Int J Thermophys (2010) 31:488–501
DOI 10.1007/s10765-010-0737-5

Viscosities of Binary Mixtures Containing Isomeric Chlorobutanes and Diisopropylether: Experimental and Predicted Values

D. Montaño · H. Guerrero · I. Bandrés · M. C. López · Carlos Lafuente

Received: 29 October 2009 / Accepted: 2 April 2010 / Published online: 21 May 2010

Abstract In this work, viscosities of binary mixtures of isomeric chlorobutanes with diisopropylether have been determined as a function of composition under atmospheric pressure and in the temperature range from 283.15 K to 313.15 K with steps of 5 K. Kinematics viscosities were measured using an Ubbelohde viscosimeter; absolute viscosities were obtained from kinematic viscosities and densities. Finally, we have used the Asfour method for predicting the dependence of viscosity with composition and comparing it with our experimental data.

Keywords Asfour method · Diisopropylether · Isomeric chlorobutane · Viscosity

1 Introduction

Thermodynamic and transport properties of liquid mixtures and their analysis in terms of molecular structures and interactions are important for both the design and development of industrial processes and the search for models capable to predict the behavior of liquid state.

We report here the viscosity of binary mixtures of isomeric chlorobutanes (1-chlorobutane, 2-chlorobutane, 2-methyl-1-chloropropane, and 2-methyl-2-chloropropane) with diisopropylether from 283.15 K to 313.15 K under atmospheric pressure over the whole composition range. This work follows our study of liquid mixtures containing cyclic ethers and chloroalkanes [1–4]. The study of these mixtures is important since they are normally used in the petroleum industry; the reformulation of gasoline

D. Montaño · H. Guerrero · I. Bandrés · M. C. López · C. Lafuente (✉)
Departamento de Química Orgánica-Química Física, Facultad de Ciencias, Universidad de Zaragoza, Ciudad Universitaria, 50009 Zaragoza, Spain
e-mail: celadi@unizar.es

includes certain oxygenated compounds such as ethers [5–7]. These oxygenated compounds are added to improve the octane rating and the pollution-reducing capability of gasoline. From a theoretical point of view, binary mixtures of ethers and chloroalkanes are particularly interesting due to their complexity, a consequence of the presence of donor–acceptor type interactions.

As far as we know, viscosity properties for these systems have not been reported in the literature. Also, we have used the Asfour method [8,9] to predict the viscosity of the studied mixtures in order to evaluate the reliability of this method.

2 Experimental

The liquids used were 1-chlorobutane, 2-chlorobutane, 2-methyl-2-chloropropane, and diisopropylether (better than 99 % in mass) obtained from Aldrich and 2-methyl-1-chloropropane (better than 99 % in mass) provided by Fluka. No additional purification has been carried out.

Kinematic viscosities, ν, were determined using an Ubbelohde viscosimeter with a Schoot-Geräte automatic measuring unit model AVS-440. The temperature was kept constant within ± 0.01 K by means of a Schoot-Geräte thermostat. The viscosimeter was calibrated with deionized, double-distilled water. The uncertainty of the time flow measurements was 0.01 s, and the corresponding uncertainty in the kinematic viscosity was 1×10^{-4} mm$^2 \cdot$ s^{-1}. Kinetic energy corrections were applied to the experimental data.

Densities, ρ, required to calculate absolute viscosities from kinematic viscosities ($\eta = \rho\nu$), were measured using an Anton Paar DMA-5000 vibrating tube densimeter in which the temperature is controlled automatically within ± 0.004 K. The apparatus was calibrated with deionized, double-distilled water and dry air. The precision of the density measurements was $\pm 1 \times 10^{-6}$ g $\cdot$ cm^{-3}.

The density and viscosity values of the pure components appear together with their corresponding literature values [10–12] at 298.15 K in Table 1.

The mixtures were prepared using a Sartorious semi-micro balance CP225-D with a precision of $\pm 10^{-5}$ g. The uncertainty in the mole fraction is 1×10^{-4}.

Table 1 Densities, ρ, and viscosities, η, of pure compounds at 298.15 K and comparisons with literature data

Compound	ρ (g $\cdot$ cm^{-3})		η (mPa $\cdot$ s)	
	Exptl.	Lit.	Exptl.	Lit.
1-Chlorobutane	0.880705	0.88095 [10]	0.4215	0.427 [11]
2-Chlorobutane	0.867474	0.8671 [10]	0.3993	
2-Methyl-1-chloropropane	0.871533	0.8719 [10]	0.4296	0.431 [11]
2-Methyl-2-chloropropane	0.837096	0.8361 [10]	0.4768	
Diisopropylether	0.718289	0.71854 [10]	0.3178	0.313 [12]

Table 2 Kinematic viscosities, ν, densities, ρ, and absolute viscosities, η, of the binary mixtures at several temperatures

