

Reference Correlations for the Viscosity of 13 Inorganic Molten Salts

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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): LiNO₃ (6.7%), NaNO₃ (3.0%), KNO₃ (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%).

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1



- 2. Data Compilation
 - 2.1. Nitrate molten salts
 - 2.1.1. LiNO3
 - 2.1.2. NaNO3
 - 2.1.3. KNO3
 - 2.2. Bromide molten salts
 - 2.2.1. NaBr
 - 2.2.2. KBr
 - 2.2.3. RbBr
 - 2,3. Chloride molten salts
 - 2.3.1. LiCl
 - 2.3.2. NaCl
 - 2.3.3. KCl, RbCl, and CsCl
 - 2.4. Iodide molten salts
- 3. Discussion
 - 3.1. Nitrate molten salts
 - 3.2. Bromide molten salts
 - 3.3. Chloride molten salts
 - 3.4. Iodide molten salts
 - 3.5. Proposed values
- 4. Conclusions Acknowledgment
- 5. References

LIST OF TABLES

- 1. Data sets considered for the viscosity of molten nitrate salts at 0.1 MPa.
- 2. Data sets considered for the viscosity of molten bromide salts at 0.1 MPa.
- 3. Data sets considered for the viscosity of molten chloride salts at 0.1 MPa.
- . Data sets considered for the viscosity of molten iodide salts at 0.1 MPa.
- Coefficients of Eq. (1), melting temperatures, maximum temperature of applications, and associated uncertainties.
- 6. Recommended values for the viscosity of molten LiNO₃, NaNO₃, and KNO₃ as a function of temperature at 0.1 MPa.

7. Recommended values for the viscosity of molten NaBr, KBr, and RbBr as a function of temperature at 0.1 MPa.

- 8. Recommended values for the viscosity of molten LiCl, NaCl, KCl, RbCl, and CsCl as a function of temperature at 0.1 MPa.
- Recommended values for the viscosity of molten NaI and RbI as a function of temperature at 0.1 MPa.

LIST OF FIGURES

- 1. Viscosity of molten NaCl at 0.1 MPa as a function of the temperature.
- 2. Percentage deviations of the primary data and previous reference correlations for the viscosity of LiNO₃, NaNO₃, and KNO₃ from the values calculated by Eq. (1), as a function of the temperature.
- 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.
- 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.
- 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.





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 viscosity³⁻⁶ 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 (LiNO₃, NaNO₃, KNO₃, 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 plants⁸ 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 authors¹¹⁻²⁷ 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 temperature. In 1988, Janz¹⁰ published reference correlations for NaCl is shown in Fig. 1 (green line). The reference correlations proposed by Janz¹⁰ 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 Janz¹⁰ 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

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of conditions, with uncertainties in the range of 1%. However, in many cases, such a narrow definition unacceptably limits the thermodynamic states for which data can be represented. Consequently, within the primary data set, 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 (LiNO₃, NaNO₃, KNO₃), bromide salts (NaBr, KBr, RbBr), chloride salts (LiCl, NaCl, KCl, RbCl, CsCl), and iodide salts (NaI, RbI). In these tables, 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 will be shown in Sections 2.1–2.4. Following our aforementioned discussion, in this work we concentrate only on measurements performed after those on which the 1988 Janz¹⁰ correlations were based. Furthermore, in our primary dataset, we also included the measurements on which Janz¹⁰ 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 elsewhere³ and will not be repeated here.

2.1. Nitrate molten salts

Three nitrate molten salts were considered: LiNO₃, NaNO₃ and KNO₃. The viscosity sets considered for each of these salts, are shown in Table 1.

2.1.1. LiNO₃

The first recommendation of the Molten Salts Data Centre, 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 Janz¹⁰ covers a temperature range 540 K to 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 540 K to 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 Janz¹⁰ were based were also included in the primary data set shown in Table 1.



1.<mark>2</mark>. NaNO₃

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 Dantuma²⁶ (not found to have the same problem noticed in the LiNO₃ measurements), and covered a temperature range 589 K to 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 Zuca³¹ 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 Karpachev²⁵ 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 590 K to 753 K with an uncertainty of 2.1%. It should be noted here than in this particular case the measurements of Ogawa²³ 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. KNO₃

KNO₃ was initially selected by the molten salts "Standards Program",¹⁰ which was initiated in 1973 by G. J. Janz (USA) jointly with S. 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 to 1978, the measurements of Zuca and Costin³⁹ were selected as the recommended reference data set, 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 Janz¹⁰ covers a temperature range 1022 K to 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.



