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Dielectric constant and dipole moment of hydrofluorocarbon refrigerant mixtures R404A, R407C, and R507

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Abstract. Reliable dielectric property information about three HFC mixtures currently regarded as replacements for R22 and R502 is given. The static dielectric constants of the ternary systems HFC125/143a/134a (R404A), HFC32/125/134a (R407C), and of the binary system HFC125/143a (R507) in the liquid phase were measured by the direct capacitance method at temperatures from 217 to 303 K and under pressures up to 16 MPa. The uncertainty of the measurements is estimated to be within 0.1% and the repeatability 0.01%. A complete set of tables is given of experimental data as a function of temperature, pressure, and density, which covers dielectric property needs for most engineering applications. The data obtained were correlated as a function of density and temperature by polynomial equations. In order to study the dependence of dielectric constant on density and temperature on a molecular basis, the theory developed by Vedam and Chen and adapted by Diguet was applied to analyse the data. Estimates for the dipole moments of the mixtures based on dielectric constant measurements are given. The Kirkwood theory was used to obtain the values of apparent dipole moments of R404A, R407C, and R507 in the liquid phase.

1 Introduction

It is practically impossible to imagine what industry, medicine, or scientific research would be possible today without the refrigeration process. Refrigeration has found widespread application in the preservation and treatment of products, foods, and industrial processes.

Based on environmental considerations, safety of use in all applications, cycle performance, material compatibility, manufacturing and economics, mixtures of HFC refrigerants have been identified as promising substitutes for HCFC refrigerants in most commercial refrigeration and air-conditioning applications. Of major interest are the refrigerant blends consisting of difluoromethane (R32), pentafluoroethane (R125), 1,1,1-trifluoroethane (R143a), and 1,1,1,2-tetrafluoroethane (R134a). In particular, R407 (R32/125/134a) is important for replacing R22 (chlorodifluoromethane), R404 (R125/143a/134a) and R507 (R125/143a) for R502 (an azeotropic mixture of R22 and R115) (Kruse 1980; Tilner-Roth et al 1988). Accurate thermodynamic and electric property information is required not only for the design and simulation of new equipment but also as a basis for the property requirements in material safety regulations. The present work contributes to this field by presenting dielectric properties of two ternary zeotropic refrigerant blends, R404A and R407C, and one binary azeotropic mixture, R507. The purpose is to help in creating optimum conditions for efficient and economic refrigerant and air-conditioning systems.

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R404A is a non-ozone-depleting compound designed to serve as a longterm alternative to R502 and HCFC22 in low and medium temperature commercial refrigeration applications. Leading refrigeration compressor and system manufacturers have approved R404A for use in new equipment, including food display and storage cases, cold storage rooms, ice machines, and transport refrigeration. R404A has a small change in composition as a result of fractionation (changes from a liquid to a vapour or vice versa). However, as it is a zeotropic blend, there will be a slight difference in the composition in the vapour phase, which is in equilibrium with the liquid. For this reason it is essential that systems be charged only with liquid from the cylinder, not vapour. Vapour charging may result in the wrong refrigerant composition and possibly damage the system.

R407C is also a zero-ozone-depletion blend. It closely matches the properties of R22 and is used in many air-conditioning systems. It has a heat capacity comparable to HCFC22, making it easier to use with few modifications in the existing equipment designs. This refrigerant may be used to replace R22 in existing medium-temperature commercial refrigeration systems, including supermarket display cases and reach-in coolers. According to American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standards, R407C is classified as nonflammable at 1 atmosphere pressure and 18 °C.

R507 (an azeotropic of HFC125 and HFC143a) has been developed to serve as a longterm substitute for the refrigerants R502 and HCFC22. This mixture is an environmentally safer, non-ozone-depleting substitute, which possesses similar energy efficiency and capacity characteristics to R502 and has an intrinsically low toxicity. These properties make it an excellent refrigerant choice for low and medium temperature refrigeration applications, such as supermarket display cases, transport refrigeration, and ice machines. It is also stable and nonflammable at ambient temperatures and atmospheric pressures. However, when mixed with air, as with most fluorocarbons, it can be combustible at higher pressures and temperatures.

The dielectric constant (relative permittivity), ε, of these fluids is of interest for fundamental reasons and for modelling intermolecular potentials. In the industry, the dielectric constant is necessary to give operational values for some design parameters of machinery used in the air-conditioning and refrigeration industry. This property also affects the electric properties of compressor oils, where the refrigerants are soluble.

In a previous study (Brito et al 1998) we measured the dielectric constant of R410A, an HFC-based refrigerant, composed 50/50 wt% of HFC32/125. The present work is undertaken to extend the investigations of the refrigerant mixtures. As part of this project, we report the experimental results of the dielectric constant and the subsequent dipole moment of the mixtures R404A, R407C, and R507 in the temperature range 217 – 303 K and pressures from 2 to 16 MPa. With a direct capacitance method, measurements were carried out in the liquid phase, which usually exists in air-conditioning and refrigeration compressors.

2 Experimental

A rather convenient method for measuring the dielectric constant of a fluid is to measure the capacitance, C, of a suitable capacitor filled with the fluid between the plates. Measurement of the vacuum capacitance, C_0, makes it possible to obtain the dielectric constant, ε, as the ratio $\varepsilon = C/C_0$. The cell of concentric-cylinders type which was used for several dielectric constant measurements was developed by Mardolcar et al (1992). The apparatus and experimental procedures were essentially the same as used in previous works (Barão et al 1997; Brito et al 1998). The data for each of the fluids were obtained from ten isotherms separated by $\approx$10 K, in steps of 1 MPa, from 2 to 16 MPa. Vacuum points were taken before and after each filling of the cell and were stable to the order of 10^{-4} pF over the duration of this study.

Table 1. Physical properties and purity of R404A, R407C, and R507.

	Pentafluoroethane/ 1,1,1-Trifluoroethane/ 1,1,1,2-Tetrafluoroethane	Difluoromethane/ Pentafluoroethane/ 1,1,1,2-Tetrafluoroethane	Pentafluoroethane/ 1,1,1-Trifluoroethane
ASHRAE Nomenclature	R404A	R407C	R507
Molecular formula	$CHF_2CF_3/CF_3CH_3/CF_3CH_2F$	$CF_2H_2/CHF_2CF_3/CF_3CH_2F$	CHF_2CF_3/CF_3CH_3
Composition/wt%	R125/R143a/R134a 44/52/4	R32/R125/R134a 23/25/52	R125/R143a 50/50
Molecular weight/g mol^{-1}	97.6	86.2	98.9
Boiling/bubble point at 1 atm/°C	−46.7	−43.6	−46.7
Estimated water content/ppm	<10	8	<10
Purity/%	>99.5	>99.5	>99.5

The blends analysed were supplied by the chemical manufacturer Solvay Fluor und Derivate GmbH, Germany, with a fixed composition. The composition of the various blends is standardised for the mass fractions of the pure components. The state of purity, according to the supplier and the physical properties of the studied fluids, can be seen in table 1. Two of the blends, R404A and R407C, are zeotropes, refrigerant mixtures that boil or condense over a temperature range, in contrast to R507, which is an azeotropic mixture. Zeotropes do not have a boiling point; instead, they undergo phase change between the bubble and dew temperatures. The mixtures were used as supplied and the composition was not confirmed.

3 Results and discussions

The measured dielectric constants of R404A, R407C, and R507 are presented as a function of pressure and density for each isotherm in tables 2–4. The values of the density were calculated by a correlation scheme for binary and ternary refrigerant mixtures in the liquid state, developed by Fialho and Nieto de Castro (1997). With the hard sphere De Santis model and mixing and combination rules, it is possible to predict the liquid state densities with an uncertainty of 1.5% for reduced temperatures $\leqslant 0.9$. We have compared these density data with the experimental values presented in the database of Tillner-Roth et al (1988) available in a large temperature range, but with a pressure limit of only 7 MPa. A comparison between the two data sets shows a deviation of the order of 2%. Due to the small pressure range of these data, we decided to apply the correlation scheme developed by Fialho and Nieto de Castro (1997).

The dependence of the dielectric constants on pressure and temperature for the measured mixtures in the liquid phase is illustrated in figures 1–3.

The dielectric constant of these refrigerants increases with increasing pressure and decreases with increasing temperature. The mixtures studied have values of dielectric constant in the liquid phase of the following order:

$$R407C > R404A > R507 \ .$$

In figures 4–6, we can see the representation of the dielectric constant as a function of density for all isotherms (for the measured blends).

Table 2. Experimental values of the dielectric constant of R404a (T_n is the nominal temperature).

