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Experimental measurements of thermal conductivity of hydrocarbon fuels by a steady and kinetic method

Jia Zhouxia[1] · Xu Guoqiang[1] · Deng Hongwu[1] · Wen Jie[1] · Fu Yanchen[1]

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Abstract A steady and kinematic thermal conductivity measurement method is proposed for the round tube flow in laminar regime under constant heat flux condition. And this method is based on the fact that heat transfer coefficient depends only on thermal conductivity λ and inner diameter and is independent of V, ρ, and Cp in laminar flow with fully developed temperature and velocity profile. This independence results from the fact that the energy transport is purely molecular conduction problem under these conditions. The uncertainty of the measurement is within $\pm$ 3.0 % (coverage factor $k = 2$) according to the uncertainty analysis. For validation, the thermal conductivity of toluene and ethanol was measured at the temperature range of (288–372) K. And the validation tests show that the relative deviation of measured thermal conductivity from standard data is within an error band of 2 %. Using this method, thermal conductivity of a typical hydrocarbon aviation fuel RP-3 was measured.

Keywords Thermal conductivity · Laminar flow · Measurement · Hydrocarbon fuel

Introduction

With the development of high-performance aeroengine, thermal management challenges the design of cooling system of aeroengine in both sub- and supersonic regimes. The compressor outlet air is used to cool the hot-end components in engine, such as turbine disk, vane, and blade. For subsonic engines, the temperature of compressor outlet air reaches the magnitude of 900 K which is too hot for the turbine components' cooling. As a result, more compressor bleed air would be utilized to cool the turbines, which offsets the advantage brought by the improvement of turbine inlet temperatures and compressing ratios. For these above reasons, the concept of cooled cooling air (CCA) was proposed [1, 2]. In order to gain the precooled cooling air, an air–fuel heat exchanger must be introduced. Some research has made progress in the design of this new heat exchanger in recent years. The air taken off the compressor exit is cooled as it passes through an air–fuel heat exchanger, and then, it is taken back into the bore of turbine to cool the rotor. Thermodynamics design of heat exchanger requires thermal physical property parameters such as density, viscosity, specific heat capacity, and thermal conductivity. Systematic studies of those thermal physical properties of mixtures and their excess properties as functions of temperature and concentration can give insight into the molecular structure of mixtures and provide information on the interaction between components, which are essential for designing and testing theoretical models of mixtures. And, the thermal conductivity is an important transport property for heat transfer calculation and design in the air–fuel heat exchanger and fuel supply system.

All the measuring methods for thermal conductivity of fluids can be divided into two categories: steady and transient methods. Steady method is the classical way to measure thermal conductivity of solids. However, considering the difficulty in eliminating the influence of natural convection in fluids which can be induced by nonuniform temperature field in heating process, the attention of thermal conductivity measurements of fluids is focused on the

✉ Jia Zhouxia
zhouxia_jia@buaa.edu.cn

1 National Key Laboratory of Science and Technology on Aero-Engine Aero-Thermodynamics, School of Energy and Power Engineering, Collaborative Innovation Center of Advanced Aero-Engine, Beijing University of Aeronautics and Astronautics, Beijing 100191, People's Republic of China

transient method in recent years. The thermal conductivity measurements of pure liquid compounds and mixtures have been investigated by many researchers in different temperature ranges [5–11].

Measurements of the thermal physical properties of China kerosene RP-3 were taken by our research team, which include density, heat capacity, and viscosity [3, 4]. For this purpose, a new method measuring thermal conductivity of fluids was proposed which is straightforward and simple, and the validation tests and measurements of aviation fuel were taken with this method.

Experimental principles

Under the condition of laminar flow, the convective heat transfer is purely thermal diffusion which is closely related to the conduction process in boundary layer. This connection between convection and heat conduction may enlighten us a way to measure the thermal conductivity coefficient through convective heat transfer coefficient. The momentum equation of fluid is as follows:

$$\rho u\frac{\partial u}{\partial x}+\rho v_r\frac{\partial u}{\partial r}=-\frac{\mathrm{d}p}{\mathrm{d}x}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial u}{\partial r}\right) \tag{1}$$

According to the definition of fully developed velocity profile, it is obvious that $v_r = 0$, $\partial u/\partial x = 0$, and u is only function of r.

