Reference Correlations for the Viscosity of 13 Inorganic Molten Salts

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ABSTRACT

In 1988, reference correlations for the viscosity of a selection of molten inorganic salts were proposed by Janz and have been used extensively. During the last 31 years, many additional measurements have been published. In a very recent paper, new reference correlations for the thermal conductivity of 13 inorganic molten salts were proposed. In this paper, reference correlations for the viscosity of those same salts are proposed. All available experimental data for the viscosity of 13 inorganic molten salts have been critically examined with the intention of establishing improved or new reference viscosity correlations. All experimental data have been categorized into primary and secondary data according to the quality of measurement specified by a series of criteria. Standard reference correlations are proposed for the following molten salts (with estimated uncertainties at the 95% confidence level given in parentheses): $LiNO_3$ (6.7%), $NaNO_3$ (3.0%), KNO_3 (3.0%), NaBr (1.6%), KBr (2.0%), RbBr (2.2%), LiCl (3.7%), NaCl (2.4%), KCl (1.6%), RbCl (3.6%), CsCl (1.1%), NaI (1.5%), and RbI (1.5%).

Key words: inorganic; molten salts; reference correlation; viscosity.

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1. Introduction

In 2016, resulting from a demonstrable need for reference values for the thermal conductivity and viscosity of molten metals, a project was initiated by the International Association for Transport Properties (IATP) [formerly Subcommittee on Transport Properties of the International Union of Pure and Applied Chemistry (IUPAC)] to critically evaluate all available measurements and propose reference correlations as a function of the temperature at atmospheric pressure. Thus, reference correlations for the thermal conductivity[1,2] and viscosity[3–6] of molten metals were proposed. Recently, this investigation was extended to the thermal conductivity of a series of molten inorganic salts. All available thermal conductivity measurements of molten nitrate, bromide, chloride, and iodide salts of Group I metals were examined.[7] For 13 of them ($LiNO_3$, $NaNO_3$, KNO_3, NaBr, KBr, RbBr, LiCl, NaCl, KCl, RbCl, CsCl, NaI, and RbI), sufficient measurements of acceptable quality existed so that reference correlations for the thermal conductivity were proposed.[7] The present work considers reference correlations for the viscosity of these same 13 inorganic molten salts.

Molten salts are employed today as heat-transfer fluids in many high-temperature applications, such as solar power plants[8] and molten-salt reactors.[9] Notwithstanding the frequent use of molten salts, their thermal conductivity and viscosity are not well established even for pure species, which is surprising given the importance of these two properties in heat transfer. The need for reference correlations for even the pure molten salts can be easily demonstrated if one examines, for example, Fig. 1, where the results of all available measurements for the viscosity of molten NaCl are shown as a function of the temperature at atmospheric pressure. As shown in Fig. 1, at temperatures near 1100 K, the results from different authors[11–27] range from 1.0 mPa s to 1.5 mPa s. These measurements are very difficult to perform because molten salts of Group I metals are highly reactive at high temperatures. In 1988, Janz[10] published reference correlations for the viscosity of most of these salts, based on critically evaluated data. His proposed reference correlation for NaCl is shown in Fig. 1 (green line). The reference correlations proposed by Janz[10] are still employed today. Nevertheless, since 1988, there have been new accurate measurements for the viscosity of these salts. Therefore, in this paper, we concentrate on the measurements published after those considered by Janz[10] and investigate whether these new measurements improve the reference correlations or extend their temperature range.

The analysis described here is applied to the best available experimental data for the viscosity of the molten salts. Thus, a prerequisite to the analysis is a critical assessment of the experimental data. For this purpose, two categories of experimental data are defined as before:[7] primary data, employed in the development of the correlation, and secondary data, used simply for comparison purposes. According to the recommendation adopted by the IUPAC Subcommittee on Transport Properties, the primary data are identified by a well-established set of criteria.[28] These criteria have been successfully employed to establish standard reference values for the viscosity and thermal conductivity of fluids over wide ranges of conditions, with uncertainties in the range of 1%. However, in many cases, such a narrow definition unacceptably

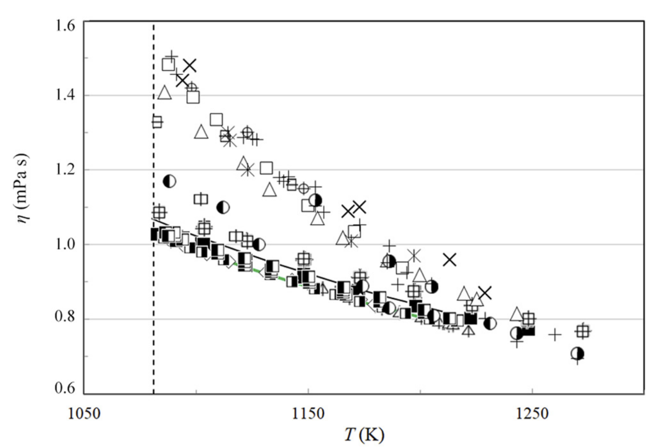

FIG. 1. Viscosity of molten NaCl at 0.1 MPa as a function of the temperature. Tolbaru *et al.*[11] (△), Ito *et al.*[12] (■), Ejima *et al.*[13] (◇), Tørklep and Øye[14] (◨), Abe *et al.*[15] (⊞), Antonov and Khokhlov[16] (—), Brockner *et al.*[17] (◧), Matsumura *et al.*[18] (⊟), Bondarenko and Strelets[19] (◐), Nishihara *et al.*[20] (◫), Murgulescu and Zuca[21] (△), Vershchetina and Luzhnaya[22] (⊕), Ogawa[23] (□), Berenblit[24] (×), Karpachev[25] (◑), Dantuma[26] (+), Fawsitt[27] (✱). Reference correlation of Janz[10] (green solid line), melting temperature (- -).

limits the thermodynamic states for which data can be represented. Consequently, within the primary dataset, it is also necessary to include results that extend over a wide range of conditions, albeit with a poorer accuracy, provided they are consistent with other more accurate data or with theory. In all cases, the accuracy claimed for the final recommended data must reflect the estimated uncertainty in the primary data.

