Study of thermal conductivity temperature dependence for amorphous materials based on Al$_2$O$_3$ and SiO$_2$ oxides

L A Maryushin$^1$, D A Tikhonova$^{1,3}$ and I I Kiryanov$^2$

$^1$Moscow Polytechnic University, 16 Avtozavodskaya street, Moscow, 115280, Russia
$^2$CHP -11 named after M. Y. Ufaeva, 32 Entuziastov highway, Moscow, 111024, Russia

$^3$E-mail: dashuta155@yandex.ru

Abstract. The purpose of this paper is to study the process of thermal energy transfer in materials with pronounced crystalline structure and to analyze thermophysical heat transfer mechanisms in Al$_2$O$_3$, SiO$_2$ oxides (fused quartz, quartz glass). The dependence of thermal conductivity versus temperature for materials in which heat transfer is determined by conduction electrons is graphically shown.

1. Introduction
Significant number of papers presented by authors of [1,2,3] are dedicated to heat transfer problem. The interest in the issue is due to aiming for the best heat exchanger design solution and performance which would determine its effective practical application, including solving heat supply and energy saving issues. Use of mobility and relaxation models for heat and momentum transfer processes makes it possible to obtain sufficiently accurate regularities of the temperature dependence on various material thermophysical properties.

2. The main provisions
Results of theoretical and experimental studies show that the material thermal conductivity significantly depends not only on temperature, but also on pressure. Therefore, a change in thermal conductivity of materials under compression becomes decisive where it is necessary to take into account the heat flows or to directly solve the thermal conductivity equation at high pressures and temperatures.

In the oxides under consideration, free electrons are carriers of thermal energy. With increasing body temperature, electron scattering increases due to the increased thermal inhomogeneity that leads to a decrease of thermal conductivity coefficient. In the presence of various kinds of impurities, thermal conductivity coefficient decreases sharply. The latter phenomenon can be explained by the increase in structural inhomogeneity leading to electron scattering.

Advanced materials used in construction and power industries, as a rule, possess a set of unique properties. One of these properties is insensitivity to sharp temperature changes.

Due to this, materials based on silicon dioxide have attracted attention of not only power engineers, but also specialists in production and operation of optically permeable media [2, 4].
Another unique property of silicon dioxide-based materials is their high resistance to aggressive media (acid resistance). For example, quartz glass is completely unaffected by most acids (nitric, hydrochloric, sulfuric, aqua regia, etc.), and this is why it is used successfully in all cases where products made of acid-resistant material are needed, and it very often displaces expensive bulky and fragile ceramic products.

Currently, the results of thermal conductivity studies for powdery silicon dioxide $\text{SiO}_2$ used as additives in the manufacture of refractory structures, as well as for fused amorphous materials, are known. However, the study of heat transfer mechanism in these materials, in our opinion, is not yet complete. This paper analyzes the temperature dependence of thermal conductivity based on the energy carrier mobility model.

Two forms of silicon dioxide $\text{SiO}_2$ were studied: fused quartz and quartz glass. Fused quartz density is 2650 kg/m$^3$, quartz glass density is 1880 kg/m$^3$. Thermal conductivity and mobility of these materials versus temperature are shown in figure 1 and figure 2, respectively. Based on the calculations, data on thermal conductivity and mobility of these oxides at temperature variation are obtained, as shown in table 1.

**Table 1. Calculations for the cooling elements.**

| Material       | Temperature range | $X_\lambda$ | $X_U$  |
|----------------|-------------------|-------------|--------|
| Fused quartz   | 70-300 K          | 0.59        | -1.33  |
| Quartz glass   | 200-300 K         | 1.43        | -1.10  |

Analysis of the graphs given in figure 2 and 3 show that, for silicon dioxide in the form of quartz glass, the thermal conductivity increases as a power function with degree of 1.5. For fused quartz, the temperature increase in thermal conductivity is proportional to the first degree. The silicon dioxide mobility in the considered temperature ranges decreases according to the law determined by the theoretical degree value of -1.5 characterizing the transfer carrier scattering on the lattice thermal vibrations. A lower degree value indicates that there is insignificant additional inelastic scattering.

Thus, in real bodies at very low temperatures (T<50-70 K), when the atom thermal vibrations are practically frozen, the electron scattering is defined by the process of atoms interaction with the sample boundaries, since the free path length becomes comparative with the body size at such low temperatures. In this case, the mobility value $U$ is proportional to the temperature according to relationship $U \sim T^3$, and
the lower value of the degree corresponds to inelastic scattering at the sample boundaries, the higher value corresponds to elastic scattering at the sample boundaries [5].

**Figure 2.** Silicon dioxide thermal conductivity versus temperature.

**Figure 3.** Silicon dioxide mobility versus temperature.
The electrons movement is determined by their scattering on the lattice thermal vibrations, that is, on phonons, at high temperatures (T > 50-70 K). In addition, the dependence of mobility $U$ on temperature is proportional to $U \sim T^{-1.5}$. However, in addition to main electron-phonon scattering phenomenon, there are also additional scattering mechanisms due to the presence of impurities, which leads to deviation of \( \chi_U \) degree from the specified – 1.5.

3. Conclusions

It is shown that the empirical temperature dependence of thermal conductivity in disordered structures based on Al$_2$O$_3$ and SiO$_2$ is described by relationship \( \lambda \sim T^{0.5} \). Insufficient deviation from the degree value (0.5) is explained by the presence of strong inelastic scattering or additional scattering mechanisms in a number of materials considered. Another cause of deviation from this degree value, especially a reduction, may be instability of number of heat transfer carriers in the oxides.

Thus, development of new methods for obtaining reliable experimental data on thermal conductivity temperature dependence for oxides based on Al$_2$O$_3$ and SiO$_2$ is an urgent task of heat engineering.

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