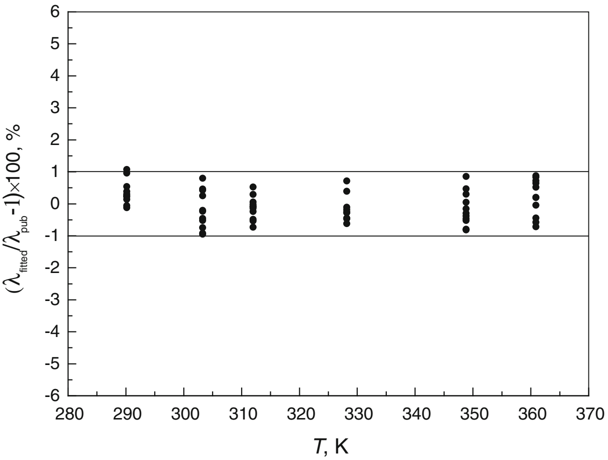

Fig. 5 Repeatability validation tests of toluene at different temperatures

carried out at a temperature from 290.21 K to 360.95 K and at a pressure of 0.1 MPa. The measured and published thermal-conductivity data [12] of toluene are listed in Table 1, where ξ_{exp} and ξ_{fit} are the relative error of published values compared to the experimental and fitted data. The maximum deviation from the published value was 0.64 %, which could be reduced to 0.47 % by data fitting. The experiment was performed ten times at six particular temperatures to validate the repeatability and accuracy, as shown in Fig. 5.

Table 2 shows the relative error of measured data versus temperatures compared to those reported in the literature. The maximum absolute deviation ($MAD = \left|\frac{\lambda_{exp}}{\lambda_{lit}} - 1\right| \times 100$) and average absolute deviation ($AAD = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\lambda_{exp,i}}{\lambda_{lit,i}} - 1\right| \times 100$)

Table 2 Relative error (ξ_{exp}, ξ_{fit}) of the measured λ_{exp} and fitted values λ_{fit} of nitrogen compared to the published data λ_{pub} at 5 MPa

T (K)	λ_{pub} (mW·m^{-1}·K^{-1})	λ_{exp} (mW·m^{-1}·K^{-1})	λ_{fit} (mW·m^{-1}·K^{-1})	$100 \times \xi_{exp}$ (%)	$100 \times \xi_{fit}$ (%)
285.65	27.80	27.63	27.62	−0.62	−0.01
313.71	29.37	29.31	29.26	−0.21	−0.17
336.17	30.63	30.51	30.56	−0.38	0.18
361.14	32.02	31.97	32.01	−0.16	−0.14
386.67	33.45	33.72	33.50	0.81	−0.66
411.51	34.84	34.69	34.94	−0.43	0.72
443.12	36.61	36.87	36.78	0.72	0.25
468.86	38.05	38.14	38.27	0.25	0.35
485.37	38.97	39.35	39.23	0.98	−0.30

of the thermal conductivity of toluene were 0.47 % and 0.14 %, respectively. The measurements were conducted ten times at six different temperatures to validate the repeatability of the experiment. The deviations of $((\lambda_{fitted} - \lambda_{pub})/\lambda_{pub}) \times 100$ are within an error band of 1 % as shown in Fig. 5.

To validate this experimental apparatus for gaseous fluids, the thermal conductivity of nitrogen was measured from 285 K to 485 K and at pressures of 5 MPa as shown in Table 3. The $MAD = \left|\frac{\lambda_{exp}}{\lambda_{lit}} - 1\right| \times 100$ and the $AAD = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\lambda_{exp,i}}{\lambda_{lit,i}} - 1\right| \times 100$ of the thermal conductivity of nitrogen are 0.72 % and 0.31 %, respectively. Notably, the measured thermal conductivity for toluene and nitrogen were compared with the standard data [12,17]. According to the validation tests with toluene and nitrogen, the *AAD* in all the tests was 0.36 %, indicating that the experimental apparatus is reliable and convincing.

