



Viscosity measurements of hydrocarbon fuel at temperatures from (303.2 to 513.2) K and pressures up to 5.1 MPa using a two-capillary viscometer



Zhuqiang Yang, Zhaohui Liu*, Qincheng Bi, Song Feng, Hui Pan, Yong Guo

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, No. 28, Xianning West Road, Xi'an 710049, PR China

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ABSTRACT

A two-capillary method based on the Hagen–Poiseuille theory was proposed for on-line measurements of dynamic viscosity of hydrocarbons at high temperatures and high pressures. A two-capillary viscometer was designed and proved to be applicable to the viscosity measurements in a mini-tube. The standard uncertainty of dynamic viscosity measurements is identified as (2.22–5.28)% (coverage factor $k=2$). N-heptane, n-octane and their binary mixture were tested respectively in the calibration experiments of the viscometer. Results showed that the measured maximum relative deviations of all substances were all within 2% and the average absolute deviations were within 0.72%. Finally viscosities of a kerosene kind hydrocarbon fuel were measured using the two-capillary viscometer at temperature from (303.2 to 513.2) K and supercritical pressures of (3.00 and 4.00) MPa.

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Abbreviations

dp	pressure drop (kPa)
L	length of tube (mm)
p	pressure (MPa)
R	radius (mm)
T	temperature (K)
Q	flow rate (mL/min)
w	mass fraction

Greek

η	dynamic viscosity ($\mu\text{Pa s}$)
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Subscripts

<i>down</i>	downstream
<i>exp</i>	experimental
<i>mea</i>	measured
<i>ref</i>	referenced
<i>up</i>	upstream

1. Introduction

Viscosity as an important transport property is widely applied in many fields, such as chemicals, food industry, petrochemicals,

biomedical, environmental science and so on. In the heat management technology for scramjet, hydrocarbons are always applied as fuel and coolant in a regenerative cooling system [1–4]. Thermo-physical properties of hydrocarbon fuel are deeply demanded in the cooling system design for future application. As a key property, viscosity is directly bound up with the resistance and kinetic energy of fluid in the cooling process. A fundamental understanding of the viscosity is an indispensable part in the theoretical analysis and numerical simulation for the hydrocarbons. The present paper aims at proposing a viscosity measurement method to obtain the dynamic viscosity of hydrocarbon fuel at high temperatures and high pressures.

Some viscosity measurement methods have been proposed, such as rolling ball viscometer [5], falling-body viscometer [6,7], vibrating wire-viscometer [8,9], capillary tube viscometer [10–12] and so on [13–16]. Most researches were conducted on the pure compounds [5,8,10–12,14] and binary mixtures [6,7,10,16]. And data were concentrated at low temperature and different pressures. Viscosities of hydrocarbon mixtures and oils were studied in some researches. Boned et al. [6] measured the viscosities of two hydrocarbon mixtures representative of some heavy petroleum distillation at (293.15–343.15) K and up to 100 MPa by a falling-body viscometer and a capillary viscometer respectively. Tate et al. [12] modified the Saybolt viscometer and measured the kinematic viscosities of three biodiesel fuels at temperatures up to 573 K. Gascoin et al. [15] proposed a novel measurement method to determine the kinematic viscosity of pure and multi-species mixture,

* Corresponding author.

E-mail address: zh.liu@mail.xjtu.edu.cn (Z. Liu).

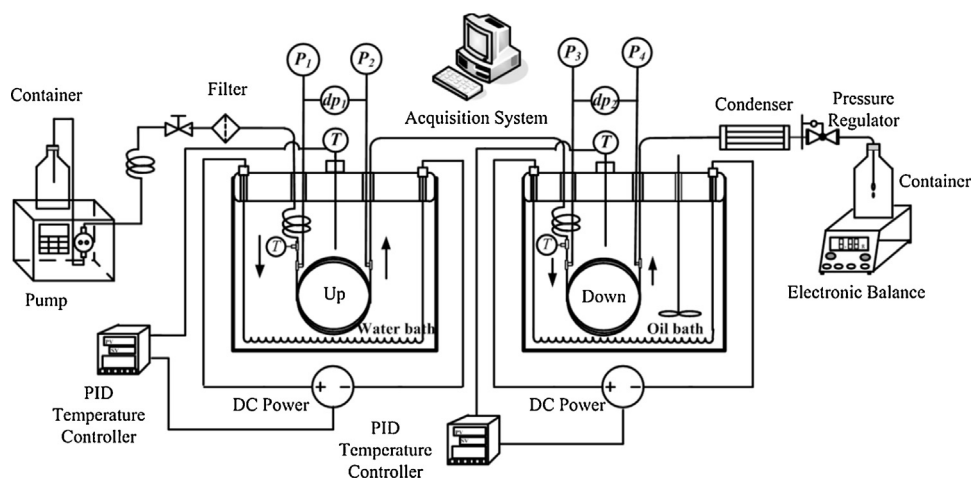


Fig. 1. Schematic diagram of experimental system.

