

INORGANIC MATERIALS AND NANOMATERIALS

Thermodynamic Properties and Vaporization Processes in the La_2C_3 –C System

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Abstract—Vaporization processes of the components in the La_2C_3 –C system were studied by Knudsen effusion mass spectrometry in the temperature range of 2196–2435 K. The main vapor species over the system under study were La and LaC_2 . The temperature dependences of the partial pressures of the identified vapor species and of the La activity, as well as the La and LaC_2 partial molar enthalpies of vaporization, were determined in the La_2C_3 –C system. It was shown that the found values of thermodynamic properties are in agreement with the literature data and with the results of modeling using the NUCLEA database for the LaC_2 –C system. This allowed the thermodynamic properties of the LaC_2 –C system to be evaluated on the basis of the obtained values. It was established that the La activity is independent of temperature, indicating a zero La partial molar enthalpy of mixing in the region of the LaC_2 and C equilibrium. The results of this study can be further used to supplement thermodynamic databases and to optimize phase diagrams of multicomponent carbide systems that are promising for various high-temperature technologies.

Keywords: Knudsen effusion mass spectrometry, carbide ceramics, lanthanum carbide, partial pressure, lanthanum activity

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INTRODUCTION

The synthesis of carbide-based materials and their application at high temperatures require reliable information on the high-temperature properties of individual lanthanum carbides as a part of multicomponent carbide ceramics [1–3]. Multicomponent carbide systems are promising for the development of carbide materials that are stable in extreme environmental conditions for various high-temperature technologies and nuclear energy [1–3]. In this regard, the study of thermal stability of carbide systems is of particular interest [4–6]. The complexity of high-temperature thermodynamic studies of multicomponent systems leads, as a rule, to the need to develop methods for calculating physicochemical properties based on data for the corresponding binary systems. This makes studying the physicochemical properties of binary systems, in particular, individual metal carbides, relevant.

In this work, the vaporization processes of La_2C_3 (in the presence of excess carbon) as one of the significant components of carbide ceramics [7, 8] were stud-

ied at temperatures up to 2435 K. In addition to their use in high-temperature protective ceramics, lanthanum carbides are used as low-work function electronic conductors [9] and doping additives, in particular, to improve the emission properties of tungsten thermionic cathodes [10], in the development of targets for producing beams of radioactive ions in the nuclear industry [11, 12], and of composites for X-ray targets in computed tomography [13].

Let us briefly review the available information on high-temperature phase equilibria and thermodynamic properties of lanthanum carbides. The phase diagram of the lanthanum-carbon system has been repeatedly studied experimentally and calculated [14, 15] based on experimental data within the framework of the CALPHAD approach [16, 17]. An optimized phase diagram of the La–C system is presented in Fig. 1 according to study [14].

It has been established that two carbides, LaC_2 and La_2C_3 , exist in the La–C system. LaC_2 has two polymorphic modifications with a phase transition tem-

