

GENERALIZATION OF THE THERMAL DIFFUSION FACTOR OF MIXTURES OF INERT GASES - Kr-Xe, Ar-Xe, Ne-Ar, Ar-Kr - ON THE BASIS OF THE THEORY OF CORRESPONDING STATES

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On the basis of the law of corresponding states, we investigate the variation with temperature and concentration of the thermal diffusion factor of four mixtures of inert gases: Kr-Xe, Ar-Xe, Ne-Ar, and Ar-Kr.

According to the law of corresponding states, as applied to thermal diffusion [1-3], the following relation holds for mixtures of inert gases:

$$\alpha_T^* = \frac{\alpha_T}{\alpha_{T_{s.sph}} \bar{M}^n} = f(T^*)$$

For convenience, mixtures of inert gases are provisionally divided into two groups, depending on the value of the exponent n: for mixtures with  $\bar{M} > 0.5$ , the exponent  $n = 0.25$ , while for  $\bar{M} < 0.5$ ,  $n = 0.125$ .

In an earlier article [3], for a group of inert-gas mixtures with  $\bar{M} > 0.5$ , we obtained a generalized relation in the form

$$\frac{\alpha_T}{\alpha_{T_{s.sph}}} = \bar{M}^k \sum_{i=1}^m c_i (T^*)^{i-1}, \quad (1)$$

where  $k = n + \Delta n$ ,  $\Delta n$  is the correction made in the exponent and depends on the concentration of the mixture.

The purpose of the present article is to obtain a generalized temperature-dependent relation for the thermal diffusion factor for a group of mixtures with  $\bar{M} < 0.5$  (Kr-Xe, Ne-Ar, Ar-Kr). It was found useful to include as a further member of this group the mixture Ar-Xe, which has  $\bar{M} = 0.53$  and  $n = 0.25$ , since, as we pointed out earlier [2], the generalized experimental data for this mixture agree with the generalized data for the group of mixtures with  $\bar{M} < 0.5$ .

For the generalization, we used the following experimental results: Kr-Xe [4-6], Ne-Ar [4, 5, 7-11, 13], Ar-Kr [4-9, 12], Ar-Xe [4, 6, 7]. The data of Atkins et al. [11] for the mixtures Ar-Kr and Ar-Xe were not included in the processing, since they are about 40% lower than the results of [4, 6].

The generalization was carried out by means of a scheme similar to the one described in [3]. For the mixtures considered, the functions representing the thermal diffusion factor in

TABLE 1. Variation of  $\Delta n$  with Concentration for the Mixtures Kr-Xe, He-Ar, Ar-Kr, Ar-Xe

Mixture	$\bar{M}$	$\Delta n$				
		$x_1=0,2$	$x_1=0,3$	$x_1=0,4 \div 0,6$	$x_1=0,7$	$x_1=0,8$
Kr-Xe	0.22	-0.026	-0.013	0	0.017	0.034
Ar-Xe	0.33	-0.03	-0.02	0	0.027	0.046
Ne-Ar	0.35	-0.0095	-0.009	0	0.02	0.04
Ar-Kr	0.53	-0.05	-0.03	0	0.05	0.08

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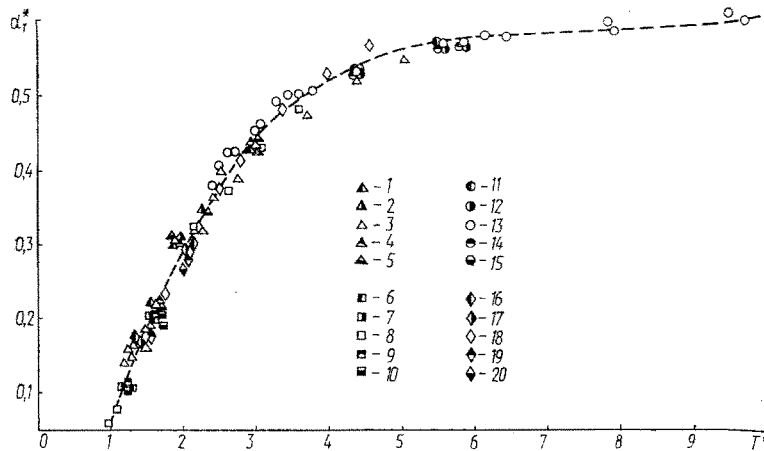


Fig. 1. Reduced thermal diffusion factor as a function of the reduced temperature for mixtures of inert gases: 1-5) Ar-Kr for concentrations of 0.2, 0.4, 0.5, 0.6, and 0.8, respectively; 6-10) Kr-Xe; 11-15) Ne-Ar; 16-20) Ar-Xe for the same concentrations.

