Kinematic Viscosity of R410A and R407C Refrigerant−Oil Mixtures in the Saturated Liquid Phase with Lubricant Mass Fraction in the Range of (0 to 0.0001)

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The kinematic viscosities of R410A and R407C refrigerant−oil mixtures in the saturated liquid phase were measured at the temperatures ranging from (256.15 to 336.15) K when the mass fractions of lubricant (polyol ester lubricant) were (0, 2, 5, 8, and 10)$\cdot 10^{-5}$. The experimental results show that, with the addition of lubricant, there is a significant impact on the kinematic viscosity of R410A and R407C refrigerant−oil mixtures in the saturated liquid phase. With the increase of lubricant concentration, the liquid kinematic viscosities of R410A and R407C refrigerant−oil mixtures under the saturation condition significantly increase, and the impact of lubricant gradually decreases with the increase of temperature.

Introduction

In recent years, the binary near-azeotropic mixture R410A and the ternary zeotropic mixture R407C are most favored worldwide as alternatives for chlorodifluoromethane (HCFC-22) in the field of air conditioning and heat pump systems, so the thermophysical properties of R410A and R407C are very important and useful. Their *PVTx* property,[1,2] phase equilibrium property,[3] thermal conductivity,[4] specific heat capacity,[5,6] and so on, have been reported. However, only a few experimental viscosity data of R410A and R407C have been reported,[7,8] and there are seldom descriptions on the experimental research of the viscosity of R410A and R407C refrigerant−oil mixtures. Only a small amount of literature covered the theoretical prediction of the oily refrigerant's thermophysical properties.[9−11] However, in the practical refrigeration cycle, the refrigerant always contains a small quantity of compressor lubricant. Investigations have shown that, with the addition of compressor lubricant, the viscosity of refrigerant−oil mixtures deviate from those of pure refrigerant, and the actual performance of the refrigeration cycle deviates from the designing performance accordingly.[12] Recently, the investigations of R410A and R407C refrigerant−oil mixtures mostly focus on their flow characteristic and heat transfer characteristic,[13,14] so it is necessary to measure the viscosity of R410A and R407C refrigerant−oil mixtures and provide the experimental viscosity data of R410A and R407C refrigerant−oil mixtures for scientific research and engineering practice.

In the present work, the liquid kinematic viscosities of R410A and R407C refrigerant−oil mixtures under saturation conditions and from (256.15 to 336.15) K were measured with (0, 2, 5, 8, and 10)$\cdot 10^{-5}$ mass fractions of lubricant (polyol ester lubricant).

Experimental Section

Measurement Method and Equipment. In this work, the inclined-tube viscometer was adopted, by measuring the flowing parameter of the liquid column which flows at a uniform speed in a thin tube which has an obliquity, and the viscosity of experimental liquid can be obtained. The measuring equation can be obtained from the equilibrium equation describing the uniform flow of the liquid column:

$$u_0 = k_1 \sin \alpha + k_2 \qquad \left(k_1 = \frac{\rho g R^2}{8\eta} = \frac{gR^2}{8\nu},\; k_2 = \frac{(\cos \theta_{c,b} - \cos \theta_{c,f})\gamma R}{4l\eta}\right) \tag{1}$$

Here, u_0 is the velocity of the liquid column from the practical measurement when the liquid column flows at a uniform speed, in mm$\cdot$s^{-1}; α is the angle between the direction of the thin pipe and horizontal direction, in degrees; ρ is the density of the experimental liquid, in g$\cdot$mm^{-3}; R is the inside radius of the thin pipe, in mm; $\theta_{c,b}$ is the contact angle of back meniscus, in degrees; $\theta_{c,f}$ is the contact angle of front meniscus, in degrees; γ is the surface tension acting on liquid, in N$\cdot$mm^{-1}; l is the length of the liquid column, in mm.

As long as a series of the velocities of the liquid column u_0 and the values of the inclination angle α are obtained, a linear curve can be fitted by the least-squares method. The rate of slope of this curve is k_1. Ultimately, kinematic viscosity ν and the dynamic viscosity η of experimental liquid can be obtained. Accordingly, the measurement equations can be depicted as follows.

$$\eta = \frac{\rho g R^2}{8k_1} \qquad \nu = \frac{gR^2}{8k_1} \tag{2}$$

Refs 12 and 15 represent the measuring principle and the experimental apparatus in detail. For this measurement, the total expanded experimental uncertainties in temperature, pressure, and viscosity are estimated to be not greater than ± 0.02 K, ± 4 kPa, and ± 0.42 %, respectively. In this study, the confidence coefficient of the compound uncertainty is taken to be 2.