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 1010 K to 1194 K, while the measurements of Murgulescu and Zuca⁵¹ 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 Janz¹⁰ covers a temperature range 971 K to 1197 K with an uncertainty of 1.5%, and it is based 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.

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 Janz¹⁰ 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 eylinder 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 state⁵⁵ 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 the 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.

3. KCl, RbCl, and CsCl

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In these three cases, the Janz¹⁰ 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 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 Janz¹⁰ 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) were fitted as a function of the absolute temperature, T (K), to an equation of the form

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

where *R* (J mol⁻¹ K⁻¹) is the molar gas constant⁶¹ and *A* (mPa s) and *B* (J mol⁻¹) are constants shown in Table 5. In the same table, 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 $T_{\rm m}$ (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 $AAD = (\sum |PCTDEV|)/n$, where the summation is over all *n* points, and the bias percent is found with the expression BIAS = $(\sum PCTDEV)/n$. 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. The variables η_{exp} , η_{fit} , and η_{av} , represent in turn, 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 three cases: a) deviations of the new reference equations from the ones proposed by Janz¹⁰ in 1988 are less than 1%, confirming the excellent work carried out by Janz¹⁰ 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 Janz¹⁰ correlation within 1%, and c) a slightly different dependence on temperature is observed in the measurements of Murgulescu and Zuca⁵¹ from the other two sets, but they are still within the mutual uncertainties.

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 the temperature dependence of the KCl and RbCl sets, leading to departures in the viscosity of less than 1.5% and 3%, respectively. d) The new correlations differ from the Janz¹⁰ correlations by up to 2%, except for RbCl, where the difference rises to 5%, and e) the inclusion of the Ejima *et al.*¹³

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 Janz¹⁰ 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 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): LiNO₃ (6.7%), NaNO₃ (3.0%), KNO₃ (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 Janz¹⁰ 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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11

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	First author	Publ. year	Purity (mass%)	Technique employed	Uncertainty quoted (%)	Uncertainty No. of quoted (%) data		Form of data ^a
				LiNO ₃				
						,		
	Previous refer	ence co	rrelation				540 650	F
	Janz ¹⁰	1988	-	Protsenko and Razumovskaya ³²	Ó		540-650	E
	Primary data				X			
	Nunes ³³	2017	98.5	Oscillating Cup	3	14	544-690	Т
	Janz ³⁰	1978	-	Capillary	1.5	16	540-645	Т
	Zuca ³¹	1970	-	Oscillating Sphere	3	18	537-698	Т
	Protsenko ³²	1965	-	Capillary		15	548-674	Т
	Secondary dat	ta						
	Smotrakov ³⁵	1972	-	Capillary	1.5	-	538-690	Е
	Dantuma ²⁶	1928	-	Oscillating Ball	_	37	533-703	Т
	Goodwin ⁴¹	1908	-	Capillary	-	9	532-618	Т
				NANO				
				NalNO3				
	Previous refer	ence co	rrelation					
	Janz ¹⁰	1988	-	Based on Dantuma ²⁶ (1928)	3	-	589-731	Е
	Primary data							
	Nunes ³⁸	2006	-	Oscillating Cup	2.1	14	590-753	Т
	Smotrakov ³⁵	1972	_	Capillary	1.5	-	593-689	Е
	Zuca ³¹	1970	-	Oscillating Sphere	3	14	598-749	Т
	Protsenko ³²	1965		Capillary	-	21	588-744	Т
	Karpachev ²⁵	1935		Oscillating Sphere	-	5	589-716	Т
	Dantuma ²⁶	1928	/- N	Oscillating Ball	-	33	589-732	Т
	Secondary dat	ta 🗸		/				
	Bondarenko ¹⁹	1965		Oscillating Cup	5	2	648-695	Т
	Ogawa ²³	1950	_	Falling Ball	_	8	599-681	D
	Fawsitt ²⁷	1908	-	Oscillating Disc	10	6	597-667	Т
	Goodwin ⁴¹	1908		Capillary	-	7	610-769	Т
	Lorenz ⁴²	1906	-	Capillary	0.1	12	581-692	Т
		5		KNO3				
	C		• .•					
	Previous refer	rence co	rrelation		•			F
6	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	Т
	Tolbaru ¹¹	1998	Spectral	Oscillating Cup	-	28	666-735	Т
	Schardey ⁴⁰	1988	99.7	Oscillating Cylinder	0.3	9	622-725	Т
	Abe ¹⁵	1980	99.99	Oscillating Cup	1.1	36	622-974	Т