which was based on fluid permeation through characterized porous media. The viscometer was validated to apply to the hydrocarbons under pyrolysis. Xing et al. [16] used an Ubbelohde viscometer to measure the viscosity of binary mixtures tricyclo [5.2.1.02.6] decane (JP-10), a high density fuel, and methylcyclohexane (MCH) at several temperatures. The viscosity of a typical endothermic hydrocarbon fuel (RP-3) at critical and supercritical conditions was measured with a capillary method by Deng et al. [11]. It covers a temperature range of (298–788) K under pressures (2.33–5) MPa.

The advantages of capillary method are low cost, high accuracy particularly with longer tubes, and the ability to achieve very high shear rates, even with high viscosity samples. A two-capillary method was first proposed based on the Hagen-Poiseuille theory by May et al. [17] on the ratio measurement of viscosities of sample gases. They measured the zero-density viscosities of H₂, CH₄ and Ar by a two-capillary viscometer at temperatures ranging from 200 K to 400 K, and Xe for the range from 200 K to 300 K [18]. Zhang et al. [19] presented an investigation on the effect of connecting tubing in a two-capillary viscometer. They found that the incompatibility of connecting tubing could cause a systematic error in the measurement of dilute gas viscosity and the error diminishes with Dean Number decreases. The two-capillary method is more accurate than an absolute viscosity method, which requires accurate knowledge of the flow field and geometric parameter. More important, it is an on-line technique for the viscosity measurements at high temperatures and high pressures.

In this paper, a two-capillary method was first applied to the on-line measurements of dynamic viscosity of hydrocarbons under liquid phase or supercritical state. A theoretical formula is deduced and a novel two-capillary viscometer was designed for hydrocarbons at high temperatures and pressures. Validations of the viscometer were validated by pure fluid and mixtures. Viscosities of a kerosene kind hydrocarbon fuel were measured at temperature from (303.2 to 513.2) K and supercritical pressures of 3.00 and 4.00 MPa by the two-capillary viscometer.

2. Experimental

2.1. Experimental system

Experiments were performed in a home-designed multiphase flow test platform in our laboratory. The schematic diagram of the experimental system is shown in Fig. 1.

Test fluid was driven by a constant flow pump (P230II) with 9.999 mL/min supply capacity. A 7 μ m filter is attached to the pump to protect the devices from entrained impurity. The prepared fluid

flowed through two coils capillaries made of 316 steel stainless in series. The capillaries had an external diameter of 1/32 inch and a nominal diameter of 0.25 mm. Each capillary was 3000 mm and coiled 17.5 times to form a helix approximately 50 mm in height and 50.8 mm in coil curvature diameter. A straight section approximately 100 mm long was located at two ends of the capacity and oriented vertically. A T-union was connected with capillary coil at the inlet and outlet of tube. The side branch led into a pressure gauge and a differential pressure gauge. Meanwhile, another T-union was located at the inlet for inlet fluid temperature measurement. The internal bore of these T-unions was 0.25 mm, same as the internal diameter of the capillaries, to minimize the entrance disruption of the flow.

Each ensemble of capillary coil apparatus was immersed in a liquid thermostat horizontally. A 300 mm coiled capillary located ahead of ensemble was also immersed in the bath to attain thermal equilibrium for the inflow. It could also minimize the flow-induced instabilities by increasing upstream resistance for fluid. The upstream water bath was maintained at 303.15 K and downstream oil bath at varied temperature T , from (303.15 to 513.15) K. The temperature of each bath was measured by a K-type sheathed thermocouple (Omega TJ2) and adjusted by a PID regulator (SHIMADEN FP23) with a DC power. As sketched in Fig. 1, four pressure transducers (Rosemount 3051) were applied to measure p_1 , p_2 , p_3 and p_4 . The transducers had full scale of 10 MPa, an uncertainty of 0.075% of full scale (± 7.5 kPa). The pressure drops of two capillaries dp_1 and dp_2 were monitored by pressure drop transducers (Rosemount 3051) with full scales of 248 kPa and an uncertainty ± 0.19 kPa. The inlet temperature of each capillary was measured with an exposed thermocouple (Omega GG-K). The thermocouples were calibrated by JOFRA temperature calibrator (650SE) with an uncertainty of ± 0.25 K. After testing, the hot fluid is cooled by a condenser and the work pressure was regulated by a back-pressure valve (BY3). An electronic balance (sartorius BSA3202S-CW) was placed at the outlet to weight the mass of test fluid, which monitored the volume flow of the pump. In experiments, all the information was recorded using a computerized data acquisition system (IMP3595).