Because the binary mixture R410A represents a near-azeotropic mixture and the ternary mixture R407C represents a

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Table 1. Kinematic Viscosity, ν, of R410A Refrigerant−Oil Mixtures under Saturation Conditions

		lubricant mass fraction									
		0		$2\cdot10^{-5}$		$5\cdot10^{-5}$		$8\cdot10^{-5}$		$1\cdot10^{-4}$	
T	p^a	ν	$10^{-3}\ U_\nu$	ν	$10^{-3}\ U_\nu$	ν	$10^{-3}\ U_\nu$	ν	$10^{-3}\ U_\nu$	ν	$10^{-3}\ U_\nu$
K	MPa	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$
256.15	0.451	0.1720	±0.79	0.267	±1.2	0.400	±1.7	0.549	±2.4	0.647	±2.8
258.15	0.485	0.1685	±0.78	0.251	±1.1	0.364	±1.6	0.488	±2.1	0.570	±2.5
260.15	0.522	0.1652	±0.77	0.237	±1.1	0.333	±1.5	0.437	±1.9	0.506	±2.2
262.15	0.560	0.1619	±0.75	0.224	±1.0	0.306	±1.4	0.394	±1.7	0.452	±1.9
264.15	0.600	0.1587	±0.74	0.2125	±0.96	0.283	±1.2	0.357	±1.6	0.406	±1.8
266.15	0.642	0.1556	±0.72	0.2022	±0.93	0.262	±1.2	0.326	±1.4	0.367	±1.6
268.15	0.687	0.1526	±0.71	0.1929	±0.88	0.244	±1.1	0.298	±1.3	0.333	±1.5
270.15	0.733	0.1497	±0.70	0.1845	±0.84	0.229	±1.0	0.275	±1.2	0.305	±1.3
272.15	0.782	0.1468	±0.68	0.1769	±0.82	0.2148	±0.98	0.255	±1.1	0.280	±1.3
274.15	0.833	0.1440	±0.67	0.1700	±0.78	0.2025	±0.91	0.237	±1.1	0.258	±1.2
276.15	0.887	0.1413	±0.65	0.1637	±0.76	0.1916	±0.88	0.221	±1.0	0.240	±1.1
278.15	0.943	0.1386	±0.65	0.1579	±0.72	0.1819	±0.83	0.2078	±0.94	0.223	±1.0
280.15	1.002	0.1360	±0.64	0.1527	±0.70	0.1733	±0.79	0.1959	±0.89	0.2091	±0.95
282.15	1.063	0.1335	±0.62	0.1479	±0.69	0.1656	±0.76	0.1853	±0.85	0.1966	±0.90
284.15	1.127	0.1310	±0.61	0.1434	±0.67	0.1587	±0.73	0.1760	±0.80	0.1856	±0.84
286.15	1.195	0.1285	±0.60	0.1394	±0.64	0.1526	±0.71	0.1678	±0.78	0.1759	±0.81
288.15	1.265	0.1262	±0.59	0.1356	±0.63	0.1470	±0.68	0.1605	±0.74	0.1672	±0.77
290.15	1.338	0.1238	±0.59	0.1321	±0.61	0.1420	±0.66	0.1539	±0.70	0.1596	±0.73
292.15	1.414	0.1215	±0.58	0.1289	±0.61	0.1374	±0.64	0.1480	±0.68	0.1527	±0.70
294.15	1.494	0.1193	±0.57	0.1259	±0.59	0.1333	±0.62	0.1427	±0.66	0.1466	±0.67
296.15	1.577	0.1171	±0.55	0.1231	±0.58	0.1295	±0.60	0.1380	±0.64	0.1411	±0.65
298.15	1.663	0.1150	±0.55	0.1204	±0.57	0.1260	±0.59	0.1337	±0.62	0.1362	±0.63
300.15	1.753	0.1129	±0.53	0.1180	±0.56	0.1229	±0.57	0.1297	±0.60	0.1317	±0.61
302.15	1.846	0.1108	±0.53	0.1156	±0.55	0.1199	±0.57	0.1261	±0.59	0.1277	±0.60
304.15	1.944	0.1088	±0.52	0.1133	±0.54	0.1172	±0.56	0.1228	±0.58	0.1240	±0.58
306.15	2.045	0.1068	±0.51	0.1112	±0.53	0.1146	±0.55	0.1197	±0.56	0.1206	±0.57
308.15	2.150	0.1048	±0.50	0.1091	±0.52	0.1122	±0.53	0.1169	±0.56	0.1174	±0.56
310.15	2.260	0.1029	±0.49	0.1071	±0.51	0.1099	±0.53	0.1141	±0.55	0.1145	±0.55
312.15	2.373	0.1010	±0.49	0.1051	±0.50	0.1077	±0.51	0.1116	±0.53	0.1118	±0.53
314.15	2.491	0.0992	±0.47	0.1032	±0.50	0.1055	±0.51	0.1091	±0.52	0.1092	±0.52
316.15	2.613	0.0973	±0.47	0.1013	±0.48	0.1034	±0.50	0.1067	±0.51	0.1067	±0.51
318.15	2.740	0.0955	±0.46	0.0994	±0.47	0.1014	±0.49	0.1043	±0.50	0.1044	±0.50
320.15	2.872	0.0938	±0.46	0.0975	±0.46	0.0993	±0.47	0.1020	±0.48	0.1021	±0.48
322.15	3.008	0.0920	±0.44	0.0956	±0.47	0.0973	±0.46	0.0996	±0.48	0.0998	±0.48
324.15	3.150	0.0903	±0.44	0.0937	±0.46	0.0952	±0.46	0.0973	±0.47	0.0976	±0.47
326.15	3.296	0.0886	±0.43	0.0918	±0.44	0.0931	±0.45	0.0949	±0.45	0.0954	±0.46
328.15	3.447	0.0870	±0.43	0.0898	±0.44	0.0909	±0.44	0.0924	±0.44	0.0931	±0.45
330.15	3.604	0.0853	±0.41	0.0878	±0.42	0.0887	±0.43	0.0899	±0.43	0.0909	±0.44
332.15	3.766	0.0837	±0.41	0.0858	±0.42	0.0865	±0.42	0.0874	±0.42	0.0885	±0.43
334.15	3.934	0.0821	±0.40	0.0837	±0.41	0.0841	±0.41	0.0847	±0.41	0.0862	±0.42
336.15	4.108	0.0806	±0.40	0.0815	±0.40	0.0817	±0.40	0.0820	±0.40	0.0837	±0.41

