Unsteady Energy Transfer in High-Temperature Gases[1]

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[1] Paper presented at the Seventeenth European Conference on Thermophysical Properties, 5-8 September Bratislava, Slovakia

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ABSTRACT

Thermodynamics description of energy transfer processes in unsteady states in the gas is presented. Specific features of the spaces of a gas state, when applied to an energy transfer process over a wide temperature range are described. The available experimental data on gas thermal conductivity at temperatures up to 6000 K are analyzed. Some of the mathematical models for the unsteady shock tube method are considered (the time of experiment in a shock tube is approximately 10 μs).

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1. INTRODUCTION

In the literature there is a great body of the experimental data on gas thermal conductivity over a broad temperature range that were obtained by steady and unsteady methods. Since any thermophysical parameter of a gas system can be interpreted as a distance between two points (two states) of the gas system, it is of interest to study the temperature dependence of thermal conductivity of gases (their mixtures) as geometrical form. If such a dependence is linear, then the state space of a considered gas system will be Euclidean.

Of special interest is the analysis of the form of such a dependence in the unsteady heat transfer state that can be made using the shock tube method.

2. ANALYSIS OF THE EXPERIMENTAL DATA ON GAS THERMAL CONDUCTIVITY

Consider unsteady energy transfer in high-temperature gases when their thermal conductivity is experimentally determined in the shock tube. The shock tube is a device, allowing gas heating up to ~ 10 000 K. Gas thermal conductivity is measured in a narrow (~ 10^{-4} m) boundary layer near the tube end where the gas is being heated by both an incident and reflected shock wave.

Shock tube measurements of thermal conductivity were begun in 1957 [1]. The mathematical model for the shock tube method is based on the conservation equations and the Fourier law. Smiley [1] measured the argon thermal conductivity over the temperature range 1100-3300 K. One of the modifications of the shock tube method [2-6] is based on assigning the form of the temperature dependence of thermal conductivity of an investigated gas as:

$$\lambda = \lambda_0 \left(T / T_0 \right)^{\nu} \qquad (1)$$

where $\nu = const$, T_0 is the gas temperature near the shock tube end in the space behind the reflected shock wave. This assigned form of the thermal conductivity temperature dependence corresponds to the description of gas properties by the intermolecular interaction potential of the form:

$$\varphi(r) \sim r^{-\delta}$$

where $\delta = 1 - 4/(1-2\nu)$. The value of the power ν in the relation $\lambda = \lambda_0 (T/T_0)^\nu$ is determined from the condition for coincidence of the predicted and measured values of heat flux or temperature profiles. According to the experimental data on thermal conductivity of high-temperature noble gases the power ν in the relation $\lambda = \lambda_0 (T/T_0)^\nu$ is approximately equal to 0.7 (Table 1). If $\nu \approx 0.7$, then the power δ in the expression $\varphi(r) \sim r^{-\delta}$ will be equal to 11; if $\nu = 1$, then $\delta = 5$. The last case represents the case of Maxwell molecules.

Consider the case when none of the restrictions are imposed on the temperature dependence of gas thermal conductivity.

The heat conduction equation for the unsteady gas state can be given in the following form [8]:

$$c_V \rho \frac{dT}{dt} = \lambda \frac{\partial^2 T}{\partial x^2} + \frac{\partial \ln \lambda}{\partial \ln T} T \sigma_S \qquad (2)$$

Here c_v is the gas heat capacity at constant volume, ρ is the density, λ is the thermal conductivity, $T\sigma_S$ is the energy transfer rate, $\sigma_S = T^{-2} \lambda (\partial T / \partial x)^2$ is the local entropy production.

The term $c_V \rho \frac{dT}{dt} = \dot{U}$ is the change in the internal energy of the gas system per unit time, i.e. the energy flux. The term $\lambda \frac{\partial^2 T}{\partial x^2}$ characterizes heat losses by heat conduction through a surface that bounds the gas system. As $T\sigma_S \to \infty$ (infinite energy transfer rate, a very small distance is assumed to be between the heated surfaces), $\partial \ln \lambda / \partial \ln T \to const$. This is supported by the experimental gas thermal conductivity data [9] obtained by the shock tube method (Fig. 1). As mentioned above, the thermal conductivity has been measured by this method in the narrow gas boundary layer (10^{-4} m) near the tube end.