T/K	p/MPa	ρ/kg m^{-3}	$\varepsilon(T, p)$	$\rho(T_n, p)$/kg m^{-3}	$\varepsilon(T_n, p)$
$T_n = 217.65$ K					
217.87	2.01	1291.5	14.6868	1292.1	14.7032
217.88	3.00	1293.9	14.7253	1294.5	14.7424
217.87	4.00	1296.3	14.7595	1296.9	14.7759
217.87	5.00	1298.7	14.7968	1299.3	14.8132
217.87	6.01	1301.1	14.8282	1301.6	14.8446
217.85	6.99	1303.3	14.8599	1303.9	14.8748
217.84	8.00	1305.6	14.8956	1306.1	14.9098
217.83	9.00	1307.9	14.9298	1308.4	14.9432
217.81	10.00	1310.1	14.9649	1310.5	14.9768
217.80	11.00	1312.3	14.9982	1312.7	15.0094
217.77	12.00	1314.5	15.0313	1314.8	15.0402
217.72	13.00	1316.7	15.0688	1316.9	15.0740
217.69	14.01	1318.9	15.1028	1319.0	15.1058
217.68	15.00	1320.9	15.1334	1321.0	15.1356
217.67	16.00	1322.9	15.1635	1323.0	15.1650
$T_n = 223.65$ K					
223.46	2.01	1276.1	14.0365	1275.5	14.0234
223.45	3.02	1278.7	14.0753	1278.2	14.0615
223.45	4.00	1281.2	14.1098	1280.7	14.0960
223.45	5.00	1283.8	14.1452	1283.2	14.1314
223.45	6.00	1286.3	14.1798	1285.7	14.1660
223.46	7.00	1288.7	14.2149	1288.2	14.2018
223.47	8.00	1291.0	14.2473	1290.6	14.2348
223.47	9.00	1293.4	14.2813	1292.9	14.2688
223.47	10.02	1295.8	14.3149	1295.3	14.3024
223.46	11.02	1298.1	14.3510	1297.6	14.3379
223.46	12.00	1300.3	14.3821	1299.8	14.3690
223.46	13.00	1302.5	14.4128	1302.0	14.3997
223.46	14.00	1304.7	14.4448	1304.2	14.4317
223.45	15.00	1306.9	14.4760	1306.4	14.4622
223.43	16.00	1309.0	14.5090	1308.5	14.4938
$T_n = 233.15$ K					
233.05	2.00	1248.9	13.0175	1248.6	13.0114
233.05	3.00	1251.8	13.0579	1251.6	13.0518
233.05	4.00	1254.8	13.0959	1254.5	13.0898
233.05	5.00	1257.6	13.1346	1257.3	13.1285
233.06	6.00	1260.4	13.1713	1260.1	13.1658
233.06	7.00	1263.1	13.2079	1262.9	13.2024
233.06	8.00	1265.8	13.2427	1265.6	13.2372
233.06	9.00	1268.5	13.2766	1268.2	13.2711
233.06	10.00	1271.0	13.3121	1270.8	13.3066
233.07	11.00	1273.6	13.3448	1273.4	13.3399
233.08	12.00	1276.0	13.3779	1275.9	13.3736
233.13	13.00	1278.4	13.4044	1278.3	13.4032
233.05	14.00	1281.0	13.4422	1280.7	13.4361
233.05	15.00	1283.4	13.4742	1283.1	13.4681
233.05	16.00	1285.7	13.5056	1285.5	13.4995

Table 2 (continued).

T/K	p/MPa	ρ/kg m^{-3}	$\varepsilon(T, p)$	$\rho(T_n, p)$/kg m^{-3}	$\varepsilon(T_n, p)$
$T_n = 243.15$ K					
243.33	2.00	1218.7	12.0184	1219.2	12.0280
243.32	3.00	1222.1	12.0630	1222.6	12.0721
243.33	4.00	1225.5	12.1024	1226.0	12.1120
243.32	5.01	1228.8	12.1447	1229.3	12.1538
243.32	6.00	1232.0	12.1847	1232.5	12.1938
243.32	7.00	1235.1	12.2245	1235.6	12.2336
243.32	8.00	1238.2	12.2638	1238.7	12.2729
243.32	9.00	1241.2	12.3001	1241.6	12.3092
243.32	10.00	1244.1	12.3366	1244.6	12.3457
243.30	11.00	1247.1	12.3752	1247.4	12.3832
243.30	12.00	1249.9	12.4130	1250.3	12.4210
243.31	13.00	1252.6	12.4456	1253.0	12.4541
243.30	14.00	1255.3	12.4791	1255.7	12.4871
243.30	15.01	1258.0	12.5145	1258.4	12.5225
243.29	16.01	1260.7	12.5477	1261.0	12.5552
$T_n = 253.15$ K					
253.24	2.00	1188.1	11.1339	1188.4	11.1381
253.24	3.00	1192.1	11.1822	1192.4	11.1864
253.24	4.00	1196.0	11.2273	1196.3	11.2315
253.24	5.00	1199.8	11.2720	1200.1	11.2762
253.25	6.00	1203.5	11.3149	1203.8	11.3196
253.25	7.00	1207.1	11.3580	1207.4	11.3627
253.25	8.00	1210.6	11.3992	1210.9	11.4039
253.25	9.00	1214.0	11.4389	1214.3	11.4436
253.23	10.00	1217.4	11.4817	1217.7	11.4855
253.23	11.00	1220.7	11.5192	1220.9	11.5230
253.23	12.00	1223.9	11.5569	1224.1	11.5607
253.22	13.00	1227.0	11.5944	1227.2	11.5977
253.22	14.00	1230.1	11.6306	1230.3	11.6339
253.23	15.00	1233.0	11.6657	1233.2	11.6695
253.23	16.00	1236.0	11.7003	1236.2	11.7041
$T_n = 263.15$ K					
263.19	2.00	1155.5	10.3090	1155.6	10.3107
263.19	3.00	1160.3	10.3614	1160.4	10.3631
263.19	4.00	1164.9	10.4115	1165.0	10.4132
263.19	5.00	1169.4	10.4605	1169.5	10.4622
263.19	6.00	1173.7	10.5077	1173.8	10.5094
263.20	7.00	1177.9	10.5525	1178.0	10.5546
263.20	8.00	1181.9	10.5966	1182.1	10.5987
263.19	9.00	1185.9	10.6406	1186.0	10.6423
263.20	10.00	1189.7	10.6826	1189.9	10.6847
263.20	11.00	1193.5	10.7240	1193.6	10.7261
263.20	12.00	1197.1	10.7637	1197.2	10.7658
263.20	13.00	1200.6	10.8030	1200.8	10.8051
263.19	14.00	1204.1	10.8436	1204.2	10.8453
263.20	15.00	1207.5	10.8797	1207.6	10.8818
263.20	16.00	1210.8	10.9172	1210.9	10.9193

Table 2 (continued).

T/K	p/MPa	ρ/kg m^{-3}	$\varepsilon(T, p)$	$\rho(T_n, p)$/kg m^{-3}	$\varepsilon(T_n, p)$
$T_n = 273.15$ K					
273.05	2.00	1120.6	9.5394	1120.2	9.5356
273.05	3.00	1126.5	9.5969	1126.1	9.5931
273.05	4.00	1132.0	9.6514	1131.7	9.6476
273.05	5.00	1137.4	9.7073	1137.0	9.7035
273.05	6.00	1142.5	9.7598	1142.2	9.7560
273.05	7.00	1147.5	9.8099	1147.1	9.8061
273.06	8.00	1152.2	9.8587	1151.9	9.8553
273.06	9.00	1156.8	9.9056	1156.5	9.9022
273.06	10.00	1161.3	9.9506	1161.0	9.9472
273.06	11.00	1165.6	9.9948	1165.3	9.9914
273.06	12.00	1169.7	10.0378	1169.5	10.0344
273.06	13.00	1173.8	10.0797	1173.5	10.0763
273.07	14.00	1177.7	10.1203	1177.5	10.1172
273.07	15.00	1181.5	10.1598	1181.3	10.1567
273.07	16.00	1185.3	10.1995	1185.0	10.1964
$T_n = 283.15$ K					
283.16	2.01	1081.3	8.7786	1081.4	8.7790
283.17	3.03	1088.8	8.8469	1088.8	8.8476
283.17	4.00	1095.5	8.9114	1095.6	8.9121
283.17	5.00	1102.1	8.9725	1102.1	8.9732
283.18	6.00	1108.3	9.0278	1108.4	9.0289
283.18	7.00	1114.2	9.0825	1114.3	9.0836
283.18	8.01	1120.0	9.1361	1120.1	9.1372
283.18	9.01	1125.4	9.1880	1125.5	9.1891
283.18	10.00	1130.6	9.2367	1130.7	9.2378
283.18	11.01	1135.7	9.2851	1135.8	9.2862
283.18	12.00	1140.6	9.3317	1140.7	9.3328
283.18	13.00	1145.3	9.3755	1145.3	9.3766
283.18	13.99	1149.8	9.4192	1149.8	9.4203
283.19	15.01	1154.2	9.4626	1154.3	9.4640
283.17	16.00	1158.5	9.5037	1158.5	9.5044
$T_n = 293.15$ K					
293.20	2.00	1036.9	8.0264	1037.2	8.0281
293.19	3.00	1046.6	8.1060	1046.7	8.1074
293.17	4.00	1055.5	8.1783	1055.6	8.1790
293.17	5.00	1063.8	8.2472	1063.9	8.2479
293.17	6.00	1071.6	8.3114	1071.7	8.3121
293.17	7.00	1078.9	8.3721	1079.0	8.3728
293.17	8.00	1085.9	8.4319	1085.9	8.4326
293.17	9.00	1092.4	8.4891	1092.5	8.4898
293.18	10.00	1098.7	8.5440	1098.8	8.5450
293.18	11.00	1104.7	8.5970	1104.8	8.5980
293.18	12.00	1110.4	8.6471	1110.5	8.6481
293.18	13.00	1115.9	8.6958	1116.0	8.6968
293.19	14.00	1121.1	8.7441	1121.3	8.7455
293.18	15.00	1126.3	8.7908	1126.3	8.7918
293.19	16.00	1131.1	8.8364	1131.2	8.8378