Boundary conditions are described as follows:

$$\frac{\mathrm{d}u}{\mathrm{d}r}=0,\quad r=0$$
$$u=0,\quad r=R \tag{2}$$

For ideal fluid with constant thermal physical properties, energy equation neglecting pressure gradient and internal heat source in cylindrical coordinate system can be described as follows:

$$\frac{u}{a}\frac{\partial t}{\partial x}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial t}{\partial r}\right)+\frac{\partial^2 t}{\partial x^2} \tag{3}$$

The boundary conditions are described as below:

$$\begin{aligned} &r=R,\quad t=t_\mathrm{w}\\ &r=0,\quad \frac{\partial t}{\partial r}=0\end{aligned} \tag{4}$$

with the temperature profile established, the mixed mean temperature can be evaluated.

$$t_\mathrm{w}-t_\mathrm{b}=\frac{11}{96}\frac{2v}{a}\left(\frac{\mathrm{d}t_\mathrm{b}}{\mathrm{d}x}\right)R^2 \tag{5}$$

And the convective heat transfer coefficient can be expressed by use of its definition

$$q_\mathrm{w}=h(t_\mathrm{w}-t_\mathrm{b})=h\cdot\frac{11}{96}\frac{2v}{a}\left(\frac{\mathrm{d}t_\mathrm{b}}{\mathrm{d}x}\right)\quad R^2=\mathrm{const} \tag{6}$$

The surface heat flux q_w can be evaluated from the conduction rate equation. Applying the conservation of energy principle and solving for the wall surface heat flux, we have [14]

$$q_\mathrm{w}=\frac{r_0V\rho c_\mathrm{p}}{2}\left(\frac{\mathrm{d}t_\mathrm{b}}{\mathrm{d}x}\right) \tag{7}$$

Combining Eq. (6) and (7), and solving for h,

$$h=\frac{48}{11}\frac{\lambda}{d} \tag{8}$$

where $d = 2r_0$

Note that the heat transfer coefficient h depends only on λ and inner diameter d but is independent of V, ρ, and c. This is only true for laminar flow, however, and only for the special case of fully developed velocity and temperature profiles. This independence results from the fact that the energy transport is purely molecular conduction problem under these conditions.

According to Newton's cooling equation:

$$h=\frac{q}{T_\mathrm{w}-T_\mathrm{b}} \tag{9}$$

Heat flux is described as below:

$$q=\frac{Q}{\pi dL} \tag{10}$$

So under the conditions of laminar flow with fully developed velocity and temperature profiles, the thermal conductivity of homogeneous fluids can be calculated as follows:

$$\lambda=\frac{11\cdot Q}{48\cdot\pi\cdot L\cdot(T_\mathrm{w}-T_\mathrm{b})} \tag{11}$$

And the inner wall temperature T_w can be calculated by solving the one-dimensional thermal conduction equation under the cylindrical coordinate system. T_b is the fluid bulk temperature. L is the heated length of the experimental tube. The thermal conductivity is the averaged one at the reference temperature

$$T=\frac{T_\mathrm{out}+T_\mathrm{in}}{2} \tag{12}$$

So when the assumptions above are satisfied, the convective heat transfer coefficient is constant. As a consequence, the temperature difference between wall temperature and flow mean temperature is constant. The energy posed on the tube Q can be gained by Eq. (13), and the length of the heated tube is easy to be measured by calipers. So the wall to mean flow temperature difference is the key parameter in determining the thermal conductivity coefficient.

$$Q = C_p \cdot m \cdot (T_{out} - T_{in}) \tag{13}$$

According to the theoretical analysis, the convective heat transfer coefficient stays constant in this particular situation. As a result, the difference between wall and bulk temperature is constant based on Newton's cooling equation:

$$t_w - t_b = \text{const} \tag{14}$$

from which

$$\frac{\partial t}{\partial x} = \frac{dt_w}{dx} = \frac{dt_b}{dx} \tag{15}$$

Equation (15) implies that the lines of temperature variations with distance are parallel. Several wall temperature thermocouples are welded onto the tube, and the distribution of these thermocouples is homogeneous along the tube. And the slope of temperature variations with distance along the tube can be gained by the elaborate measurements of inlet and outlet temperatures of flow bulk temperature which is shown by equation below.

$$\frac{dt_w}{dx} = \frac{dt_b}{dx} = \frac{T_{out} - T_{in}}{L} \tag{16}$$

And linear regression of wall temperatures along the distance is made with a fixed slope for the elimination of random errors. And then, the temperature difference between tube wall and flow can be gained. According to the deduction described above, this measurement applied to any homogeneous Newtonian fluid. And this thermal conductivity measurement method has been patented (CN103728340A).