Fig. 2 shows the comparison of the gas thermal conductivity data obtained by the unsteady shock tube method with those obtained by another methods, in particular by the steady hot-wire method. From this figure it is seen that the data obtained by the shock tube method ($\nu \approx 0.7$) are underestimated as against those obtained by the steady methods ($\nu \approx 1$).

In the case when no restrictions are imposed on the temperature dependence of thermal conductivity [10], the experimental temperature-dependent gas thermal conductivity data are as a rule described by the linear dependence (Figs. 3-5).

3. CONCLUSION

Analysis of the experimental data on thermal conductivity of high-temperature gases and their mixtures shows that in the considered cases the temperature dependence of the gas thermal conductivity is practically linear, and the discrepancy in the experimental data plotted in Fig. 2 points to two different states of the Euclidean state space.

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Table 1

Coefficient ν of the temperature dependence of noble gas thermal conductivity in

$\lambda = \lambda_0 (T / T_0)^{\nu}$

Gas	Reference	Temperature range	ν
He	Zemlyanych [3]	1000-4000	0.7
	Collins, Greif [4]	1600-6700	0.69
Ne	Collins, Menard [5]	1500-5000	0.637
	Saxena [7]	300-2720	0.73
Ar	Collins, Menard [5]	1500-5000	0.703
	Matula [6]	1500-4800	0.68
	Zemlyanych [3]	1000-6000	0.71
	Saxena [7]	300-6000	0.8
Kr	Collins, Menard [5]	1000-5000	0.695
Xe	Matula [6]	1400-5000	0.72

Figure Captions

Fig.1. Temperature dependence of noble gas thermal conductivity

Fig.2. Temperature dependence of thermal conductivity of Ne, Kr, Xe

Ne: □ – [11], × - [12], ⬘ - [4], ◐ - [2], ○ – [13]

Xe: □ – [14], Δ - [13], × - [15], + [16]

Kr: × - [12], Δ - [13], ○ – [2], + [17], ● – [5]