x_1	ν ($mm^2 \cdot s^{-1}$)	ρ ($g \cdot cm^{-3}$)	η ($mPa \cdot s$)	x_1	ν ($mm^2 \cdot s^{-1}$)	ρ ($g \cdot cm^{-3}$)	η ($mPa \cdot s$)
1-Chlorobutane (1) + diisopropylether (2) at $T = 283.15$ K							
0.0000	0.4968	0.733833	0.3646	0.6230	0.5364	0.826434	0.4433
0.0466	0.4997	0.740095	0.3698	0.7154	0.5421	0.842630	0.4568
0.0991	0.5026	0.747139	0.3755	0.8157	0.5476	0.861003	0.4715
0.1918	0.5084	0.759833	0.3863	0.9098	0.5525	0.879099	0.4857
0.3234	0.5173	0.778726	0.4028	0.9559	0.5547	0.888280	0.4927
0.4199	0.5235	0.793339	0.4153	1.0000	0.5564	0.897339	0.4993
0.5160	0.5297	0.808586	0.4283				
1-Chlorobutane (1) + diisopropylether (2) at $T = 288.15$ K							
0.0000	0.4784	0.728692	0.3486	0.6230	0.5118	0.821073	0.4202
0.0466	0.4810	0.73499	0.3535	0.7154	0.5161	0.837246	0.4321
0.0991	0.4838	0.741966	0.3590	0.8157	0.5205	0.855588	0.4453
0.1918	0.4888	0.754629	0.3689	0.9098	0.5241	0.873635	0.4579
0.3234	0.4962	0.773471	0.3838	0.9559	0.5257	0.882810	0.4641
0.4199	0.5014	0.788055	0.3951	1.0000	0.5271	0.891855	0.4701
0.5160	0.5064	0.803274	0.4068				
1-Chlorobutane (1) + diisopropylether (2) at $T = 293.15$ K							
0.0000	0.4616	0.723509	0.3340	0.6230	0.4889	0.815680	0.3988
0.0466	0.4638	0.729792	0.3385	0.7154	0.4922	0.831821	0.4094
0.0991	0.4662	0.736750	0.3435	0.8157	0.4955	0.850133	0.4212
0.1918	0.4708	0.749383	0.3528	0.9098	0.4980	0.868142	0.4323
0.3234	0.4767	0.768192	0.3662	0.9559	0.4991	0.877303	0.4379
0.4199	0.4808	0.782731	0.3763	1.0000	0.5001	0.886335	0.4433
0.5160	0.4848	0.797924	0.3868				
1-Chlorobutane (1) + diisopropylether (2) at $T = 298.15$ K							
0.0000	0.4424	0.718289	0.3178	0.6230	0.4682	0.810177	0.3793
0.0466	0.4447	0.724560	0.3222	0.7154	0.4711	0.826321	0.3893
0.0991	0.4474	0.731492	0.3273	0.8157	0.4740	0.844587	0.4003
0.1918	0.4516	0.744091	0.3360	0.9098	0.4765	0.862556	0.4110
0.3234	0.4571	0.762854	0.3487	0.9559	0.4775	0.871691	0.4162
0.4199	0.4609	0.777351	0.3583	1.0000	0.4785	0.880705	0.4214
0.5160	0.4646	0.792506	0.3682				
1-Chlorobutane (1) + diisopropylether (2) at $T = 303.15$ K							
0.0000	0.4209	0.713032	0.3001	0.6230	0.4508	0.804761	0.3628
0.0466	0.4238	0.719283	0.3048	0.7154	0.4539	0.820882	0.3726
0.0991	0.4266	0.726204	0.3098	0.8157	0.4573	0.839124	0.3837
0.1918	0.4315	0.738777	0.3188	0.9098	0.4602	0.857076	0.3944
0.3234	0.4380	0.757526	0.3318	0.9559	0.4616	0.866204	0.3998

Table 2 continued

x_1	ν ($mm^2 \cdot s^{-1}$)	ρ ($g \cdot cm^{-3}$)	η (mPa · s)	x_1	ν ($mm^2 \cdot s^{-1}$)	ρ ($g \cdot cm^{-3}$)	η (mPa · s)
0.4199	0.4424	0.771984	0.3415	1.0000	0.4627	0.875204	0.4050
0.5160	0.4464	0.787119	0.3514				
1-Chlorobutane (1) + diisopropylether (2) at $T = 308.15$ K							
0.0000	0.4037	0.707727	0.2857	0.6230	0.4344	0.799266	0.3472
0.0466	0.4066	0.713967	0.2903	0.7154	0.4377	0.815358	0.3569
0.0991	0.4096	0.720870	0.2953	0.8157	0.4411	0.833567	0.3677
0.1918	0.4149	0.733414	0.3043	0.9098	0.4440	0.851486	0.3781
0.3234	0.4215	0.752126	0.3170	0.9559	0.4454	0.860595	0.3833
0.4199	0.4261	0.766553	0.3266	1.0000	0.4468	0.869585	0.3885
0.5160	0.4301	0.781656	0.3362				
1-Chlorobutane (1) + diisopropylether (2) at $T = 313.15$ K							
0.0000	0.3877	0.702378	0.2723	0.6230	0.4125	0.793704	0.3274
0.0466	0.3902	0.708604	0.2765	0.7154	0.4148	0.809769	0.3359
0.0991	0.3929	0.715486	0.2811	0.8157	0.4174	0.827935	0.3456
0.1918	0.3971	0.728002	0.2891	0.9098	0.4195	0.845816	0.3548
0.3234	0.4025	0.746649	0.3005	0.9559	0.4204	0.854913	0.3594
0.4199	0.4060	0.761063	0.3090	1.0000	0.4216	0.863882	0.3642
0.5160	0.4091	0.776136	0.3175				
2-Chlorobutane (1) + diisopropylether (2) at $T = 283.15$ K							
0.0000	0.4968	0.733833	0.3646	0.6244	0.5126	0.819223	0.4199
0.0519	0.4976	0.740159	0.3683	0.7260	0.5158	0.835602	0.4310
0.0988	0.4982	0.745897	0.3716	0.8163	0.5186	0.850907	0.4413
0.2006	0.5003	0.758792	0.3796	0.8817	0.5205	0.862411	0.4489
0.3211	0.5033	0.774756	0.3899	0.9634	0.5228	0.877390	0.4587
0.4201	0.5061	0.788575	0.3991	1.0000	0.5237	0.884340	0.4631
0.5320	0.5095	0.804971	0.4101				
2-Chlorobutane (1) + diisopropylether (2) at $T = 288.15$ K							
0.0000	0.4784	0.728692	0.3486	0.6244	0.4891	0.813814	0.3980
0.0519	0.4788	0.734981	0.3519	0.7260	0.4915	0.830144	0.4080
0.0988	0.4791	0.740712	0.3549	0.8163	0.4935	0.845414	0.4172
0.2006	0.4805	0.753569	0.3621	0.8817	0.4948	0.856901	0.4240
0.3211	0.4825	0.769483	0.3713	0.9634	0.4962	0.871819	0.4326
0.4201	0.4845	0.783251	0.3795	1.0000	0.4967	0.878756	0.4365
0.5320	0.4870	0.799602	0.3894				
2-Chlorobutane (1) + diisopropylether (2) at $T = 293.15$ K							
0.0000	0.4616	0.723509	0.3340	0.6244	0.4708	0.808369	0.3806
0.0519	0.4619	0.729792	0.3371	0.7260	0.4729	0.824657	0.3900
0.0988	0.4623	0.735485	0.3400	0.8163	0.4747	0.839877	0.3987
0.2006	0.4634	0.748303	0.3468	0.8817	0.4758	0.851332	0.4051
0.3211	0.4652	0.764161	0.3555	0.9634	0.4769	0.866214	0.4131