TABLE 2. Values of  $\bar{M}^k$  for Different Ranges of Concentrations

Mixture	$x_1$ (light component)		
	0,2-0,3	0,4-0,6	0,7-0,8
Kr-Xe	0,855	0,83	0,79
Ne-Ar	0,89	0,87	0,835
Ar-Kr	0,89	0,88	0,85
Ar-Xe	0,87	0,85	0,815

terms of the reduce temperature, i.e.,  $\alpha^*T = f(T^*)$  for light-component concentrations of 0.2, 0.4, 0.6, and 0.8 mole fractions were compared with the curve of  $\alpha^*T = f(T^*)$  for equimolar concentration. It should be noted that for the mixture Ne-Ar the values of  $\alpha^*T$  were taken with the coefficient  $z = 0.91$ , i.e.,  $0.91\alpha^*T$ . This coefficient had to be introduced because over the entire interval of  $T^*$  the values of  $\alpha^*T$  for an equimolar mixture Ar-Ne lay systematically above the generalized curve for the other three mixtures. Therefore, if we wish to make the functions  $\alpha^*T = f(T^*)$  for all four mixtures coincide and have a uniform definition of  $\Delta n$ , and hence of  $\bar{M}^k$ , we must "lower" in advance the values of  $\alpha^*T$  for the mixture Ne-Ar.

Table 1 shows the values of  $\Delta n$  for the mixtures studied.

In Table 2 we give the averaged values of  $\bar{M}^k$  for the mixtures considered, in the range of concentrations of the light component from 0.2 to 0.3 and from 0.7 to 0.8, for concentrations of 0.4, 0.5, and 0.6,  $\Delta n = 0$ , and  $\bar{M}^n = \bar{M}^k$ .

Using the method of least squares and the polynomial

$$\alpha_T = \frac{1}{Z} \bar{M}^k \alpha_{T, \text{sph}} \sum_{i=1}^m c_i (T^*)^{i-1} \quad (2)$$

we processed the reduced values of the thermal diffusion factor for the reduced temperature; this enabled us to describe the experimental data over the temperature range 200-750°K and the concentration range 0.2-0.8 with an error of 3-10% (5 points out of 114 have an error of more than 10%) by means of a single generalized curve (see Fig. 1) with the following coefficients:

$i$	1	2	3	4	5
$c_i$	-0,329	0,451	-0,0829	0,00669	-0,000196

TABLE 3. Values of  $\alpha_{T_s.sph}$  for Inert Gases at Various Concentrations

Mixture	$x_1$ (light component)								
	0,9	0,8	0,7	0,6	0,5	0,4	0,3	0,2	0,1
Kr—Xe	0,2539	0,2439	0,2347	0,2263	0,2185	0,2114	0,2047	0,1985	0,1928
Ne—Ar	0,4415	0,4070	0,3778	0,3527	0,3309	0,3118	0,2949	0,2799	0,2664
Ar—Kr	0,3725	0,3552	0,3398	0,3260	0,3135	0,3023	0,2921	0,2828	0,2744
Ar—Xe	0,6239	0,5671	0,5205	0,4815	0,4486	0,4204	0,3960	0,3746	0,3559

TABLE 4. Values of the Coefficients a and b for Mixtures of Inert Gases

Mixture	a	b
Kr—Xe	5,3510	-1,5610
Ne—Ar	3,9470	-1,8604
Ar—Kr	3,7793	-1,2004
Ar—Xe	2,9743	-1,5094

The values of  $\alpha_{T_s.sph}$  calculated for the above-mentioned mixtures of inert gases over a light-component concentration range of 0.1-0.9 are shown in Table 3. The diameters of the solid spheres needed for calculating  $\alpha_{T_s.sph}$  were determined from the experimental viscosity values obtained from [14]. To determine the reduced values of the temperature, we used the Lennard-Jones force constants  $\epsilon_{12}/k$  (12-6) [1]. The quantity  $\epsilon_{12}$  was determined by using the simple combination rules  $\epsilon_{12} = \sqrt{\epsilon_1 \epsilon_2}$ .

As was shown by our calculations, and in accordance with [13],  $\alpha_T^{-1}$  and  $\alpha_{T_s.sph}^{-1}$  for mixtures of inert gases is a linear function of the concentration

$$\alpha_{T_s.sph}^{-1} = a + bx, \quad (3)$$

where x is the concentration of the light component of the mixture. In Table 4 we give the values of the coefficients a and b obtained from Eq. (3) for four mixtures of inert gases, using which we can determine fairly simply the values of  $\alpha_{T_s.sph}$  for any concentration.