Table 2 (continued).

T/K	p/MPa	ρ/kg m^{-3}	$\varepsilon(T, p)$	$\rho(T_n, p)$/kg m^{-3}	$\varepsilon(T_n, p)$
$T_n = 303.15$ K					
303.14	2.00	985.1	7.3081	985.0	7.3078
303.14	3.00	998.3	7.3989	998.3	7.3986
303.15	4.00	1010.2	7.4876	1010.2	7.4876
303.15	5.00	1021.1	7.5675	1021.1	7.5675
303.15	6.00	1031.1	7.6443	1031.1	7.6443
303.14	7.01	1040.5	7.7194	1040.4	7.7191
303.14	8.00	1049.0	7.7854	1049.0	7.7851
303.14	9.01	1057.2	7.8534	1057.1	7.8531
303.14	10.01	1064.8	7.9162	1064.8	7.9159
303.14	11.02	1072.1	7.9739	1072.0	7.9736
303.15	12.00	1078.7	8.0298	1078.7	8.0298
303.14	13.00	1085.2	8.0845	1085.2	8.0842
303.14	14.01	1091.5	8.1379	1091.5	8.1376
303.14	15.03	1097.5	8.1892	1097.5	8.1889
303.14	16.00	1103.1	8.2367	1103.0	8.2364

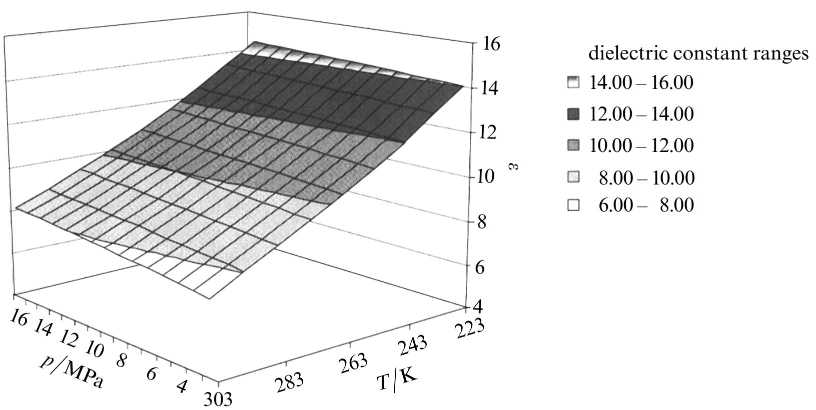

Figure 1. Dielectric constant of R404A in the measured thermodynamic range.

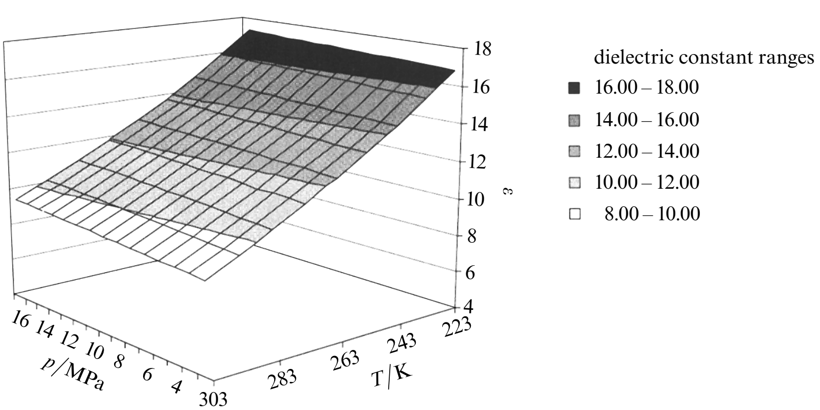

Figure 2. Dielectric constant of R407C in the measured thermodynamic range.

Table 3. Experimental values of the dielectric constant of R407C (T_n is the nominal temperature).

T/K	p/MPa	ρ/kg m^{-3}	$\varepsilon(T, p)$	$\rho(T_n, p)$/kg m^{-3}	$\varepsilon(T_n, p)$
$T_n = 220.15$ K					
220.37	2.00	1383.3	17.2692	1383.9	17.2872
220.36	3.00	1385.1	17.3067	1385.7	17.3239
220.35	4.00	1387.0	17.3335	1387.5	17.3499
220.32	5.00	1388.9	17.3739	1389.3	17.3878
220.30	6.00	1390.7	17.4103	1391.1	17.4226
220.26	7.00	1392.6	17.4513	1392.9	17.4603
220.20	8.00	1394.5	17.4953	1394.6	17.4994
220.18	9.00	1396.3	17.5326	1396.3	17.5351
220.15	10.00	1398.1	17.5694	1398.1	17.5694
220.12	11.00	1399.8	17.6072	1399.7	17.6047
220.09	12.00	1401.6	17.6471	1401.4	17.6422
220.07	13.00	1403.3	17.6809	1403.0	17.6743
220.03	14.00	1405.0	17.7183	1404.7	17.7084
219.95	15.00	1406.8	17.7635	1406.3	17.7470
219.73	16.00	1409.0	17.8263	1407.9	17.7916
$T_n = 223.65$ K					
223.82	2.00	1373.5	16.7792	1373.9	16.7926
223.82	3.00	1375.4	16.8174	1375.9	16.8308
223.81	4.00	1377.3	16.8540	1377.8	16.8666
223.80	5.00	1379.2	16.8816	1379.6	16.8934
223.81	6.00	1281.1	16.9162	1281.5	16.9288
223.79	7.00	1382.9	16.9542	1383.3	16.9652
223.76	8.00	1384.8	16.9930	1385.1	17.0017
223.74	9.00	1386.7	17.0294	1386.9	17.0365
223.73	10.00	1388.5	17.0653	1388.7	17.0716
223.73	11.00	1390.2	17.0986	1390.4	17.1049
223.73	12.00	1392.0	17.1327	1392.2	17.1390
223.72	13.00	1393.7	17.1665	1393.9	17.1720
223.69	14.00	1395.5	17.2031	1395.6	17.2063
223.73	15.00	1397.0	17.2327	1397.2	17.2390
223.71	16.00	1398.7	17.2655	1398.9	17.2702
$T_n = 233.15$ K					
233.18	2.00	1346.5	15.5513	1346.6	15.5534
233.19	3.00	1348.6	15.5891	1348.7	15.5919
233.19	4.00	1350.8	15.6255	1350.9	15.6283
233.19	5.00	1352.9	15.6592	1353.0	15.6620
233.18	6.00	1355.0	15.6984	1355.1	15.7005
233.19	7.00	1357.0	15.7319	1357.1	15.7347
233.19	8.00	1359.0	15.7667	1359.1	15.7695
233.19	9.00	1361.0	15.8005	1361.1	15.8033
233.18	10.00	1363.0	15.8297	1363.1	15.8318
233.18	11.00	1364.9	15.8645	1365.0	15.8666
233.16	12.00	1366.9	15.9012	1366.9	15.9019
233.16	13.00	1368.8	15.9343	1368.8	15.9350
233.16	14.00	1370.7	15.9696	1370.7	15.9703
233.17	15.00	1372.5	16.0032	1372.5	16.0046
233.12	16.00	1374.4	16.0391	1374.4	16.0370

Table 3 (continued).