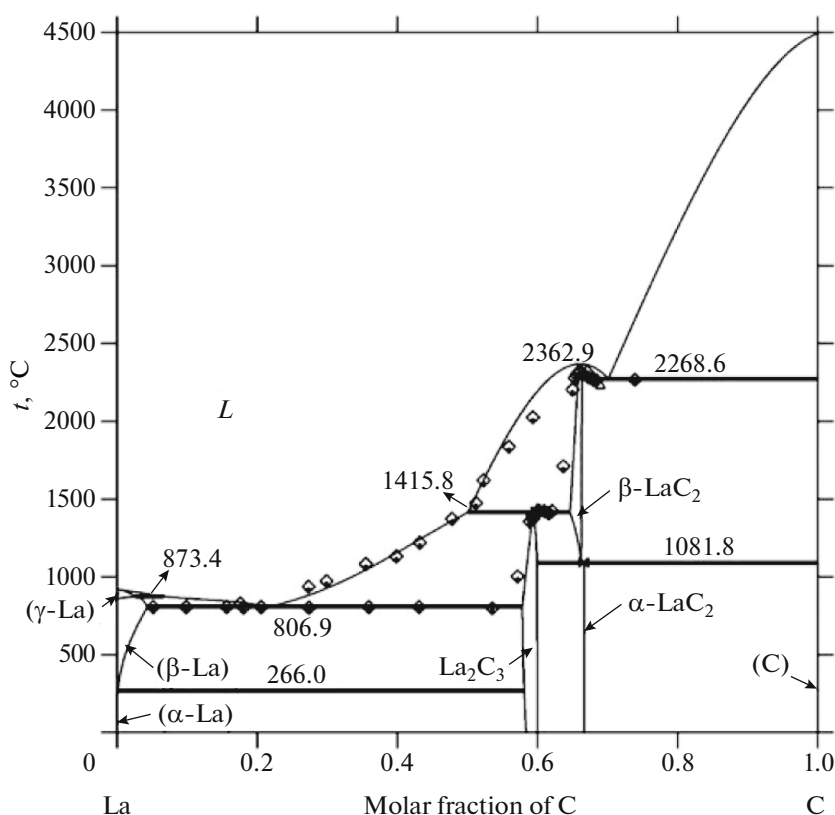


Fig. 1. Phase diagram of the La–C system according to [14].

perature of 1355 K. The high-temperature modification has a homogeneity region, while the low-temperature modification is a stoichiometric compound. A high-temperature modification of LaC_2 melts congruently at 2636 K. La_2C_3 also has a homogeneity region and melts by a peritectic reaction at a temperature of 1689 K with the formation of the high-temperature modification of LaC_2 [14].

The thermodynamic properties of lanthanum carbides have been studied experimentally [18–24], calculated [25–27], and optimized [14, 15] in a significant number of works. Available data relating to the vaporization of samples of the La–C system have been systematized in monograph [28]. Vaporization processes in the La–C system were first studied in work [18] in the temperature range of 2200–2500 K by Knudsen effusion mass spectrometry. The samples were vaporized from a tungsten effusion cell with graphite deposited on its inner surface. LaC_2 and atomic lanthanum were identified in the vapor above the studied system in the ion current ratio of 16 : 1 and partial pressure ratio of 0.66 : 1 at a temperature of 2500 K. The temperature dependence of the equilibrium constant of reaction (1) obtained in the range of 2200–2500 K is given in Table 1.



The value of the standard enthalpy of formation of gaseous LaC_2 according to Eq. (1) at a temperature of 0 K was 190 ± 40 kJ/mol when calculated according to the second law of thermodynamics and 160 ± 40 kJ/mol when calculated according to the third law [18].

Study [19] presents experimental results obtained by the Knudsen effusion method for the total vapor pressure over LaC_2 , vaporization of which was carried out from an effusion cell with a graphite liner in the temperature range of 1920–2270 K. The temperature dependence of the total vapor pressure over the LaC_2 –C system was obtained (Table 1). The authors of study [19] note that the vapor pressure was not measured over pure lanthanum carbide LaC_2 , but over a carbon-rich system. Partial pressures of vapor species have been calculated [19] based on the equation for the equilibrium constant of reaction (1) from study [18]. Temperature dependences of partial pressures of atomic lanthanum and LaC_2 in the range of 1920–2270 K calculated in study [19] are given in Table 1. The value of the standard enthalpy of formation of LaC_2 according to Eq. (1) at a temperature of 0 K was 188 kJ/mol when calculated according to the second law and 164 ± 6 kJ/mol when calculated according to the third law [19].

In study [20], in the mass spectrum of the vapor over the La–C system, samples of which were

Table 1. Results of examining the vaporization processes of the La–C system in studies [18–20]: (I) description of the sample under study, (II) equations of the temperature dependences of equilibrium constant K_p of reaction (1), total vapor pressure p and partial pressures $p(i)$ of vapor species over the system under study. $\Delta_f H_0^{o,II \text{ Law}}$ are values of the standard enthalpy of formation of gaseous LaC_2 at the temperature of 0 K obtained by the second law; $\Delta_f H_0^{o,III \text{ Law}}$ are values of the standard enthalpy of formation of gaseous LaC_2 at the temperature of 0 K obtained by the third law. (III) is the reference