[a] Note: vapor phase pressure.

zeotropic mixture, they must be restricted to the liquid phase to maintain the mixtures at the certified composition of the manufacturer for the complete temperature range investigated. To keep the change in composition to a minimum, the experimental cell was improved to keep the vapor space of the measuring cell as small as possible.

Material. The samples of R410A and R407C were manufactured by DuPont. The mass fraction purity of two refrigerant mixtures was better than 0.995, and they were used without further purification. The binary near-azeotropic mixture R410A consists of HFC-125 (pentafluoroethane) and HFC-32 (difluoromethane), and the mass fractions were certified to be in a range of (0.495 to 0.515) for HFC-125 and (0.485 to 0.505) for HFC-32, respectively. The ternary nonazeotropic mixture R407C consists of HFC-134a (1,1,1,2-tetrafluoroethane), HFC-125, and HFC-32. The mass fractions of these three compositions are 0.51, 0.26, and 0.23, and the uncertainty of the mass fraction is certified to be ± 0.02 for each component. A kind of commonly used lubricant (Solest 120) provided by CPI company was chosen to conduct the experimental measurements in this work. Solest 120 is a kind of POE (polyol ester) lubricant which is specially designed for an HFC (hydrofluorocarbon) compressor, and it can be applied to R134a, R404, R407, R507, and so on.

Results and Discussion

Tables 1 and 2 list the liquid kinematic viscosities of R410A and R407C refrigerant−oil mixtures under the saturation state from (256.15 to 336.15) K when the mass factions of lubricant were (0, 2, 5, 8, and 10)$\cdot10^{-5}$, and the experimental data are also given for R410A and R407C without lubricant. The experimental uncertainties of every measuring point were calculated according to the regulation of the experimental uncertainty given by the International Organization for Standardization (ISO).[16]

Adopting the modified Andrade correlation of liquid viscosity which is developed by Yaws et al.,[17] the correlation between the liquid kinematic viscosity under the saturation state and the temperature for refrigerants R410A and R407C without lubricant were established as follows, respectively

$$\text{R410A: } \ln(\nu/\text{mm}^2\cdot\text{s}^{-1}) = -10.09 + 1075.49/(T/\text{K}) + 0.026(T/\text{K}) + 0.000039(T/\text{K})^2 \quad (3)$$

$$\text{R407C: } \ln(\nu/\text{mm}^2\cdot\text{s}^{-1}) = -16.40 + 1787.38/(T/\text{K}) + 0.046(T/\text{K}) - 0.000060(T/\text{K})^2 \quad (4)$$