2. Data Compilation

Tables 1–4 present the datasets found for the measurement of the viscosity of some molten nitrate salts ($LiNO_3$, $NaNO_3$, and KNO_3), bromide salts (NaBr, KBr, and RbBr), chloride salts (LiCl, NaCl, KCl, RbCl, and CsCl), and iodide salts (NaI and RbI). In Tables 1–4, the purity of the sample, the technique employed, and the uncertainty quoted are also presented. Furthermore, the form in which the data are reported and the temperature range covered are also noted. The datasets have been classified into primary and secondary sets, as shown in Secs. 2.1–2.4. Following our aforementioned discussion, in this work we concentrate only on measurements performed after those on which the 1988 Janz[10] correlations were based. Furthermore, in our primary dataset, we also included the measurements on which Janz[10] based his reference correlations since they were considered as the best available at that time.

Finally, we note that a detailed analysis of the experimental techniques employed for the measurement of melts is published elsewhere[3] and will not be repeated here.

2.1. Nitrate molten salts

Three nitrate molten salts were considered: $LiNO_3$, $NaNO_3$, and KNO_3. The viscosity sets considered for each of these salts are shown in Table 1.

2.1.1. $LiNO_3$

The first recommendation of the Molten Salts Data Center, published by Janz *et al.*[29] in 1968, was based on the early work of Dantuma,[26] which was later found to be seriously flawed.[30] The current 1988 recommendation by Janz[10] covers a temperature range of 540 K–650 K with an uncertainty of 2%, and is based on the work of Janz *et al.*,[30] Zuca,[31] and Protsenko and Razumovskaya.[32] In 2017, Nunes *et al.*[33] employed an oscillating-cup viscometer originally designed by Lanca *et al.*[34] and published new accurate data covering a temperature range of 540 K–690 K with an uncertainty of 3%. The measurements of Nunes *et al.*[33] satisfy the criteria for primary data and are thus included in our primary dataset. Additionally, as already mentioned, the measurements upon which the reference correlation of Janz[10] were based were also included in the primary dataset shown in Table 1.

2.1.2. $NaNO_3$

The recommended viscosity values published by Janz[10] in 1988 were the same as the values proposed by Janz *et al.*[29] in 1968. Those were based on the 1928 measurements of Dantuma[26] (not found to have the same problem noticed in the $LiNO_3$ measurements) and covered a temperature range of 589 K–729 K, with an uncertainty of 3%. In the present primary dataset, shown in Table 1, we included the capillary measurements of Smotrakov *et al.*[35] and Protsenko and Razumovskaya,[32] as well as the oscillating-sphere measurements of Zuca[31] and Karpachev.[25] These four sets satisfy our criteria for primary measurements (doubts about the use of the correct working equation[3,36,37] by Karpachev[25] would not have an effect on the data greater than their claimed uncertainty). Finally, in the primary dataset, we also included the measurements of Nunes *et al.*[38] As mentioned above, in 2006 Nunes *et al.*[38] employed an oscillating-cup viscometer and published new data covering a temperature range of 590 K–753 K with an uncertainty of 2.1%. It should be noted here that in this particular case the measurements of Ogawa,[23] obtained in a falling-ball viscometer, and of Bondarenko and Strelets,[19] were not taken into consideration, since they were of inferior uncertainty (>5%).

2.1.3. KNO_3

KNO_3 was initially selected by the molten salts "Standards Program,"[10] which was initiated in 1973 by Janz (USA) jointly with Zuca (Romania). It was part of a 3-year cooperative research program under the InterAcademy Agreement and supported by the National Science Foundation (USA) and Ministry of Science and Technology (Romania), to meet the need for measurements at moderately high temperatures. Following an examination of all viscosity measurements in the period 1907–1978, the measurements of Zuca and Costin[39] were selected as the recommended reference dataset, consequently forming the recommendations in the 1988 publication of Janz.[10] These measurements were included in the primary dataset. We also included the measurements of Lanca *et al.*,[34] Tolbaru *et al.*,[11] Schardey *et al.*,[40] and Abe *et al.*,[15] which were obtained in oscillating-body viscometers that operated according to the proper working equation,[3,36,37] and the measurements of Janz,[30] obtained in a capillary viscometer, as they all satisfy the criteria for primary data.

2.2. Bromide molten salts

Three bromide molten salts were considered: NaBr, KBr, and RbBr. The viscosity sets considered for each of these salts are shown in Table 2. In this case, very few viscosity measurements exist.

2.2.1. NaBr

The 1988 recommendation by Janz[10] covers a temperature range of 1022 K–1192 K with an uncertainty of 1.5% and is based on the measurements of Ejima and Sato.[49] In 1997, Sato *et al.*[50] remeasured the viscosity of NaBr over the same range in an improved capillary viscometer with an uncertainty of 0.7%. Both these sets satisfy our criteria for primary data and form the primary dataset.