I	II	$\Delta_f H_0^{o,II \text{ Law}}$, kJ/mol	$\Delta_f H_0^{o,III \text{ Law}}$, kJ/mol	III
La in a graphite effusion cell	$\log K_p = -\frac{8600}{T} + 3.26$, (2200–2500 K)	190 ± 40	160 ± 40	[18]
LaC ₂ in a tungsten effusion cell with a graphite liner	$\log p(\text{atm}) = -\frac{27300 \pm 850}{T} + (5.8 \pm 0.4)$, $\log p(\text{La, atm}) = -\frac{26240}{T} + 5.25$, $\log p(\text{LaC}_2, \text{atm}) = -\frac{34770}{T} + 8.53$, (1920–2270 K)	188	164 ± 6	[19]
Mixture of lanthanum filings and graphite powder in a tungsten effusion cell with a graphite liner	$\log p(\text{La, Pa}) = -\frac{26\,060 \pm 310}{T} + (10.162 \pm 0.140)$, $\log p(\text{LaC}_2, \text{Pa}) = -\frac{33\,270 \pm 310}{T} + (12.813 \pm 0.140)$, $\log p(\text{LaC}_3, \text{Pa}) = -\frac{44\,140 \pm 1090}{T} + (14.557 \pm 0.439)$, $\log p(\text{LaC}_4, \text{Pa}) = -\frac{43\,010 \pm 460}{T} + (15.067 \pm 0.190)$, (1900–2600 K)	162 ± 8	163 ± 22	[20]

obtained directly by heating in an effusion cell at a temperature of 2300 K from lanthanum filings and graphite powder on a graphite liner, C_3^+ , La^+ , LaC^+ , LaO^+ , LaF^+ , LaC_2^+ , LaC_3^+ , LaF_2^+ , and LaC_4^+ ions were identified at a temperature of 2651 K. The main components of the vapor were La, C₃, LaC₂, LaC₃, and LaC₄. The temperature dependences of the ion current intensities of LaC₂⁺, LaC₃⁺, and LaC₄⁺ were determined relative to the intensity of La⁺ in the mass spectra of vapor over the La–C system in the range of 2267–2600 K, as well as the enthalpies of formation and atomization of the LaC₂, LaC₃, and LaC₄ vapor species. The value of the standard enthalpy of formation of LaC₂ according to Eq. (1) at a temperature of 0 K was 162 ± 8 kJ/mol when calculated according to the second law and 163 ± 22 kJ/mol when calculated according to the third law [20]. Combining the obtained data and results [19] allowed the authors of [20] to find the temperature dependences of the partial pressures of La, LaC₂, LaC₃, and LaC₄ over LaC₂ in excess carbon in the range of 1900–2600 K [20] (Table 1).

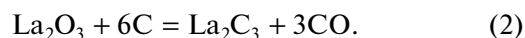
La₂C₂, La₂C₃, La₂C₄, La₂C₅, La₂C₆, and La₂C₈ gaseous lanthanum carbides have been identified in an

equilibrium vapor over the La–Ir–C system in study [29]. For these carbides, the enthalpies of atomization and standard enthalpies of formation are determined.

Thus, as follows from the above consideration, the high-temperature description of the La–C system has been studied repeatedly, but there are no data on the vaporization processes and thermodynamic properties of La₂C₃. In this regard, in this paper, the vaporization of the La₂C₃–C system was studied with the Knudsen effusion mass spectrometric method [30–32] at temperatures up to 2435 K.

EXPERIMENTAL

For the synthesis of lanthanum carbide (La₂C₃), powders of La₂O₃ (content of the main phase 99.8%, RareMetalRF, Russia) and carbon black (grade K-354, OOO BIOAMIN-RUS LLC) were used as initial components. Synthesis of La₂C₃ was carried out in accordance with the reaction



Lanthanum oxide powder was ground in a laboratory planetary mill PULVERISETTE 5 (Fritsch, Germany) using grinding balls made of high-density silicon carbide in an isopropyl alcohol medium. The

Table 2. Content of elements in the La_2C_3 sample obtained by electron probe microanalysis

Element	x_i content, mol %	x_i/x_{La} by analysis	x_i/x_{La} by synthesis
La	40 ± 4	1.0 ± 0.1	1.0
C	58 ± 9	1.5 ± 0.3	1.5
O	2.3 ± 0.3	0.06 ± 0.01	0.0