Experimental section

Materials

A typical aviation kerosene RP-3 is used in this work. Composition analysis by using GC6890-MS5975 shows that RP-3 consists of 52.44 % alkanes, 7.64 % alkenes, 18.53 % benzenes, 15.54 % cycloalkanes, 4.39 % naphthalenes, and 1.46 % other compositions; the detailed compositions of RP-3 are listed in Deng's work [3]. The critical point of RP-3 was identified as ($Tc = 645.04$ K, $Pc = 2.34$ MPa) [13] due to the most obvious critical opalescence phenomenon conducted in our previous work. Besides, the phase transient point of RP-3 at 2 MPa was determined as 601.3 K. Toluene used in the validation tests is purified with a purity of 99.9 %.

Experimental system

The experimental system includes preparative system, measured system, and reclaimed system as shown in Fig. 1. In preparative system, the fuel in tank 1 is pumped up to 16 MPa by a piston pump (2J-Z 104/16). A 45-micron filter (filter 1 of Fig. 1) is attached to the suction side of the piston pump both to protect the pump from any entrained debris and to serve as an inlet accumulator to ensure the pump is not starved on the suction stroke. The pre-pressed fuel from the piston pump was pushed into an attached airbag pulsation damper (NXQ-L04/16-H) to reduce the pressure pulsation to lower than 0.5 % of the test section inlet pressure. The fuel from the damper is divided into a major path fuel and a bypass fuel separately: The latter was collected for reuse, and its pressure was controlled by a back-pressure valve (0–10) MPa in the bypass system; the mass flow rate of the major path fuel was measured using a Coriolis force flow meter (DMF-1-1, 0.15 %), and a 30-μm filter was installed to the upstream of the flow control valve (SS-426F3)to keep the passage clear. In order to achieve the required inlet fuel temperature of the test section, the pre-pressurized major path fuel was heated by two preheaters (preheater 1 and preheater 2) which were controlled by independent available current power supplies with a capacity of 15 kW. The fluid can be heated up to 600 K in two stages of preheater. The fuel temperature was measured at inlet and outlet with armored thermocouples. All data were recorded and logged onto the computer system.

After flowing through the test section, the heated fuel is cooled to the temperature lower than 310 K by water-cooled shell and tube heat exchanger, and then, the fuel pressure releases to ambient pressure through a back-pressure valve. The fuel is collected in tank 2 for other usages, and the water out from heat exchanger is cooled in cooling tower and then collected in tank 3 for recycling.

Test section

The test section was composed of a 1600-mm stainless steel circular tube with an inner diameter of 1.8 mm and a wall thickness of 0.2 mm. And the test section is covered with thermally insulated material (Aspen 5650) with the thermal conductivity of 0.02 W m^{-1} k^{-1} as shown in Fig. 2.

The test section is installed horizontally for the reason that buoyancy effects should be eliminated for the wall temperature measurements. To make sure the accurate measurements of inlet and outlet fluid bulk temperatures in heated part of the tube, two K-type armored thermocouples are designed which can be inserted to the exact position in start and end of the heated tube. Besides, mixing chambers are installed at the inlet and outlet for the measurements of fluid temperatures.

Experimental description

The test section is a stainless steel round tube with outside diameter of 2.2 mm and wall thickness of 0.2 mm. In order