Table 2 continued

x_1	ν ($mm^2 \cdot s^{-1}$)	ρ ($g \cdot cm^{-3}$)	η ($mPa \cdot s$)	x_1	ν ($mm^2 \cdot s^{-1}$)	ρ ($g \cdot cm^{-3}$)	η ($mPa \cdot s$)
0.4201	0.4669	0.777889	0.3632	1.0000	0.4772	0.873130	0.4167
0.5320	0.4690		0.3725				
2-Chlorobutane (1) + diisopropylether (2) at $T = 298.15$ K							
0.0000	0.4424	0.718289	0.3178	0.6244	0.4532	0.802882	0.3639
0.0519	0.4430	0.724535	0.3210	0.7260	0.4555	0.819123	0.3731
0.0988	0.4436	0.730220	0.3239	0.8163	0.4575	0.834307	0.3817
0.2006	0.4450	0.742995	0.3306	0.8817	0.4587	0.845724	0.3879
0.3211	0.4470	0.758802	0.3392	0.9634	0.4600	0.860570	0.3959
0.4201	0.4488	0.772485	0.3467	1.0000	0.4603	0.867474	0.3993
0.5320	0.4512	0.788750	0.3559				
2-Chlorobutane (1) + diisopropylether (2) at $T = 303.15$ K							
0.0000	0.4209	0.713032	0.3001	0.6244	0.4332	0.797355	0.3454
0.0519	0.4217	0.719276	0.3033	0.7260	0.4357	0.813555	0.3545
0.0988	0.4223	0.724919	0.3061	0.8163	0.4378	0.828698	0.3628
0.2006	0.4239	0.737649	0.3127	0.8817	0.4392	0.840084	0.3690
0.3211	0.4263	0.753411	0.3212	0.9634	0.4406	0.854895	0.3767
0.4201	0.4284	0.767060	0.3286	1.0000	0.4410	0.861779	0.3800
0.5320	0.4309	0.783263	0.3375				
2-Chlorobutane (1) + diisopropylether (2) at $T = 308.15$ K							
0.0000	0.4037	0.707727	0.2857	0.6244	0.4151	0.791784	0.3287
0.0519	0.4044	0.713939	0.2887	0.7260	0.4176	0.807944	0.3374
0.0988	0.4051	0.719569	0.2915	0.8163	0.4195	0.823046	0.3453
0.2006	0.4065	0.732261	0.2977	0.8817	0.4208	0.834402	0.3511
0.3211	0.4088	0.747973	0.3058	0.9634	0.4221	0.849179	0.3584
0.4201	0.4106	0.761571	0.3127	1.0000	0.4223	0.856044	0.3615
0.5320	0.4130	0.777737	0.3212				
2-Chlorobutane (1) + diisopropylether (2) at $T = 313.15$ K							
0.0000	0.3877	0.702378	0.2723	0.6244	0.3985	0.786180	0.3133
0.0519	0.3884	0.708573	0.2752	0.7260	0.4007	0.802287	0.3215
0.0988	0.3891	0.714181	0.2779	0.8163	0.4025	0.817349	0.3290
0.2006	0.3905	0.726833	0.2838	0.8817	0.4037	0.828683	0.3345
0.3211	0.3925	0.742484	0.2914	0.9634	0.4047	0.843420	0.3413
0.4201	0.3943	0.756049	0.2981	1.0000	0.4049	0.850266	0.3443
0.5320	0.3965	0.772166	0.3062				
2-Methyl-1-chloropropane (1) + diisopropylether (2) at $T = 283.15$ K							
0.0000	0.4968	0.733833	0.3646	0.6034	0.5353	0.818258	0.4380
0.0549	0.4990	0.740509	0.3695	0.6769	0.5423	0.830206	0.4502
0.0910	0.5004	0.745071	0.3728	0.8059	0.5559	0.852473	0.4739
0.1977	0.5056	0.758960	0.3837	0.9111	0.5684	0.871773	0.4955

