

## Coefficients of Thermal Expansion of Solids

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**Received:** 2025, 15, Nov

**Accepted:** 2025, 21, Dec

**Published:** 2026, 07, Jan

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**Annotation:** This paper examines changes in the linear dimensions of solids associated with anharmonicity in the thermal vibrations of molecules that make up the crystal lattice of the solid as the temperature changes. As a result of these vibrations, the distances between the solid's particles change with temperature. It is also shown that the thermal expansion coefficients of many solids are small, on the order of  $10^{-5} \div 10^{-6} \text{ K}^{-1}$ .

**Keywords:** anharmonicity, linear size, vibrations, size, solid, particles, atoms, ions, Kelvin, thermal vibration, thermal expansion, temperature.

Thermal (temperature) expansion is a change in the linear dimensions of bodies when the temperature of these bodies changes.

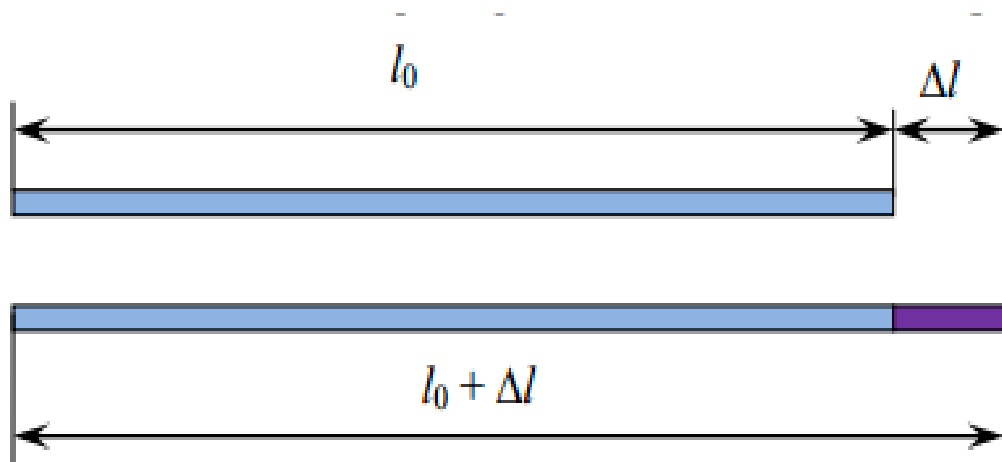
Thermal expansion or contraction is characterized by the corresponding coefficient.

Thermal expansion can be linear or volumetric, they are characterized by coefficients of thermal expansion [1-2]:

$\alpha_l$  is the coefficient of linear thermal expansion,

$\alpha_v$  - coefficient of volumetric thermal expansion

Experimental data shows that most solids contract as temperature decreases, while their linear dimensions increase as temperature increases. This process is called thermal expansion. The expansion of a solid relative to one of its dimensions is called linear expansion (Fig. 1).



**Fig. 1. Elongation of a solid body upon heating.**

Here  $l_0$  – initial body length at temperature  $T_1$ ,

$\Delta l$  – change in the length of a solid body.

The change in the length of a body  $\Delta l$  when it is heated to a certain temperature  $T_2$  is proportional to the initial length  $l_0$ , as well as to the change in temperature

$$\Delta T = T_2 - T_1:$$

$$\Delta l = l_0 \alpha_l \Delta T \quad (1)$$

where  $\alpha_l$  is the coefficient of linear thermal expansion, which determines the relative elongation of a body  $\Delta l/l_0$ , when its temperature changes by 1 degree.

Body length at temperature  $T_2$ :

$$l = l_0 + \Delta l = l_0 + l_0 \alpha_l \Delta T, \quad (2)$$

$$\alpha_l = \frac{l - l_0}{l_0 \Delta T} = \frac{1}{l_0} \frac{\Delta l}{\Delta T}. \quad (3)$$

When the temperature changes, the volume of the body also changes.

The volume of solids and liquids with a change in temperature can be determined by the formula:

$$V = V_0 (1 + \alpha_v \Delta T), \quad (4)$$

where  $V_0$  – the initial volume of the body at temperature  $T_1$ ,

$\alpha_v$  is the coefficient of volumetric thermal expansion of the body,

$\Delta T$  – change in body temperature.