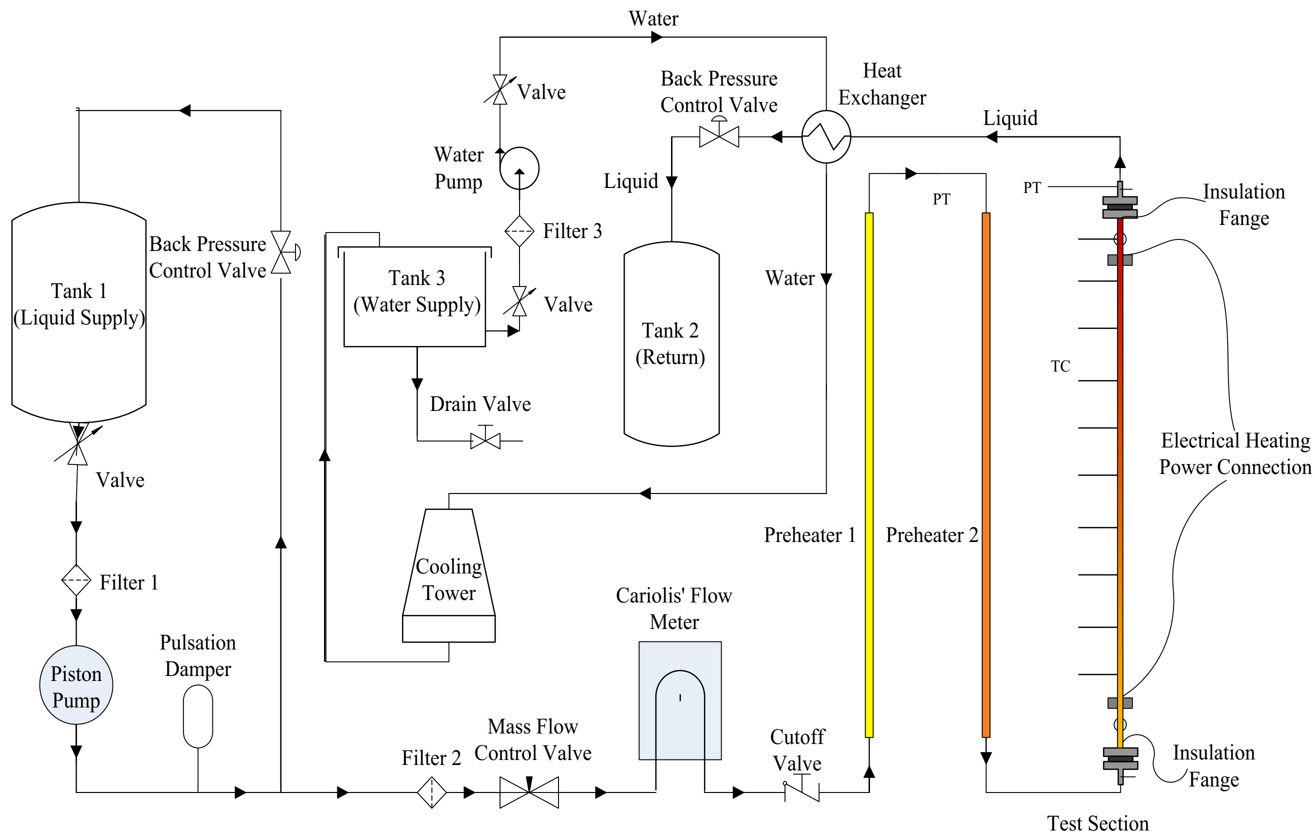

Fig. 1 Schematic of the experimental system

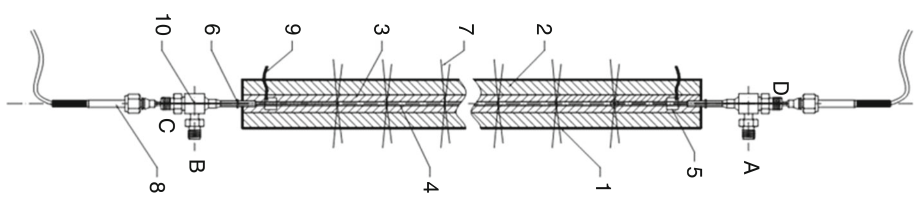

Fig. 2 Test section

to make sure the velocity and temperature profiles are fully developed, the length of the pipe is set as 1600 mm. And to reduce end effects on temperature measurements, temperatures of the 10 % length near the outlet are not measured. The thermal entry length in round tube in laminar regime is described as below [12]

$$\frac{L_{\text{ini}}}{d} \approx \frac{\text{Re} * \text{Pr}}{20} \tag{17}$$

The most difficult part for calculating thermal conductivity of fluids using this method is to gain the wall to mean flow temperature differences precisely. So the wall temperature thermocouples should be installed elaborately. At any specific position, two K-type thermocouples are welded in the same location as shown in Fig. 3. And 10 pairs of thermocouples are distributed along the fully developed section of the tube uniformly. Besides, all the thermocouples are calibrated with an accuracy of ±0.1 K from 280 to 485 K in standard oil bath equipment. The K-type thermocouple wires used to measure outside tube wall temperatures are wrapped by glass cloth. And two thermocouples are welded on one axial location with a 180° spacing as shown in Fig. 3. The wall temperatures at each location are averaged with these two thermocouples to eliminate random error. Moreover, inlet fluid bulk temperatures are measured with platinum resistance thermometer. A temperature difference thermocouple is used to measure the temperature difference at inlet and outlet of the heated part of the tube. Two mixing chambers are installed to make sure that the fluid passing through is mixed sufficiently.