2.2. Experimental material

The physical properties of test fluids are listed in Table 1. The hydrocarbon fuel I is made up of a blend of hydrocarbons, with $w=0.8140$ cycloalkanes, $w=0.0475$ alkanes, $w=0.0488$ alkenes, $w=0.0400$ aromatics and $w=0.0497$ others. The fuel's critical pressure and temperature are measured to be about 2.35 MPa and

Table 1
Sample description.

Chemical name	Source	Initial mole fraction purity	Purification method
Cyclohexane	Sinopharm Chemical Reagent Co., Ltd	0.995	Distillation
n-Heptane	Sinopharm Chemical Reagent Co., Ltd	0.995	Distillation
n-Octane	Sinopharm Chemical Reagent Co., Ltd	0.995	Distillation
Fuel	Karamay Oil		Distillation

694.1 K due to the critical opalescence phenomenon. And detailed compositions and densities of the hydrocarbon fuel were given in previous work [20].

2.3. Theory

The capillary viscometer is based on the Hagen–Poiseuille's Law in a laminar flow. The volume flow rate Q through a capillary with internal radius R and length L depends on the fluid viscosity η and pressure drop Δp .

$$Q = \frac{\pi}{8\eta} \cdot \frac{\Delta p}{L} \cdot R^4 = \frac{\pi R^4}{8L} \cdot \frac{\Delta p}{\eta} = \frac{\Delta p}{Z\eta} \quad (1)$$

Z represents structure coefficient of the capillary, related to internal radius and length:

$$Z = \frac{8L}{\pi R^4} \quad (2)$$

Thus, when mass flow rate and structure coefficient of capillary are constant, the fluid viscosity could be obtained by measuring the pressure drop.

$$\eta = \frac{\Delta p}{ZQ} = \frac{\Delta p}{Z} \cdot \frac{\rho}{m} \quad (3)$$

A two-capillary viscometer, comprising two capillaries in series, was developed to measure the temperature dependence of viscosity ratios. It is convenient for viscosity measurements without a flow meter and geometric size measurement [18].

Firstly the upstream coil was maintained in water bath at the reference temperature of T_0 and the downstream coil in oil bath at T . The referenced fluid at a constant mass flow rate flowed through two capillaries in series and the relation was:

$$\frac{\Delta p_{up,T_0}^{ref} \rho_{T_0}^{ref}}{Z_{up,T_0}^{ref} \eta_{up,T_0}^{ref}} = \frac{\Delta p_{down,T}^{ref} \rho_T^{ref}}{Z_{down,T}^{ref} \eta_{down,T}^{ref}} \quad (4)$$

Then, the temperatures in the upstream and downstream bath were maintained at T_0 and T , the test fluid flowed through the two capillaries and the relation was:

$$\frac{\Delta p_{up,T_0}^{mea} \rho_{T_0}^{mea}}{Z_{up,T_0}^{mea} \eta_{up,T_0}^{mea}} = \frac{\Delta p_{down,T}^{mea} \rho_T^{mea}}{Z_{down,T}^{mea} \eta_{down,T}^{mea}} \quad (5)$$

Comparing Eq. (4) with (5), the relation was transformed:

$$\frac{\eta_{down,T}^{mea}}{\eta_{up,T_0}^{mea}} \cdot \frac{\eta_{up,T_0}^{ref}}{\eta_{down,T}^{ref}} = \left(\frac{\Delta p_{down,T}^{mea} \rho_T^{mea}}{Z_{down,T}^{mea}} \cdot \frac{Z_{up,T_0}^{mea}}{\Delta p_{up,T_0}^{mea} \rho_{T_0}^{mea}} \right) \left(\frac{\Delta p_{up,T_0}^{ref} \rho_{T_0}^{ref}}{Z_{up,T_0}^{ref}} \cdot \frac{Z_{down,T}^{ref}}{\Delta p_{down,T}^{ref} \rho_T^{ref}} \right) \quad (6)$$

Simplifying the expression in Eq. (6), a variable $X_{T,T_0}^{mea,ref}$ was defined:

$$X_{T,T_0}^{mea,ref} = \frac{\eta_{down,T}^{mea}}{\eta_{up,T_0}^{mea}} \cdot \frac{\eta_{up,T_0}^{ref}}{\eta_{down,T}^{ref}} = \frac{\Delta p_{down,T}^{mea} \rho_T^{mea}}{\Delta p_{up,T_0}^{mea} \rho_{T_0}^{mea}} \cdot \frac{\Delta p_{up,T_0}^{ref} \rho_{T_0}^{ref}}{\Delta p_{down,T}^{ref} \rho_T^{ref}} \quad (7)$$