Table 2 continued

x_1	ν ($mm^2 \cdot s^{-1}$)	ρ ($g \cdot cm^{-3}$)	η (mPa · s)	x_1	ν ($mm^2 \cdot s^{-1}$)	ρ ($g \cdot cm^{-3}$)	η (mPa · s)
0.2934	0.5112	0.772077	0.3947	0.9646	0.5753	0.881981	0.5074
0.3911	0.5177	0.785941	0.4069	1.0000	0.5800	0.888845	0.5155
0.5137	0.5272	0.804210	0.4240				
2-Methyl-1-chloropropane (1) + diisopropylether (2) at $T = 288.15$ K							
0.0000	0.4784	0.728692	0.3486	0.6034	0.5108	0.812821	0.4152
0.0549	0.4803	0.735346	0.3532	0.6769	0.5167	0.824734	0.4261
0.0910	0.4818	0.739888	0.3565	0.8059	0.5278	0.846936	0.4470
0.1977	0.4864	0.753737	0.3666	0.9111	0.5378	0.866179	0.4658
0.2934	0.4910	0.766807	0.3765	0.9646	0.5433	0.876368	0.4761
0.3911	0.4965	0.780617	0.3876	1.0000	0.5472	0.883211	0.4833
0.5137	0.5045	0.798831	0.4030				
2-Methyl-1-chloropropane (1) + diisopropylether (2) at $T = 293.15$ K							
0.0000	0.4616	0.723509	0.3340	0.6034	0.4881	0.807350	0.3941
0.0549	0.4633	0.730142	0.3383	0.6769	0.4929	0.819228	0.4038
0.0910	0.4644	0.734678	0.3412	0.8059	0.5018	0.841356	0.4222
0.1977	0.4682	0.748467	0.3504	0.9111	0.5097	0.860549	0.4386
0.2934	0.4721	0.761481	0.3595	0.9646	0.5143	0.870717	0.4478
0.3911	0.4765	0.775245	0.3694	1.0000	0.5173	0.877539	0.4540
0.5137	0.4829	0.793406	0.3831				
2-Methyl-1-chloropropane (1) + diisopropylether (2) at $T = 298.15$ K							
0.0000	0.4424	0.718289	0.3178	0.6034	0.4674	0.801699	0.3747
0.0549	0.4441	0.724887	0.3219	0.6769	0.4713	0.813519	0.3834
0.0910	0.4452	0.729395	0.3247	0.8059	0.4791	0.835530	0.4003
0.1977	0.4491	0.743114	0.3337	0.9111	0.4863	0.854603	0.4156
0.2934	0.4527	0.756060	0.3423	0.9646	0.4901	0.864749	0.4238
0.3911	0.4566	0.769763	0.3515	1.0000	0.4929	0.871533	0.4296
0.5137	0.4625	0.787825	0.3644				
2-Methyl-1-chloropropane (1) + diisopropylether (2) at $T = 303.15$ K							
0.0000	0.4209	0.713032	0.3001	0.6034	0.4483	0.796305	0.3570
0.0549	0.4229	0.719603	0.3043	0.6769	0.4528	0.808110	0.3659
0.0910	0.4238	0.724110	0.3069	0.8059	0.4609	0.830111	0.3826
0.1977	0.4283	0.737798	0.3160	0.9111	0.4681	0.849196	0.3975
0.2934	0.4324	0.750738	0.3246	0.9646	0.4722	0.859307	0.4058
0.3911	0.4371	0.764421	0.3341	1.0000	0.4748	0.866096	0.4112
0.5137	0.4434	0.782446	0.3469				
2-Methyl-1-chloropropane (1) + diisopropylether (2) at $T = 308.15$ K							
0.0000	0.4037	0.707727	0.2857	0.6034	0.4305	0.790719	0.3404
0.0549	0.4054	0.714280	0.2896	0.6769	0.4348	0.802492	0.3489
0.0910	0.4071	0.718759	0.2926	0.8059	0.4424	0.824422	0.3647
0.1977	0.4113	0.732397	0.3012	0.9111	0.4495	0.843468	0.3791