The relative average deviations of eqs 3 and 4 are 0.27 % and 0.19 %, respectively. Comparing the experimental results of

Table 2. Kinematic Viscosity, ν, of R407C Refrigerant−Oil Mixtures under Saturation Conditions

		lubricant mass fraction									
		0		$2\cdot10^{-5}$		$5\cdot10^{-5}$		$8\cdot10^{-5}$		$1\cdot10^{-4}$	
T	p^a	ν	$10^{-3}\ U_\nu$	ν	$10^{-3}\ U_\nu$	ν	$10^{-3}\ U_\nu$	ν	$10^{-3}\ U_\nu$		$10^{-3}\ U_\nu$
K	MPa	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$	$mm^2\cdot s^{-1}$
256.15	0.317	0.2117	±0.93	0.304	±1.3	0.446	±1.9	0.586	±2.4	0.669	±2.8
258.15	0.341	0.2070	±0.92	0.287	±1.3	0.408	±1.7	0.525	±2.2	0.595	±2.5
260.15	0.367	0.2024	±0.89	0.272	±1.2	0.375	±1.6	0.473	±2.0	0.532	±2.2
262.15	0.394	0.1980	±0.88	0.258	±1.1	0.346	±1.5	0.429	±1.8	0.478	±2.0
264.15	0.423	0.1936	±0.86	0.246	±1.1	0.321	±1.4	0.391	±1.7	0.433	±1.9
266.15	0.453	0.1894	±0.85	0.234	±1.0	0.299	±1.3	0.358	±1.5	0.394	±1.7
268.15	0.485	0.1853	±0.83	0.2239	±0.99	0.279	±1.2	0.330	±1.4	0.360	±1.5
270.15	0.518	0.1814	±0.82	0.2145	±0.95	0.262	±1.2	0.305	±1.3	0.331	±1.4
272.15	0.553	0.1775	±0.79	0.2059	±0.91	0.247	±1.1	0.284	±1.2	0.306	±1.3
274.15	0.590	0.1738	±0.78	0.1981	±0.88	0.234	±1.0	0.265	±1.2	0.284	±1.2
276.15	0.629	0.1702	±0.76	0.1910	±0.84	0.2215	±0.97	0.248	±1.1	0.265	±1.1
278.15	0.669	0.1666	±0.75	0.1844	±0.83	0.2108	±0.93	0.234	±1.0	0.248	±1.1
280.15	0.712	0.1632	±0.73	0.1784	±0.79	0.2012	±0.88	0.2207	±0.96	0.234	±1.0
282.15	0.756	0.1599	±0.72	0.1729	±0.77	0.1926	±0.85	0.2092	±0.92	0.2207	±0.97
284.15	0.803	0.1566	±0.71	0.1678	±0.75	0.1848	±0.82	0.1990	±0.88	0.2092	±0.93
286.15	0.852	0.1535	±0.70	0.1630	±0.73	0.1779	±0.79	0.1900	±0.85	0.1989	±0.88
288.15	0.903	0.1504	±0.68	0.1586	±0.72	0.1715	±0.77	0.1819	±0.80	0.1899	±0.84
290.15	0.956	0.1474	±0.67	0.1545	±0.70	0.1658	±0.74	0.1746	±0.78	0.1818	±0.81
292.15	1.012	0.1445	±0.65	0.1507	±0.68	0.1606	±0.72	0.1681	±0.75	0.1745	±0.77
294.15	1.070	0.1417	±0.64	0.1471	±0.66	0.1558	±0.70	0.1622	±0.72	0.1680	±0.75
296.15	1.130	0.1389	±0.63	0.1438	±0.65	0.1514	±0.68	0.1568	±0.70	0.1621	±0.72
298.15	1.193	0.1362	±0.63	0.1406	±0.64	0.1474	±0.67	0.1520	±0.69	0.1568	±0.71
300.15	1.259	0.1336	±0.61	0.1376	±0.63	0.1437	±0.65	0.1475	±0.67	0.1520	±0.68
302.15	1.327	0.1310	±0.60	0.1348	±0.62	0.1402	±0.64	0.1434	±0.65	0.1476	±0.67
304.15	1.398	0.1285	±0.58	0.1320	±0.60	0.1369	±0.62	0.1397	±0.63	0.1435	±0.659
306.15	1.472	0.1261	±0.58	0.1294	±0.59	0.1339	±0.61	0.1362	±0.62	0.1398	±0.64
308.15	1.549	0.1237	±0.56	0.1269	±0.58	0.1309	±0.59	0.1329	±0.61	0.1363	±0.62
310.15	1.628	0.1213	±0.56	0.1244	±0.57	0.1282	±0.58	0.1298	±0.59	0.1331	±0.61
312.15	1.711	0.1190	±0.54	0.1220	±0.55	0.1255	±0.57	0.1269	±0.58	0.1300	±0.59
314.15	1.796	0.1167	±0.54	0.1196	±0.55	0.1229	±0.56	0.1240	±0.57	0.1271	±0.58
316.15	1.885	0.1145	±0.53	0.1173	±0.55	0.1203	±0.56	0.1213	±0.55	0.1243	±0.56
318.15	1.977	0.1123	±0.52	0.1150	±0.53	0.1178	±0.54	0.1187	±0.54	0.1215	±0.55
320.15	2.072	0.1101	±0.51	0.1127	±0.52	0.1153	±0.53	0.1160	±0.54	0.1189	±0.55
322.15	2.170	0.1080	±0.50	0.1104	±0.51	0.1128	±0.52	0.1134	±0.52	0.1162	±0.53
324.15	2.272	0.1059	±0.49	0.1081	±0.50	0.1102	±0.51	0.1108	±0.51	0.1136	±0.52
326.15	2.377	0.1038	±0.48	0.1058	±0.49	0.1077	±0.50	0.1082	±0.51	0.1110	±0.52
328.15	2.485	0.1017	±0.48	0.1034	±0.48	0.1050	±0.49	0.1056	±0.49	0.1083	±0.51
330.15	2.597	0.0996	±0.47	0.1010	±0.47	0.1024	±0.48	0.1028	±0.47	0.1056	±0.49
332.15	2.713	0.0976	±0.46	0.0986	±0.46	0.0996	±0.46	0.1001	±0.47	0.1028	±0.48
334.15	2.832	0.0955	±0.44	0.0962	±0.45	0.0968	±0.45	0.0972	±0.45	0.1000	±0.46
336.15	2.955	0.0935	±0.44	0.0937	±0.44	0.0939	±0.44	0.0943	±0.44	0.0970	±0.45