3.2 Thermal Conductivity of RP-3

The thermal-conductivity measurements of RP-3 were conducted using the transient hot-wire method as described above from 0.1 MPa to 5 MPa and from 295 K to 513 K. Every experimental run was repeated six to ten times at each identical condition. The experimental fluid was gradually heated at a fixed pressure covering the entire testing range. Figure 6 shows that as the temperature increases, the thermal conductivity of RP-3 decreases. At higher pressures, the thermal conductivity of RP-3 increased slightly. The effect of pressure on the thermal conductivity was relatively insignificant, similar to Zhang's measurements on liquid dimethoxymethane [13]. In this study, all the experimental data were correlated using the following polynomial equation:

$$\lambda = \sum_{i=0}^{3} A_i \, (T/\mathrm{K})^i \, ,$$

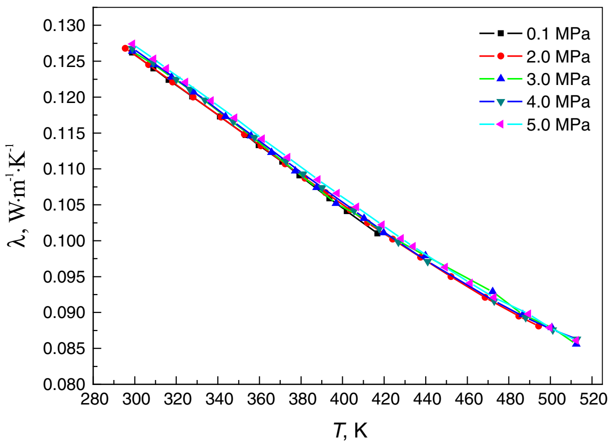

Fig. 6 Variations of the thermal conductivity of RP-3 with temperature at different pressures

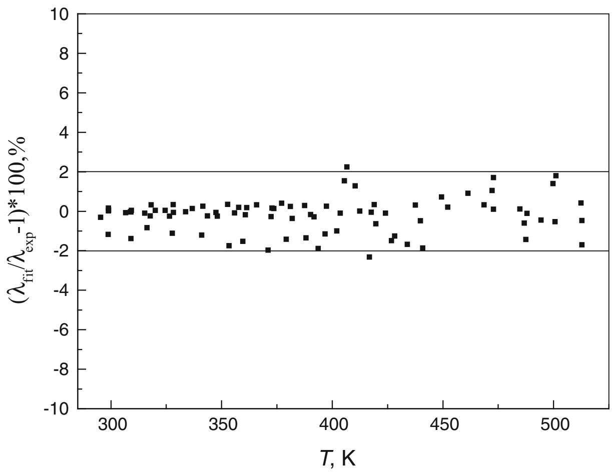

Fig. 7 Deviations of $(\lambda_{\mathrm{fit}}/\lambda_{\mathrm{exp}} - 1)$ of the thermal conductivity versus temperatures

where A_i is the polynomial coefficient. Notably, the above formula cannot be extrapolated and is valid in the range from 285 K to 513 K and from 0.1 MPa to 5 MPa.

Similar to other fluids, at higher pressures and lower temperatures, the thermal conductivity of RP-3 increased as shown in Fig. 6, which is mainly dominated by temperature. The difference in the measured data at different pressures is insignificant. The thermal conductivity of a liquid is affected by the distance between the molecules. The distance becomes larger after heating, decreasing the thermal conductivity. The effect of pressure on the thermal conductivity was insignificant in this temperature range. However, for thermal-conductivity measurements at higher temperatures, the effects of thermal radiation must be taken into account. Perkins et al. [6] developed the methods for the thermal radiation correction for the transient hot-wire method for both gas and liquid. For a gas such as nitrogen that is transparent to the thermal radiation, the

Table 3 Fitted experimental thermal conductivity (λ) of RP-3 at $T = 298$ K to 513 K under sub- and supercritical pressures ($P = 0.1$ MPa to 5 MPa)

