An easy investigation of negative thermal expansion in plastic bottle

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Abstract. We have easily investigated the negative thermal expansion of plastic bottle. Plastic bottle contracts its diameter due to the temperature enhancement when it loaded by heated water. Length ratio of diameter contraction compared with the initial diameter is considered as the negative thermal expansion. We have calculated the negative thermal coefficient in two kinds of plastic bottles as \( \sigma_A = 860 \times 10^{-6}/^\circ C \) for bottle A and \( \sigma_B = 620 \times 10^{-6}/^\circ C \) for bottle B. Those coefficients confirmed at the range thermal coefficient of polyethylene as common raw material of plastic bottles. This investigation completes the student understanding in term of thermal expansion subject in physics classroom. They shall not only learn the expansion due to the temperature enhancement but they also learn the contraction as well through negative thermal expansion of plastic bottle.

1. Introduction

The contraction and expansion of length, area as well as volume dimensions due to the change of temperature shows the fundamental characteristic of the material such as metal, wood, and plastics. In physics subject, a coefficient that describes how the size of an object changed with a change in temperature is known as the coefficient of thermal expansion [1-2]. Thermal expansion phenomena are easy to observe in daily life. The cable of electricity expands their length at daylight and its contract while the night is coming. Furthermore, thermal expansion also occurs at metal railway, metal bridges, metal or wooden window’s frames and etc. [3]. Those phenomena show that the understanding of thermal expansion concept and its application are literally necessary for the students.

Generally, student have well-acknowledged the expansion of an object due to the enhancement of its temperature. On the other hand, some objects i.e. rubber and plastic bottle are contracted while their temperature is increased. This could possibly perform confusion for the students. Generally students have only considered that objects expand their size due to the enhancement of their temperature and inversely. While in the fact, an object can contracts and expand their dimension due to the alteration of their temperature. Apparently, this concept is similar to the concept of expansion and compression gas in thermodynamics that describes the ratio compression and expansion of system’s volume as a result of the volume alteration due to the temperature and the volume alteration due to the compression [4]. Size contraction due to the change of temperature has similar analogy to the coefficient of gas compression where the coefficient has negative value that it represents the contraction of size.

In this paper, we have simply explained the negative thermal expansion in plastic bottle. This investigation could be a simple way to reveal a missing concept of thermal expansion to the students.
This experiment is a very simple therefore makes it demonstrable and easy to be doing by students as a project in classroom as well as at home. This kind of experiment learning is a way to enhance the students’ psychomotor skill and cognitive skill [5, 6].

2. Method

This simple experiment used plastic bottle loaded by heated water to investigate the negative thermal expansion. The experiment required two kind of bottle type A and type B with similar volume capacity 600 ml. Both plastic bottles were loaded by various temperature water which are 30ºC, 60ºC, and 90ºC. The diameter size of plastic bottles then measured after 10 minutes from the water been loaded. The size contraction investigated from the diameter of plastic bottles compared with their initial size. The contraction size is performed as Eq. 1.

$$\ell_f = \ell_0 \pm \Delta\ell$$

where $\ell_0$ is initial length, $\Delta\ell$ is contraction or expansion length, $\ell_f$ is final length after temperature alteration. Positive sigh of $+\Delta\ell$ shows the expansion of size and negative sign of $-\Delta\ell$ shows the contraction of size. Coefficient of thermal expansion is generally estimated by ratio of contraction or expansion due to the temperature alteration $\Delta\ell/\Delta T$ with the initial length $\ell_0$ as shown in Eq. 2 [7].

$$\alpha = \pm \frac{1}{\ell_0} \left( \frac{\Delta\ell}{\Delta T} \right)$$

Coefficient of thermal expansion has positive sign (+) to show that the object expands its size due to the alteration of temperature. Coefficient of thermal expansion has negative sign (-) to show that the object contracts its size due to the alteration of temperature.