Table 2 continued

x_1	ν ($mm^2 \cdot s^{-1}$)	ρ ($g \cdot cm^{-3}$)	η (mPa · s)	x_1	ν ($mm^2 \cdot s^{-1}$)	ρ ($g \cdot cm^{-3}$)	η (mPa · s)
0.2934	0.4151	0.745300	0.3094	0.9646	0.4531	0.853542	0.3867
0.3911	0.4195	0.758935	0.3184	1.0000	0.4558	0.860319	0.3921
0.5137	0.4258	0.776901	0.3308				
2-Methyl-1-chloropropane (1) + diisopropylether (2) at $T = 313.15$ K							
0.0000	0.3877	0.702378	0.2723	0.6034	0.4128	0.784802	0.3240
0.0549	0.3895	0.708887	0.2761	0.6769	0.4171	0.796487	0.3322
0.0910	0.3908	0.713334	0.2788	0.8059	0.4243	0.818264	0.3472
0.1977	0.3948	0.726882	0.2870	0.9111	0.4309	0.837168	0.3607
0.2934	0.3985	0.739693	0.2948	0.9646	0.4340	0.847176	0.3677
0.3911	0.4027	0.753227	0.3033	1.0000	0.4363	0.853902	0.3726
0.5137	0.4085	0.771077	0.3150				
2-Methyl-2-chloropropane (1) + diisopropylether (2) at $T = 283.15$ K							
0.0000	0.4998	0.733833	0.3646	0.6213	0.5742	0.802211	0.4606
0.0490	0.5001	0.738510	0.3693	0.7152	0.5970	0.814386	0.4862
0.0996	0.5038	0.743477	0.3746	0.8138	0.6260	0.827842	0.5182
0.1991	0.5122	0.753625	0.3860	0.9079	0.6597	0.841347	0.5550
0.3212	0.5250	0.766738	0.4025	0.9552	0.6790	0.848401	0.5761
0.4189	0.5378	0.777752	0.4183	1.0000	0.6992	0.855249	0.5980
0.5148	0.5532	0.789053	0.4365				
2-Methyl-2-chloropropane (1) + diisopropylether (2) at $T = 288.15$ K							
0.0000	0.4784	0.728692	0.3486	0.6213	0.5433	0.796590	0.4328
0.0490	0.4815	0.733338	0.3531	0.7152	0.5625	0.808683	0.4549
0.0996	0.4849	0.738271	0.3580	0.8138	0.5874	0.822038	0.4829
0.1991	0.4921	0.748350	0.3683	0.9079	0.6169	0.835446	0.5154
0.3212	0.5026	0.761373	0.3827	0.9552	0.6341	0.842442	0.5342
0.4189	0.5131	0.772308	0.3963	1.0000	0.6521	0.849243	0.5538
0.5148	0.5258	0.783527	0.4120				
2-Methyl-2-chloropropane (1) + diisopropylether (2) at $T = 293.15$ K							
0.0000	0.4616	0.723509	0.3340	0.6213	0.5152	0.790929	0.4075
0.0490	0.4643	0.728121	0.3381	0.7152	0.5315	0.802935	0.4268
0.0996	0.4672	0.733024	0.3425	0.8138	0.5528	0.816186	0.4512
0.1991	0.4731	0.743024	0.3515	0.9079	0.5782	0.829489	0.4796
0.3212	0.4816	0.755959	0.3641	0.9552	0.5932	0.836437	0.4962
0.4189	0.4903	0.766815	0.3760	1.0000	0.6090	0.843191	0.5135
0.5148	0.5005	0.777959	0.3894				
2-Methyl-2-chloropropane (1) + diisopropylether (2) at $T = 298.15$ K							
0.0000	0.4424	0.718289	0.3178	0.6213	0.4897	0.785231	0.3845
0.0490	0.4450	0.722867	0.3217	0.7152	0.5035	0.797145	0.4014
0.0996	0.4477	0.727738	0.3258	0.8138	0.5219	0.810301	0.4229
0.1991	0.4531	0.737666	0.3342	0.9079	0.5435	0.823502	0.4476
0.3212	0.4608	0.750506	0.3458	0.9552	0.5562	0.830397	0.4619

Table 2 continued

x_1	ν (mm$^2 \cdot$ s^{-1})	ρ (g $\cdot$ cm^{-3})	η (mPa $\cdot$ s)	x_1	ν (mm$^2 \cdot$ s^{-1})	ρ (g $\cdot$ cm^{-3})	η (mPa $\cdot$ s)
0.4189	0.4682	0.761288	0.3564	1.0000	0.5696	0.837096	0.4768
0.5148	0.4772	0.772351	0.3686				
2-Methyl-2-chloropropane (1) + diisopropylether (2) at $T = 303.15$ K							
0.0000	0.4209	0.713032	0.3001	0.6213	0.4668	0.779484	0.3639
0.0490	0.4236	0.717578	0.3040	0.7152	0.4791	0.791308	0.3791
0.0996	0.4263	0.722412	0.3080	0.8138	0.4947	0.804365	0.3979
0.1991	0.4321	0.732264	0.3164	0.9079	0.5127	0.817467	0.4191
0.3212	0.4399	0.745013	0.3277	0.9552	0.5232	0.824312	0.4313
0.4189	0.4471	0.755716	0.3379	1.0000	0.5341	0.830958	0.4438
0.5148	0.4555	0.766702	0.3492				
2-Methyl-2-chloropropane (1) + diisopropylether (2) at $T = 308.15$ K							
0.0000	0.4037	0.707727	0.2857	0.6213	0.4482	0.773688	0.3468
0.0490	0.4060	0.712240	0.2892	0.7152	0.4600	0.785436	0.3613
0.0996	0.4083	0.717039	0.2928	0.8138	0.4743	0.798392	0.3787
0.1991	0.4136	0.726821	0.3006	0.9079	0.4905	0.811393	0.3980
0.3212	0.4212	0.739479	0.3115	0.9552	0.4995	0.818179	0.4087
0.4189	0.4287	0.750102	0.3216	1.0000	0.5087	0.824772	0.4196
0.5148	0.4372	0.761005	0.3327				
2-Methyl-2-chloropropane (1) + diisopropylether (2) at $T = 313.15$ K							
0.0000	0.3877	0.702378	0.2723	0.6213	0.4306	0.767848	0.3306
0.0490	0.3892	0.706856	0.2751	0.7152	0.4408	0.779502	0.3436
0.0996	0.3911	0.711610	0.2783	0.8138	0.4526	0.792362	0.3586
0.1991	0.3959	0.721328	0.2856	0.9079	0.4646	0.805256	0.3741
0.3212	0.4037	0.733893	0.2963	0.9552	0.4709	0.811996	0.3824
0.4189	0.4112	0.744440	0.3061	1.0000	0.4770	0.818536	0.3904
0.5148	0.4199	0.755257	0.3171				

3 Results and Discussion

The kinematic viscosities, densities, and viscosities of the studied binary mixtures at work temperatures are given in Table 2.

