GENERALIZATION OF EXPERIMENTAL DATA ON THERMAL CONDUCTIVITY OF NITROGEN, OXYGEN, AND AIR AT ATMOSPHERIC PRESSURE

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Results are presented for the generalization of experimental data on thermal conductivity of nitrogen, oxygen, and air in the temperature range from normal boiling points to dissociation temperatures at atmospheric pressure.

A large body of experimental data on thermal conductivity of nitrogen, oxygen, and air at atmospheric pressure over the temperature range from normal boiling points to dissociation temperatures has been obtained. On the basis of artificially selected data arrays, tables of standard reference data for nitrogen to a temperature of 2500 K [1] and for oxygen to 500 K [2], of recommended data for O_2 to 2000 K [3], and of reference data for N_2, O_2, and air from 150 to 2500 K [4, 5] are developed.

Generalizing values of the thermal conductivity λ over a wider temperature range up to dissociation temperatures is complicated by a systematic discrepancy between the values of λ, obtained by stationary methods in the temperature range from normal boiling points to 2500 K and by a nonstationary shock tube method (1000-5000 K), in an overlapping temperature range of 1000-2500 K. The problem of correlation of these data was considered in the works [6-9].

The aim of the present work is to generalize the experimental data on thermal conductivity of nitrogen, oxygen, and air at atmospheric pressure in the temperature range from normal boiling points to dissociation temperatures on the basis of the entire available body of experimental values obtained to date [10-61], with allowance made for their error.

It is common knowledge that, when experimentally determined, the value of the effective thermal conductivity λ_{ef}, which is not equal to its true value (by λ_{tr} is meant the characteristic of heat transfer due to a temperature gradient [8, 9]), is measured. In the present work the generalization is carried out by the true values of thermal conductivity obtained from the experimental data [10-61] by the procedure of [8, 9], establishing the relationship between λ_{tr} and λ_{ef} for polyatomic gases.

The Eucken factor and values of viscosity, necessary for the correction of the experimental data, were calculated according to the procedure of [8, 9] with the aid of the Hanley–Klein intermolecular interaction function (m–6–8) [63].

The temperature dependence of thermal conductivity was approximated by the polynomial of one variable

$$\lambda_i = a_0 + a_1T_i + a_2T_i^2 + \ldots + a_pT_i^p. \quad (1)$$

In selecting the polynomial use was made of a weighted least-squares method consisting in minimization of the sum:

$$S_p = \sum_{i=1}^{N} \omega_i (\lambda_i - a_0 - a_1T_i - \ldots - a_pT_i^p),$$

where ω_i is the weight of the i-th point. The reciprocal of the square of the absolute error was taken as a weight.

The construction of the regression equation and the subsequent regression analysis were carried out with the help of the program [64] on a ES-1060 computer. The numerical calculation was performed using orthogonal polynomials. The regression coefficients were tested for regression by the t-criterion, and the degree of the polynomial was established by the F-criterion.

The error of the generalized smoothed values of thermal conductivity was taken as equal to the sum of the simple and systematic errors (the computational error was disregarded on the because it is infinitesimal):

$$\Delta\lambda = \pm t\,(\sigma_{i\,r} + \sigma_{i\,syst}),$$

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TABLE 1. Coefficients of the Polynomial ($\lambda = \Sigma_{i=1}^{n} a_i T^{i-1}$ W/(m·K) Approximating the Temperature Dependence of Thermal Conductivity of Nitrogen and Oxygen

Coefficient	N_2	O_2
	T, K	
	80—4500	100—2500
a_1	$-0{,}814736 \cdot 10^{-3}$	$0{,}685176 \cdot 10^{-3}$
a_2	$0{,}11613984 \cdot 10^{-3}$	$0{,}939908 \cdot 10^{-4}$
a_3	$-0{,}11361942 \cdot 10^{-6}$	$-0{,}244914 \cdot 10^{-7}$
a_4	$0{,}10617612 \cdot 10^{-9}$	$0{,}431987 \cdot 10^{-11}$
a_5	$-0{,}54055704 \cdot 10^{-13}$	
a_6	$0{,}14541066 \cdot 10^{-16}$	
a_7	$-0{,}1941557 \cdot 10^{-20}$	
a_8	$0{,}10105922 \cdot 10^{-24}$	

TABLE 2. Thermal Conductivity of Air $\lambda \cdot 10^{-3}$, W/(m·K) at Atmospheric Pressure

T, K	λ	*T*, K	λ	*T*, K	λ
100	9,78	420	34,74	1200	79,12
120	11,65	440	36,04	1300	84,35
140	13,46	460	37,33	1400	89,50
160	15,22	480	38,61	1500	94,53
180	16,94	500	39,87	1600	99,47
200	18,62	550	42,95	1700	104,3
220	20,24	600	45,96	1800	108,9
240	21,83	650	48,90	1900	113,4
260	23,39	700	51,78	2000	117,8
280	24,91	750	54,63	2100	122,1
300	26,39	800	57,44	2200	126,2
320	27,84	850	60,22	2300	130,3
340	29,27	900	62,98	2400	134,3
360	30,67	950	65,72	2500	138,3
380	32,05	1000	68,43		
400	33,40	1100	73,81		

where t was determined from the Student distribution table. At a 99% confidence level t = 2.576 for a large number of experimental points (371 points for N_2, 82 for O_2).