[a] Note: vapor phase pressure.

R410A and R407C with the literature data from NIST-REFPROP 7.0, the average deviations are 1.71 % for R410A and 2.13 % for R07C, and the maximum deviations are 1.83 % for R410A and 2.53 % for R07C.

Some investigations have shown that the curve shape of the modified Andrade correlation could not represent the relationship between the liquid kinematic viscosity under saturation conditions and the temperature of R410A and R407C refrigerant−oil mixtures, so the experiential correlation shown as eq 5 was adopted to correlate the liquid kinematic viscosity under saturation conditions and the temperature for refrigerant R410A and R407C refrigerant−oil mixtures. Table 3 lists the values of the parameters (A, B, C, and D) and the relative deviations, respectively.

$$\log_{10}(\nu/\mathrm{mm}^2\cdot\mathrm{s}^{-1}) = A + B/(T/\mathrm{K}) + C(T/\mathrm{K}) + D(T/\mathrm{K})^2 \tag{5}$$

Figure 1 depicts the variation of kinematic viscosity of R410A refrigerant−oil mixtures with temperature under the conditions of (0, 2, 5, 8, and 10)$\cdot10^{-5}$ lubricant mass fractions, and Figure 2 depicts those of R407C refrigerant−oil mixtures. From Figures 1 and 2, it can be seen that, with the addition of lubricant, there is a significant impact on the liquid kinematic viscosity of R410A and R407C refrigerant−oil mixtures under saturation conditions. For the temperature range investigated in this work, the impact of lubricant gradually decreases with the increase of temperature. When the temperature is higher than 300 K, the impact of lubricant is tiny and can be neglected.