powder : grinding balls : alcohol ratio was 1 : 10 : 1. The wear of grinding media did not exceed 0.05%. Ground La_2O_3 powder was dried in a vacuum drying oven at a temperature of 343 K for 3 h and mixed with carbon black in an MLSh-1P laboratory ball mill (OOO KOLBA, Russia) in steel drums lined with wear-resistant rubber for 12 h using high-density silicon carbide balls as grinding media. The powder : grinding media ratio was 1 : 2. The powders were granulated by sifting through a sieve with a mesh size of 100 μm , after which they were formed into $10 \times 5\text{-mm}$ samples in metal molds under a pressure of 80 MPa. Heat treatment was carried out in graphite containers in an SShVE 1.2.5/25 high-temperature resistance furnace (OOO TD Lab-Term, Russia) with tungsten heaters and molybdenum lining at a temperature of 1973 K for 2 h. Synthesis was carried out under vacuum conditions with a residual gas pressure of 10^{-2} Pa. After synthesis, the sample was ground in a mortar under argon and placed in a hermetic ampoule. The ampoule was filled with argon and then sealed with wax.

The chemical composition of the obtained sample was studied using electron probe microanalysis on a TESCAN Vega II scanning electron microscope (TESCAN sro, Czech Republic). Carbon conductive tape was used as a substrate for powder analysis. The results of electron probe microanalysis are given in Table 2 and indicate the correspondence of the

obtained chemical composition and the stoichiometry of the sample selected during synthesis.

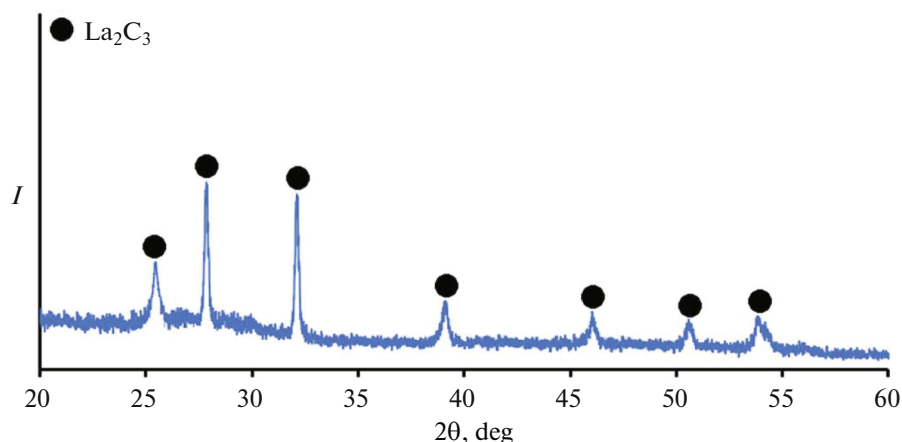
X-ray phase analysis was performed on a Rigaku Smartlab 3 diffractometer (Rigaku Holdings Corp., Japan) with a nickel filter in $\text{CuK}\alpha$ -radiation. To identify peaks in the diffraction pattern, the PDWin 4.0 software package (NPO Burevestnik, Russia) and the Crystallographica Search-Match package (Oxford Cryosystems Ltd, United Kingdom) with the PDF2 powder diffraction database (International Diffraction Data Center, United States) were used. The card number of the standard is 000-82-0622. The results of X-ray phase analysis are shown in Fig. 2 and indicate the receipt of the La_2C_3 target phase.

La_2C_3 vaporization processes were studied using high-temperature mass spectrometry [30–32] on an MS-1301 mass spectrometer (SCB of Analytical Instrumentation, Russia) at an ionizing voltage of 30 V. The sample was vaporized from a Knudsen graphite effusion cell placed in a molybdenum shell. The ratio of the vaporization area to the effusion area of the cell was not less than 100 : 1. The effusion cell was heated by electron bombardment, and the vaporization temperature of the sample was determined by an optical pyrometer with an accuracy of ± 10 K in the range of 1400–2500 K.

Partial pressures p_i of vapor species over the sample were obtained by the ion current comparison method:

$$p_i = p_s \frac{I_i^+ T_i \sigma_s \gamma_s}{I_s^+ T_s \sigma_i \gamma_i}, \quad (3)$$

where I_i^+ and I_s^+ are the intensity of ion currents i and s in the mass spectra of the vapor over the sample and standard, respectively, with correction for the isotopic distribution; T_i and T_s are the vaporization temperatures of the sample and standard; σ_i and σ_s are the ionization cross sections of vapor species i and s over the sample and standard, respectively; and γ_i and γ_s are the

**Fig. 2.** X-ray diffraction pattern of the La_2C_3 sample obtained in the present study by X-ray phase analysis.

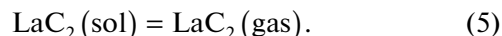
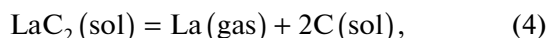
conversion factors of the secondary electron multiplier for ions i and s , proportional to $1/\sqrt{M}$, where M is the molecular mass of the ion.