The viscosities were correlated by means of a Redlich–Kister equation [13] of the form,

$$\eta = x_1\eta_1 + (1 - x_1)\eta_2 + x_1\,(1 - x_1)\sum_{i=0}^{i=n} A_i\,(2x_1 - 1)^i \tag{1}$$

where A_i's are adjustable parameters obtained by the least-squares method, their values are given together with standard deviations, σ, in Table 3.

The viscosities are graphically represented in Figs. 1, 2, 3, and 4.

Table 3 Parameters, A_i, and standard deviations, $\sigma(\eta)$, for the Redlich–Kister equation

T (K)	A_0	A_1	A_2	A_3	$\sigma(\eta)$
1-Chlorobutane + diisopropylether					
283.15	−0.0234	0.0052	0.0013	−0.0002	0.0001
288.15	−0.0181	0.0031	0.0013	−0.0024	0.0001
293.15	−0.0143	0.0007	0.0004	−0.0020	0.0001
298.15	−0.0125	−0.0008	0.0016	−0.0030	0.0001
303.15	−0.0111	−0.0022	0.0006	−0.0027	0.0001
308.15	−0.0099	−0.0029	−0.0001	−0.0031	0.0000
313.15	−0.0085	−0.0035	0.0003	−0.0042	0.0000
2-Chlorobutane + diisopropylether					
283.15	−0.0278	0.0043	0.0014	−0.0006	0.0000
288.15	−0.0242	0.0031	0.0017	0.0016	0.0000
293.15	−0.0223	0.0033	0.0024	0.0020	0.0001
298.15	−0.0215	0.0025	0.0041	0.0019	0.0001
303.15	−0.0207	0.0029	0.0051	0.0019	0.0001
308.15	−0.0193	0.0025	0.0053	0.0026	0.0001
313.15	−0.0179	0.0028	0.0051	0.0004	0.0000
2-Methyl-1-chloropropane + diisopropylether					
283.15	−0.0721	−0.0096	−0.0025	0.0007	0.0000
288.15	−0.0593	−0.0090	−0.0019	0.0002	0.0001
293.15	−0.0497	−0.0068	−0.0016	−0.0013	0.0001
298.15	−0.0430	−0.0076	−0.0027	0.0004	0.0001
303.15	−0.0410	−0.0059	−0.0025	0.0011	0.0001
308.15	−0.0383	−0.0059	−0.0012	−0.0001	0.0001
313.15	−0.0354	−0.0051	0.0012	0.0024	0.0001
2-Methyl-2-chloropropane + diisopropylether					
283.15	−0.1914	−0.0648	−0.0160	−0.0040	0.0000
288.15	−0.1673	−0.0652	−0.0163	−0.0042	0.0001
293.15	−0.1460	−0.0601	−0.0150	−0.0051	0.0001
298.15	−0.1231	−0.0516	−0.0111	−0.0033	0.0000
303.15	−0.0984	−0.0390	−0.0079	−0.0026	0.0001
308.15	−0.0872	−0.0249	−0.0047	−0.0012	0.0001
313.15	−0.0642	−0.0010	−0.0004	0.0014	0.0001

4 Viscosity Prediction

McAllister equation [14], which is based on Eyring's absolute rate theory, is considered as one of the best available correlative method for the dependence of kinematic viscosity on composition. This equation contains parameters of the pure components, the kinematic viscosities of compounds ν_1 and ν_2, their corresponding molecular masses M_1 and M_2, and also two adjustable parameters, ν_{12} and ν_{21}:

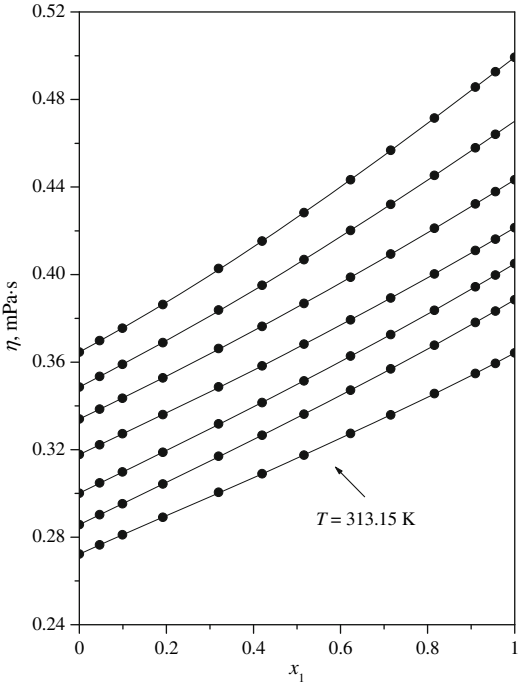

Fig. 1 Viscosities, η, for 1-chlorobutane (1) with diisopropylether (2): experimental (•); correlated values (—)

$$\begin{aligned}\ln \nu = {} & x_1^3 \ln \nu_1 + 3x_1^2 x_2 \ln \nu_{12} + 3x_1 x_2^2 \ln \nu_{21} + x_2^3 \ln \nu_2 \\ & - \ln [x_1 + x_2 M_2/M_1] + 3x_1^2 x_2 \ln [(2 + M_2/M_1)/3] \\ & + 3x_1 x_2^2 \ln [(1 + 2M_2/M_1)/3] + x_2^3 \ln (M_2/M_1) \end{aligned} \tag{2}$$

These adjustable parameters mean that this model can be considered only as a correlated method. With the goal of taking advantage of the McAllister equation as a predictive model, the Asfour method [8,9] was proposed. It is based on the effective carbon number for estimating the McAllister model interaction parameters from pure component and molecular properties for liquid binary mixtures, making it possible to predict the dependence of viscosity on composition over the entire composition range. In order to evaluate the suitability of this method, in this work experimental data have been compared with viscosity predicted values for the studied binary mixtures.