The representation of  $\alpha_T^{-1}$  in the form of a linear function of the concentration enables us to extrapolate the results calculated according to formula (2), with little error, to any concentration range. Table 5 shows a comparison of the results obtained by comparing the thermal diffusion factors calculated by formula (2) with some experimental data available in the literature. As can be seen from the table, the calculated values of the thermal diffusion factors are in fairly good agreement with the experimental data. The maximum divergence is 5-10%, which does not exceed the differences between the experimental data of other authors on these mixtures.

In conclusion, it should be pointed out that the semiempirical methods given in the literature for the calculation (prediction) of the thermal diffusion characteristics (separation factor, thermal diffusion factor) [16, 17] presuppose the availability of (one or two) reliable values of these characteristics. Accordingly, there is an indeterminacy in the estimate of the reliability of data obtained by different authors and diverging from one another.

As was shown in [16], for the mixture Ar-Ne the coefficients A and B needed for calculating the separation values (or the  $\alpha_T$ ) in the concentration interval that was not investigated were obtained from the data of various authors and show considerable divergence.

In the method proposed in [17], scale separation factors obtained from individual experimental data are also used for predicting the separation factors. Thus, for example, in Table 16 and 17 of [17] calculated values are given for the separation factors for the mixtures Ar-Kr and Ar-Xe over a wide range of temperatures and concentrations. The calculations made use of the experimental data of Atkins et al. [11] which, as mentioned earlier, are about 40% lower than the results of later studies.

It follows from the foregoing that a generalization method based on the processing of a mass of experimental data can be useful in estimating the reliability of results relating to thermal diffusion.

TABLE 5. Comparison of the Experimental and Calculated Values of the Thermal Diffusion Factor for Mixtures of Inert Gases

Mixture	Molar concn. of the light component	$\bar{T} = \frac{T_1 T_2}{T_1 - T_2} \times \ln T_1 / T_2$	$\alpha_{T \text{ exp}}$	$\alpha_{T \text{ calc}}$	$\epsilon = \frac{\alpha_{T \text{ e}} - \alpha_{T \text{ c}}}{\alpha_{T \text{ e}}} \times 100 \%$	Literature source of the exptl. data	
Kr—Xe	0,5	248	0,0196	0,0184	6	[4]	
		451	0,0590	0,0583	1		
		752	0,0891	0,0908	2		
	0,2	340	340	0,0350	0,0363	4	[6]
			0,4	0,0366	0,0375	2,5	
			0,5	0,0375	0,0387	3	
0,6			0,0384	0,0401	4,5		
0,8			0,0404	0,0411	2		
Ar—Xe	0,5	249	0,0654	0,0677	3,5	[4]	
		451	0,160	0,1583	1		
		752	0,223	0,2121	5		
	0,2	340	340	0,0973	0,0997	2,5	[6]
			0,4	0,1074	0,1104	3	
			0,5	0,1133	0,1178	4	
0,6			0,1198	0,1264	5,5		
0,8			0,1355	0,1424	5		
Ar—Ne	0,5	208	0,1547	0,1448	6,5	[8]	
		221,8	0,1577	0,1510	4		
		250	0,162	0,1620	0,5	[4]	
		551	0,194	0,1983	2		
		750	0,198	0,2013	4		
	0,2	295	295	0,148	0,1505	5	[9]
			0,4	0,163	0,1638	1	
			0,5	0,170	0,1738	2	
			0,6	0,178	0,1854	4	
			0,8	0,199	0,2064	4	
Ar—Kr	0,5	210,7	0,0402	0,0413	3	[8]	
		250	0,0597	0,0589	1,5		
		550	0,132	0,1400	6	[4]	
	751	0,153	0,1573	3			
	0,2	295	0,0771	0,0695	10		[9]
	0,4	0,0816	0,0734	10			
0,5	0,0841	0,0762	9,5				
0,6			0,0867	0,0792	8,5		
Ar—Kr	0,42	340	0,0974	0,0922	5,5	[6]	
	0,79		0,106	0,1034	2,5		

NOTATION

$\alpha_{T \text{ s, sph}}$ , theoretical value of the thermal diffusion factor calculated for the solid-sphere model;  $M = (M_1 - M_2)/(M_1 + M_2)$ ,  $M_1, M_2$ , masses of the molecules of the components of the mixture;  $T^* = \bar{T}/(\epsilon_{12}/k)$ .