Table 3. Parameters of Equation 5 and Relative Deviations of Experiential Correlations

	lubricant mass fraction	A	B	C	D	% relative deviation
R410A	$2\cdot10^{-5}$	−71.85	7525.76	0.23	−0.00025	0.15
	$5\cdot10^{-5}$	−112.29	11895.31	0.35	−0.00037	0.24
	$8\cdot10^{-5}$	−139.08	14783.11	0.43	−0.00046	0.30
	$1\cdot10^{-4}$	−132.68	14345.93	0.41	−0.00043	0.29
R407C	$2\cdot10^{-5}$	−64.69	6789.89	0.20	−0.00022	0.14
	$5\cdot10^{-5}$	−106.15	11219.32	0.33	−0.00036	0.22
	$8\cdot10^{-5}$	−123.85	13231.44	0.39	−0.00041	0.27
	$1\cdot10^{-4}$	−129.61	13921.57	0.40	−0.00042	0.29

Conclusions

In this work, with the (0, 2, 5, 8, and 10)$\cdot10^{-5}$ lubricant mass fractions, the kinematic viscosity of R410A and R407C

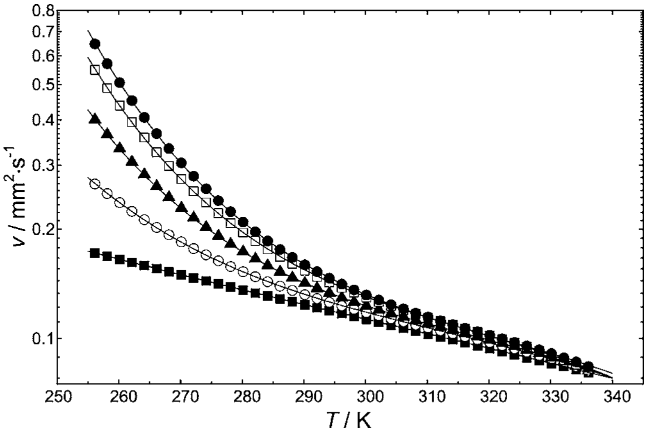

Figure 1. Kinematic viscosity of R410A refrigerant−oil mixtures: lubricant mass fraction: ■, 0; ○, $2 \cdot 10^{-5}$; ▲, $5 \cdot 10^{-5}$; □, $8 \cdot 10^{-5}$; ●, $1 \cdot 10^{-4}$; —, correlation equation.

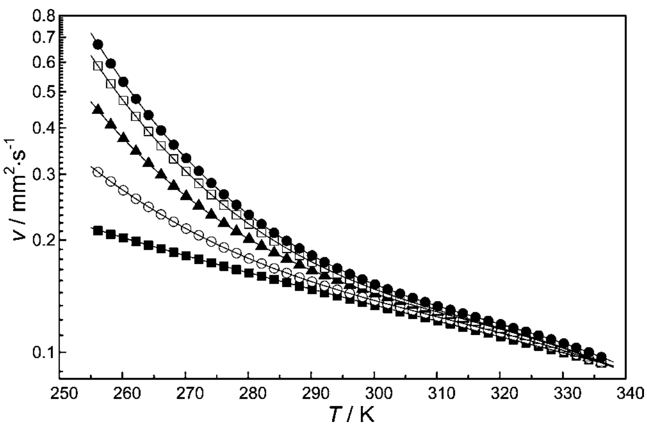

Figure 2. Kinematic viscosity of R407C refrigerant−oil mixtures: lubricant mass fraction: ■, 0; ○, $2 \cdot 10^{-5}$; ▲, $5 \cdot 10^{-5}$; □, $8 \cdot 10^{-5}$; ●, $1 \cdot 10^{-4}$; —, correlation equation.

refrigerant−oil mixtures in the saturated liquid phase were measured at the temperatures ranging from (256.15 to 336.15) K. The experimental results show that, with the addition of lubricant, there is a significant impact on liquid kinematic viscosity of R410A and R407C refrigerant−oil mixtures under saturation conditions. With the increase in lubricant concentration, liquid kinematic viscosities of R410A and R407C refrigerant−oil mixtures significantly increase, and the impact of lubricant gradually decreases with the increase of temperature. According to the experimental results, the correlations were established for R410A and R407C refrigerant−oil mixtures under the conditions of (0, 2, 5, 8, and 10)$\cdot 10^{-5}$ lubricant mass fractions.

Supporting Information Available:

The experimental results and literature data of R410A and the relative deviation between them are listed in Table A. The experimental results and literature data of R407C and the relative deviation between them are listed in Table B. The main physical properties of lubricant (Solest 120) are listed in Table C. The components of R410A and R407C are listed in Table D. The general properties information of R410A and R407C are listed in Table E. This material is available free of charge via the Internet at http://pubs.acs.org.

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