T/K	p/MPa	$\rho/\mathrm{kg\ m^{-3}}$	$\varepsilon(T, p)$	$\rho(T_n, p)/\mathrm{kg\ m^{-3}}$	$\varepsilon(T_n, p)$
$T_n = 243.15\,\mathrm{K}$					
243.21	2.00	1316.8	14.3610	1317.0	14.3648
243.21	3.00	1319.3	14.3993	1319.5	14.4031
243.22	4.00	1321.7	14.4374	1321.9	14.4418
243.22	5.00	1324.1	14.4764	1324.3	14.4808
243.23	6.00	1326.4	14.5141	1326.7	14.5192
243.23	7.00	1328.8	14.5516	1329.0	14.5567
243.22	8.00	1331.1	14.5890	1331.3	14.5934
243.22	9.00	1333.3	14.6260	1333.5	14.6304
243.22	10.00	1335.5	14.6637	1335.7	14.6681
243.22	11.00	1337.7	14.6980	1337.9	14.7024
243.22	12.00	1339.9	14.7340	1340.0	14.7384
243.22	13.00	1342.0	14.7691	1342.2	14.7735
243.22	14.00	1344.1	14.7941	1344.3	14.7985
243.22	15.00	1346.1	14.8276	1346.3	14.8320
243.22	16.00	1348.2	14.8609	1348.4	14.8653
$T_n = 253.15\,\mathrm{K}$					
253.31	2.02	1285.9	13.2794	1286.4	13.2885
253.31	3.00	1288.8	13.3182	1289.2	13.3273
253.31	4.02	1291.6	13.3600	1292.1	13.3691
253.31	5.00	1294.3	13.4009	1294.8	13.4100
253.31	6.00	1297.0	13.4402	1297.5	13.4493
253.30	7.00	1299.7	13.4808	1300.1	13.4893
253.30	8.00	1302.3	13.5189	1302.7	13.5274
253.30	9.00	1304.9	13.5577	1305.3	13.5662
253.29	10.00	1307.4	13.5969	1307.8	13.6048
253.30	11.02	1309.9	13.6346	1310.3	13.6431
253.30	12.00	1312.3	13.6707	1312.7	13.6792
253.30	13.00	1314.7	13.7051	1315.1	13.7136
253.29	14.00	1317.1	13.7417	1317.4	13.7496
253.29	15.00	1319.4	13.7768	1319.7	13.7847
253.29	16.00	1321.6	13.8119	1322.0	13.8198
$T_n = 263.15\,\mathrm{K}$					
263.12	2.00	1254.5	12.3057	1254.4	12.3042
263.12	3.00	1257.8	12.3516	1257.7	12.3501
263.12	4.00	1261.1	12.3964	1261.0	12.3949
263.12	5.00	1264.3	12.4391	1264.2	12.4376
263.12	6.00	1267.4	12.4824	1267.3	12.4809
263.12	7.00	1270.5	12.5244	1270.4	12.5229
263.12	8.00	1273.4	12.5646	1273.4	12.5631
263.13	9.00	1276.3	12.6044	1276.3	12.6034
263.13	10.00	1279.2	12.6441	1279.2	12.6431
263.13	11.00	1282.0	12.6828	1282.0	12.6818
263.13	12.00	1284.8	12.7205	1284.7	12.7195
263.14	13.00	1287.5	12.7588	1287.4	12.7583
263.14	14.00	1290.1	12.7952	1290.1	12.7947
263.13	15.00	1292.8	12.8318	1292.7	12.8308
263.13	16.00	1295.3	12.8682	1295.3	12.8672

Table 3 (continued).

T/K	p/MPa	ρ/kg m^{-3}	$\varepsilon(T, p)$	$\rho(T_n, p)$/kg m^{-3}	$\varepsilon(T_n, p)$
$T_n = 273.15$ K					
273.02	2.00	1221.1	11.3546	1220.6	11.3484
273.02	3.00	1225.0	11.4034	1224.6	11.3972
273.00	4.00	1229.0	11.4531	1228.5	11.4460
273.02	5.00	1232.6	11.4982	1232.2	11.4920
273.01	6.00	1236.3	11.5459	1235.9	11.5392
273.00	7.00	1239.9	11.5910	1239.4	11.5839
273.00	8.00	1243.4	11.6395	1242.9	11.6324
273.00	9.00	1246.8	11.6822	1246.3	11.6751
273.01	10.00	1250.0	11.7206	1249.6	11.7139
273.01	11.00	1253.3	11.7619	1252.8	11.7552
272.99	12.00	1256.5	11.8053	1256.0	11.7977
272.99	13.00	1259.6	11.8450	1259.1	11.8374
273.00	14.00	1262.6	11.8823	1262.1	11.8752
272.99	15.10	1265.9	11.9262	1265.4	11.9186
273.00	16.00	1268.4	11.9630	1268.0	11.9559
$T_n = 283.15$ K					
283.02	2.00	1185.0	10.4396	1184.5	10.4338
283.03	3.00	1189.7	10.4919	1189.3	10.4866
283.02	4.00	1194.4	10.5472	1193.9	10.5414
283.03	5.00	1198.9	10.6003	1198.4	10.5950
283.03	6.00	1203.2	10.6502	1202.8	10.6449
283.03	7.00	1207.4	10.6985	1207.0	10.6932
283.03	8.00	1211.5	10.7463	1211.1	10.7410
283.03	9.00	1215.5	10.7931	1215.1	10.7878
283.03	10.00	1219.3	10.8396	1218.9	10.8343
283.03	11.00	1223.1	10.8833	1222.7	10.8780
283.03	12.00	1226.7	10.9271	1226.4	10.9218
283.03	13.00	1230.3	10.9699	1229.9	10.9646
283.03	14.00	1233.8	11.0118	1233.4	11.0065
283.03	15.00	1237.2	11.0516	1236.8	11.0463
283.04	16.00	1240.5	11.0918	1240.2	11.0869
$T_n = 293.15$ K					
293.23	2.00	1144.8	9.5458	1145.1	9.5492
293.24	3.00	1150.8	9.6058	1151.1	9.6096
293.23	4.00	1156.5	9.6677	1156.9	9.6711
293.24	5.01	1162.1	9.7277	1162.4	9.7315
293.24	6.00	1167.3	9.7843	1167.6	9.7881
293.23	7.00	1172.4	9.8391	1172.7	9.8425
293.24	8.00	1177.3	9.8946	1177.6	9.8984
293.24	9.00	1182.0	9.9429	1182.3	9.9467
293.24	10.00	1186.6	9.9942	1186.9	9.9980
293.24	11.01	1191.1	10.0439	1191.4	10.0477
293.24	12.00	1195.3	10.0921	1195.6	10.0959
293.24	13.00	1199.5	10.1373	1199.8	10.1411
293.24	14.00	1203.5	10.1831	1203.8	10.1869
293.23	15.00	1207.5	10.2294	1207.7	10.2328
293.23	16.00	1211.3	10.2733	1211.6	10.2767

Table 3 (continued).

T/K	p/MPa	ρ/kg m^{-3}	$\varepsilon(T, p)$	$\rho(T_n, p)$/kg m^{-3}	$\varepsilon(T_n, p)$
T_n = 303.15 K					
303.11	2.00	1101.5	8.6985	1101.4	8.6968
303.11	3.00	1109.2	8.7753	1109.1	8.7736
303.11	4.00	1116.5	8.8442	1116.3	8.8425
303.11	5.00	1123.4	8.9114	1123.2	8.9097
303.11	6.00	1129.9	8.9751	1129.8	8.9734
303.12	7.00	1136.1	9.0390	1136.0	9.0377
303.11	8.00	1142.1	9.0961	1142.0	9.0944
303.11	9.00	1147.8	9.1536	1147.7	9.1519
303.12	10.00	1153.3	9.2084	1153.2	9.2071
303.12	11.02	1158.6	9.2623	1158.5	9.2610
303.12	12.00	1163.6	9.3142	1163.5	9.3129
303.12	13.00	1168.5	9.3653	1168.4	9.3640
303.13	14.00	1173.2	9.4129	1173.1	9.4121
303.13	15.00	1177.8	9.4613	1177.7	9.4605
303.12	16.00	1182.2	9.5080	1182.2	9.5067

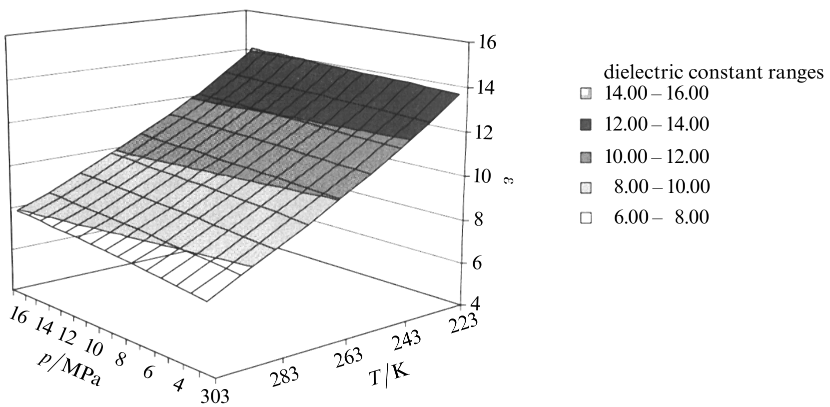

Figure 3. Dielectric constant of R507 in the measured thermodynamic range.