The contribution of the random error σ_{ir} was calculated by employing the covariance matrix G of the coefficients:

$$\sigma_{i\mathbf{r}} = (V^T G r)^{1/2},$$

where $r = (1, T, T^2, \dots, T^{n-1})$.

The systematic error σ_{isyst} was estimated by distorting the generalized values according to the possible systematic errors thereof.

The coefficients for the regression equation are obtained by averaging over all series of the conducted mathematical experiment:

$$a = \sum_{l=0}^{L} S_l^2 a_l \Big/ \sum_{l=0}^{L} S_l^2 ,$$

where S_l^2 is the residual variance of the *l*-th variant of distortion of the experimental array.

The calculation of the error $\sigma_{\text{isyst}} = (V^T Q r)^{1/2}$ was performed using the covariance matrix

$$Q = \frac{1}{L} \sum_{l=0}^{L} (S_l^2 a_l - a)(S_k^2 a_k - a),$$

where k = 0, 1, 2, ..., L.

Values of the coefficients of the polynomial (1) approximating the temperature dependence of thermal conductivity of nitrogen and oxygen are presented in Table 1.

The thermal conductivity of air (Table 2) was calculated as the thermal conductivity of the binary mixture: 76.15% N_2 + 23.85% O_2 [65].

TABLE 3. Magnitudes of the Deviations $\delta\lambda = (\lambda - \lambda_{g.w})/\lambda_{g.w}\cdot 100\%$ of the Standard [1, 2], Recommended [3], Reference [4, 5], Calculated [65, 67] and Generalized Values [68] of the Thermal Conductivity $\lambda\cdot 10^{-3}$, W/(m·K), of Nitrogen, Oxygen and Air from $\lambda_{g.w}$ Obtained in the Given Work

T, K	Literary source				
	[1]	[67]	[68]	[5]	[65]
			Nitrogen		
80	−0,8	−3,8	−4,6		0,6
100	−1,0	−3,5	−4,1		−0,7
300	−0,6	−2,0	−2,2		−0,2
400	−1,1	−2,2	−2,2		−0,3
500	−0,9	−1,9	−1,7	−1,7	
600	−0,4	−1,1	−0,8	−1,4	0,4
800	1,0	0,8	1,3	0,2	2,0
1000	1,8	1,7	2,5	1,3	2,7
1200	1,5	1,7	2,5	1,5	
1400	0,9	1,1	2,1	1,3	1,8
1600	0,4	0,6	1,5		
1800	−0,1	0,2	1,0		0,3
2000	−0,2	0,1	0,7	0,7	
2200	0,01		0,7		−0,1
2400	0,4		0,9		
2500	0,5		1,0	1,6	
2600					0,2
3000					−0,1

T, K	Literary source					
	[3]	[67]	[68]	[5]	[65]	[2]
			Oxygen			
100	−5,3	−5,7	−5,7		−2,4	−5,5
200	1,2	−1,2	−1,6			0,9
300	0,2	−1,9	−1,8		−1,1	0,4
400	−0,3	−2,9	−1,7		−0,7	−0,1
500	−0,1	−2,8	−1,0	−2,6		0,0
600	0,7	−2,4	−0,2	−2,6	0,6	
800	1,2	1,4	−1,1	−1,9	1,5	
1000	2,2	−0,8	1,7	−1,6	1,6	
1200	2,2	−0,4	2,0	−0,4		
1400	3,8	−0,6	2,1	0,1	1,0	
1500	3,7	0,2	2,3	0,2		
1700	3,7	0,5	2,3			
1800	3,8	0,7	2,3		−0,2	
2000	4,9	0,9	2,2	0,2		
2200			2,1		−2,1	
2500			1,0	−1,9		

T, K	Literary source			
	[65]	[68]	[5]	[4]
		Air		
100	−1,3	−5,5		−2,2
300	−0,5	−3,1		−0,7
500		−2,7	−2,7	−0,9
600	0,4	−1,8	−2,5	−0,6
800	1,8	−0,02	−1,2	0,5
1000	2,3	1,0	−0,1	1,1
1200		1,1	0,2	1,2
1400	1,5	0,8	0,2	0,9
1500		0,6	0,1	0,7
1800	0,1	0,0		
2000		−0,2	0,0	
2200	−0,7	−0,2		
2500		−0,3	0,2	

Calculations of the thermal conductivity of oxygen and air are limited by a temperature of 2500 K due to a substantial contribution of dissociated oxygen molecules into the heat transfer at higher temperatures [66].