Finally, the upstream capillary's temperature was controlled at the reference temperature T_0 , the reference and test fluid flowed alternately through the upstream capillary while two pressure drops were made the same. Eq. (8) was yielded:

$$\frac{\eta_{up,T_0}^{mea}}{\eta_{up,T_0}^{ref}} = \frac{Q_{up,T_0}^{ref}}{Q_{up,T_0}^{mea}} = \frac{m_{up,T_0}^{ref}}{m_{up,T_0}^{mea}} \cdot \frac{\rho_{T_0}^{mea}}{\rho_{T_0}^{ref}} \quad (8)$$

Combing the expressions in Eqs. (4)–(8), the temperature dependence viscosity of the test fluid would be calculated as:

$$\eta_{down,T}^{mea} = \eta_{up,T_0}^{ref} \left(\frac{\eta_{down,T}^{ref}}{\eta_{up,T_0}^{ref}} \right) \left(\frac{\eta_{up,T_0}^{mea}}{\eta_{up,T_0}^{ref}} \right) X_{T,T_0}^{mea,ref} \\ = \eta_{down,T}^{ref} \left(\frac{m_{up,T_0}^{ref}}{m_{up,T_0}^{mea}} \right) \left(\frac{\Delta p_{down,T}^{mea}}{\Delta p_{up,T_0}^{mea}} \right) \cdot \left(\frac{\Delta p_{up,T_0}^{ref}}{\Delta p_{down,T}^{ref}} \cdot \frac{\rho_T^{mea}}{\rho_T^{ref}} \right) \quad (9)$$

According to Eq. (9), the combined relative standard uncertainty of measured viscosity $u_r(\eta_{down,T}^{mea})$ is:

$$u_r^2(\eta_{down,T}^{mea}) = u_r^2(\eta_{down,T}^{ref}) + u_r^2(m_{up,T_0}^{ref}) + u_r^2(m_{up,T_0}^{mea}) + u_r^2(\Delta p_{down,T}^{mea}) \\ + u_r^2(\Delta p_{up,T_0}^{mea}) + u_r^2(\Delta p_{up,T_0}^{ref}) + u_r^2(\Delta p_{down,T}^{ref}) \\ + u_r^2(\rho_T^{ref}) + u_r^2(\rho_T^{mea}) + \left[\frac{\partial \eta_{down,T}^{mea}}{\partial T} \frac{u(T)}{\eta_{down,T}^{mea}} \right]^2 \\ + \left[\frac{\partial \eta_{down,T}^{mea}}{\partial T_0} \frac{u(T_0)}{\eta_{down,T}^{mea}} \right]^2 + \left[\frac{\partial \eta_{down,T}^{mea}}{\partial P} \frac{u(P)}{\eta_{down,T}^{mea}} \right]^2 \quad (10)$$

In this work, the pressure drops of two capillaries were monitored by two pressure drop transducers with full scales of 248 kPa and an uncertainty ± 0.19 kPa. Fluid temperature was measured by a K-type sheathed thermocouple (Omega TJ2), which was calibrated by a JOFRA temperature calibrator (650SE). The uncertainty of the sheathed thermocouples was within ± 0.48 K at the temperatures from (303.2 to 513.2)K. The volume flow rate was supplied by constant flow pump with 9.999 mL/min capacity and an uncertainty ± 0.010 mL/min. The viscosity of reference fluid and the densities of fluid except test fuel were referred from NIST Standard Reference Database. Thus, the combined standard uncertainty of dynamic viscosity is calculated as 1.11–2.64%. The relative expanded uncertainty of dynamic viscosity measurements is identified as 2.22–5.28% (coverage factor $k=2$).

3. Results and discussion

For high-pressure viscosity ratio measurements, a stable flow should be satisfied in capillaries. Some measures and good signal-to-noise ratios were adopted in experiments. Small flow rate (0.3–1.2 mL/min) was used with obvious pressure drop (20–248 kPa) in a minitube (0.25 mm). The internal bore of T unions matching the capillaries reduced the entrance and the exit effects. A coiled capillary was located ahead of each ensemble to suppress flow-induced instabilities. Good signal-to-noise ratios were satisfactorily obtained and a typical condition was shown in Fig. 2. In

Table 2
Experimental values and reference data of viscosity η at temperature T , pressure p and relative differences $\Delta\eta/\eta = (\eta_{\text{exp}} - \eta_{\text{lit}})/\eta_{\text{lit}}$ for n-heptane.^a