Fig.3. Experimental data on He and Ar thermal conductivity

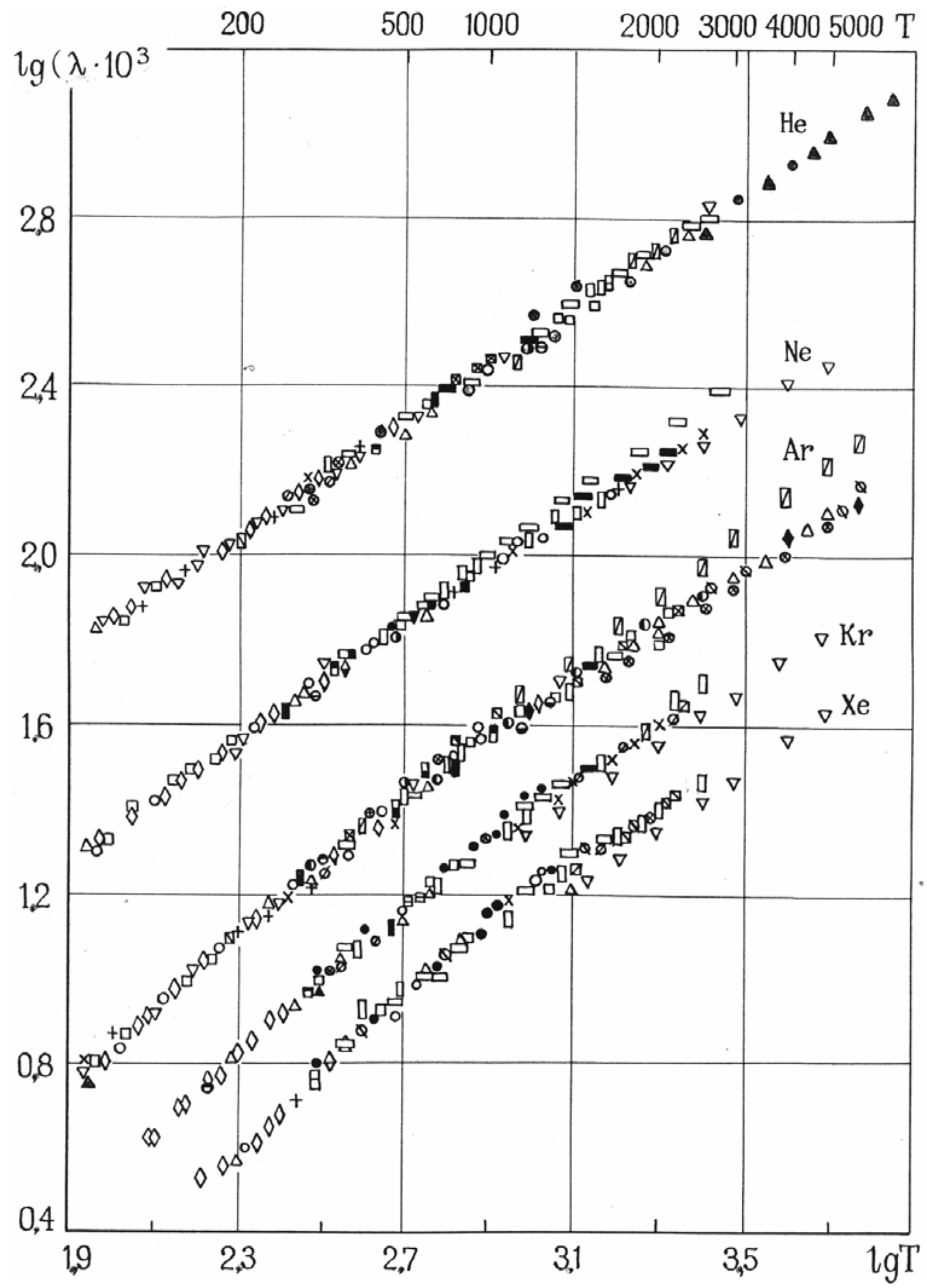
He: ○ – [3], × - [18], □ – [11], Δ - [4], ◊ - [19]

Ar: □ – [11], Δ - [1], ∅ - [20], ◑ - [10], ○ – [2], ● – [6], ⊙ - [18], ■ – [5], × - [3], ● - [17]

Fig.4. Temperature dependence of thermal conductivity of a He-Ar mixture [21]

● - $x_1 = 0.1$; ○ - $x_1 = 0.5$

Fig.5. Temperature dependence of thermal conductivity of a He-Ne mixture [20]



200
500
1000
2000
3000
4000
5000
T
lg(λ·10³
He
Ne
Ar
Kr
Xe
2,8
2,4
2,0
1,6
1,2
0,8
0,4
1,9
2,3
2,7
3,1
3,5
lgT