Error analysis

According to Eq. (11), the total uncertainty of measured thermal conductivity using this method is as follows

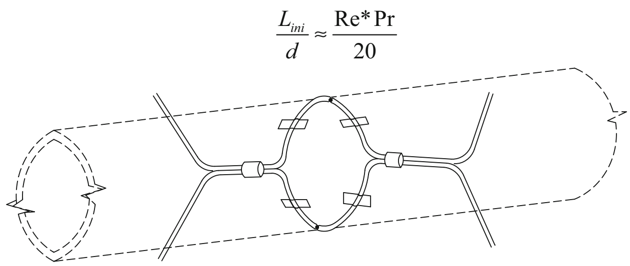

Fig. 3 Detailed installation of thermocouple

$$\Delta\lambda/\lambda = \sqrt{\xi(m)^2 + \xi(T_{\text{out}} - T_{\text{in}})^2 + \xi(L_x)^2 + \xi(T_{\text{w}} - T_{\text{b}})^2} \tag{18}$$

The accuracy of flow rate m is 0.15 %, and the length of experimental tube was measured by micrometer caliper with an accuracy of 0.03 %. The thermocouple measuring flow mean temperature is calibrated in water bath and oil bath with an accuracy of ±0.1 K. And this $T_{\text{out}} - T_{\text{in}}$ is measured with a temperature difference thermocouple directly, which is about 18 K for all measurements. Besides, the main error of this method results from the temperature difference between wall and fluid. For the consideration above, this temperature difference is more than 10 K in all measurements by elaborate experimental parameter configuration. As a result, the uncertainty of $T_{\text{out}} - T_{\text{in}}$ and $T_{\text{w}} - T_{\text{b}}$ is 0.5 and 1.41 %. Accounting for all effects estimated above, the global uncertainty of measured thermal conductivity is 1.5 %. The relative expanded uncertainty of thermal conductivity measurement of this method is determined as ±3.0 % (coverage factor $k = 2$).