T/K	$\eta_{\text{exp}}/\mu\text{Pa s}$	$\eta_{\text{lit}}/\mu\text{Pa s}$	$\Delta\eta/\eta/\%$	T/K	$\eta_{\text{exp}}/\mu\text{Pa s}$	$\eta_{\text{lit}}/\mu\text{Pa s}$	$\Delta\eta/\eta/\%$
$p = 3.10 \text{ MPa}$							
303.2	384.8	381.9	0.76	413.2	148.8	149.0	-0.18
313.2	342.2	343.5	-0.39	423.2	139.2	138.8	0.25
323.0	309.7	310.5	-0.27	433.2	130.8	129.3	1.19
333.1	283.4	282.8	0.22	443.4	119.3	120.5	-0.96
343.3	256.2	258.4	-0.85	453.1	113.5	112.3	1.14
353.3	238.2	236.4	0.75	463.2	104.7	104.5	0.28
363.2	220.7	218.0	1.24	473.2	97.8	97.0	0.84
373.3	202.7	201.0	0.86	483.1	89.6	89.9	-0.33
383.2	185.3	186.1	-0.46	493.2	81.7	82.9	-1.47
393.2	171.7	172.6	-0.52	503.2	74.5	76.0	-1.91
403.2	159.0	159.4	-0.23				

^a Standard uncertainties u are $u(T) = 0.5 \text{ K}$, $u(p) = 7.5 \text{ kPa}$ and combined expanded uncertainty U_c is $U_c(\eta) = 4.2 \mu\text{Pa s}$ (0.95 level of confidence).

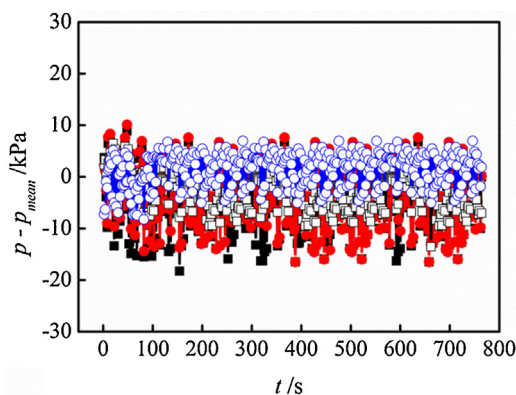


Fig. 2. Time dependence of measured pressures for n-octane flow in the two-capillary viscometer. ■, $p_1 = 3224 \text{ kPa}$; ●, $p_2 = 3094 \text{ kPa}$; □, $p_3 = 3044 \text{ kPa}$; ○, $p_4 = 2964 \text{ kPa}$.

experiments, the test pressure was averaged along the length of the capillary and cyclohexane was chosen as the reference fluid.

3.1. Calibration of the two-capillary viscometer

The validity of the two-capillary viscosity method was firstly verified by measuring the dynamics viscosities of n-heptane and n-octane at 3.10 MPa. The binary mixture of n-heptane and n-octane were further tested. Viscosities of the reference fluids measured in experiments were compared with the data available at NIST. In calculation, the percentage deviation (PD), the average absolute deviation (AAD) and the maximum absolute deviation (MAD) of the results were defined:

$$PD = \left(\frac{\eta_{\text{exp}}}{\eta_{\text{lit}}} - 1 \right) \times 100\% \quad (11)$$

$$AAD = \frac{\sum_{i=1}^n \text{abs}(PD_i)}{n} \quad (12)$$

$$MAD = \max(\text{abs}(PD_i)) \quad (13)$$

where the subscripts ‘exp’ and ‘lit’ represent experimental value and reference data at NIST, respectively.

The dynamic viscosities of n-heptane were measured at a constant pressure $p = 3.10 \text{ MPa}$ with a wide temperature range (303.2–503.2) K under a liquid state. The measurement results are compared with reference data in Table 2 and Fig. 3. Good agreement is obtained within 1.91% MAD and 0.72% AAD in Table 2. The relative errors of the viscosity data are shown in Fig. 3 and within $\pm 2.00\%$ error band.

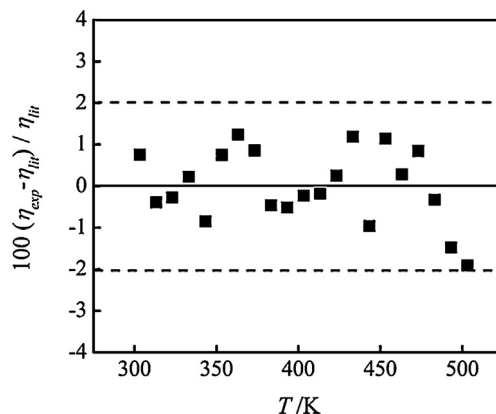


Fig. 3. Deviations of measured and referenced viscosities of n-heptane versus temperature at $p = 3.10 \text{ MPa}$.

N-octane used as test fluid was measured at a constant pressure $p = 3.10 \text{ MPa}$ and varied temperature (303.2–503.2) K. The viscosities of n-octane are shown in Table 3 and Fig. 4. It can be seen that the MAD was within 1.70% and the AAD was limited to 0.63%. The relative errors are all within $\pm 2.00\%$ error band and most within $\pm 1.50\%$.