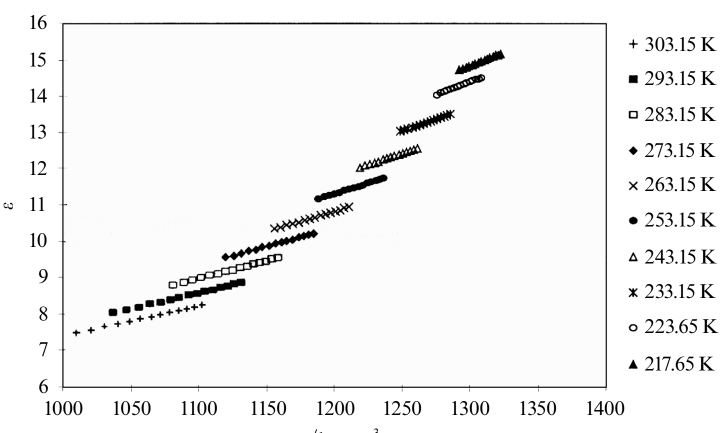

Figure 4. Graphical representation of the dielectric constant as a function of density for R404A.

Table 4. Experimental values of the dielectric constant of R507 (T_n is the nominal temperature).

T/K	p/MPa	ρ/kg m^{-3}	$\varepsilon(T, p)$	$\rho(T_n, p)$/kg m^{-3}	$\varepsilon(T_n, p)$
$T_n = 219.15$ K					
219.10	2.00	1309.1	14.1328	1309.0	14.1292
219.12	3.00	1311.6	14.1664	1311.5	14.1642
219.13	4.00	1314.1	14.1999	1314.0	14.1985
219.15	5.00	1316.5	14.2329	1316.5	14.2329
219.15	6.00	1318.9	14.2645	1318.9	14.2645
219.18	7.00	1321.2	14.2949	1321.3	14.2971
219.29	8.00	1323.2	14.3159	1323.6	14.3258
219.27	9.00	1325.6	14.3529	1325.9	14.3614
219.18	10.00	1328.1	14.3940	1328.2	14.3961
218.99	11.00	1330.8	14.4462	1330.4	14.4348
218.99	12.00	1333.0	14.4755	1332.6	14.4641
219.01	13.00	1335.1	14.4995	1334.7	14.4896
219.03	14.00	1337.2	14.5265	1336.9	14.5180
219.07	15.00	1339.2	14.5525	1339.0	14.5468
219.08	16.00	1341.2	14.5805	1341.1	14.5755
$T_n = 223.15$ K					
223.39	2.00	1296.9	13.6500	1297.6	13.6662
223.40	3.00	1299.6	13.6879	1300.3	13.7047
223.40	4.00	1302.2	13.7227	1302.9	13.7395
223.41	5.00	1304.8	13.7573	1305.5	13.7748
223.41	6.00	1307.3	13.7922	1308.0	13.8097
223.39	7.00	1309.9	13.8279	1310.5	13.8440
223.38	8.00	1312.4	13.8631	1313.0	13.8785
223.36	9.00	1314.8	13.8979	1315.4	13.9120
223.36	10.00	1317.2	13.9306	1317.7	13.9447
223.37	11.00	1319.5	13.9621	1320.1	13.9769
223.35	12.00	1321.8	13.9952	1322.4	14.0086
223.36	13.00	1324.1	14.0213	1324.6	14.0354
223.37	14.00	1326.3	14.0510	1326.8	14.0658
223.38	15.00	1328.5	14.0803	1329.0	14.0957
223.39	16.00	1330.6	14.1094	1331.2	14.1255
$T_n = 233.15$ K					
233.42	2.00	1267.8	12.6122	1268.6	12.6282
233.43	3.00	1270.9	12.6495	1271.7	12.6661
233.43	4.00	1273.9	12.6870	1274.7	12.7035
233.42	5.01	1276.9	12.7261	1277.6	12.7421
233.42	6.03	1279.8	12.7639	1280.6	12.7799
233.40	7.00	1282.6	12.8010	1283.3	12.8157
233.39	8.00	1285.4	12.8369	1286.1	12.8510
233.39	9.00	1288.1	12.8747	1288.8	12.8889
233.38	10.00	1290.8	12.9079	1291.4	12.9215
233.38	11.00	1293.4	12.9413	1294.0	12.9549
233.36	12.00	1296.0	12.9761	1296.6	12.9886
233.36	13.00	1298.6	13.0059	1299.1	13.0183
233.34	14.04	1301.2	13.0402	1301.7	13.0514
233.35	15.00	1303.5	13.0700	1304.0	13.0818
233.34	16.00	1305.9	13.1017	1306.4	13.1129

Table 4 (continued).

T/K	p/MPa	ρ/kg m^{-3}	$\varepsilon(T, p)$	$\rho(T_n, p)$/kg m^{-3}	$\varepsilon(T_n, p)$
$T_n = 243.15$ K					
243.23	2.00	1238.3	11.6820	1238.5	11.6862
243.23	3.00	1241.8	11.7250	1242.1	11.7292
243.23	4.00	1245.3	11.7656	1245.5	11.7697
243.24	5.00	1248.6	11.8066	1248.9	11.8113
243.23	6.00	1251.9	11.8452	1252.1	11.8494
243.23	7.00	1255.1	11.8838	1255.4	11.8879
243.23	8.00	1258.3	11.9218	1258.5	11.9260
243.23	9.00	1261.3	11.9595	1261.6	11.9637
243.24	10.00	1264.3	11.9946	1264.6	11.9992
243.23	11.00	1267.3	12.0303	1267.5	12.0344
243.24	12.00	1270.1	12.0653	1270.4	12.0700
243.24	13.00	1273.0	12.0991	1273.2	12.1038
243.24	14.00	1275.8	12.1319	1276.0	12.1366
243.24	15.00	1278.5	12.1656	1278.7	12.1703
243.24	16.00	1281.1	12.1943	1281.4	12.1990
$T_n = 253.15$ K					
253.00	2.00	1207.4	10.8357	1206.9	10.8288
253.00	3.00	1211.5	10.8818	1211.0	10.8748
253.01	4.00	1215.5	10.9243	1215.1	10.9178
253.01	5.00	1219.4	10.9688	1219.0	10.9623
253.01	6.00	1223.2	11.0120	1222.8	11.0055
253.01	7.00	1226.9	11.0530	1226.5	11.0465
253.01	8.00	1230.5	11.0940	1230.1	11.0875
253.01	9.00	1234.0	11.1334	1233.6	11.1269
253.01	10.00	1237.4	11.1714	1237.0	11.1649
253.01	11.00	1240.7	11.2087	1240.3	11.2022
253.02	12.00	1244.0	11.2455	1243.6	11.2395
253.01	13.00	1247.2	11.2821	1246.8	11.2756
253.01	14.00	1250.3	11.3173	1249.9	11.3108
253.01	15.00	1253.4	11.3521	1253.0	11.3456
253.02	16.00	1256.3	11.3864	1256.0	11.3804
$T_n = 263.15$ K					
262.96	2.03	1174.1	10.0287	1173.4	10.0208
262.96	3.01	1178.9	10.0791	1178.3	10.0712
262.96	3.96	1183.4	10.1261	1182.8	10.1182
262.96	4.99	1188.2	10.1752	1187.6	10.1674
262.96	6.01	1192.7	10.2229	1192.1	10.2150
262.96	7.05	1197.2	10.2694	1196.6	10.2615
262.95	7.99	1201.1	10.3124	1200.5	10.3041
262.96	9.01	1205.2	10.3545	1204.6	10.3466
262.95	10.00	1209.1	10.3976	1208.5	10.3892
262.95	11.00	1213.0	10.4366	1212.4	10.4282
262.96	12.00	1216.6	10.4757	1216.1	10.4678
262.95	13.00	1220.3	10.5143	1219.7	10.5060
262.94	14.01	1223.9	10.5527	1223.3	10.5440
262.95	15.00	1227.3	10.5893	1226.7	10.5810
262.95	16.00	1230.6	10.6252	1230.1	10.6169

Table 4 (continued).