2.2.2. KBr

There is no previous reference correlation for the KBr molten salt. The measurements of Sato *et al.*[50] were performed in a capillary viscometer with an uncertainty of 0.7% over the temperature range of 1010 K–1194 K, while the measurements of Murgulescu and Zuca[51] were obtained in an oscillating-sphere viscometer with a 3% uncertainty. Both these instruments satisfy our criteria for primary data.

2.2.3. RbBr

The 1988 recommendation by Janz[10] covers a temperature range of 971 K–1197 K with an uncertainty of 1.5%, and it is based

TABLE 1. Datasets considered for the viscosity of molten nitrate salts at 0.1 MPa

First author	Publication year	Purity (mass %)	Technique employed	Uncertainty quoted (%)	No. of data	Temperature range (K)	Form of data[a]
$LiNO_3$							
Previous reference correlation							
Janz[10]	1988	. . .	Based on Janz *et al.*,[30] Zuca,[31] and Protsenko and Razumovskaya[32]	2	. . .	540–650	E
Primary data							
Nunes[33]	2017	98.5	Oscillating cup	3	14	544–690	T
Janz[30]	1978	. . .	Capillary	1.5	16	540–645	T
Zuca[31]	1970	. . .	Oscillating sphere	3	18	537–698	T
Protsenko[32]	1965	. . .	Capillary	. . .	15	548–674	T
Secondary data							
Smotrakov[35]	1972	. . .	Capillary	1.5	. . .	538–690	E
Dantuma[26]	1928	. . .	Oscillating ball	. . .	37	533–703	T
Goodwin[41]	1908	. . .	Capillary	. . .	9	532–618	T
$NaNO_3$							
Previous reference correlation							
Janz[10]	1988	. . .	Based on Dantuma[26] (1928)	3	. . .	589–731	E
Primary data							
Nunes[38]	2006	. . .	Oscillating cup	2.1	14	590–753	T
Smotrakov[35]	1972	. . .	Capillary	1.5	. . .	593–689	E
Zuca[31]	1970	. . .	Oscillating sphere	3	14	598–749	T
Protsenko[32]	1965	. . .	Capillary	. . .	21	588–744	T
Karpachev[25]	1935	. . .	Oscillating sphere	. . .	5	589–716	T
Dantuma[26]	1928	. . .	Oscillating ball	. . .	33	589–732	T
Secondary data							
Bondarenko[19]	1965	. . .	Oscillating cup	5	2	648–695	T
Ogawa[23]	1950	. . .	Falling ball	. . .	8	599–681	D
Fawsitt[27]	1908	. . .	Oscillating disc	10	6	597–667	T
Goodwin[41]	1908	. . .	Capillary	. . .	7	610–769	T
Lorenz[42]	1907	. . .	Capillary	0.1	12	581–692	T
KNO_3							
Previous reference correlation							
Janz[10]	1988	. . .	Based on Zuca and Costin[39]	2	. . .	615–760	E
Primary data							
Lanca[34]	2001	99.99	Oscillating cup	2.3	14	634–761	T
Tolbaru[11]	1998	Spectral	Oscillating cup	. . .	28	666–735	T
Schardey[40]	1988	99.7	Oscillating cylinder	0.3	9	622–725	T
Abe[15]	1980	99.99	Oscillating cup	1.1	36	622–974	T
Janz[30]	1978	. . .	Capillary	1.5	14	613–743	T
Zuca[39]	1976	. . .	Oscillating sphere	2	. . .	615–760	E
Secondary data							
Ohta[43]	1975	. . .	Oscillating sphere	1.2	6	625–686	T
Protsenko[44]	1972	. . .	Capillary	. . .	5	613–694	T
Smotrakov[35]	1972	. . .	Capillary	1.5	. . .	613–684	E
Dumas[45]	1970	. . .	Oscillating sphere	2	3	615–672	T
Zuca[31]	1970	. . .	Oscillating sphere	3	22	615–765	T
Wellman[46]	1966	. . .	Capillary	2	18	617–766	T
Protsenko[32]	1965	. . .	Capillary	. . .	9	621–765	T
Rhodes[47]	1965	99.99	Capillary	0.5	. . .	620–660	E

TABLE 1. (*Continued.*)

First author	Publication year	Purity (mass %)	Technique employed	Uncertainty quoted (%)	No. of data	Temperature range (K)	Form of data[a]
Janz[48]	1963	...	Oscillating crucible	...	4	632–765	T
Ogawa[23]	1950	...	Falling ball	...	9	614–702	D
Karpachev[25]	1935	...	Oscillating sphere	...	6	621–816	T
Dantuma[26]	1928	...	Oscillating ball	...	35	621–816	T
Fawsitt[27]	1908	...	Oscillating disc	10	7	622–681	T
Goodwin[41]	1908	...	Capillary	...	7	620–780	T
Lorenz[42]	1907	...	Capillary	0.1	9	606–687	T

[a]D = diagram, E = equation, T = tabulated experimental data.

entirely on the measurements of Ejima and Sato.[49] In 1997, Sato *et al.*[50] remeasured the viscosity of RbBr over the same range in an improved capillary viscometer with an uncertainty of 0.7%. Both these sets of measurements, together with the oscillating-sphere measurements of Murgulescu and Zuca,[51] formed the primary dataset for the viscosity of RbBr.