The viscosities of $w = 0.500$ n-heptane and $w = 0.500$ n-octane mixture were measured at a constant pressure 5.10 MPa with temperature from (303.2 to 513.2) K. The results are compared with the values available at NIST as shown in Table 4 and Fig. 5. The MAD is limited to 1.13% and the AAD was 0.47%. All data points are within $\pm 1.50\%$ error band and 20 data points could be within $\pm 1.00\%$ error band. Further, different mass ratio mixtures of n-heptane and n-octane were tested and compared with viscosity values reported in

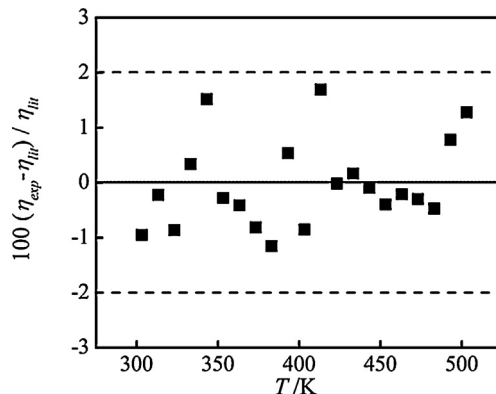


Fig. 4. Deviations of measured and referenced viscosities of n-octane versus temperature at $p = 3.10 \text{ MPa}$.

Table 3Experimental values and reference data of viscosity η at temperature T , pressure p and relative differences $\Delta\eta/\eta = (\eta_{\text{exp}} - \eta_{\text{lit}})/\eta_{\text{lit}}$ for n-octane.^a

T/K	$\eta_{\text{exp}}/\mu\text{Pa s}$	$\eta_{\text{lit}}/\mu\text{Pa s}$	$\Delta\eta/\eta/\%$	T/K	$\eta_{\text{exp}}/\mu\text{Pa s}$	$\eta_{\text{lit}}/\mu\text{Pa s}$	$\Delta\eta/\eta/\%$
$p = 3.10 \text{ MPa}$							
303.2	491.1	495.8	-0.95	413.2	192.4	189.2	1.69
313.3	441.4	442.4	-0.22	423.2	176.2	176.2	-0.02
323.2	396.7	400.1	-0.86	433.1	164.2	163.9	0.16
333.2	363.2	362.0	0.34	443.2	152.7	152.8	-0.09
343.2	335.2	330.2	1.52	453.1	141.6	142.2	-0.40
353.1	301.2	302.0	-0.28	463.2	132.2	132.4	-0.21
363.2	276.6	277.8	-0.41	473.1	122.8	123.2	-0.30
373.3	254.5	256.5	-0.81	483.1	113.9	114.5	-0.47
383.0	234.1	236.8	-1.16	493.1	106.9	106.1	0.78
393.1	220.8	219.6	0.54	503.0	99.5	98.2	1.28
403.2	202.1	203.9	-0.85				

^a Standard uncertainties u are $u(T) = 0.5 \text{ K}$, $u(p) = 7.5 \text{ kPa}$ and combined expanded uncertainty U_c is $U_c(\eta) = 6.4 \mu\text{Pa s}$ (0.95 level of confidence).**Table 4**Experimental values and reference data of viscosity η at temperature T , pressure p and relative differences $\Delta\eta/\eta = (\eta_{\text{exp}} - \eta_{\text{lit}})/\eta_{\text{lit}}$ for $w = 0.500$ n-heptane and $w = 0.500$ n-octane mixture.^a

T/K	$\eta_{\text{exp}}/\mu\text{Pa s}$	$\eta_{\text{lit}}/\mu\text{Pa s}$	$\Delta\eta/\eta/\%$	T/K	$\eta_{\text{exp}}/\mu\text{Pa s}$	$\eta_{\text{lit}}/\mu\text{Pa s}$	$\Delta\eta/\eta/\%$
$p = 5.10 \text{ MPa}$							
303.2	437.3	438.4	-0.26	413.2	172.1	170.7	0.77
313.2	393.1	393.5	-0.10	423.2	160.4	159.2	0.76
323.4	353.5	355.0	-0.40	433.1	149.5	148.6	0.61
333.2	322.7	323.1	-0.12	443.2	137.5	138.7	-0.86
343.2	295.8	295.1	0.22	453.2	130.0	129.5	0.36
353.2	271.5	270.6	0.35	463.2	120.3	120.9	-0.47
363.2	249.1	248.9	0.07	473.1	113.8	112.9	0.77
373.2	231.6	229.9	0.76	483.2	106.1	105.3	0.72
383.2	213.8	212.8	0.48	493.2	99.2	98.1	1.13
393.1	198.2	197.4	0.38	503.2	91.5	91.3	0.28
403.2	184.3	183.4	0.47	513.2	84.8	84.7	0.05