T (K)	λ ($W \cdot m^{-1} \cdot K^{-1}$)	T (K)	λ ($W \cdot m^{-1} \cdot K^{-1}$)	T (K)	λ ($W \cdot m^{-1} \cdot K^{-1}$)	T (K)	λ ($W \cdot m^{-1} \cdot K^{-1}$)
$P = 0.1$ MPa							
298.74	0.1262	327.73	0.1201	359.68	0.1133	393.71	0.1059
309.07	0.1240	341.01	0.1173	371.05	0.1110	402.09	0.1041
316.4	0.1224	353.39	0.1147	379.28	0.1091	416.84	0.1010
$P = 2$ MPa							
295.42	0.1268	352.83	0.1148	403.66	0.1043	468.63	0.0921
306.71	0.1245	360.74	0.1132	412.08	0.1025	484.84	0.0895
318.26	0.1221	372.45	0.1107	424.15	0.1002	494.33	0.0881
328.14	0.120	381.91	0.1087	437.56	0.0977		
341.59	0.1172	391.8	0.1067	452.21	0.095		
$P = 3$ MPa							
298.87	0.1264	343.65	0.1173	387.53	0.1074	439.91	0.0979
309.25	0.1245	355.93	0.1146	396.85	0.1052	472.27	0.0929
317.76	0.1228	365.86	0.1123	410.35	0.1031	486.78	0.0897
328.27	0.1207	377.23	0.1097	419.73	0.1011	500.75	0.0879
						512.46	0.0856
$P = 4$ MPa							
298.91	0.1268	347.54	0.1166	405.57	0.1042	488.09	0.0893
308.9	0.1248	357.72	0.1144	417.66	0.1017	501.12	0.0876
320.06	0.1225	372.86	0.1111	426.82	0.0998	512.83	0.0863
326.56	0.1211	381.09	0.1093	440.94	0.0971		
333.84	0.1196	390.23	0.1074	472.94	0.0916		

Table 3 continued

T (K)	λ (W·m^{-1}·K^{-1})	T (K)	λ (W·m^{-1}·K^{-1})	T (K)	λ (W·m^{-1}·K^{-1})	T (K)	λ (W·m^{-1}·K^{-1})
$P = 5$ MPa							
298.98	0.1274	348.09	0.1171	406.71	0.1047	461.37	0.0941
309.11	0.1253	361.37	0.1142	418.98	0.1022	472.89	0.0921
315.28	0.1240	373.63	0.1116	428.25	0.1003	489.55	0.0898
324.55	0.1221	388.17	0.1085	433.93	0.0992	499.80	0.0879
336.82	0.1195	397.44	0.1066	449.40	0.0963	512.47	0.0861

contribution to the measured thermal conductivity is <0.5 % near 486 K. The contribution of thermal radiation from fluid emission to the measured thermal conductivity for supercritical pressure kerosene RP-3 is <2.4 % near 513 K using their method. Therefore, the real thermal conductivity without thermal radiation effects should be lower at the corresponding temperatures. Figure 7 shows that the maximum absolute deviation (*MAD*) and average absolute deviation (*AAD*) between the experimental and fitted data were 2.3 % and 0.8 %, respectively. The relative errors were within an error band of 2 %. Figure 7 also shows that the experimental deviation becomes relatively large at higher temperatures. This can be explained by the fact that the transient double hot-wire method relies on an absolute homogeneous temperature field that is difficult to achieve. The heating of fluids in the gravitational field causes free convection in the system. Therefore, a larger data deviation appears at higher temperatures.

4 Conclusion

In this study, a modified experimental apparatus is proposed based on the transient hot-double-wire method, which was validated to have an uncertainty of 0.72 % by measuring the thermal conductivity of hydrocarbon toluene and nitrogen. The thermal conductivity of one typical hydrocarbon aviation fuel was measured at sub- and supercritical pressures. The measured data cover a temperature range of 285 K to 513 K and a pressure range of 0.1 MPa to 5 MPa. The measured data were fitted by polynomials; the *MAD* and *AAD* were 1.05 % and 0.5 %, respectively. These measured thermal-conductivity data of hydrocarbon fuel may facilitate the simulation of the thermal conductivity of a fuel system.

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