TABLE 2. Datasets considered for the viscosity of molten bromide salts at 0.1 MPa

First author	Publication year	Purity (mass %)	Technique employed	Uncertainty quoted (%)	No. of data	Temperature range (K)	Form of data[a]
NaBr							
Previous reference correlation							
Janz[10]	1988	...	Based on Ejima and Sato[49] (1985)	1.5	...	1022–1192	E
Primary data							
Sato[50]	1997	...	Capillary	0.7	14	1022–1193	T
Ejima[49]	1985	...	Capillary	1.6	...	1022–1192	E
Secondary data							
Antonov[16]	1978	...	Oscillating sphere	...	...	1039–1181	E
Matsumura[18]	1967	...	Oscillating disc	...	3	1083–1144	T
Murgulescu[51]	1962	...	Oscillating sphere	3.0	10	1053–1213	T
Fawsitt[27]	1908	...	Oscillating disc	10	5	1035–1154	T
KBr							
Primary data							
Sato[50]	1997	...	Capillary	0.7	19	1010–1194	T
Murgulescu[51]	1962	...	Oscillating sphere	3.0	11	1017–1181	T
Secondary data							
Smirnov[52]	1975	...	Oscillating sphere	...	...	1015–1215	E
Matsumura[18]	1967	...	Oscillating disc	...	3	1073–1134	T
Karpachev[53]	1938	...	Oscillating sphere	...	5	973–1174	T
Fawsitt[27]	1908	...	Oscillating disc	10	5	1018–1136	T
RbBr							
Previous reference correlation							
Janz[10]	1988	...	Based on Ejima and Sato[49] (1985)	1.5	...	971–1197	E
Primary data							
Sato[50]	1997	...	Capillary	0.7	13	971–1197	T
Ejima[49]	1985	...	Capillary	1.5	...	971–1197	E
Murgulescu[51]	1962	...	Oscillating sphere	3.0	11	959–1140	T

[a]T = tabulated experimental data, E = equation.

TABLE 3. Datasets considered for the viscosity of molten chloride salts at 0.1 MPa

First author	Publication year	Purity (mass %)	Technique employed	Uncertainty quoted (%)	No. of data	Temperature range (K)	Form of data[a]
LiCl							
Previous reference correlation							
Janz[10]	1988	...	Based on Brockner *et al.*[54] (1981)	1	...	894–1113	E
Primary data							
Ejima[13]	1982	...	Capillary	0.7	15	886–1170	T
Brockner[54]	1981	...	Oscillating cylinder	0.5	13	894–1132	T
Secondary data							
Wakao[55]	1991	99.9	Oscillating cup	2	13	886–1275	T
Bondarenko[56]	1969	...	Oscillating cup	5	5	911–1024	T
Smirnov[57]	1967	...	Oscillating sphere	...	...	930–1068	E
Brockner[17]	1975	...	Oscillating sphere	1	33	896–1119	D
Nishihara[20]	1964	...	Oscillating disc	...	4	890–1014	T
Murgulescu[21]	1963	...	Oscillating sphere	3	11	902–1083	T
Karpachev[25]	1935	...	Oscillating sphere	...	5	923–1124	T
Fawsitt[27]	1908	...	Oscillating disc	10	6	890–1039	T
NaCl							
Previous reference correlation							
Janz[10]	1988	...	Based on Tørklep and Øye[14] (1979)	0.2	...	1080–1210	E
Primary data							
Tolbaru[11]	1998	Spectral	Oscillating cup	...	18	1156–1222	T
Ito[12]	1989	...	Oscillating cup	2.4	40	1082–1249	T
Ejima[13]	1982	...	Capillary	0.7	12	1077–1180	T
Tørklep[14]	1979	...	Oscillating cup	1.5	78	1085–1205	T
Secondary data							
Abe[15]	1980	99.99	Oscillating cup	0.9	39	1083–1474	T
Antonov[16]	1978	...	Oscillating sphere	...	...	1073–1212	E
Brockner[17]	1975	...	Oscillating sphere	1	27	1086–1217	D
Matsumura[18]	1967	...	Oscillating disc	...	3	1083–1144	T
Bondarenko[19]	1965	...	Oscillating cup	5	7	1088–1232	T
Nishihara[20]	1964	...	Oscillating disc	...	2	1102–1119	T
Murgulescu[21]	1963	...	Oscillating sphere	3	11	1085–1244	T
Vershchetina[22]	1954	...	Oscillating disc	...	3	1098–1149	T
Ogawa[23]	1950	...	Falling ball	...	6	1087–1193	D
Berenblit[24]	1937	...	Capillary	...	6	1094–1230	T
Karpachev[25]	1935	...	Oscillating sphere	...	6	1121–1271	T
Dantuma[26]	1928	...	Oscillating ball	...	21	1089–1271	T
Fawsit[27]	1908	...	Oscillating disc	10	5	1114–1198	T
KCl							
Previous reference correlation							
Janz[10]	1988	...	Based on Brockner *et al.*[54] (1981)	1	...	1111–1162	E
Primary data							
Ejima[13]	1982	...	Capillary	0.7	15	1050–1191	T
Brockner[54]	1981	...	Oscillating cylinder	0.5	13	1054–1175	T
Secondary data							
Antonov[16]	1978	...	Oscillating sphere	...	...	1056–1216	E
Brockner[17]	1975	...	Oscillating sphere	1	23	1068–1177	D
Matsumura[18]	1967	...	Oscillating disc	...	3	1098–1179	T
Bondarenko[19]	1965	...	Oscillating cup	3	3	1070–1188	T

TABLE 3. (*Continued.*)