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ΔII -)		_					
Dublichi	Jan z ³⁰	1978	-	Capillary	1.	5 14	613-743	Т
PUDIISII	Alca ³⁹	1976	-	Oscillating Sphere	2	-	615-760	Е
	Secondary	data						
	Ohta ⁴³	1975	-	Oscillating Sphere	1.	2 6	625-686	Т
	Protsenko44	1972	-	Capillary	-	5	613-694	Т
	Smotrakov ³	³⁵ 1972	-	Capillary	1.	5 -	613-684	Е
	Dumas ⁴⁵	1970	-	Oscillating Sphere	2	3	615-672	Т
	Zuca ³¹	1970	-	Oscillating Sphere	3	22	615-765	Т
	Wellman ⁴⁶	1966	-	Capillary	2	18	617-766	Т
	Protsenko ³²	1965	-	Capillary		9	621-765	Т
	Rhodes47	1965	99.99	Capillary	0.	5 -	620-660	Е
	Janz ⁴⁸	1963	-	Oscillating Crucible		4	632-765	Т
	Ogawa ²³	1950	-	Falling Ball		9	614-702	D
	Karpachev ²	⁵ 1935	-	Oscillating Sphere		6	621-816	Т
	Dantuma ²⁶	1928	-	Oscillating Ball	- () · · ·	35	621-816	Т
	Fawsitt ²⁷	1908	-	Oscillating Disc	= 10	7	622-681	Т
	Goodwin ⁴¹	1908	-	Capillary		7	620-780	Т
	Lorenz42	1906	-	Capillary	0.	19	606-687	Т

^a D = diagram, E = equation, T = tabulated experimental data

Publishing. TABLE 2. Data sets considered for the viscosity of molten bromide salts at 0.1 MPa

First author	Publ. year	Purity (mass%)	Technique employed	Uncertainty N quoted (%)	No. of data	Temp. Range (K)	Form of data ^a
			NaBr				
Previous refer	ence co	rrelation					
Janz ¹⁰	1988	-	Based on Ejima and Sato ⁴⁹ (1985)	1.5		1022-1192	Е
Determination			,				
Primary data	1007		Constituents	0.7	14	1022 1102	т
Sato ³⁰	1997	-	Capillary	0./	14	1022-1193	I
Ejima ⁴⁹	1985	-	Capillary	1.0	-	1022-1192	E
Secondary dat	ta						
Antonov ¹⁶	1978	-	Oscillating Sphere	-	-	1039-1181	Е
Matsumura ¹⁸	1967	-	Oscillating Disc		3	1083-1144	Т
Murgulescu ⁵¹	1962	-	Oscillating Sphere	3.0	10	1053-1213	Т
Fawsitt ²⁷	1908	-	Oscillating Disc	10	5	1035-1154	Т
			L'D.				
			KBr				
Primary data							
Sato ⁵⁰	1997	-	Capillary	0.7	19	1010-1194	Т
Murgulescu ⁵¹	1962	-	Oscillating Sphere	3.0	11	1017-1181	Т
Secondary dat	ta						
Smirnov ⁵²	1975	-	Oscillating Sphere	-	-	1015-1215	Е
Matsumura ¹⁸	1967	-	Oscillating Disc	-	3	1073-1134	Т
Karpachev ⁵³	1938	-	Oscillating Sphere	-	5	973-1174	Т
Fawsitt ²⁷	1908	-	Oscillating Disc	10	5	1018-1136	Т
			DhPa				
			KUDr				
Previous refer	ence co	rrelation	\checkmark				
Janz ¹⁰	1988	-	Based on Ejima and Sato ⁴⁹ (1985)	1.5	-	971-1197	Е
Primary data		\sim	7				
Sato ⁵⁰	1997		Capillary	0.7	13	971-1197	Т
Ejima ⁴⁹	1985	_	Capillary	1.5	_	971-1197	Е
Murgulescu ⁵¹	1962	-	Oscillating Sphere	3.0	11	959-1140	Т