Fig. 1

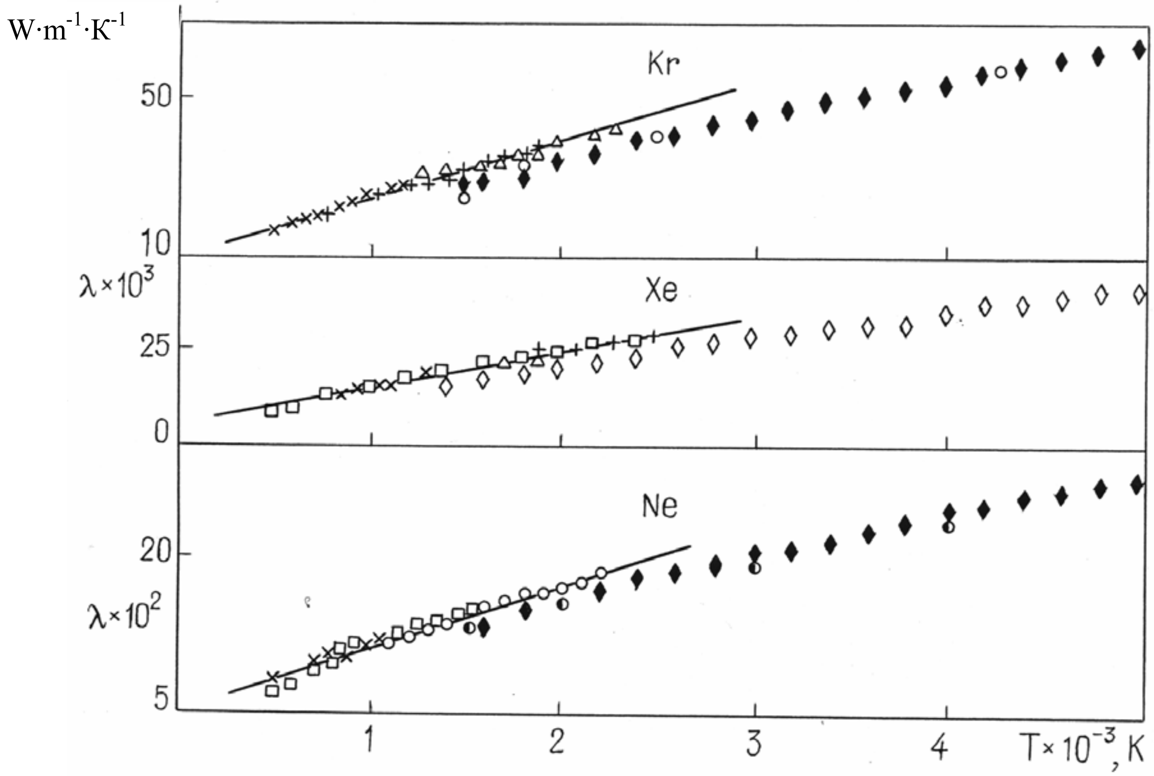


Fig. 2