T/K	p/MPa	ρ/kg m^{-3}	$\varepsilon(T, p)$	$\rho(T_n, p)$/kg m^{-3}	$\varepsilon(T_n, p)$
$T_n = 273.15$ K					
273.02	2.01	1137.5	9.2550	1137.0	9.2501
273.02	3.00	1143.5	9.3133	1143.0	9.3084
273.02	4.00	1149.2	9.3675	1148.8	9.3626
273.02	5.00	1154.7	9.4237	1154.3	9.4188
273.03	6.00	1160.0	9.4737	1159.6	9.4692
273.03	7.03	1165.2	9.5236	1164.8	9.5190
273.02	8.01	1170.1	9.5702	1169.7	9.5653
273.03	9.01	1174.8	9.6167	1174.4	9.6122
273.03	10.06	1179.6	9.6631	1179.2	9.6586
273.02	11.02	1183.9	9.7052	1183.5	9.7003
273.02	12.01	1188.1	9.7485	1187.7	9.7435
273.02	13.00	1192.2	9.7892	1191.9	9.7843
273.02	14.02	1196.4	9.8304	1196.0	9.8255
273.02	15.01	1200.3	9.8675	1199.9	9.8626
273.02	16.00	1204.0	9.9049	1203.7	9.9000
$T_n = 283.15$ K					
283.15	2.00	1096.8	8.5016	1096.8	8.5016
283.15	3.00	1104.4	8.5680	1104.4	8.5680
283.15	4.00	1111.6	8.6307	1111.6	8.6307
283.15	5.00	1118.4	8.6903	1118.4	8.6903
283.15	6.00	1124.9	8.7470	1124.9	8.7470
283.15	7.00	1131.0	8.8011	1131.0	8.8011
283.16	8.00	1136.9	8.8536	1136.9	8.8540
283.15	9.00	1142.5	8.9035	1142.5	8.9035
283.15	10.00	1147.9	8.9518	1147.9	8.9518
283.15	11.00	1153.1	8.9980	1153.1	8.9980
283.15	12.00	1158.2	9.0425	1158.2	9.0425
283.15	13.00	1163.0	9.0862	1163.0	9.0862
283.15	14.00	1167.7	9.1285	1167.7	9.1285
283.15	15.00	1172.2	9.1698	1172.2	9.1698
283.15	16.00	1176.6	9.2111	1176.6	9.2111
$T_n = 293.15$ K					
293.24	2.00	1050.8	7.7622	1051.3	7.7653
293.23	3.01	1060.9	7.8139	1061.3	7.8166
293.23	4.08	1070.8	7.8918	1071.2	7.8945
293.23	5.02	1078.9	7.9566	1079.2	7.9593
293.23	5.96	1086.5	8.0176	1086.8	8.0203
293.24	6.98	1094.2	8.0814	1094.6	8.0845
293.23	7.98	1101.5	8.1427	1101.7	8.1454
293.23	9.10	1109.1	8.2069	1109.3	8.2096
293.23	10.03	1115.1	8.2571	1115.4	8.2598
293.23	11.03	1121.3	8.3104	1121.5	8.3131
293.24	12.03	1127.1	8.3639	1127.4	8.3669
293.24	13.00	1132.6	8.4094	1132.9	8.4124
293.24	14.00	1138.1	8.4570	1138.4	8.4600
293.23	15.00	1143.4	8.5030	1143.6	8.5057
293.24	16.00	1148.4	8.5483	1148.6	8.5514

Table 4 (continued).

T/K	p/MPa	ρ/kg m^{-3}	$\varepsilon(T, p)$	$\rho(T_n, p)$/kg m^{-3}	$\varepsilon(T_n, p)$
$T_n = 303.15$ K					
303.07	2.00	997.7	7.0326	997.2	7.0300
303.06	3.00	1011.6	7.1283	1011.1	7.1253
303.07	4.00	1024.0	7.2186	1023.6	7.2160
303.07	5.00	1035.3	7.3028	1034.9	7.3002
303.07	6.00	1045.7	7.3806	1045.3	7.3779
303.07	7.00	1055.3	7.4559	1054.9	7.4533
303.08	8.00	1064.2	7.5240	1063.9	7.5216
303.08	9.00	1072.6	7.5887	1072.3	7.5864
303.08	10.00	1080.4	7.6520	1080.2	7.6496
303.09	11.01	1087.9	7.7106	1087.7	7.7087
303.08	12.00	1094.9	7.7677	1094.7	7.7654
303.09	13.00	1101.6	7.8213	1101.4	7.8193
303.08	14.00	1108.0	7.8744	1107.8	7.8720
303.08	15.00	1114.1	7.9245	1113.9	7.9222
303.08	16.00	1120.0	7.9717	1119.8	7.9694

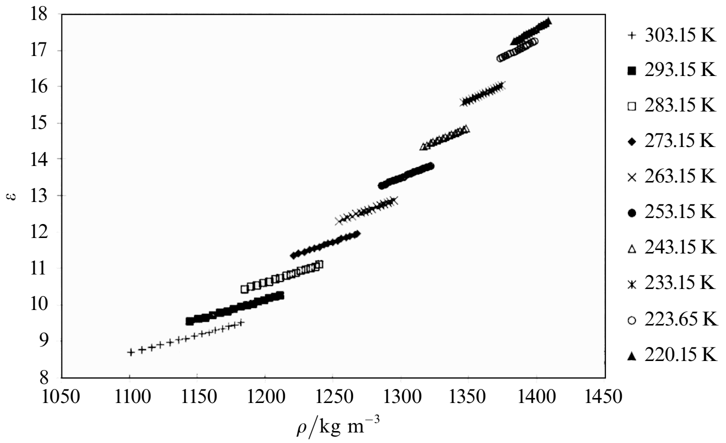

Figure 5. Graphical representation of the dielectric constant as a function of density for R407C.

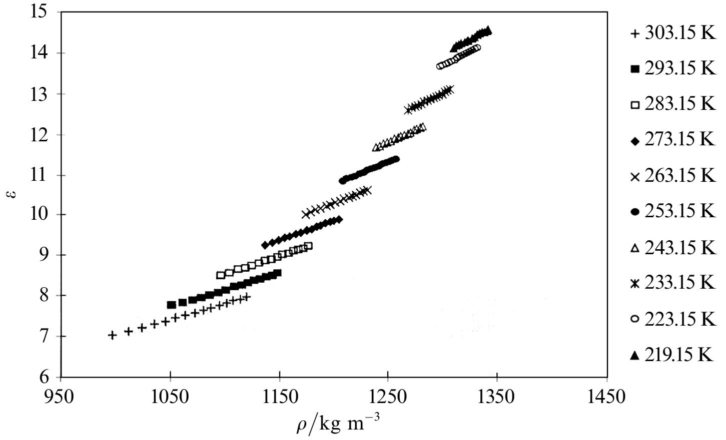

Figure 6. Graphical representation of the dielectric constant as a function of density for R507.

Table 5. Coefficients of equation (1).

Mixture	a	b/K	$10^{-3}c$/kg^{-1} m^3	d/K m^3 kg^{-1}
R404A	3.365 ± 0.248	-1376 ± 80	-4.4687 ± 0.1843	3.950 ± 0.058
R407C	2.803 ± 0.403	-1932 ± 14	-4.0544 ± 0.2727	4.596 ± 0.091
R507	1.974 ± 0.273	-992 ± 88	-3.3067 ± 0.1998	3.519 ± 0.063

The experimental data of the dielectric constant were fitted to a function in density and temperature of the following form:

$$\varepsilon(T, \rho) = a + \frac{b}{T} + c\rho + \frac{d\rho}{T} \ , \tag{1}$$

with constants a, b, c, and d, with the mean deviations of 0.14% for R404A and 0.15% for R407C and R507.

The data were fitted by an iterative χ^2 method, each iteration implementing a Levenberg–Marquardt method. The coefficients of equation (1) and their uncertainty are given in table 5.