First author	Publication year	Purity (mass %)	Technique employed	Uncertainty quoted (%)	No. of data	Temperature range (K)	Form of data[a]
Nishihara[20]	1964	...	Oscillating disc	...	3	1056–1088	T
Murgulescu[51]	1962	...	Oscillating sphere	3	11	1056–1202	T
Ogawa[23]	1950	...	Falling ball	...	4	1061–1174	D
Berenblit[24]	1937	...	Capillary	...	7	1074–1226	T
Fawsitt[27]	1908	...	Oscillating disc	10	5	1063–1309	T
RbCl							
Previous reference correlation							
Janz[10]	1988	...	Based on Brockner *et al.*[54] (1981)	1	...	1023–1172	E
Primary data							
Ejima[13]	1982	...	Capillary	0.7	16	999–1182	T
Brockner[54]	1981	...	Oscillating cylinder	0.5	15	996–1134	T
Secondary data							
Desyatnik[58]	1977	...	Oscillating crucible	...	...	1000–1250	E
Brockner[17]	1975	...	Oscillating sphere	1	16	1011–1177	D
Reeves[59]	1965	...	Oscillating hollow cylinder	4	11	1007–1225	T
Murgulescu[21]	1963	...	Oscillating sphere	3	11	1005–1149	T
CsCl							
Previous reference correlation							
Janz[10]	1988	...	Based on Brockner *et al.*[54] (1981)	1	...	934–1074	E
Primary data							
Ejima[13]	1982	...	Capillary	0.7	17	933–1184	T
Brockner[54]	1981	...	Oscillating cylinder	0.5	14	923–1087	T
Secondary data							
Desyatnik[58]	1977	...	Oscillating crucible	...	...	930–1185	E
Brockner[17]	1975	...	Oscillating sphere	1	20	944–1058	D
Smirnov[57]	1967	...	Oscillating sphere	...	...	930–1030	E
Reeves[59]	1965	...	Oscillating hollow cylinder	4	14	930–1153	T
Murgulescu[21]	1963	...	Oscillating sphere	3	11	927–1111	T

[a]D = diagram, E = equation, T = tabulated experimental data.

2.3. Chloride molten salts

Five chloride molten salts were examined: LiCl, NaCl, KCl, RbCl, and CsCl. The viscosity sets considered for each of these salts are shown in Table 3.

2.3.1. LiCl

The 1988 viscosity recommendation by Janz[10] is based entirely on the measurements of Brockner *et al.*[54] Since then, only two other sets of measurements have been published: the measurements of Ejima *et al.*[13] which were carried out in a capillary viscometer with 0.7% uncertainty, and the measurements of Wakao *et al.*[55] performed in an oscillating cylinder with 0.5% uncertainty. The measurements of Wakao *et al.*[55] show, however, an unexplained, very different temperature dependence than the other two sets, with differences increasing to about 10% at higher temperatures. Because the authors state[55] that "*the origin of these discrepancies is not presently clear*," it was preferred not to include this set in the primary dataset. Hence, only the measurements of Brockner *et al.*[54] and Ejima *et al.*[13] were considered as primary data.

2.3.2. NaCl

The 1988 viscosity reference correlation for NaCl was based on the 1979 measurements of Tørklep and Øye.[14] Since 1979, three more sets of measurements have been published. Ejima *et al.*[13] measured the viscosity of molten NaCl by the capillary technique with an uncertainty of 0.7%, while Ito *et al.*[12] employed an oscillating-cup viscometer with a 2.4% uncertainty. Tolbaru *et al.*[11] also used an oscillating-cup viscometer and measured the viscosity of NaCl with improved uncertainty. These three sets satisfy the criteria for primary data and thus formed the primary dataset. The measurements of Abe *et al.*[15] were not included because Ito *et al.*[12] from the same group produced more recent measurements.

2.3.3. KCl, RbCl, and CsCl

In these three cases, the Janz[10] viscosity reference correlations are based only on the corresponding measurements of Brockner *et al.*[54] Since then, Ejima *et al.*[13] published viscosity measurements performed in a capillary viscometer with a 0.7% uncertainty. The measurements of

TABLE 4. Datasets considered for the viscosity of molten iodide salts at 0.1 MPa

First author	Publication year	Purity (mass %)	Technique employed	Uncertainty quoted (%)	No. of data	Temperature range (K)	Form of data[a]
NaI							
Previous reference correlation							
Janz[10]	1988	...	Based on Ejima and Sato[49] (1985)	1.5	...	941–1017	E
Primary data							
Sato[50]	1997	...	Capillary	0.7	18	940–1117	T
Ejima[13]	1982	...	Capillary	0.7	17	941–1017	E
Secondary data							
Antonov[16]	1978	...	Oscillating sphere	...	...	946–1083	E
Murgulescu[60]	1965	...	Oscillating sphere	3	13	946–1108	T
Karpachev[53]	1938	...	Oscillating sphere	...	6	923–1124	T
RbI							
Previous reference correlation							
Janz[10]	1988	...	Based on Ejima and Sato[49] (1985)	1.5	...	934–1194	E
Primary data							
Ejima[13]	1982	...	Capillary	0.7	17	934–1194	E
Sato[50]	1997	...	Capillary	0.7	14	933–1194	T
Secondary data							
Murgulescu[60]	1965	...	Oscillating sphere	3	16	922–1127	T

[a]T = tabulated experimental data, E = equation.

Ejima *et al.*[13] have already been successfully included in other reference correlations, as they satisfy the criteria for primary data. These two sets form our primary dataset for each of the three salts.