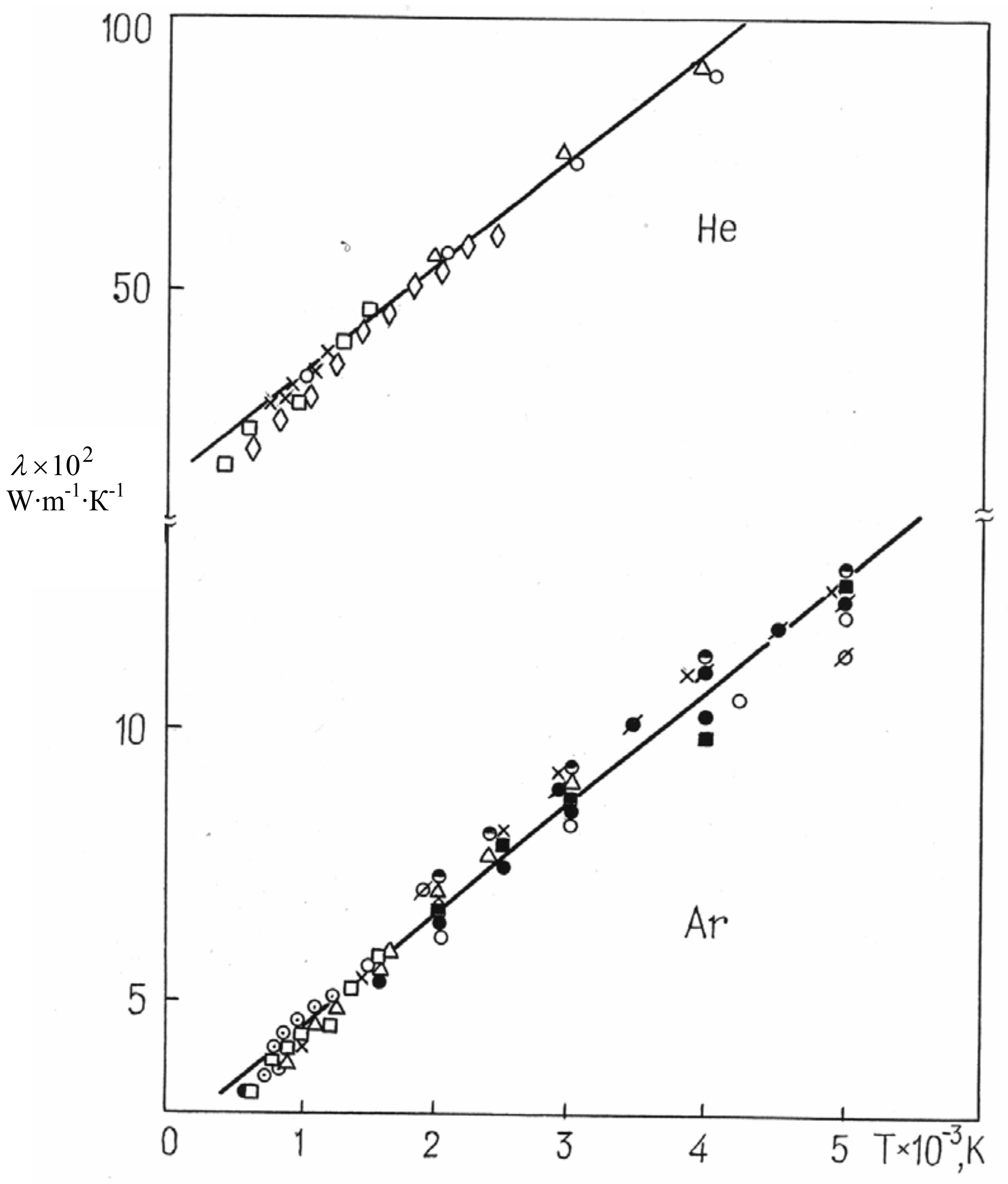


Fig. 3

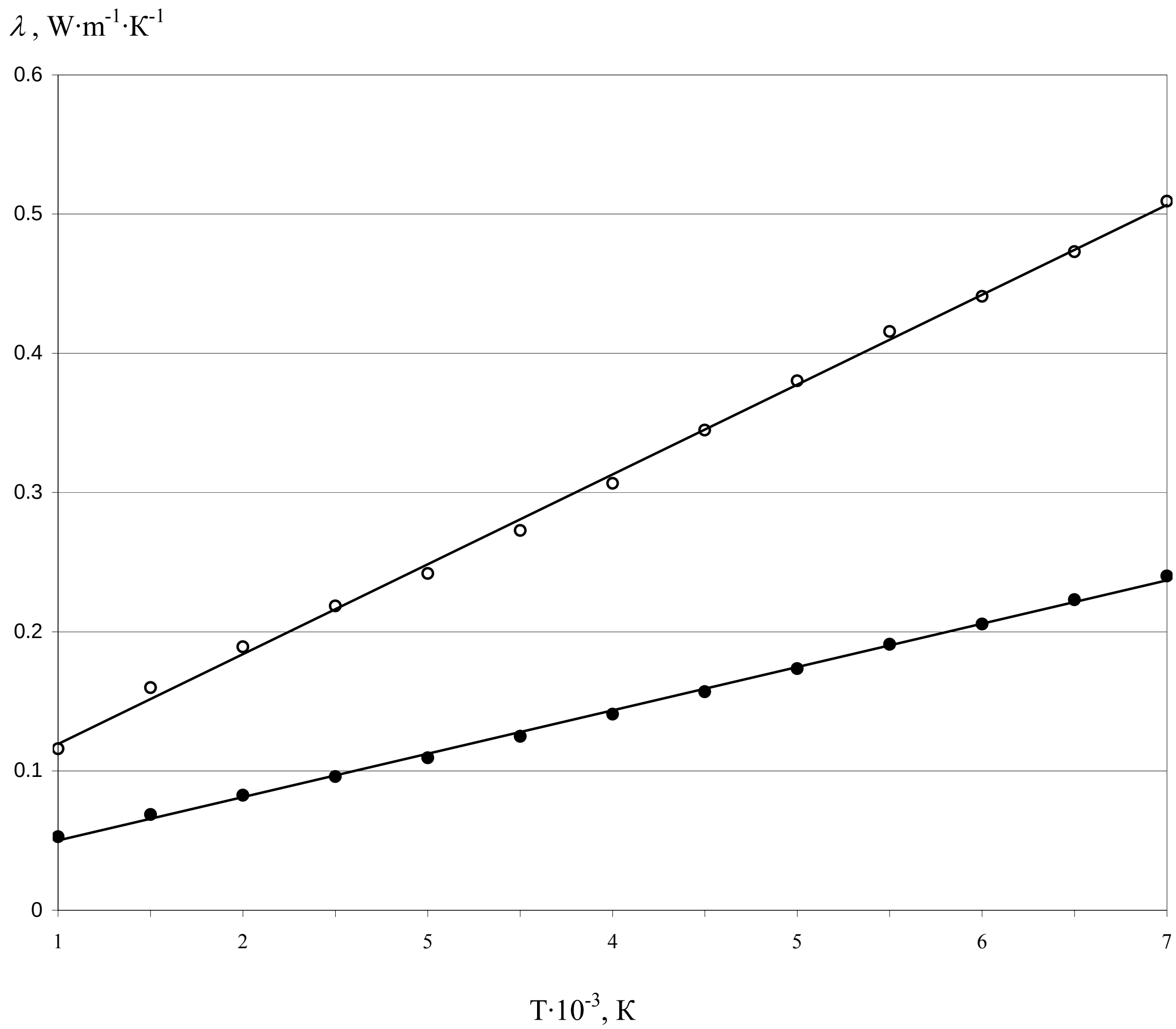