^a T = tabulated experimental data, E = equation

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First author Publ. Purity year (mass %)		Purity (mass %)	Technique employed	Uncertainty quoted (%)	No. of data	Temp. Range (K)	Form of data ^a
			LiCl				
Previous referen	ce corr	elation					
Janz ¹⁰	1988	-	Based on Brockner <i>et al</i> ⁵⁴ (1981)			894-1113	Е
	1700					0, 1110	2
Primary data				\sim			
Ejima ¹³	1982	-	Capillary	0.7	15	886-1170	T
Brockner ⁵⁴	1981	-	Oscillating Cylinder	0.5	13	894-1132	Т
Secondary data							
Wakao ⁵⁵	1991	99.9	Oscillating Cup	2	13	886-1275	Т
Bondarenko56	1969	-	Oscillating Cup	5	5	911-1024	Т
Smirnov ⁵⁷	1967	-	Oscillating Sphere	<u> </u>	-	930-1068	Е
Brockner ¹⁷	1975	-	Oscillating Sphere	1	33	896-1119	D
Nishihara ²⁰	1964	-	Oscillating Disc	-	4	890-1014	Т
Murgulescu ²¹	1963	-	Oscillating Sphere	3	11	902-1083	Т
Karpachev ²⁵	1935	-	Oscillating Sphere	-	5	923-1124	Т
Fawsitt ²⁷	1908	-	Oscillating Disc	10	6	890-1039	Т
Previous referen	ce corr	elation	NaCl				
Janz ¹⁰	1988	-	Based on Tørklep and Øye ¹⁴ (1979)	0.2	-	1080-1210	Е
Primary data							
Tolbaru ¹¹	1998	Spectral	Oscillating Cup	-	18	1156-1222	Т
Ito ¹²	1989		Oscillating Cup	2.4	40	1082-1249	Т
Ejima ¹³	1982		Capillary	0.7	12	1077-1180	Т
Tørklep ¹⁴	1979		Oscillating Cup	1.5	78	1085-1205	Т
Secondary data							
Abe ¹⁵	1980	99.99	Oscillating Cup	0.9	39	1083-1474	Т
Antonov ¹⁶	1978		Oscillating Sphere	-	-	1073-1212	Е
Brockner ¹⁷	1975	-	Oscillating Sphere	1	27	1086-1217	D
Matsumura ¹⁸	1967	-	Oscillating Disc	-	3	1083-1144	Т
Bondarenko ¹⁹	1965	-	Oscillating Cup	5	7	1088-1232	Т
Nishihara ²⁰	1964	-	Oscillating Disc	-	2	1102-1119	Т
Murgulescu ²¹	1963	-	Oscillating Sphere	3	11	1085-1244	Т
Vershchetina ²²	1954	-	Oscillating Disc	-	3	1098-1149	Т
Ogawa ²³	1950	-	Falling Ball	-	6	1087-1193	D
Berenblit ²⁴	1937	-	Capillary	-	6	1094-1230	Т
Karpachev ²⁵	1935	-	Oscillating Sphere	-	6	1121-1271	Т
Dantuma ²⁶	1928	-	Oscillating Ball	-	21	1089-1271	Т
Fawsit ²⁷	1908	-	Oscillating Disc	10	5	1114-1198	Т