2.4. Iodide molten salts

Two iodide molten salts were examined: NaI and RbI. The viscosity sets considered for each of these salts are shown in Table 4. In both these salts, the 1988 viscosity recommendations by Janz[10] were based on the measurements of Ejima and Sato.[49] Since then, only Sato *et al.*[50] remeasured the viscosity of these two salts in an improved capillary instrument with a 0.7% uncertainty. The measurements of Sato *et al.*[50] satisfy the criteria for the primary data, and the above two sets form our primary dataset.

3. Discussion

The primary data for the viscosity, η (mPa s), are shown in Tables 1–4 for each molten salt. For each fluid, the data (at 0.1 MPa)

TABLE 5. Coefficients of Eq. (1), melting temperatures (from Ref. 7), maximum temperature of application, and associated uncertainties

Molten salt	T_m (K)	T_{max} (K)	A (mPa s)	B (J mol^{-1})	AAD (%)	BIAS (%)	Uncertainty 2σ (%)
$LiNO_3$	527.15	697	0.0805	18 725.7	3.0	0.06	6.7
$NaNO_3$	583.15	753	0.1037	16 250.7	1.1	0.01	3.0
KNO_3	610.15	974	0.0840	17 994.1	1.1	0.01	3.0
NaBr	1020.15	1193	0.1034	20 479.2	0.1	0.00	1.6[a]
KBr	1007.15	1194	0.0797	22 814.5	0.7	0.05	2.0
RbBr	953.15	1197	0.0888	22 681.4	0.8	0.01	2.2
LiCl	883.15	1170	0.1103	19 129.1	1.7	0.02	3.7
NaCl	1081.15	1249	0.0973	21 209.3	1.0	0.01	2.4
KCl	1045.15	1191	0.0689	24 105.6	0.8	0.00	1.6
RbCl	990.15	1182	0.0792	23 595.5	1.7	0.02	3.6
CsCl	918.15	1184	0.0630	24 655.8	0.4	0.00	1.1
NaI	935.15	1117	0.0995	19 087.7	0.1	0.00	1.5[a]
RbI	913.15	1194	0.0763	23 088.1	0.1	0.00	1.5[a]

[a]Preferred to use the measurement uncertainty as it is higher.

were fitted as a function of the absolute temperature [T(K)] to an equation of the form

$$\eta = A\,e^{B/(RT)}, \tag{1}$$

where R (J mol^{-1} K^{-1}) is the molar gas constant[61] and A (mPa s) and B (J mol^{-1}) are constants shown in Table 5. In Table 5, the maximum temperature of applicability of Eq. (1), derived from the corresponding maximum temperatures in Tables 1–4, is also presented. Equation (1) is valid from the normal melting temperature,[7] T_m (K), up to this maximum temperature. We note that measurements were weighted in the fitting process in inverse proportion to the square of their claimed uncertainty.

Three more quantities are shown in Table 5. We have defined the percent deviation as PCTDEV = $100^*(\eta_{exp} - \eta_{fit})/\eta_{fit}$, where η_{exp} is the experimental value of the viscosity and η_{fit} is the value calculated from the correlation. Thus, the average absolute percent deviation (AAD) is found with the expression AAD = $(\Sigma|\text{PCTDEV}|)/n$, where the summation is over all n points, and the bias percent is found with the expression BIAS = $(\Sigma\text{PCTDEV})/n$. Finally, the uncertainty at a 95% confidence level (k = 2) defined as $2\left(\frac{100}{\eta_{av}}\right)\sqrt{\left[\sum_n (\eta_{exp} - \eta_{fit})^2\right]/n}$ is also shown. η_{exp}, η_{fit}, and η_{av} represent the experimental, the fitted with Eq. (1), and the average viscosity of each salt for the range examined, while n indicates the number of measurements.

3.1. Nitrate molten salts

Figure 2 shows, for the three nitrate salts, the percentage deviations of the primary viscosity data from those calculated by Eq. (1), as a function of the temperature. The following can be noted in all

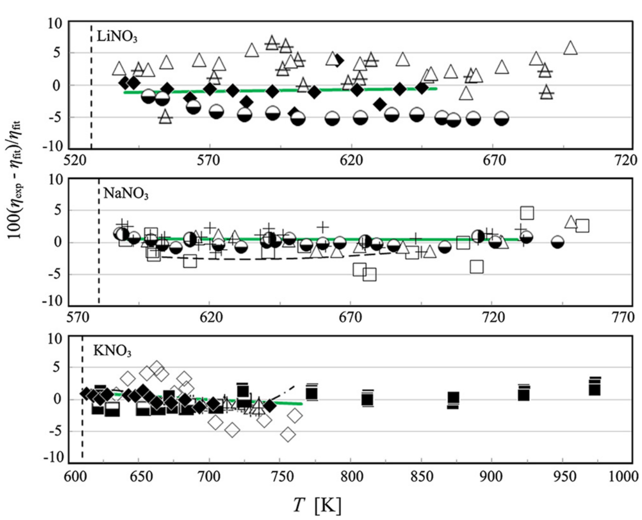

FIG. 2. Percentage deviations of the primary data and previous reference correlations for the viscosity of $LiNO_3$, $NaNO_3$, and KNO_3 from the values calculated by Eq. (1), as a function of the temperature. Nunes *et al.*[33] (⊼), Janz *et al.*[30] (◆), Zuca[31] (△), Tolbaru *et al.*[11] (⏃), Lanca *et al.*[34] (◇), Schardey *et al.*[40] (⊟), Abe *et al.*[15] (■), Zuca and Costin[39] (– · –), Nunes *et al.*[38] (□), Smotrakov *et al.*[35] (— —), Protsenko and Razumovskaya[32] (◒), Karpachev[25] (◑), Dantuma[26] (+). Reference correlations of Janz[10] (green solid line), melting temperature (- -).