^a Standard uncertainties u are $u(T) = 0.5 \text{ K}$, $u(p) = 7.5 \text{ kPa}$ and combined expanded uncertainty U_c is $U_c(\eta) = 5.7 \mu\text{Pa s}$ (0.95 level of confidence).**Table 5**Experimental values and reference data of viscosity η at temperature T , pressure p and Relative differences $\Delta\eta/\eta = (\eta_{\text{exp}} - \eta_{\text{lit}})/\eta_{\text{lit}}$ for n-heptane and n-octane mixture.^a

p/MPa	T/K	$\eta_{\text{exp}}/\mu\text{Pa s}$	p/MPa	T/K	$\eta_{\text{lit}}/\mu\text{Pa s}$	$\Delta\eta/\eta/\%$
$w = 0.255$ n-heptane and $w = 0.745$ n-octane						
This work			Abdulagatov et al. [10]			
0.1	303.5	442.2	0.1	303.85	441	0.27
0.1	333.8	323.4	0.1	333.54	322	0.43
0.1	363.4	244.7	0.1	363.71	245	-0.12
5.0	303.9	466.3	5.0	303.85	465	0.28
5.0	373.2	241.5	5.0	373.51	241	0.21
5.0	413.9	179.2	5.0	413.60	178	0.67
5.0	473.5	118.6	5.0	473.46	118	0.51
$w = 0.510$ n-heptane and $w = 0.490$ n-octane						
This work			Abdulagatov et al. [10]			
0.1	303.5	414.9	0.1	303.39	414	0.22
0.1	333.5	301.1	0.1	333.73	300	0.37
0.1	363.4	232.9	0.1	363.74	232	0.39
5.0	303.5	436.2	5.0	303.39	435	0.28
5.0	373.6	227.7	5.0	373.97	227	0.31
5.0	413.7	170.2	5.0	415.96	167	1.92
5.0	473.4	112.4	5.0	473.10	112	0.36

^a Standard uncertainties u are $u(T) = 0.5 \text{ K}$, $u(p) = 7.5 \text{ kPa}$ and combined expanded uncertainty U_c is $U_c(\eta) = 5.8 \mu\text{Pa s}$ (0.95 level of confidence).

literature [10] as shown in Table 5. The excellent agreement confirms the accuracy of the viscometer for binary mixtures, which illustrating that the two-capillary viscometer could be applied to the multi-component mixtures measurement.

Thus, the viscosity of a kerosene kind hydrocarbon fuel was measured at supercritical pressures in the following part.

3.2. Viscosity of hydrocarbon fuel

The viscosity of the hydrocarbon fuel was measured covering a temperature range of (303.2–513.2) K at supercritical pressure 3.00 MPa and 4.00 MPa. The data is shown in Table 6 and the variation of viscosity is presented in Fig. 6. The viscosity decreases with

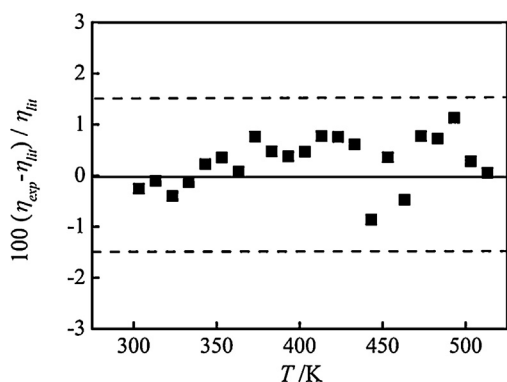


Fig. 5. Deviations of measured and referenced viscosities of $w=0.500$ n-heptane and $w=0.500$ n-octane mixture versus temperature at $p=5.10$ MPa.

Table 6
Experimental values of viscosity η at temperature T , pressure p for the fuel at supercritical Pressure conditions.^a

T/K	$\eta/\mu\text{Pa}\cdot\text{s}$	T/K	$\eta/\mu\text{Pa}\cdot\text{s}$	T/K	$\eta/\mu\text{Pa}\cdot\text{s}$
$p=3.10$ MPa					
303.1	1738.4	383.2	581.1	463.1	275.2
313.2	1448.2	393.2	530.3	473.2	251.2
323.2	1253.8	403.2	477.7	483.1	228.4
333.1	1088.6	413.1	433.4	493.1	205.4
343.1	946.6	423.2	396.4	503.1	183.7
353.1	833.0	433.2	358.9	513.1	167.1
363.2	736.9	443.2	329.5		
373.2	656.0	453.1	303.7		
$p=4.00$ MPa					
303.1	1768.9	383.2	595.5	463.1	276.8
313.2	1529.6	393.2	534.6	473.2	252.8
323.1	1289.7	403.1	482.4	483.2	231.1
333.2	1112.7	412.9	438.9	493.2	208.9
343.1	962.5	423.2	397.8	503.1	189.6
353.2	842.5	433.2	361.3	513.2	169.1
363.1	746.4	443.2	329.6		
373.3	663.7	453.2	304.3		

^a Standard uncertainties u are $u(T)=0.5$ K, $u(p)=7.5$ kPa and combined expanded uncertainty U_c is $U_c(\eta)=14.2$ $\mu\text{Pa}\cdot\text{s}$ (0.95 level of confidence).

