LINEAR EFFECTS OF THE ENERGY TRANSFER IN GASES

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The authors discuss the linear effects of energy transfer in a gas that can attain a steady state and the linear similarity theory based on geometric transformations preserving the distance between points.

Transport phenomena in gases appear when the random motion of molecules becomes ordered due to temperature and velocity gradients etc. imposed on the investigated gas system. The transport phenomena can be described in terms of the thermodynamics of irreversible processes, which relates fluxes \( I_i \) with thermodynamic forces \( x_i \). It is generally assumed that near thermodynamic equilibrium, the linear relations for the fluxes and thermodynamic forces are, in a first approximation,

\[
I_i = \sum_{j=1}^{2} L_{ij} x_j.
\]

Here the proper phenomenological coefficients \( L_{iij} \), \( L_{ij} \) are always positive while the mutual coefficients \( L_{ij} \), \( L_{ij} \) can have any sign [1]: \( L_{ij} > 0, L_{jj} > 0, L_{ij} = L_{ji} \).

There is a large group of systems that satisfy this assumption. In such systems the linear effects of transfer are manifested, the phenomenological coefficients \( L_{iij} \), \( L_{ij} \) are linear functions of the parameters of state and the systems themselves are stationary (the mass flow is equal to zero).

The geometric structure of a gas is a set of elements (molecules) with a given type of relations between them that are determined by the rate of energy transfer. In a steady-state gas, the rate of energy transfer is infinite:

\[
I_\eta = -\lambda \nabla T, \quad \lambda = (L_{22} - U^* L_{11}) / T^2.
\]

This relation is known as the Fourier law, which is of a purely heuristic nature and is used to determine the thermal conductivity of a steady-state gas.

The space of states of a system is a metric space ("metric" means the presence of length) where any parameter of the system can play the role of distances between two points (two states of the system) [2]. Note that any thermodynamic process is a path into the space of states.

The linear effects of transfer are determined in the Euclidean space of states.

The linear similarity theory of transfer processes is a theory based on geometric transformations in which the distance between two points is specified and which is valid in the case of linear metric spaces.

Two physical processes are said to be similar if they obey the same laws and all physical quantities characterizing one process can be transformed into quantities characterizing another process by simple multiplication of the former by constant coefficients, which are called similarity coefficients [3].

According to [4], a "dimensionless" description of the temperature dependence of the transfer coefficients from the viewpoint of the phenomenological theory of thermodynamic similarity is based on formulas of the type:
TABLE 1. \( T \) and \( \lambda \) Values at the Critical Point

<table>
<thead>
<tr>
<th>Gas</th>
<th>( T_{cr}, \text{K} )</th>
<th>( \lambda_{cr}, \text{W/(m} \cdot \text{K)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ne</td>
<td>44.5</td>
<td>0.0033</td>
</tr>
<tr>
<td>Ar</td>
<td>151.2</td>
<td>0.0030</td>
</tr>
<tr>
<td>Kr</td>
<td>209.4</td>
<td>0.0021</td>
</tr>
<tr>
<td>Xe</td>
<td>289.8</td>
<td>0.0017</td>
</tr>
</tbody>
</table>

\[
\frac{Y}{Y^*} = f(\tau),
\]

where \( Y \) is the transfer coefficient; \( Y^* \) is a parameter with \( Y \) dimensionality composed either of critical data or of molecular parameters.

We now determine the extent to which relation (2) is valid over a wide temperature range. For this, in [5] the thermal conductivities of argon, neon, krypton, and xenon were generalized in the temperature range of 90−7000 K by the relation

\[
\lambda^* = \frac{\lambda}{\lambda_{cr}} = f\left(\frac{T}{T_{cr}}\right),
\]

where \( \lambda_{cr}, T_{cr} \) are the variables at the critical point (Table 1).

In performing the generalization, results [6-15] for Ar, [8-11, 13-15] for Ne, [8, 9, 11-14] for Kr, [9-11, 13, 16-18] for Xe were used.

Processing of the indicated thermal conductivities by the least-squares method with the aid of the polynomial

\[
\ln \lambda^* = \sum_{i=1}^{3} c_i (\ln T^*)^{i-1}
\]

allowed the experimental data to be described in the following temperature ranges: 160−7000 K, \( \ln T^* = -0.5-4.0 \) for Xe; 129−7000 K, \( \ln T^* = -0.5-4.0 \) for Kr; 90−7000 K, \( \ln T^* = -0.5-4.0 \) for Ar; 120−2500 K, \( \ln T^* = 1.0-4.0 \) for Ne with an error of 0.5−3.5% by a single generalized curve with the following coefficients: \( c_i = 1.1822; 0.8739; -0.0415 \) at \( i = 1, 2, 3 \), respectively (with the exception of the thermal conductivity of argon at \( T = 90.34 \text{ K} \) [6] and xenon at \( T = 194.74 \text{ K} \) [9]: the error attains 5.5 and 6%, respectively).

As for the thermal conductivity of neon in the low (90−120 K) and high (2500−6000 K) temperature ranges, its reduced value is systematically overestimated by up to 6% with respect to the generalized dashed curve (Fig. 1a).

To clarify a behavior of the temperature-dependent thermal conductivity of neon, a method of reduction with the aid of molecular parameters was used [19]:

\[
\lambda^* = \frac{\sigma^2 m^{1/2}}{\epsilon^{1/2} k} \lambda = f(T^*), \quad T^* = \frac{T k}{\epsilon}.
\]

Processing of the reduced values by the polynomial dependence

\[
\ln \lambda^* = \sum_{i=1}^{4} c_i (\ln T^*)^{i-1}
\]

allowed the experimental data to be described in the following temperature ranges: 165−2500 K, \( \ln T^* = -0.3-2.4 \); for Kr, 120−2500 K, \( \ln T^* = -0.46-2.6 \); for Ar, 90−2500 K, \( \ln T^* = -0.3-3.1 \); for Ne, 115−850 K,