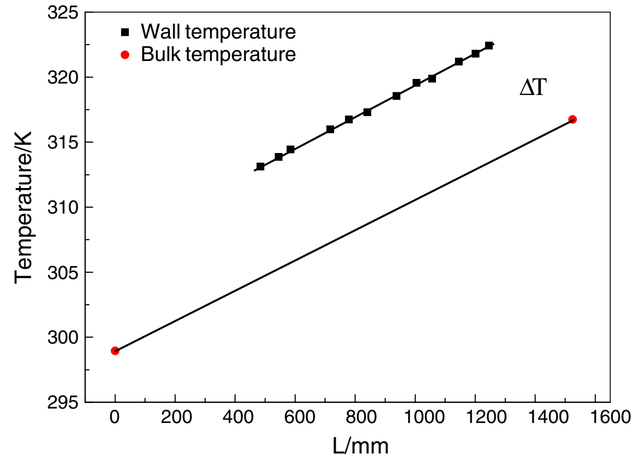

Fig. 4 Wall temperature variations with the tube length

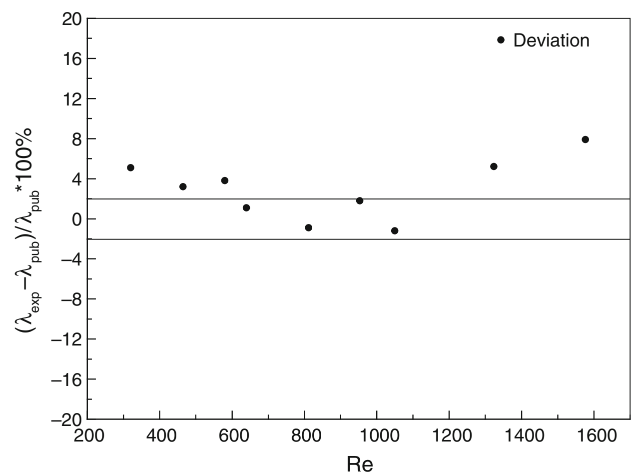

Fig. 5 Measurements deviation variation with Re

Results and discussion

Validation of the method

A typical relation of wall and fluid temperature variations with tube length is shown in Fig. 4. In this method, a hypothesis is made that the specific heat capacity at constant pressure is constant for each measurement run. This fact indicated that the fluid bulk temperature varies with tube length linearly. In all the experimental runs, the temperature difference between inlet and outlet of the tube is smaller than 18 K. It is demonstrated that the wall temperatures to distance line is parallel with fluid bulk temperature lines. It is shown that the slope (11.79 °C m^{-1}) of wall temperatures with tube length is equal to that(11.67 °C m^{-1}) of the fluid bulk temperatures with tube length, which is consistent with the theoretical deduction results shown in Eq. (15). For all the measurements, the deviation of the slops of two lines is <1 %. And this consistence can validate that this method acts in accord with the theory of it. Besides, the linearity of the wall temperature distributions along the tube is relatively good, which demonstrate that the experimental configurations and temperature measurements are reasonable and convincing. In the calculation, the wall temperatures on the developing flow section of the tube are excluded to eliminate the influence of flow development on the constant heat transfer coefficient at each temperature.

One of the assumptions of the method is that thermal physical properties are constant with temperature. However, the thermal physical properties of liquids depend sensitively on temperature. Considering the temperature difference, the specific heat capacity varies 0.8–1.7 % during one experimental run that is negligible. The flow is believed to be in the laminar regime when Reynolds number is less than 2000 in round tube flow. Fig. 5 shows the variations in relative measurement error with Reynolds

Table 1 Relative error (ξ_{exp}, ξ_{fit}) of the measured λ_{exp} and the fitted value λ_{fit} of methylbenzene compared with published data λ_{pub} at 0.1 MPa

T/K	λ_{pub}/W K^{-1} m^{-1}	λ_{exp}/W K^{-1} m^{-1}	λ_{fit}/W K^{-1} m^{-1}	100 % × ξ_{exp}	100 % × ξ_{fit}
First measurements					
304.66	0.1289	0.1307	0.1311	1.35	1.66
319.36	0.1250	0.1268	0.1265	1.44	1.18
324.41	0.1237	0.1233	0.1249	−0.29	1.00
330.77	0.1220	0.1228	0.1229	0.65	0.77
341.82	0.1191	0.1206	0.1195	1.33	0.37
343.11	0.1187	0.1205	0.1191	1.49	0.32
350.1	0.1169	0.1163	0.1168	−0.44	0.05
349.96	0.1169	0.1175	0.1169	0.53	0.05
349.66	0.1170	0.1177	0.1171	0.61	0.06
354.31	0.1157	0.1161	0.1156	0.35	−0.12
356.1	0.1153	0.1149	0.1150	−0.31	−0.19
360.57	0.1140	0.1125	0.1136	−1.40	−0.37
Second measurements					
304.83	0.1289	0.1303	0.1314	1.11	1.91
314.85	0.1262	0.1291	0.1280	2.30	1.37
316.96	0.1257	0.1265	0.1272	0.63	1.25
319.02	0.1251	0.1263	0.1265	0.92	1.14
325.48	0.1234	0.1256	0.1244	1.75	0.77
329.63	0.1223	0.1235	0.1229	0.95	0.53
331.87	0.1217	0.1234	0.1222	1.41	0.40
339.97	0.1195	0.1187	0.1194	−0.72	−0.09
342.56	0.1189	0.1183	0.1186	−0.44	−0.25
345.16	0.1182	0.1171	0.1177	−0.91	−0.41
349.70	0.1170	0.1169	0.1161	−0.06	−0.70
357.79	0.1148	0.1128	0.1134	−1.75	−1.23

Table 2 Relative error (ξ_{exp}, ξ_{fit}) of the measured λ_{exp} and the fitted value λ_{fit} of ethanol compared with published data λ_{pub} at 3.0 MPa