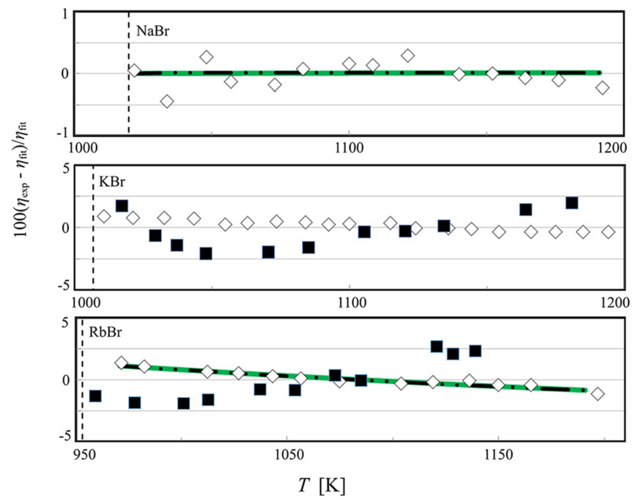

FIG. 3. Percentage deviations of the primary data and previous reference correlations for the viscosity of NaBr, KBr, and RbBr from the values calculated by Eq. (1), as a function of the temperature. Sato *et al.*[50] (◇), Ejima and Sato[49] (– · · –), Murgulescu and Zuca[51] (■). Reference correlations of Janz[10] (green solid line), melting temperature (- -).

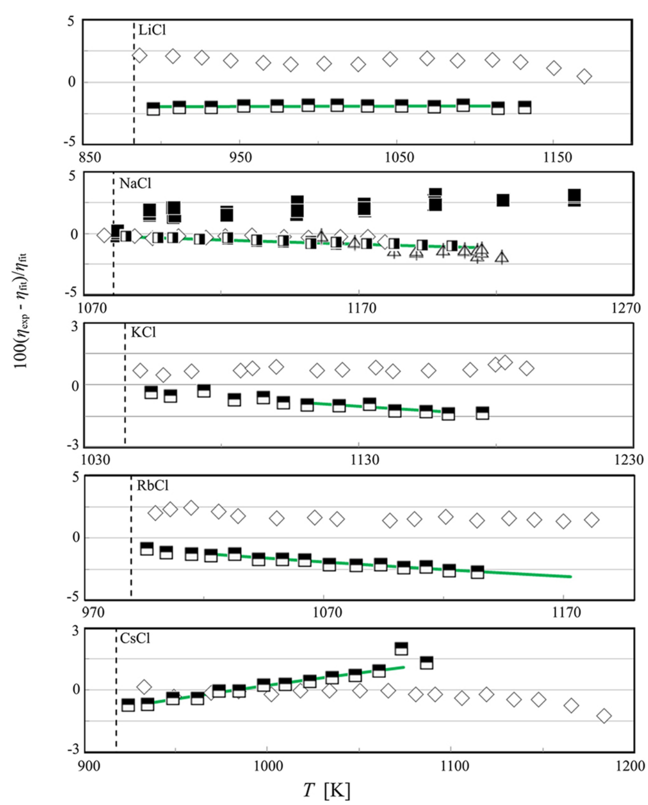

FIG. 4. Percentage deviations of the primary data and previous reference correlation for the viscosity of LiCl, NaCl, KCl, RbCl, and CsCl from the values calculated by Eq. (1), as a function of the temperature. Ejima *et al.*[13] (◇), Brockner *et al.*[54] (⊟), Tolbaru *et al.*[11] (⏃), Ito *et al.*[12] (■), Tørklep and Øye[14] (◨). Reference correlations of Janz[10] (green solid line), melting temperature (- -).

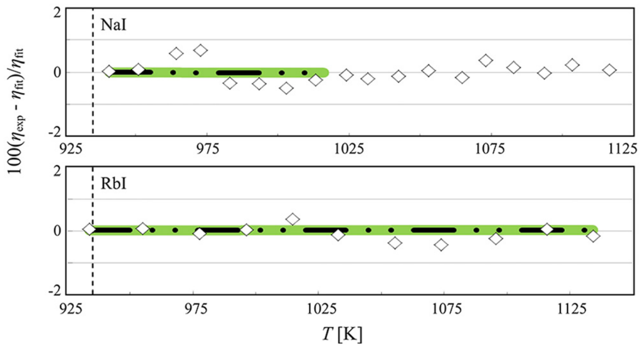

FIG. 5. Percentage deviations of the primary data and previous reference correlation for the viscosity of NaI and RbI from the values calculated by Eq. (1), as a function of the temperature. Sato *et al.*[50] (◇), Ejima *et al.*[13] (– · · –). Reference correlations of Janz[10] (green solid line), melting temperature (- -).

three cases: (a) deviations of the new reference equations from the ones proposed by Janz[10] in 1988 are less than 1%, confirming the excellent work carried out by Janz,[10] and (b) the temperature range of the new equations is much larger, attributed to the new measurements considered.

3.2. Bromide molten salts

Figure 3 shows, for the three bromide salts, the percentage deviations of the primary viscosity data from those calculated by Eq. (1), as a function of the temperature. The following can be noted: (a) for the first time, a reference correlation is given for KBr, (b) the new reference correlations for the other two salts agree with the Janz[10] correlation within 1%, and (c) a slightly different dependence on temperature is observed in the measurements of Murgulescu and Zuca[51] from the other two sets, but they are still within the mutual uncertainties.