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Publishin	g <mark>e</mark> vious referen	ce correlati	ion					
Jĩ	anz^{10}	1988	-	Based on Brockner et al. ⁵⁴ (1981)	1	-	1111-1162	Е
Р	rimarv data							
E	jima ¹³	1982	-	Capillary	0.7	15	1050-1191	Т
В	Brockner ⁵⁴	1981	-	Oscillating Cylinder	0.5	13	1054-1175	Т
S	econdary data							
Ă	$ntonov^{16}$	1978	-	Oscillating Sphere			1056-1216	Е
В	Brockner ¹⁷	1975	_	Oscillating Sphere		23	1068-1177	D
N	latsumura ¹⁸	1967	_	Oscillating Disc		3	1098-1179	T
В	ondarenko ¹⁹	1965	_	Oscillating Cup	3	3	1070-1188	Т
N	lishihara ²⁰	1964	_	Oscillating Disc		3	1056-1088	Т
N	/urgulescu ⁵¹	1962	_	Oscillating Sphere	3	11	1056-1202	Т
0)gawa ²³	1950	_	Falling Ball	-	4	1061-1174	D
B	Berenblit ²⁴	1937	_	Capillary	V _	7	1074-1226	Т
F	awsitt ²⁷	1908	_	Oscillating Disc	10	5	1063-1309	Т
					-	-		
				PLC				
				RUCI				
Р	revious referen	ce correlati	ion					
Ja	anz^{10}	1988	-	Based on Brockner et al.54 (1981)	1	-	1023-1172	Е
Р	rimary data							
Е	jima ¹³	1982	-	Capillary	0.7	16	999-1182	Т
В	brockner ⁵⁴	1981	-	Oscillating Cylinder	0.5	15	996-1134	Т
S	econdery dete							
יפ	econual y uata	1077		Oscillating Crucible			1000-1250	Б
D B	rockner ¹⁷	1977	-	Oscillating Sphere	-	-	$1000 \ 1230$ 1011 - 1177	D
D	anvas ⁵⁹	1975		Oscillating Hollow Cylinder	1	10	1007-1225	л Т
K M	lurgulescu ²¹	1903		Oscillating Sphere	4	11	1007 1223	т Т
14.	luiguieseu	1905		Oscillating Sphere	5	11	1005 1149	1
				7				
			\checkmark	CsCl				
Р	revious referen	ce correlati	ion					
Ja	anz ¹⁰	1988	-	Based on Brockner et al.54 (1981)	1	-	934-1074	Е
Р	rimary data							
E	jima ¹³	1982	-	Capillary	0.7	17	933-1184	Т
В	Brockner ⁵⁴	1981	-	Oscillating Cylinder	0.5	14	923-1087	Т
e	econdery date							
	econual y uata	1077		Oscillating Crucible	_		030-1185	F
ם 🖉	rocknor ¹⁷	1977	-	Oscillating Sphere	-	20	930-1183	ь р
B	mirnov ⁵⁷	19/5	-	Oscillating Sphere	1	20	944 ⁻¹⁰³⁸	Б
3	animic v	1907	-	Oscillating Hollow Cylinder	-	- 1/	930-1030 020-1152	Е Т
R.	lurgulescu ²¹	1905	-	Oscillating Sphere	4	14 11	930-1133 027-1111	і Т
IV.	Turguiescu	1703	-	Osemaning spilere	ر	11	741-1111	1

^a D = diagram, E = equation, T = tabulated experimental data

TAELE 4. Data sets considered for the viscosity of molten iodide salts at 0.1 MPa

First author	Publ. year	Purity (mass %)	Technique employed	Uncertainty No quoted (%) da	o. of ata	Temp. Range (K)	Form of data ^a
			NaI				
Previous refer	ence coi	rrelation					
Janz ¹⁰	1988	-	Based on Ejima and Sato ⁴⁹ (1985)	1.5		941-1017	Е
Primarv data							
Sato ⁵⁰	1997	-	Capillary	0.7	18	940-1117	Т
Ejima ¹³	1982	-	Capillary	0.7	17	941-1017	Е
Secondary dat	a						
Antonov ¹⁶	1978	-	Oscillating Sphere	-	-	946-1083	Е
Murgulescu ⁶⁰	1965	-	Oscillating Sphere	3	13	946-1108	Т
Karpachev ⁵³	1938	-	Oscillating Sphere	<u> </u>	6	923-1124	Т
			RbI				
Previous refer	ence coi	rrelation					
Janz ¹⁰	1988	-	Based on Ejima and Sato ⁴⁹ (1985)	1.5	-	934–1194	Е
Primary data							
Ejima ¹³	1982	-	Capillary	0.7	17	934-1194	Е
Sato ⁵⁰	1997	-	Capillary	0.7	14	933-1194	Т
Secondary dat	a						
Murgulescu ⁶⁰	1965	-	Oscillating Sphere	3 1	16	922-1127	Т

^a T = tabulated experimental data, E = equation

Ρι

No.

20

E	LE 5. Coefficients of Eq. (1), melting temperatures (from Ref. 7), maximum temperature of application, ar	ıd
	iated uncertainties.	

Molten salt	T _m (K)	T _{max} (K)	A (mPa s)	<i>B</i> (J mol ⁻¹)	AAD (%)	BIAS (%)	Uncertainty 2σ (%)
LiNO ₃	527.15	697	0.0805	18725.7	3.0	0.06	6.7
NaNO ₃	583.15	753	0.1037	16250.7	1.1	0.01	3.0
KNO ₃	610.15	974	0.0840	17994.1	1.1	0.01	3.0
NaBr	1020.15	1193	0.1034	20479.2	0.1	0.00	1.6 ^a
KBr	1007.15	1194	0.0797	22814.5	0.7	0.05	2.0
RbBr	953.15	1197	0.0888	22681.4	0.8	0.01	2.2
LiCl	883.15	1170	0.1103	19129.1	1.7	0.02	3.7
NaCl	1081.15	1249	0.0973	21209.3	1.0	0.01	2.4
KCl	1045.15	1191	0.0689	24105.6	0.8	0.00	1.6
RbCl	990.15	1182	0.0792	23595.5	1.7	0.02	3.6
CsCl	918.15	1184	0.0630	24655.8	0.4	0.00	1.1
NaI	935.15	1117	0.0995 🔦	19087.7	0.1	0.00	1.5 ^a
RbI	913.15	1194	0.0763	23088.1	0.1	0.00	1.5 ^a

^a preferred to use the measurement uncertainty as it is higher.