T/K	λ_{pub}/W K^{-1} m^{-1}	λ_{exp}/W K^{-1} m^{-1}	λ_{fit}/W K^{-1} m^{-1}	100 % × ξ_{exp}	100 % × ξ_{fit}
288.59	0.1689	0.1706	0.1692	0.98	0.17
292.47	0.1681	0.1702	0.1683	1.24	0.15
300.74	0.1663	0.1648	0.1665	−0.88	0.11
308.81	0.1645	0.1657	0.1646	0.72	0.07
319.49	0.1621	0.1601	0.1622	−1.29	0.01
328.14	0.1602	0.1587	0.1602	−0.98	−0.03
332.59	0.1592	0.1575	0.1592	−1.1	−0.06
346.37	0.1562	0.1563	0.1560	0.08	−0.14
350.24	0.1554	0.1555	0.1551	0.09	−0.16
359.41	0.1533	0.1546	0.1530	0.81	−0.21
364.86	0.1521	0.1513	0.1518	−0.57	−0.25
371.26	0.1507	0.1512	0.1503	0.3	−0.29

number. The optimum Reynolds number interval for measuring thermal conductivity by this method is between 600 from 1000, whose accuracy is within ±2.0 %.

As a result, the Reynolds number is within this range in all the measurements according to the calibration tests described above. And the determination of this Reynolds number range is based on experimental measurements. Thus, the thermal conductivity in this region is considered to be accurate. Influence of natural convection in small horizontal tube is assumed to be insignificant when the

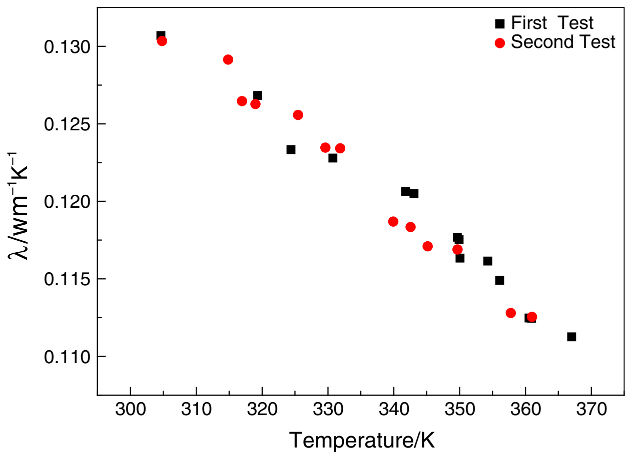

Fig. 6 Thermal conductivity of toluene variations with temperature

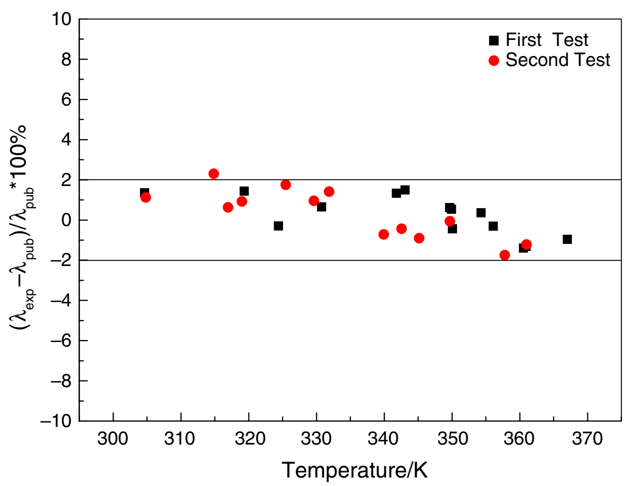

Fig. 7 Measurement deviation variations with temperature

Reynolds number is relatively small. According to the definition of Reynolds number, the flow rate at different temperatures can be calculated using the equation below:

$$m = \frac{\mathrm{Re}\pi d\mu}{4} \tag{19}$$

Accuracy and repeatability

Methylbenzene was used as the calibrating fluid with the consideration of its hydrocarbon characteristics and vast experimental data reported in the literature. The validation experiment was carried out at temperatures from 304.7 to 360.6 K at 0.1 MPa. The measured and published thermal conductivity data of methylbenzene are listed in Table 1; the second column is considered as the accurate value; the data in the third column were acquired using Eq. 11; and the fourth is the fitted value of the third column. The ξ_{exp} and ξ_{fit} represent the relative error of published values

Table 3 Fitted experimental thermal conductivity (λ) of RP-3 from T = (311–399) K under supercritical pressures (P = 3 MPa)