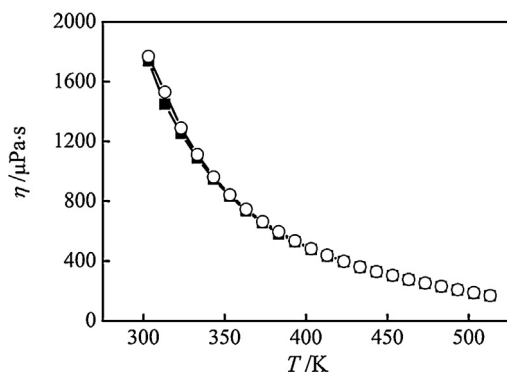


Fig. 6. Viscosity variations of hydrocarbon fuel versus temperature at \blacksquare , $p=3.00$ MPa; \circ , $p=4.00$ MPa.

the increase of temperature and the variation becomes smooth at high temperature. In working conditions, pressure has little effect on the viscosity of the fuel in a liquid state. The experimental dynamic viscosities at a fixed pressure are fitted as a function of temperature according to the following equation:

$$\log_{10} \eta_{\text{exp}} = A + \frac{B}{T} + CT + DT^2 \quad (14)$$

where η_{exp} is the experimental viscosity of fuel; A , B , C and D are the regression coefficients.

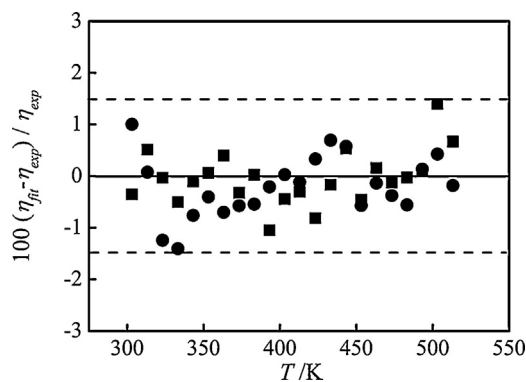


Fig. 7. Deviations $(\eta_{\text{fit}} - \eta_{\text{exp}})/\eta_{\text{exp}}$ of the dynamic viscosity of hydrocarbon fuel versus temperature at \blacksquare , $p=3.00$ MPa; \bullet , $p=4.00$ MPa.

Finally, the relative error between the fitted viscosity and the experimental data is shown in Fig. 7. All points are within $\pm 1.50\%$ error band. The maximum absolute deviation (MAD) and the average deviation (AAD) are 1.41% and 0.45%, respectively.

4. Conclusions

A two-capillary method is proposed for the viscosity measurements of hydrocarbon fuel at supercritical pressure. The measurement theory and experimental system were described in detail. The accuracy of the viscometer was calibrated by n-heptane, n-octane and their binary mixture. The viscosity of n-heptane was measured at the temperature range of (303.2–503.2) K at a pressure of 3.10 MPa. The measured average absolute deviation (AAD) was 0.72% and the maximum absolute deviation (MAD) was 1.91%, respectively. The viscosity of octane was also measured at 3.10 MPa and (303.2–503.2) K. The measured average absolute deviation (AAD) was 0.63% and the maximum absolute deviation (MAD) was limited to 1.70%. The viscosities of $w=0.500$ n-heptane and $w=0.500$ n-octane binary mixture were measured at a constant pressure 5.10 MPa with a temperature range of (303.2–513.2) K. The maximum absolute deviation (MAD) was limited to 1.13% and the average absolute deviation (AAD) was 0.47%. Different mass ratio mixtures of n-heptane and n-octane were also tested and compared with viscosity values reported in literature. Excellent agreement between measured viscosities and literature values further confirms the reliability and accuracy of the two-capillary viscometer. Finally, the viscosity of hydrocarbon fuel was obtained at temperature range of (303.2–513.2) K at supercritical pressures 3.00 MPa and 4.00 MPa. The results were fitted with polynomials and the relative error between the fitted viscosity and the experimental data was analyzed. The maximum absolute deviation (MAD) and the average deviation (AAD) are 1.24% and 0.52%, respectively.

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