Fig. 4

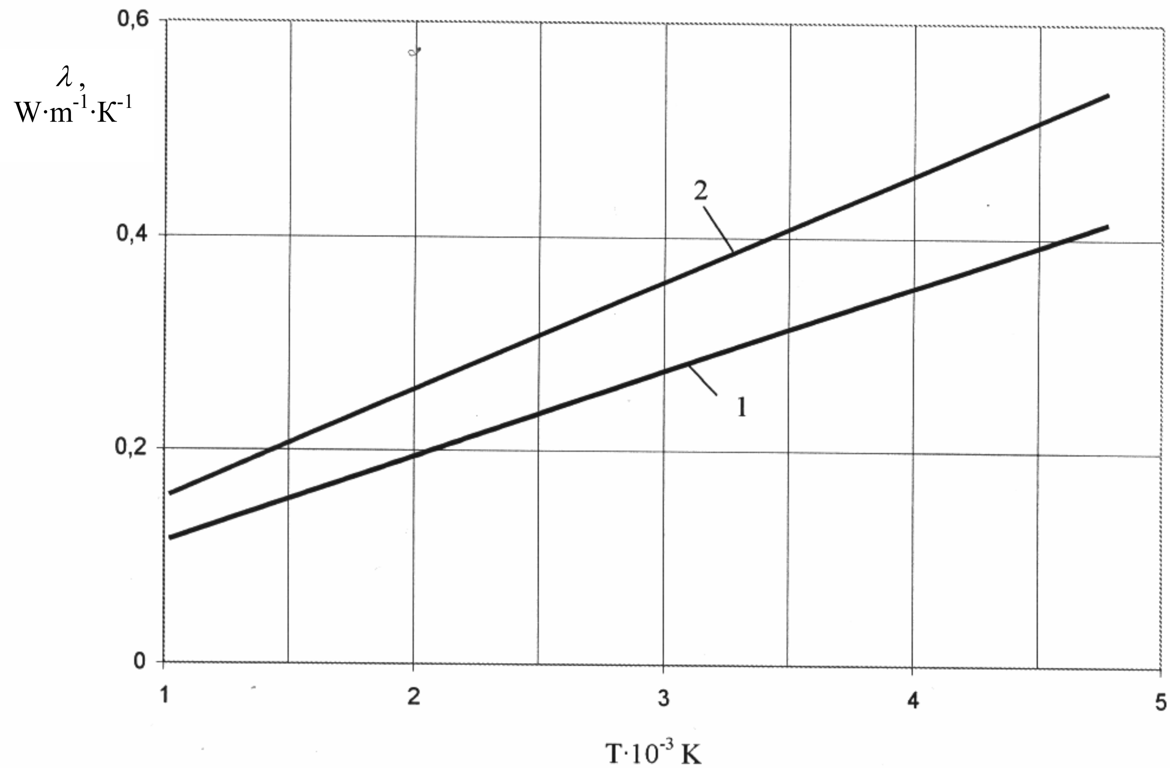


Fig. 5