T/K	λ_{exp}/W K^{-1} m^{-1}	λ_{fit}/W K^{-1} m^{-1}	100 % × ξ_{fit}
311.50	0.1346	0.1363	−1.25
320.82	0.1318	0.1339	−1.57
325.54	0.1327	0.1326	0.08
331.51	0.1322	0.1310	0.92
337.28	0.1292	0.1295	−0.23
338.73	0.1309	0.1291	1.39
347.86	0.1298	0.1267	2.45
352.84	0.1269	0.1254	1.20
359.38	0.1237	0.1237	0.00
367.70	0.1209	0.1214	−0.41
371.98	0.1210	0.1203	0.58
378.45	0.1175	0.1186	−0.93
379.79	0.1167	0.1182	−1.27
395.26	0.1157	0.1141	1.40
395.68	0.1135	0.1140	−0.44

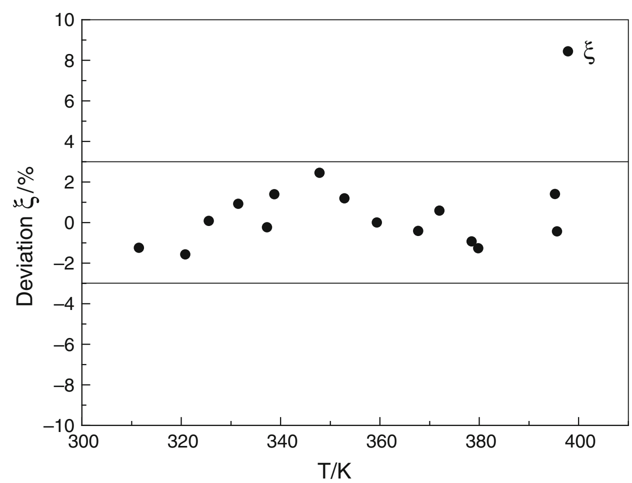

Fig. 8 Deviation of measured and fitted thermal conductivity of RP-3

compared with experimental data and fitted data. It is observed that the maximum deviation from published value is 1.91 %, which can be reduced to 0.47 % by data fitting. The experiment was conducted 10 times at one particular temperature to testify the repeatability and accuracy. All the published data of toluene are cited from Ramires' work [15]. Besides, the thermal conductivity of ethanol was measured to validate this method. The relative deviation between measured data and standard data is within the range of ±1.3 % as shown in Table 2. Similar validation results were demonstrated using ethanol as the calibrating fluid as shown in Table 2 (Fig. 6).

To validate the repeatability of this method and the experimental figuration, the measurements of thermal conductivity were taken twice. As is shown in Fig. 7, the distinction between two sets of measurements is insignificant. The test result indicates that this thermal conductivity measurement method is feasible and convincing.

Results and discussion

Using this method and experimental apparatus, the thermal conductivity of a special aviation hydrocarbon fuel RP-3 was measured from 311 to 399 K at the supercritical pressure of 3 MPa [13]. The test results are listed in Table 3. And the deviation $\xi_{\mathrm{fit}} = (\lambda_{\mathrm{exp}} - \lambda_{\mathrm{fit}})/\lambda_{\mathrm{fit}} \times 100\ \%$ with temperatures is shown in Fig. 8.

Like other fluids, with lower temperatures, the thermal conductivity of RP-3 increases as shown in Table 3, which is mainly dominated by temperatures. The thermal conductivity of liquid is influenced by distance between molecules. The distance is larger after heating leading to the decrease in thermal conductivity. It should be noted that the measured thermal conductivity is an average one, which is different from the accurate measurement based on the transient hot-wire method. And a quick and convenient way for the determination of thermal conductivity of fluids can be gained using this steady and kinematic method.

Conclusions

A novel thermal conductivity measurement method is proposed based on heat transfer in laminar regime for round tube flow. And this method is based on the fact that heat transfer coefficient depends only on thermal conductivity λ and inner diameter d and is independent of V, ρ, and Cp in laminar flow with fully developed temperature and velocity profile. According to the error analysis, this measuring method has an accuracy of 3.0 % (coverage factor $k = 2$). And for validation, the thermal conductivity of toluene and ethanol was measured at the temperature range of (288–370) K under pressure at 0.1 and 3.0 MPa. The results show that the deviation of measured thermal conductivity of toluene from standard data is within an error band of 3 %, which is consistent with the uncertainty analysis above. And this method provides a straightforward and efficient way to measurement thermal conductivity of fluids.

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