As in previous studies (Barão et al 1996, 1997; Brito et al 1998) we have analysed the dependence of dielectric constant on density employing the formalism of Vedam and Chen (1982), Vedam (1983), and Diguet (1986). These authors found that the Eulerian representation of strain in liquids under pressure is very convenient to describe the optical and electric properties of liquids, based on the fact that the increase in pressure only rearranges the molecules, decreasing the 'free volume' available to them and conditioning their movement. It is possible to verify that the Eulerian strain, Σ, also named Eulerian deformation, provides a linear relationship with $\Delta\varepsilon$ (the variation of $\varepsilon^{1/2}$), independently of the type of molecules which compose the fluid. We have used the relationship between $\varepsilon^{1/2}$ and Σ which is defined, according to the Vedam relationship, as:

$$\mathit{\Delta} = \varepsilon^{1/2}(\rho) - \varepsilon^{1/2}(\rho_0) = A\Sigma + B \ , \tag{2}$$

with

$$\Sigma = \frac{1}{2}\left[1 - \left(\frac{\rho}{\rho_0}\right)^{2/3}\right] \ . \tag{3}$$

Here ρ_0 is the reference density, chosen as the saturation value for each isotherm.

The saturation density data of the mixtures studied were calculated with the correlating scheme proposed by Fialho and Nieto de Castro (1997). We have used pressure values at the saturation line fitting the data presented in the database by Tillner-Roth et al (1988). The temperature range of validity of the saturation properties for R404A and R507 is from -80 °C to 70 °C and for R407C it is -80 °C to 86 °C.

From the data obtained, it is possible to conclude that the function $\mathit{\Delta}$ indeed represents a linear variation with the Eulerian strain Σ, as can be seen in figures 7–9. Tables 6–8 present the values of coefficients A and B of the Vedam equation for each isotherm. The slope of linear variation of $\mathit{\Delta}$ with Σ is negative for all temperatures and the y axis crossing values are close to zero for all isotherms, ie $B \cong 0$ for all refrigerant blends studied. Therefore, the use of the Eulerian strain concept seems to be completely appropriate for the interpretation of dielectric constant data dependence on density, for the analysed mixtures.

If we assume that $B = 0$ in equation (2), the Vedam relationship can be used to estimate the dielectric constant. In this work, the experimental value of ε for each refrigerant blend was again fitted as a function of Σ, forcing in this case the constant B to be equal to zero. With the new fit (slope A') it is possible to calculate the dielectric

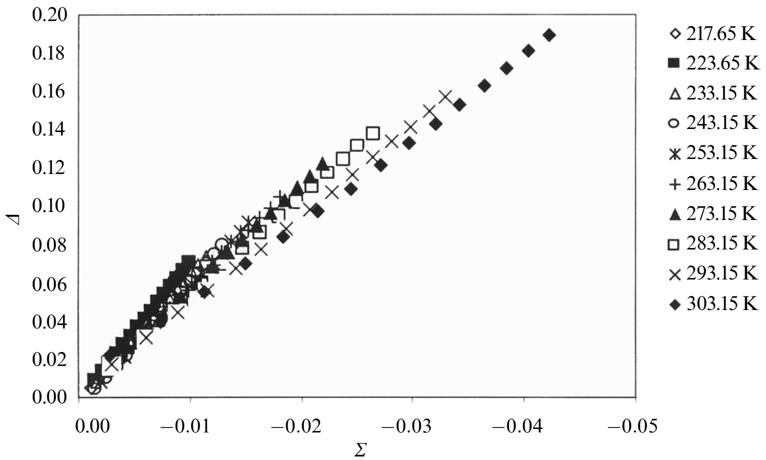

Figure 7. Variation of Δ with the Eulerian strain, Σ, for R404A.

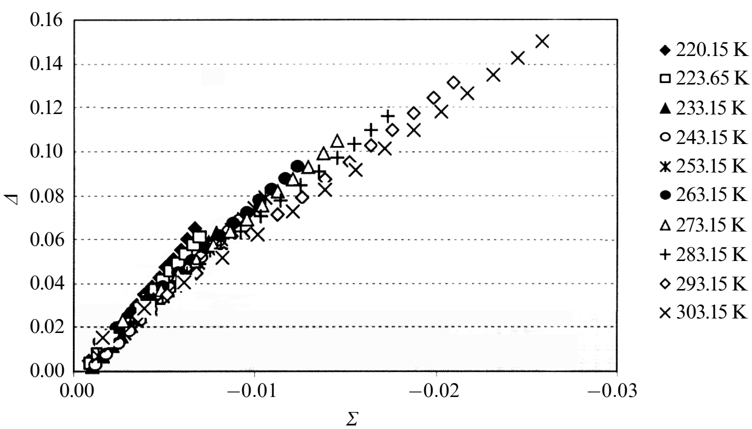

Figure 8. Variation of Δ with the Eulerian strain, Σ, for R407C.

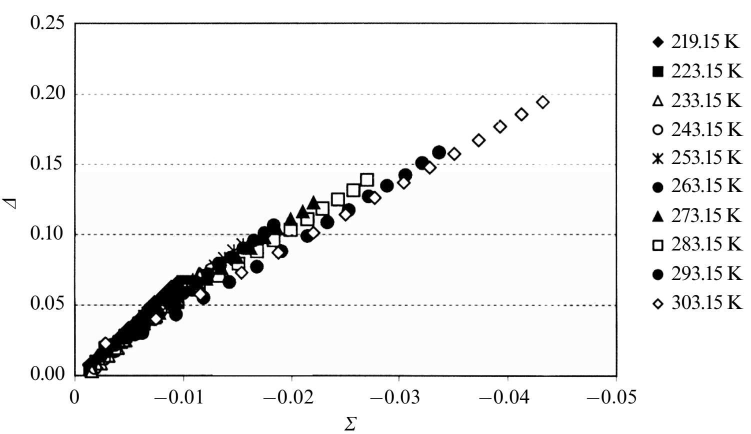

Figure 9. Variation of Δ with the Eulerian strain, Σ, for R507.

Table 6. Values of constants A and B of the Vedam equation (2) for R404A.

T/K	ρ_{sat}/kg m^{-3}	$\varepsilon(\rho_{sat})$	A	B
217.65	1287.3	14.651	−7.622	−0.00385
223.65	1270.4	13.971	−7.257	−0.00216
233.15	1242.9	12.964	−6.799	−0.00331
243.15	1212.8	11.987	−6.593	−0.00612
253.15	1181.3	11.081	−6.259	−0.00410
263.15	1147.8	10.234	−5.865	−0.00155
273.15	1111.7	9.434	−5.492	0.00201
283.15	1072.1	8.670	−5.062	0.00383
293.15	1027.8	7.926	−4.644	0.00278
303.15	976.7	7.187	−4.262	0.00720

Table 7. Values of constants A and B of the Vedam equation (2) for R407C.

T/K	ρ_{sat}/kg m^{-3}	$\varepsilon(\rho_{sat})$	A	B
220.15	1380.2	17.247	−10.363	−0.00542
223.65	1370.2	16.767	−9.610	−0.00611
233.15	1342.4	15.537	−8.792	−0.00708
243.15	1312.4	14.344	−8.316	−0.00694
253.15	1281.3	13.240	−7.871	−0.00417
263.15	1248.9	12.211	−7.313	0.00258
273.15	1214.7	11.244	−6.879	0.00403
283.15	1178.3	10.329	−6.390	0.00472
293.15	1139.1	9.453	−6.019	0.00408
303.15	1096.1	8.604	−5.531	0.00636

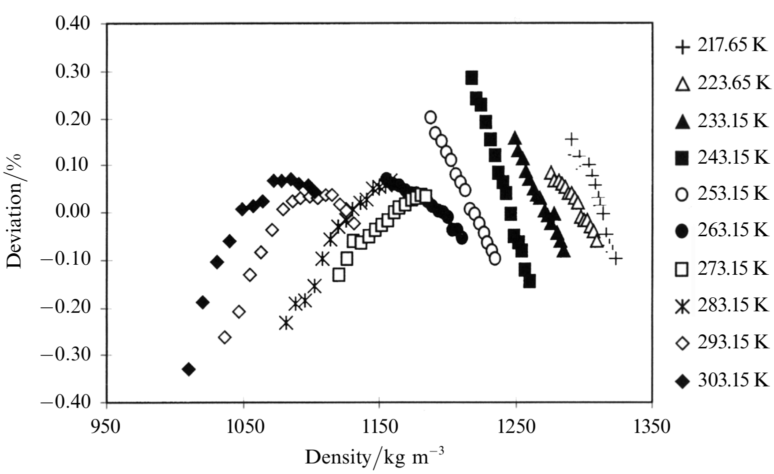

Figure 10. Deviations $[100(\varepsilon_{VR} - \varepsilon_{exp})/\varepsilon_{exp}]$ of dielectric constant values, estimated according to the Vedam relationship from the experimental data for R404A.

constant of all mixtures within the experimental ranges and accuracy. The Vedam equation takes the following form:

$$\Delta = \varepsilon^{1/2}(\rho) - \varepsilon^{1/2}(\rho_0) = A'\Sigma \ . \qquad (4)$$

The new values of slope A' according to equation (4) are presented in table 9 for R404A, R407C, and R507. We can estimate the dielectric constant as a function of density for each isotherm, using equation (4), where $\varepsilon^{1/2}(\rho_0)$ is constant at a given temperature.