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Publishing at 0 MPa. Estimated uncertainties at the 95% confidence level are: LiNO₃ (6.7%), NaNO₃ (3.0%), and KNO₃

(3.0%).

		η (mPa s)		
$T(\mathbf{K})$	LiNO ₃	NaNO3	KNO3	
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	4		1.26	
830		\sim	1.14	
860			1.04	
890			0.96	
920			0.88	
950	$I \square$		0.82	
980			0.76	



Publishing 0 PMPa. Estimated uncertainties at the 95% confidence level are: NaBr (1.6%), KBr (2.0%), and RbBr (2.2%).

		η (mPa s)	
$T(\mathbf{K})$	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	4	0.784	0.862

TAFLE 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%).

		1	η (mPa s)		
$T(\mathbf{K})$	LiCl	NaCl	KCl	RbCl	CsCl
880	1.51				
910	1.38				\frown
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)		
$T(\mathbf{K})$	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	
	<i>T</i> (K) 920 950 980 1010 1040 1070 1100 1130 1160 1190	η (m T (K) NaI 920 950 1.12 980 1.04 1010 0.966 1040 0.905 1070 0.850 1100 0.802 1130 0.759 1160 1190	

24

FIGURE CAPTIONS

Fig. 1. Viscosity of molten NaCl at 0.1 MPa as a function of the temperature. Tolbaru *et al.*¹¹ (Δ), Ito *et al.*¹² (\blacksquare), Ejima *et al.*¹³ (\bigcirc), Tørklep and Øye¹⁴ (\blacksquare), Abe *et al.*¹⁵ (\bigoplus), Antonov and Khokhlov¹⁶ (\frown), Brockner *et al.*¹⁷ (\blacksquare), Matsumura *et al.*¹⁸ (\bigoplus), Bondarenko and Strelets¹⁹ (\bigcirc), Nishihara *et al.*²⁰ (\square), Murgulescu and Zuca²¹ (Δ), Vershchetina and Luzhnaya²² (\bigoplus), Ogawa²³ (\square), Berenblit²⁴ (X), Karpachev²⁵ (\bigcirc), Dantuma²⁶ (+), Fawsitt²⁷ (X). Reference correlation of Janz¹⁰ (\frown), Melting temperature (- -)

FIGURE 2. Percentage deviations of the primary data and previous reference correlations for the viscosity of LiNO₃, NaNO₃, and KNO₃ from the values calculated by Eq. (1), as a function of the temperature. Nunes *et al.*³³ (Δ), Janz *et al.*³⁰ (\blacklozenge), Zuca³¹ (Δ), Tolbaru *et al.*¹¹ (Δ), Lanca *et al.*³⁴ (\diamondsuit), Schardey *et al.*⁴⁰ (\Box), Abe *et al.*¹⁵ (\Box), Zuca and Costin³⁹ ($-\cdot-$), Nunes *et al.*³⁸ (\Box), Smotrakov *et al.*³⁵ (--), Protsenko and Razumovskaya³² (\bigcirc), Karpachev²⁵ (\bigcirc), Dantuma²⁶ (+). Reference correlations of Janz¹⁰ (-), Melting temperature (- -).

FIGURE 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 (\bigcirc), Ejima and Sato⁴⁹ (-··-), Murgulescu and Zuca⁵¹ (\square). Reference correlations of Janz¹⁰ (\square), Melting temperature (- -).

FIGURE 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 (\diamond), Brockner *et al.*⁵⁴ (\square), Tolbaru *et al.*¹¹ (\diamond), Ito *et al.*¹² (\square), Tørklep and Øye¹⁴ (\square). Reference correlations of Janz¹⁰ (\square), Melting temperature (- -).

FIGURE 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 (\diamondsuit), Ejima *et al.*¹³ (-··-). Reference correlations of Janz¹⁰ (---), Melting temperature (--).







 $100(\eta_{exp} - \eta_{fit})/\eta_{fit}$



 $100(\eta_{exp} - \eta_{fit})/\eta_{fit}$



 $100(\eta_{exp} - \eta_{fit})/\eta_{fit}$