3. Results and discussion

Plastic bottles contract their diameter size after loaded by heated water as shown in Figure 1. Plastic bottle commonly made from thermoplastic polymer such as polyethylene that means easily to change their size by temperature alteration [8]. Diameter contraction of plastic bottle is related to the enhancement of temperature where the diameter decreased due to the temperature increased.

**Figure 1.** Contraction of plastic bottle

Contraction size of bottle A and bottle B have been measured and show in Figure 2. The measurement result shows that bottles diameter contraction is a non-linear function. This phenomenon is quite different with the general thermal expansion that already understood by students which is
thermal expansion approaches with linear function. Generally, contraction as well as expansion due to thermal alteration can be expressed in the form of exponential function as shown in following Eq. 3.

Thermal expansion coefficient with the initial length \( \ell_0 = \ell \)

\[
\alpha = \pm \frac{1}{\ell} \left( \frac{d\ell}{dT} \right)
\]

\[
\int_\ell^{\ell_f} \alpha dT = \int_\ell^{\ell_0} \frac{d\ell}{\ell}
\]

\[
\alpha(T_f - T_i) = \ln \frac{\ell_f}{\ell_0}
\]

with \( \ell_f = \ell_0 \pm \Delta\ell \) and \( \Delta T = T_f - T_i \)

\[
\alpha \Delta T = \ln \left( \frac{\ell_0 \pm \Delta\ell}{\ell_0} \right)
\]

\[
e^{\alpha \Delta T} = \left( \frac{\ell_0 \pm \Delta\ell}{\ell_0} \right)
\]

\[
\ell_0 e^{\alpha \Delta T} = \ell_0 \pm \Delta\ell
\]

expansion \( +\Delta\ell \) and contraction \( -\Delta\ell \) are due to the temperature alteration \( \Delta T \) as shown in Eq. 3:

\[
\Delta\ell = \pm \ell_0 \left( e^{\alpha\Delta T} - 1 \right)
\] (3)

Expansion size of \( +\Delta\ell \) and contraction size of \( -\Delta\ell \) are due to the temperature alteration \( \Delta T \) as in Eq. 3. If considered that the initial condition with no alteration temperature \( \Delta T = 0 \) and \( \Delta\ell = 0 \) then we have \( \ell_f = \ell_0 \).

Figure 2. Diameter contraction \( \Delta\ell \) of plastic bottle A and B

Coefficient of negative thermal expansion on plastic bottle contraction is estimated using graphical method linearization of Eq. 3. into Eq. 4.
Consider the Eq. 4, coefficient of negative thermal expansion $\alpha$ is a gradient from a linear equation that the value can be estimated as $\alpha \approx \tan \theta$ [9]. Using graphical fitting as shown in Figure 3 then can be obtained that the coefficients of negative thermal expansion are $\sigma_A = 860 \times 10^{-6}/^\circ C$ for bottle A and $\sigma_B = 620 \times 10^{-6}/^\circ C$ for bottle B. Both of those coefficients are stated at the range thermal coefficient of polyethylene as raw material of plastic bottles [10].

\[ \ln \frac{\Delta \ell}{\ell_0} = \alpha \Delta T \]  \hspace{1cm} (4)

\textbf{Figure 3.} Graphical analysis to estimate the coefficient of negative thermal expansion

For $\Delta T$ almost to zero, contraction or expansion $\Delta \ell$ in Eq. 3 could be estimated in the form of linear equation as shown in Eq. 5. Apparently, this Eq. 5 is the form that well understood by students.

\[ \Delta \ell = \pm \ell_0 (1 + \alpha \Delta T - 1) \]

\[ \Delta \ell = \pm \ell_0 \alpha \Delta T \]  \hspace{1cm} (5)

This investigation has revealed the hidden side of thermal expansion that possibly missed from students’ understanding. Through this simple experiment student will understand completely about contraction and expansion due to the temperature alteration. Furthermore, students shall know that not all objects will expand while the temperature is increased.

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