Table 8. Values of constants A and B of the Vedam equation (2) for R507.

T/K	ρ_{sat}/kg m^{-3}	$\varepsilon(\rho_{sat})$	A	B
219.15	1303.9	14.072	−7.279	−0.00202
223.15	1292.4	13.634	−7.150	−0.00509
233.15	1262.8	12.602	−6.840	−0.00698
243.15	1232.0	11.649	−6.472	−0.00596
253.15	1199.6	10.763	−6.122	−0.00258
263.15	1165.2	9.932	−5.780	0.00033
273.15	1128.1	9.145	−5.395	0.00317
283.15	1087.4	8.388	−4.940	0.00499
293.15	1041.7	7.650	−4.607	0.00176
303.15	988.9	6.910	−4.276	0.00813

Table 9. Values of constant A' in equation (4).

R404A		R407C		R507	
T/K	A'	T/K	A'	T/K	A'
217.65	−7.0253	220.15	−9.2021	219.15	−6.9751
223.65	−6.9538	223.65	−8.3602	223.15	−6.4259
233.15	−6.3883	233.15	−7.5165	233.15	−5.9789
243.15	−5.9301	243.15	−7.2301	243.15	−5.8390
253.15	−5.8826	253.15	−7.3099	253.15	−5.8886
263.15	−5.7453	263.15	−7.6099	263.15	−5.8048
273.15	−5.6205	273.15	−7.2706	273.15	−5.5951
283.15	−5.2622	283.15	−6.7727	283.15	−5.1963
293.15	−4.7601	293.15	−6.2912	293.15	−4.6790
303.15	−4.4942	303.15	−5.8727	303.15	−4.5324

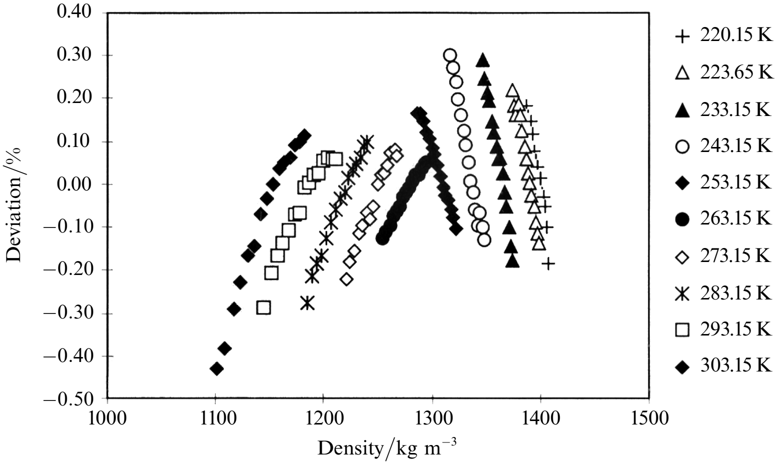

Figure 11. Deviations [$100(\varepsilon_{VR} - \varepsilon_{exp})/\varepsilon_{exp}$] of dielectric constant values, estimated according to the Vedam relationship from the experimental data for R407C.

In figures 10 – 12, we can see the deviations from the estimated values of the dielectric constant, calculated according to equation (4) from the experimental data.

In this work, the dipole moments of refrigerant blends were determined from dielectric constant measurements in the liquid state at various temperatures and pressures.

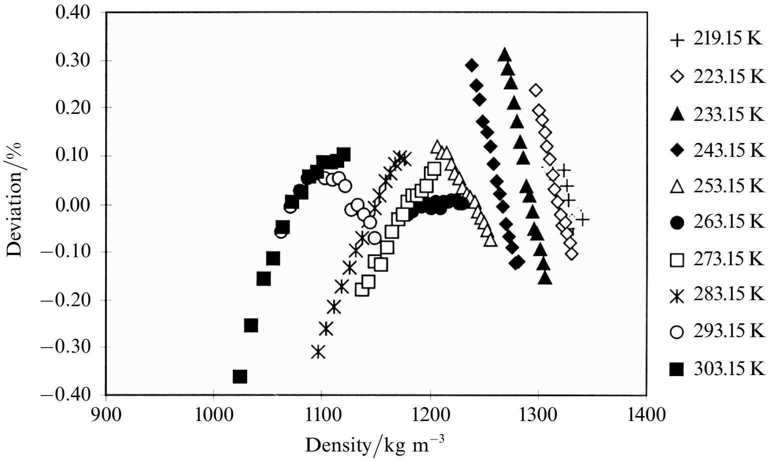

Figure 12. Deviations $[100(\varepsilon_{VR} - \varepsilon_{exp})/\varepsilon_{exp}]$ of dielectric constant values, estimated according to the Vedam relationship from the experimental data for R507.

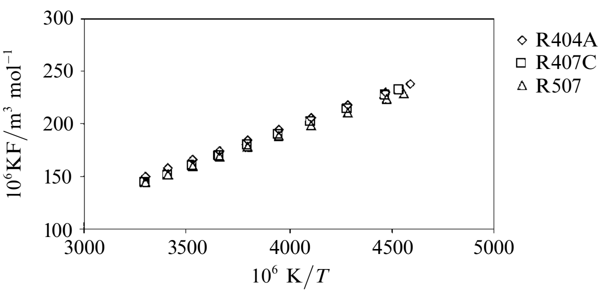

Figure 13. Kirkwood function (KF) versus $1/T$ for R404A, R407C, and R507.

Dielectric constant data were correlated with the apparent dipole moment, μ^*, with the equation developed by Kirkwood (1939) for fluids in the liquid state:

$$\frac{(\varepsilon - 1)(2\varepsilon + 1)}{9\varepsilon}\frac{M}{\rho} = \frac{N_0}{3}\left(\alpha + \frac{\mu^{*2}}{3\varepsilon_0 k_B T}\right) . \tag{5}$$

The value of μ^* was obtained from the slope of the line, representing the left side of the equation (Kirkwood function) as a function of $1/T$. Here M is the molar weight of the fluid, N_0 the Avogadro number, α the molecular polarisability, ε_0 the electric permittivity of vacuum, T the temperature, and k_B the Boltzmann constant.

Figure 13 shows the plot of the Kirkwood function versus $1/T$ for all mixtures studied and the values of the apparent dipole moment, μ^*, which were found to be equal to 3.356D for R404A, 3.427D for R407C, and 3.316D for R507, where D is the Debye radius. .

4 Conclusions

As a part of a project for measuring the dielectric constant of binary and ternary HFC mixtures, we report new experimental results for the dielectric constant and the subsequent dipole moment of the mixtures R404A, R407C, and R507. There is no single-component refrigerant to replace R502, and a binary mixture of HFC125/HFC143a (R507) and a ternary mixture of HFC125/134a/143a (R404A) are considered to be the most adequate substitute to replace R502.

Our measurements have been performed in the temperature range 217 to 303 K under pressures up to 16 MPa. The uncertainty of the measurements is estimated to be within 0.1% and the repeatability 0.01%.

After analysing the data, we found that the use of the Eulerian strain concept seems to interpret successfully the dependence of the dielectric constant on density. It is possible to estimate dielectric constant data at any given temperature, assuming that $B = 0$ in equation (2). As shown, the Vedam relationship can be used as a predictive tool for the dielectric constant of refrigerant mixtures in the thermodynamic domains studied. Using this relationship, we have estimated the dielectric constant of the studied blends with a mean deviation of 0.6% for R404A, 0.4% for R407C, and 0.8% for R507.

In addition, for the first time, dipole moments were determined for these mixtures by means of dielectric constant measurements. The values of the dipole moment were obtained for all mixtures by a linear regression of the Kirkwood function as a function of $1/T$. The refrigerants studied have dipole moments in the liquid phase in the following order: R407C $>$ R404A $>$ R507.

It was found that the value of μ^* for R404A is equal to $3.356D$, for R407C it is $3.427D$, and for R507 it is $3.316D$.

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