The results of comparing the generalized data obtained by us with the available standard [1, 2], recommended [3], reference [4, 5], calculated [65, 67] and generalized [68] data on thermal conductivity of nitrogen, oxygen and air are given in Table 3. Over the entire temperature range in question there is good agreement: for N_2 with the standard [1] and reference data [5], for O_2 with the standard [2] and calculated data [65].

TABLE 4. Magnitudes of the Deviations $\delta\eta = (\eta - \eta_{g.w})/\eta_{g.w} \cdot 100\%$ of the Standard [1, 2], Reference [4, 5], Recommended [3], Theoretical [65, 67], and Generalized [68, 69] Values of the Dynamic Viscosity $\eta \cdot 10^{-6}$ Pa·sec for Nitrogen, Oxygen, and Air from $\eta_{g.w}$ Obtained in the Given Work

T, K	Literary source					
	[1]	[67]	[68]	[5]	[65]	[69]
			Nitrogen			
80	—0,7	—0,6	2,8		—0,6	—3,9
100	1,9	2,4	3,3		0,8	4,0
300	0,2	0,4	0,3		—0,2	0,1
500	—1,0	—0,8	—0,6	—1,9		—0,5
600	—0,4	—0,2	0,1	—1,4	0,6	0,1
800	1,2	1,4	1,6	0,1	2,2	1,5
1000	2,2	2,3	2,4	1,1	3,0	2,3
1200	2,4	2,6	2,5	1,3		2,7
1400	1,8	2,0	1,6	0,8	2,3	2,2
1500	1,7	1,8	1,3	0,6		2,1
1600	1,5	1,5	0,9			1,8
1800	1,0	1,2	0,1		1,1	1,3
2000	1,0	1,1	—0,2	0,01		1,4
2200	1,3		—0,2		1,0	
2400	1,7		—0,1			
2500	1,9		—0,05	0,8		
3000					1,4	

T, K	Litetary source					
	[3]	[67]	[68]	[5]	[65]	[2]
			Oxygen			
100	—0,8		2,1		0,9	—0,8
200	1,2	0,8	1,1			1,2
300	—0,5	—0,8	—0,4		—1,0	—0,5
500	—1,7	—2,0	—0,8	—1,9		—1,7
600	—1,4	1,7	—0,3	—1,6	1,0	
800	—0,8	—0,8	0,5	—1,0	2,0	
1000	—0,4	—0,4	0,8	—0,7	2,3	
1200	—0,02	0,2	1,0	—0,3		
1400	1,0	0,6	1,1	—0,05	2,6	
1500	0,8	0,9	1,2	0,2		
1600	0,7	1,1	1,2			
1800	1,1	1,6	1,3		2,9	
2000	2,2	2,2	1,4	1,1		
2200			1,3		2,9	
2500			0,6	0,8		

T, K	Literary source			
	[65]	[68]	[5]	[4]
		Air		
100	—0,1	3,1		1,3
300	—1,3	0,5		1,2
500		—1,5	—1,5	—1,1
600	—0,4	—0,8	—1,1	—0,6
800	1,1	0,5	0,1	0,6
1000	1,7	1,1	0,9	1,4
1200		1,2	1,2	1,8
1400	1,3	0,5	0,9	1,4
1500		0,3	0,8	1,3
1750		—0,3	0,5	
2000		—0,7	0,6	
2200	0,4	—0,7		
2500		—0,8	1,1	

Table 4 gives discrepancies between the standard [1, 2], reference [4, 5], recommended [3], calculated [65, 67], and generalized [68, 69] values of dynamic viscosity and those obtained in the given work for nitrogen, oxygen, and air. The magnitudes of dynamic viscosity for these gases were calculated using their thermal conductivities obtained the given work by the known dependence of molecular-kinetic theory [62]:

$$\eta = \lambda / f^E c_v, \tag{2}$$

where f^E is the Eucken law for polyatomic gases; c_v is the specific heat at constant volume.

A correlation of the dynamic viscosity values obtained by formula (2) with the data from the above-enumerated works shows that a discrepancy between them is no more than 2.7% excluding the low temperature range (80-200 K) for [68, 69].

Polynomial (1) obtained in the present work permits the calculation of values of thermal conductivity for nitrogen to a temperature of 4500 K, for oxygen and air to 2500 K.

The magnitudes of the errors of λ calculated by polynomial (1) are 0.4-3.1% for nitrogen in the temperature range 100-4500 K and 3.3-2.8% for oxygen at T = 100-2500 K.

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