To identify molecular precursors of ions in the mass spectra of vapor over La_2C_3 , the values of the ion appearance energies were determined using the vanishing ion current method. Silver was used as a standard for partial vapor pressure [33] and was vaporized from the effusion cell with the La_2C_3 sample, but at lower temperatures. When determining the partial pressures of atomic lanthanum and LaC_2 over the sample under study, the ionization cross sections of silver, carbon, and lanthanum were taken from work [34]. The ionization cross section of LaC_2 was calculated according to the additivity rule. The equipment was precalibrated by vaporizing calcium fluoride in separate experiments [35].

RESULTS AND DISCUSSION

In the mass spectrum of the vapor over La_2C_3 , the vaporization of which was carried out from a graphite cell, La^+ and LaC_2^+ ions were identified starting from a temperature of 2190 K. The appearance energy of the La^+ ion amounted to 6.0 ± 0.3 eV, which, within the measurement error, corresponds to the ionization energy of atomic lanthanum [36]. The appearance energy of the LaC_2^+ ion was not determined due to the low intensity of the ion current of LaC_2^+ in the mass spectrum of the vapor above the studied sample of the $\text{La}_2\text{C}_3\text{--C}$ system; however, according to the data of [20], this ion is also molecular. Other carbon-containing ions, the intensity of which exceeded the background signal, in addition to CO^+ and CO_2^+ , were not found in the mass spectrum of the vapor over La_2C_3 vaporized from the graphite cell. The appearance of CO^+ and CO_2^+ ions in the mass spectrum of vapor over the $\text{La}_2\text{C}_3\text{--C}$ system from the start of the Knudsen effusion cell heating up to a temperature of 2435 K was caused by gas evolution from the graphite cell. Thus, the main vapor species over the $\text{La}_2\text{C}_3\text{--C}$ system, starting from a temperature of 2190 K, were La and LaC_2 .

It should be noted that peritectic melting temperature of La_2C_3 is 1689 K [14]. According to the phase diagram of the $\text{La}\text{--C}$ system (Fig. 1), in the temperature range 2196–2435 K, in which the present study was carried out, the $\text{La}_2\text{C}_3\text{--LaC}_2$ concentration range corresponds to the region of coexistence of two phases: high-temperature modification of LaC_2 and a melt enriched in lanthanum. It can be concluded that the vaporization of La_2C_3 from the graphite cell, starting at a temperature of 2190 K, proceeds through reactions corresponding to the vaporization of a sample of LaC_2 in excess carbon [19, 20]:



The temperature dependences of partial pressures of atomic lanthanum and LaC_2 over La_2C_3 , the vaporization of which is carried out from a graphite effusion cell, in the range of 2196–2435 K can be represented by the equations

$$\log p(\text{La}, \text{Pa}) = -\frac{21700 \pm 1100}{T} + (8.2 \pm 0.5), \quad (6)$$

$$\log p(\text{LaC}_2, \text{Pa}) = -\frac{36200 \pm 1100}{T} + (14.0 \pm 0.5). \quad (7)$$

The obtained data are presented in Table 3 and Fig. 3. The enthalpies of reactions (4) and (5) at an average measurement temperature of 2316 K are 420 ± 20 and 690 ± 20 kJ/mol, respectively.

The data obtained in this study allow the thermodynamic properties of the $\text{La}\text{--C}$ system at high temperatures to be evaluated. Lanthanum activity $a(\text{La})$ in the system under study can be obtained as the ratio of the partial pressures of atomic lanthanum vapor over the system $p(\text{La})$ and metal $p^\circ(\text{La})$:

$$a(\text{La}) = \frac{p(\text{La})}{p^\circ(\text{La})}. \quad (8)$$

According to data of study [35], the partial pressure of atomic lanthanum over metallic lanthanum in the temperature range of 2000–2500 K can be expressed as follows:

$$\log p^\circ(\text{La}, \text{Pa}) = -\frac{21861}{T} + 10.95. \quad (9)$$

The values of partial pressure of atomic lanthanum over the $\text{La}_2\text{C}_3\text{--C}$ system and metallic lanthanum are compared in Table 3. From the data presented in Table 3, it follows that the partial pressure of atomic lanthanum over La_2C_3 vaporized from a graphite effusion cell is significantly lower than over metallic lanthanum. The activity values of La in the $\text{La}_2\text{C}_3\text{--C}$ system, calculated according to Eq. (8), indicate negative deviations from ideality and, within the experimental error of $\pm 15\%$, do not depend on temperature in the studied range of 2196–2435 K. Therefore, the partial molar enthalpy of mixing of La , calculated through the slope of the temperature dependence of the logarithm of the La activity, is statistically insignificantly different from zero and is equal to 0 ± 2 J/mol at an average temperature of 2316 K.

When discussing the results obtained in this study, it is necessary to pay attention to two circumstances. First, as noted above, the melting point of La_2C_3 is 1689 K [14], which is significantly less than the temperature range of the present study. Therefore, in the temperature range of 2196–2435 K, the original sample containing La_2C_3 corresponds to the equilibrium of two phases: LaC_2 and a melt enriched in lantha-

Table 3. The values of the partial pressures ($\pm 15\%$) of atomic lanthanum and LaC_2 over the La_2C_3 vaporized from a graphite effusion cell obtained in the present study, as well as of the partial pressure of atomic lanthanum over metallic lanthanum according to Eq. (9) and of the La activity in the LaC_2 –C two-phase region

T, K	p_i, Pa			$a(\text{La})$
	La over the La_2C_3 –C system	LaC_2 over the La_2C_3 –C system	La over individual La	
2196	0.02	0.003	9.89	2.0×10^{-3}
2242	0.03	0.008	15.82	1.9×10^{-3}
2286	0.05	0.015	24.38	2.1×10^{-3}
2312	0.07	0.024	31.23	2.2×10^{-3}
2348	0.10	0.034	43.60	2.3×10^{-3}
2398	0.12	0.085	68.18	1.8×10^{-3}
2435	0.19	0.134	93.79	2.0×10^{-3}

num. Second, vaporization of La_2C_3 from a graphite cell at high temperatures can lead not only to peritectic melting of La_2C_3 with formation of LaC_2 and melt, but also to the interaction of the studied sample with excess carbon with the formation of a two-phase LaC_2 –C region, as shown in the phase diagram of the La–C system (Fig. 1). Due to the impossibility of

determining the phase composition of the sample under study during the mass spectrometric experiment or removing the sample from the effusion cell after measurements, the composition of the condensed phase to which the obtained data relate can be estimated by two indirect signs when compared with literature values and the results of modeling using the NUCLEA database [37, 38].