The coefficient of volumetric expansion of a body  $\alpha_v$  is a physical quantity that determines the relative change in the volume of a body ( $\Delta V/V_0$ ) that occurs when its temperature changes by 1 K (while the pressure must remain constant).

Coefficient  $\alpha_v$  is determined by the formula:

$$\alpha_v = \frac{1}{V_0} \frac{\Delta V}{\Delta T}. \quad (5)$$

Changes in the linear dimensions of solids are associated with the anharmonicity of thermal vibrations of the molecules that make up the body's crystal lattice as the temperature changes. As

a result of these vibrations, the distances between the body's particles change with temperature. A change in the body's volume also entails a change in its density:

Thermal expansion coefficients depend on the substance and temperature. They are independent of temperature only over a small range of temperatures. There are also substances that have a negative coefficient of thermal expansion; materials made from such substances contract with increasing temperature. However, this only occurs over a narrow temperature range.

There are substances whose coefficient of thermal expansion is approximately zero over a certain temperature range. As a first approximation, the coefficients of linear and volumetric expansion of a homogeneous body are related by the formula:

The coefficients of thermal expansion of many solids are small, of the order of  $10^{-5} \div 10^{-6} \text{ K}^{-1}$ .

It follows from this that at room temperatures the elongation of bodies differs slightly from its length at  $0^\circ\text{C}$ .

A solid is a state of matter characterized by stability of shape and the nature of the thermal motion of atoms, which differs from other possible states of matter (plasma, gas, liquid). The atoms of solids are arranged symmetrically at the nodes of a crystal lattice. The type of crystal lattice itself depends on the nature of the interaction forces between atoms and ( or ions).

Atoms in crystal lattices oscillate around their equilibrium positions (nodes) at any temperature, and the amplitude of their oscillations increases with increasing temperature. The expansion of solids upon heating is caused by the increase in the amplitude of atomic oscillations and the increasing distance between atoms. If atomic oscillations were harmonic (described by a sinusoidal function), then the increase in oscillation amplitude with increasing temperature would not affect the thermal expansion of the substance.

This means that increasing the amplitude of harmonic oscillations of two adjacent atoms of a given solid will not lead to an increase in the distance between them, since each atom individually approaches its neighbor just as much as it moves away. However, for a solid, particle oscillations are not described by harmonic laws.

This deviation from the harmonic oscillations of particles in a crystal lattice ( anharmonicity ) is explained by the fact that the attractive and repulsive forces between adjacent atoms are not symmetrical. As the oscillation amplitude increases, the repulsive forces between adjacent atoms increase faster than the attractive forces decrease. As a consequence, the dependence of the potential energy  $E$  on the lattice is different .

At any temperature, even absolute zero, the atoms of solids undergo thermal vibrations around their equilibrium positions. Many physical phenomena in solids, including heat capacity, thermal expansion, heat, and electrical conductivity, are associated with these vibrations of the atoms in the crystal lattice.

Due to their strong interaction with each other, the nature of these oscillations turns out to be very complex, therefore, to describe this process, they resort to approximate methods and various kinds of simplifications.

Let us assume that, due to the action of powerful binding forces, an oscillation initiated in one particle is immediately transmitted to neighboring particles, and a collective motion is excited in the crystal in the form of an elastic wave encompassing all the particles of the crystal. This collective motion is called a normal vibration of the lattice. The number of normal vibrations that can occur in the lattice is equal to the number of degrees of freedom of the crystal particles, i.e.

When considering the vibrations of atoms in a crystal lattice, as well as the heat capacity of solids associated with these vibrations, it was assumed that the forces acting between atoms are elastic and that the atoms perform harmonic vibrations with small amplitudes around their average equilibrium positions [3-22].

This made it possible to divide the entire spectrum of oscillations into independent modes, calculate the thermal energy of the crystal in this approximation, and obtain a formula for heat capacity that describes its behavior well at low and high temperatures.

However, to explain a number of phenomena, such as the thermal expansion of solids and thermal conductivity, the assumptions made are no longer sufficient. It is necessary to take into account the fact that the forces of interaction between ions in the lattice are not entirely elastic; that is, they do not depend linearly on the displacement of atoms from their equilibrium positions, but contain anharmonic terms of the second and higher degrees, the influence of which increases with increasing temperature.

First of all, we will show that if the forces maintaining this state of equilibrium were linearly dependent on its displacement, then thermal expansion would be absent altogether, i.e. the dimensions of the solid would not depend on temperature.

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