TABLE 6. Recommended values for the viscosity of molten $LiNO_3$, $NaNO_3$, and KNO_3 as a function of temperature at 0.1 MPa. Estimated uncertainties at the 95% confidence level are $LiNO_3$ (6.7%), $NaNO_3$ (3.0%), and KNO_3 (3.0%)

	η (mPa s)		
T (K)	$LiNO_3$	$NaNO_3$	KNO_3
530	5.64		
560	4.49		
590	3.66	2.85	
620	3.04	2.43	2.76
650	2.57	2.10	2.35
680	2.21	1.84	2.03
710		1.63	1.77
740		1.45	1.56
770			1.40
800			1.26
830			1.14
860			1.04
890			0.96
920			0.88
950			0.82
980			0.76

TABLE 7. Recommended values for the viscosity of molten NaBr, KBr, and RbBr as a function of temperature at 0.1 MPa. Estimated uncertainties at the 95% confidence level are NaBr (1.6%), KBr (2.0%), and RbBr (2.2%)

	η (mPa s)		
T (K)	NaBr	KBr	RbBr
960			1.52
980			1.44
1000			1.36
1020	1.16	1.17	1.29
1040	1.10	1.12	1.22
1060	1.06	1.06	1.16
1080	1.01	1.01	1.11
1100	0.970	0.966	1.06
1120	0.932	0.924	1.01
1140	0.897	0.885	0.972
1160	0.864	0.849	0.933
1180	0.834	0.815	0.896
1200		0.784	0.862

3.3. Chloride molten salts

Figure 4 shows, for the five chloride salts, the percentage deviations of the primary viscosity data from those calculated by Eq. (1), as a function of the temperature. The following can be noted: (a) in the case of deviations of the LiCl measurements, there is an unexplained systematic discrepancy between the data of Ejima *et al.*[13] and Brockner *et al.*[54] (b) There is excellent agreement among all the data for NaCl; only the measurements of Ito *et al.*[12] show a slightly different temperature dependence. (c) There is a small difference in

TABLE 8. Recommended values for the viscosity of molten LiCl, NaCl, KCl, RbCl, and CsCl as a function of temperature at 0.1 MPa. Estimated uncertainties at the 95% confidence level are LiCl (3.7%), NaCl (2.4%), KCl (1.6%), RbCl (3.6%), and CsCl (1.1%)

	η (mPa s)				
T (K)	LiCl	NaCl	KCl	RbCl	CsCl
880	1.51				
910	1.38				
940	1.28				1.48
970	1.18				1.34
1000	1.10			1.35	1.22
1030	1.03			1.25	1.12
1060	0.966		1.06	1.15	1.03
1090	0.910	1.01	0.985	1.07	0.957
1120	0.860	0.949	0.917	0.998	0.890
1150	0.816	0.894	0.857	0.934	0.830
1180	0.775	0.845	0.804	0.877	0.778
1210		0.801	0.757		
1240		0.761			

TABLE 9. Recommended values for the viscosity of molten NaI and RbI as a function of temperature at 0.1 MPa. Estimated uncertainties at the 95% confidence level are NaI (1.5%), and RbI (1.5%)

	η (mPa s)	
T (K)	NaI	RbI
920		1.56
950	1.12	1.42
980	1.04	1.30
1010	0.966	1.19
1040	0.905	1.10
1070	0.850	1.02
1100	0.802	0.953
1130	0.759	0.891
1160		0.836
1190		0.787

the temperature dependence of the KCl and RbCl sets, leading to departure in the viscosity of less than 1.5% and 3%, respectively. (d) The new correlations differ from the Janz[10] correlations by up to 2%, except for RbCl, where the difference rises to 5%. (e) The inclusion of the Ejima *et al.*[13] measurements in the primary dataset allows the extension of the correlations to higher temperatures.

3.4. Iodide molten salts

Figure 5 shows, for the 2 iodide salts, the percentage deviations of the primary viscosity data from those calculated by Eq. (1), as a function of the temperature. We note that (a) the agreement with the correlation of Janz[10] is excellent and (b) the new measurements allowed the extension of the new reference correlations to higher temperatures.

3.5. Proposed values

In Tables 6–9, recommended values are given for the 13 molten salts studied in this work. These values are calculated by employing Eq. (1), and the coefficients and parameters are shown in Table 5.

4. Conclusions

The available experimental data for the viscosity of 13 inorganic molten salts have been critically examined, and new reference correlations for the viscosity as a function of temperature at atmospheric pressure were proposed. Standard reference correlations were proposed for the following molten salts (with estimated uncertainties at the 95% confidence level given in parentheses): $LiNO_3$ (6.7%), $NaNO_3$ (3.0%), KNO_3 (3.0%), NaBr (1.6%), KBr (2.0%), RbBr (2.2%), LiCl (3.7%), NaCl (2.4%), KCl (1.6%), RbCl (3.6%), CsCl (1.1%), NaI (1.5%), and RbI (1.5%).

It should be noted that (a) for the first time, a reference correlation is proposed for KBr; (b) the new proposed reference correlations agree in all other cases within 2% with the previous reference correlations by Janz[10] except for RbCl, where deviations between the two correlations rise to a maximum of 5%; (c) the new measurements considered allowed the extension of the reference correlations to higher temperatures.

Finally, as a conclusion of this work, we believe that considering the uncertainty of the experimental methods available, as well as the uncertainty required by industry, additional viscosity measurements for these salts at atmospheric pressure are unnecessary.

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