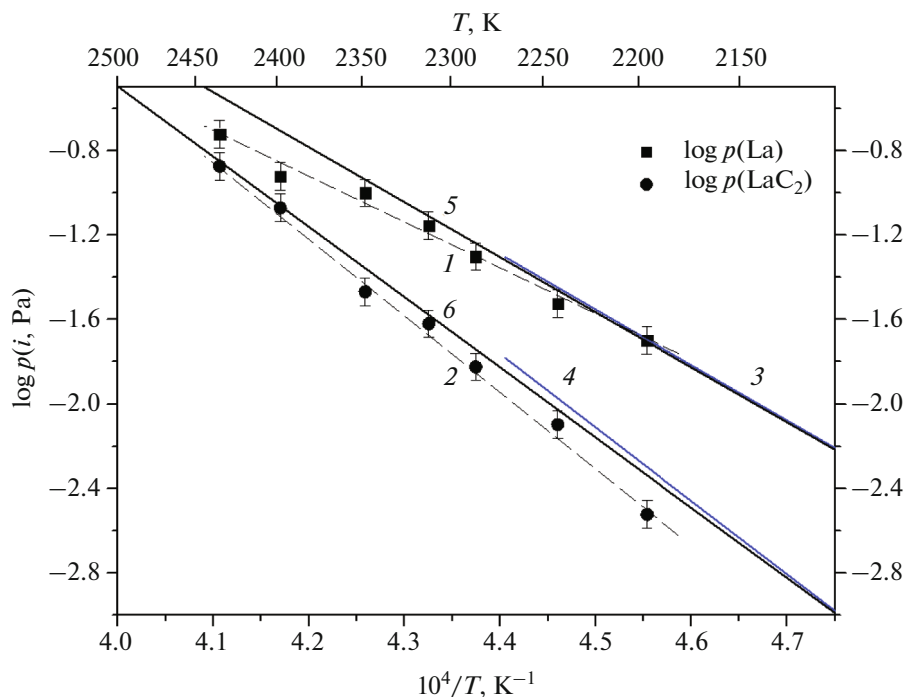


Fig. 3. Partial pressures of the (1) La and (2) LaC_2 vapor species over La_2C_3 vaporized from the graphite effusion cell in the present study as well as of the (3, 5) La and (4, 6) LaC_2 vapor species over the LaC_2 –C system according to data from studies [19, 20]. ■ and ● are experimental values of the La and LaC_2 partial vapor pressures obtained in the present study, 1 and 2 are an approximation of the results of the present study by Eqs. (6) and (7); 3 and 4 are an approximation of the results of study [19] by equations from Table 1; 5 and 6 are an approximation of results of [20] by equations from Table 1.

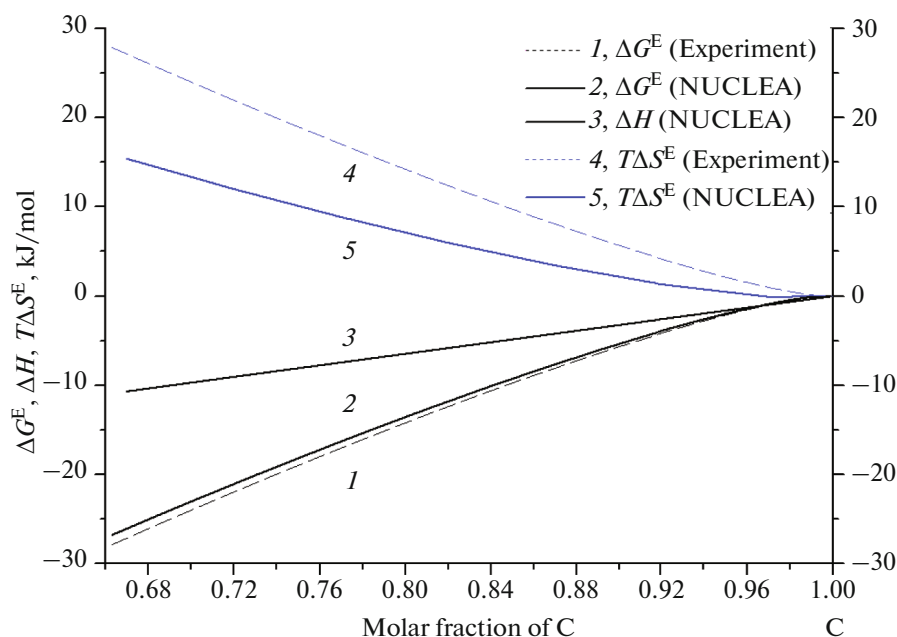


Fig. 4. (1, 2) Excess Gibbs energy ΔG^E , (3) enthalpy of mixing ΔH , and (4, 5) excess entropy multiplied by temperature $T\Delta S^E$ in the two-phase region of carbon and LaC_2 equilibrium in the La–C system at a temperature of 2316 K (1, 4) obtained on the basis of the experimental data of the present study and (2, 3, 5) calculated based on the NUCLEA database.

As shown in Fig. 3, the obtained data on the partial pressures of the La and LaC_2 vapor species over La_2C_3 during vaporization from a graphite cell are consistent within the experimental error with the results of studies [19, 20], in which the vaporization of the LaC_2 –C system was previously studied. The observed mutual correspondence of the obtained values may be a confirmation of the formation of LaC_2 according to the phase diagram because of high-temperature interaction of La_2C_3 with graphite, from which the effusion cell is made.

Calculation of the activities of components in the La–C system at 2316 K using the NUCLEA database [37, 38] allowed us to obtain the following results. At the above temperature, the calculated values of La activity were 8.4×10^{-2} in the two-phase equilibrium region of LaC_2 and melt and 2.4×10^{-3} in the two-phase equilibrium region of LaC_2 and carbon. It should be noted that, according to the results of this study, the activity of lanthanum in the studied sample is $(2.0 \pm 0.3) \times 10^{-3}$ in the temperature range of 2196–2435 K, including at an average temperature of 2316 K. Consequently, the experimental value of La activity found within twice the determination error corresponds to the calculated value for the two-phase equilibrium region of LaC_2 and carbon and is 42 times as low as the value for the two-phase equilibrium region of LaC_2 and melt.