The effective carbon number, N, is an intrinsic property of each compound which can be calculated from the kinematic viscosity of the pure components at the temperature of 308.15 K using the following equation:

$$\ln \nu = -1.943 + 0.193\ N \tag{3}$$

The kinematic viscosity at 308.15 K and the calculated effective carbon number value for the studied compounds are collected in Table 4.

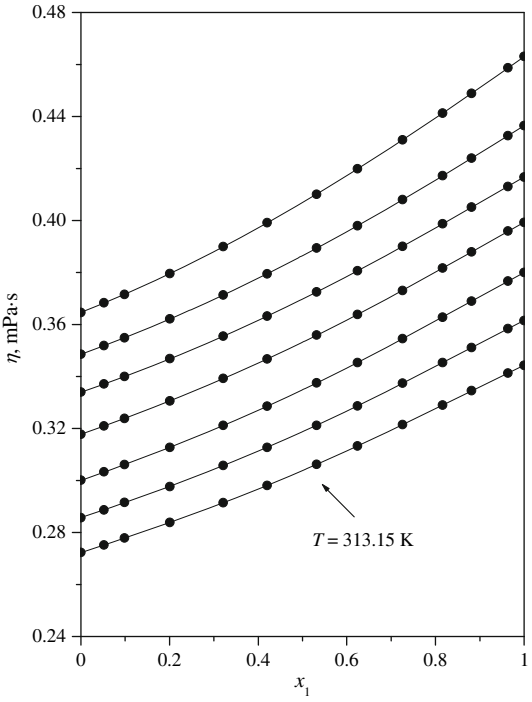

Fig. 2 Viscosities, η, for 2-chlorobutane (1) with diisopropylether (2): experimental (•); correlated values (—)

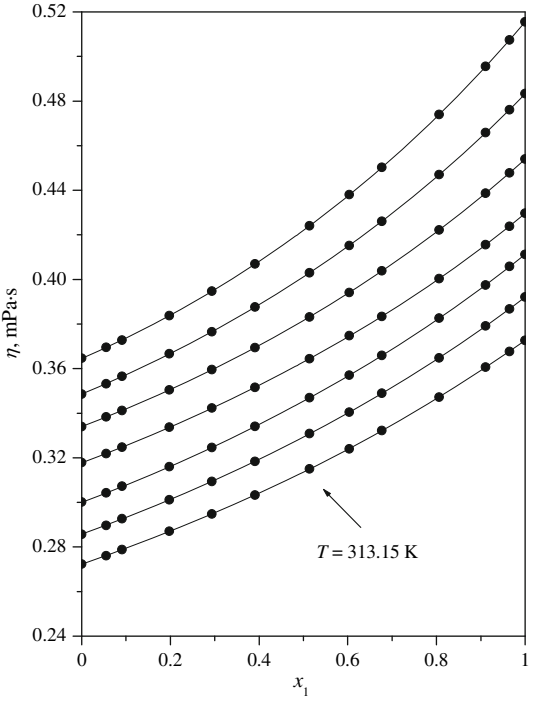

Fig. 3 Viscosities, η, for 2-methyl-1-chloropropane (1) with diisopropylether (2): experimental (•); correlated values (—)

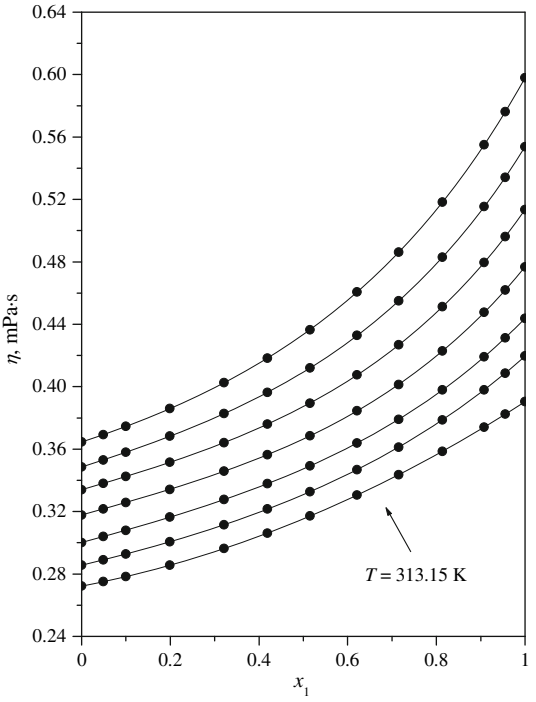

Fig. 4 Viscosities, η, for 2-methyl-2-chloropropane (1) with diisopropylether (2): experimental (•); correlated values (—)

Table 4 Experimental kinematic viscosities at 308.15 K and effective carbon number, *N*, for pure compounds

Compound	ν ($mm^2 \cdot s^{-1}$)	*N*
1-Chlorobutane	0.4468	5.89
2-Chlorobutane	0.4223	5.60
2-Methyl-1-chloropropane	0.4558	6.0
2-Methyl-2-chloropropane	0.5087	6.57
Diisopropylether	0.4037	5.37