LITERATURE CITED

1. J. O. Hirschfelder, C. Curtiss, and R. Bird, Molecular Theory of Gases and Liquids, Wiley (1964).
2. A. F. Zolotukhina, M. V. Sagarda, and I. P. Evmenova, "Generalization of experimental data on the thermal diffusion factor of gases within the framework of the theory of corresponding states," Vestsi Akad. Nauk BSSR, Ser. Fiz.-Energ. Navuk, No. 4, 93-95 (1983).
3. A. F. Zolotukhina, M. V. Sagarda, and E. A. Shashkov, "Application of the law of corresponding states for generalizing the thermal diffusion factor of mixtures of inert gases," Inzh.-Fiz. Zh., 48, No. 6 (1985).
4. W.L. Taylor, "Thermal diffusion factor for the binary noble-gas mixtures," J. Chem. Phys., 79, No. 9, 4973-4984 (1980).
5. K. E. Grew, F. A. Johnson, and W. E. J. Neal, "The thermal diffusion factor and temperature," Proc. R. Soc., 224, 513-526 (1954).
6. C. M. Santamaria, J. M. Saviron, and J. C. Yarza, "Thermal diffusion factor for binary gas mixtures from column measurement," J. Chem. Phys., 64, No. 3, 1095 (1976).
7. K. E. Grew, "Thermal diffusion mixtures of the inert gases," Proc. R. Soc., 189A, No. 1018, 402-410 (1947).
8. K. E. Grew and W. A. Wakeham, "A redetermination of the thermal diffusion factor for some inert-gas mixtures," J. Phys. B: Atom. Molec. Phys., 4, 1548-1563 (1971).

9. G. P. Titov and P. E. Suetin, "Investigation of the variation of the thermal diffusion constant as a function of concentration, using the method of the nonstationary thermal diffusion effect," *Zh. Tekh. Fiz.*, 46, No. 3, 587-591 (1976).
10. V. P. S. Nain and S. C. Saxeva, "Composition dependence of the thermal diffusion factor of binary gas systems," *J. Chem. Phys.*, 51, No. 4, 1541-1545 (1969).
11. B. E. Atkins, R. E. Bastick, and T. L. Ibbs, "Thermal diffusion in mixtures of the inert gases," *Proc. R. Soc.*, 172A, 142-158 (1939).
12. S. K. Bhattacharya and A. K. Pal, "Thermal diffusion in the inert-gas mixtures Ne-Kr, Ar-Kr," *J. Phys. Soc. Jpn.*, 34, No. 5, 1356-1359 (1973).
13. T. L. Ibbs and K. E. Grew, "The influence of low temperatures on the thermal diffusion effect," *Proc. Phys. Soc.*, 43, 142-154 (1931).
14. N. B. Vargaftik, *Handbook of the Thermophysical Properties of Gases and Liquids* [in Russian], Nauka, Moscow (1972).
15. M. F. Laranjeira, "An elementary theory of thermal and pressure diffusion in gaseous binary and complex mixtures," *Physica*, 26, 406-417 (1960).
16. A. F. Bogatyrev and V. F. Kryuchkov, "On the calculation of thermal-diffusion separation in binary gas mixtures," in: *Applied and Theoretical Physics* [in Russian], No. 8, Alma-Ata (1976), pp. 107-111.
17. A. G. Usmanov and A. N. Berezhnoi, "Separation factors, thermal-diffusion ratios, and thermal-diffusion constants, calculated on the basis of the method of similarity," in: *Thermophysical Characteristics of Substances* [in Russian], No. 1, Moscow (1968), pp. 17-32.

METHOD OF DETERMINING TEMPERATURE AND CALCULATION OF THERMAL STRESSES  
IN POROUS PERMEABLE WALLS

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The article suggests a method of determining temperature and of calculating thermal stresses in the range of elastic deformations and of the boundaries of the plastic zones in elastoplastic deformation of the material of a permeable cylindrical wall with porous cooling in steady-state heating.

When units of heat machines made of permeable materials with porous cooling are designed, the permissible temperature of the working surface is specified, and from it the required flow intensity of the coolant is determined. To save coolant and to reduce the weight of the machine, it is advantageous to have the permissible temperature of the working surface as high as possible, but then the reduced strength of the wall has to be taken into account, and this is the decisive factor in the evaluation of its durability. Consequently, the permissible temperature and the necessary flow rate of the coolant have to be chosen such that the thermal stresses in the wall do not exceed the permissible values.

The known methods of measuring thermal stresses (the optical method, the method of lacquer coatings, x-raying, strain-gauge methods) [1] are practically unsuitable in this case because the results of measurements are difficult to process and insufficiently accurate.

Good results in determining thermal stresses in a permeable wall are attained by a method based on measuring the temperature of both its surfaces [2]; however, when contact sensors are used for the purpose, a considerable error arises because of the local infringement of permeability of the material at the place of contact and because of large temperature gradients across the wall. Measuring the temperature of porous walls with contactless means also encounters great difficulties because they do not act rapidly enough and because the measuring apparatus is too complex.

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