Thus, the values of partial pressures of vapor species and the La activity obtained in this study, within twice the error, correspond to the literature data and

the results of modeling based on the NUCLEA database for the two-phase region of LaC_2 –C. Taking this into account, it can be assumed that lanthanum carbide La_2C_3 , located in a graphite cell, interacts with carbon when the temperature rises, which leads to the formation of lanthanum carbide LaC_2 in equilibrium with carbon. Therefore, in the following discussion it is assumed that as a result of high-temperature interaction of La_2C_3 with graphite, the obtained values of thermodynamic properties should be attributed to the LaC_2 –C system. The values of thermodynamic properties obtained in this way are of an evaluative nature as a certain approximation of the high-temperature description of the LaC_2 –C system.

To further calculate the excess Gibbs energy in the LaC_2 –C system, one should take into account the following. Due to the fact that, according to the conditions of phase equilibrium, the activities of the components are equal in the phases coexisting in equilibrium, it is possible to extend the obtained value of lanthanum activity to the entire region of two-phase equilibrium of carbon and LaC_2 at temperatures of 2196–2435 K. Next, the excess Gibbs energy was calculated for the average temperature in the studied range, taking into account that the activity of carbon in the two-phase region under consideration is equal to unity.

The concentration dependence of excess Gibbs energy in a two-phase equilibrium LaC_2 region and carbon in the concentration range of 66–100 mol % C at 2316 K is given in Fig. 4. The obtained values of excess Gibbs energy (Fig. 4) indicate negative devia-

tions from ideality in the $\text{LaC}_2\text{--C}$ system and correspond to the results of modeling of this value using the NUCLEA database [37, 38]. As noted above, the enthalpy of mixing in the considered concentration region of the $\text{LaC}_2\text{--C}$ system is equal to 0 in the temperature range of 2196–2435 K. Therefore, negative deviations from ideal behavior are associated with the entropy factor due to the deviation of the system components from the uniform distribution characteristic of an ideal solution. At the same time, according to the available thermodynamic description in the NUCLEA database, the enthalpy of mixing and excess entropy make a comparable contribution to the total value of excess Gibbs energy in the two-phase equilibrium region of carbon and LaC_2 at a temperature of 2316 K, as shown in Fig. 4. The observed contradiction between the values of the enthalpy of mixing and excess entropy estimated from experimental data and optimized in the NUCLEA database indicates the need for a new optimization of the high-temperature description of the La--C system taking into account not only the known data on phase equilibria, but also the experimental values of thermodynamic properties obtained for the first time in this study.

CONCLUSIONS

The vaporization processes of lanthanum carbide La_2C_3 from a graphite effusion cell were studied for the first time using Knudsen effusion mass spectrometry in the temperature range of 2196–2435 K. Atomic lanthanum La and lanthanum dicarbide LaC_2 were identified in the vapor over the studied system. The temperature dependences of the partial pressures of the La and LaC_2 vapor species were determined, which made it possible to evaluate the thermodynamic properties of the $\text{LaC}_2\text{--C}$ system, including the partial molar enthalpies of vaporization of La and LaC_2 , La partial molar enthalpy of mixing, and La activity. The correspondence of the obtained values of partial pressures of vapor species and the La activity with the data available in the literature for the $\text{LaC}_2\text{--C}$ system is illustrated [19, 20], as well as with the results of modeling of the thermodynamic properties of the La--C system using the NUCLEA database. It has been established that the activity of lanthanum, within the limits of experimental determination error, does not depend on temperature in the range of 2196–2435 K, which indicates that the partial molar enthalpy of mixing of lanthanum in the region of $\text{LaC}_2\text{--C}$ is equal to zero. The values of thermodynamic properties in the $\text{LaC}_2\text{--C}$ system estimated in this study indicate negative deviations from ideal behavior in the studied concentration region.

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AUTHOR CONTRIBUTION

All authors made a substantial contribution to the conceptualization, investigation, and preparation of the manuscript.

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CONFLICT OF INTEREST

The authors of this study declare that they have no conflicts of interest.

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