Then, the McAllister model interaction parameters can be calculated by means of these expressions:

$$\frac{\nu_{AB}}{\left(\nu_A^2 \nu_B\right)^{1/3}} = 0.8735 + 0.0715 \frac{(N_B - N_A)^2}{\left(N_A^2 N_B\right)^{1/3}} \tag{4}$$

$$\nu_{BA} = \nu_{AB} \left(\frac{\nu_B}{\nu_A}\right)^{1/3} \tag{5}$$

The kinematic viscosity can be estimated once the values of the parameters have been obtained. The agreement between experimental and estimated values can be evaluated through the absolute average deviation, AAD, calculated using the following equation:

Table 5 Parameters of the Asfour method together with the corresponding absolute average deviations, AADs

T (K)	ν_{12}	ν_{21}	AAD (%)
1-Chlorobutane + diisopropylether			
283.15	0.4698	0.4524	6.27
288.15	0.4475	0.4333	6.33
293.15	0.4270	0.4158	6.37
298.15	0.4088	0.3983	6.41
303.15	0.3932	0.3809	6.52
308.15	0.3785	0.3661	6.62
313.15	0.3635	0.3515	5.76
2-Chlorobutane + diisopropylether			
283.15	0.4498	0.4420	5.97
288.15	0.4288	0.4235	6.00
293.15	0.4126	0.4080	6.04
298.15	0.3971	0.3919	6.07
303.15	0.3796	0.3737	6.09
308.15	0.3637	0.3583	6.11
313.15	0.3489	0.3439	6.14
2-Methyl-1-chloropropane + diisopropylether			
283.15	0.4839	0.4595	4.70
288.15	0.4596	0.4395	4.94
293.15	0.4375	0.4212	5.10
298.15	0.4177	0.4029	5.22
303.15	0.4006	0.3849	5.30
308.15	0.3846	0.3693	5.31
313.15	0.3685	0.3542	5.39
2-Methyl-2-chloropropane + diisopropylether			
283.15	0.5554	0.4956	1.21
288.15	0.5236	0.4722	1.42
293.15	0.4943	0.4507	1.63
298.15	0.4661	0.4285	2.06
303.15	0.4392	0.4057	2.72
308.15	0.4193	0.3882	2.97
313.15	0.3963	0.3698	3.69

$$\mathrm{AAD}(\%) = 100\left(\frac{1}{m}\sum_{i=1}^{m}\left(\frac{\nu_{i,\mathrm{exp}} - \nu_{i,\mathrm{Asfour}}}{\nu_{i,\mathrm{exp}}}\right)^2\right)^{1/2} \tag{6}$$

where m is the number of experimental data.

Table 5 shows the interaction parameters, ν_{12} and ν_{21}, calculated according to the Asfour method, used for predicting the viscosity of all the systems over the whole

composition and temperature range. In this table, the corresponding AADs are also given. The smallest deviations of about 2.2 % are shown for the system containing 2-methyl-2-chloropropane, whereas the largest deviation of about 6.3 % are found for the system containing 1-chlorobutane. These results show quite good agreement between experimental and predicted values using the Asfour method.

5 Conclusions

The viscosity behavior of binary mixtures of isomeric chlorobutanes with diisopropylether have been studied under atmospheric pressure and at temperatures from 283.15 K to 313.15 K through the determination of kinematic and absolute viscosities.

The experimental viscosity data have been used to check the predictive ability of the Asfour method, and comparisons between experimental and predicted values are satisfactory.

Acknowledgments We are grateful for financial assistance from Diputación General de Aragón and Universidad de Zaragoza. D. Montaño wishes to thank Banco Santander and I. Bandrés wishes to thank D.G.A. for predoctoral grants.

References

1. B. Giner, I. Gascón, A. Villares, P. Cea, C. Lafuente, J. Chem. Eng. Data **51**, 1321 (2006)
2. B. Giner, I. Gascón, H. Artigas, M.C. López, C. Lafuente, Int. J. Thermophys. **27**, 1406 (2006)
3. B. Giner, H. Artigas, M. Haro, C. Lafuente, M.C. López, J. Mol. Liquids **129**, 176 (2006)
4. I. Bandrés, C. Lahuerta, A. Villares, S. Martín, C. Lafuente, Int. J. Thermophys. **29**, 457 (2008)
5. A. Heine, K. Fischer, J. Gmehling, J. Chem. Eng. Data **44**, 373 (1999)
6. E.C. Ihmels, J. Gmehling, J. Chem. Eng. Data **47**, 1307 (2002)
7. I.C. Hwang, M.Y. Jo, H.Y. Kwak, S.J. Park, K.J. Han, J. Chem. Eng. Data **52**, 2503 (2007)
8. A.A. Asfour, E.F. Cooper, J. Wu, R.R. Zahran, Ind. Eng. Chem. Res. **30**, 1666 (1991)
9. A.H. Nhaesi, A.A. Asfour, Ind. Eng. Chem. Res. **37**, 4893 (1998)
10. J.A. Riddick, W.B. Bunger, T.K. Sakano, *Organic Solvents: Physical Properties and Methods of Purification. Techniques of Chemistry*, 4th edn. (Wiley Interscience, New York, 1986)
11. J. Timmermans, *Physico-Chemical Constants of Pure Organic Compounds, vol II* (Elsevier, Amsterdam, 1965)
12. J.D. Ye, C.H. Tu, J. Chem. Eng. Data **50**, 1060 (2005)
13. E. Calvo, A. Penas, M. Pintos, R. Bravo, A. Amigo, J. Chem. Eng. Data **46**, 692 (2001)
14. R.A. McAllister, AIChE J. **6**, 427 (1960)