Received : 26 October 2018
Revised : 7 December 2018
Accepted : 31 December 2018
Published: 31 December 2018

DOI: doi.org/10.21009/1.04211

The Development of Experimental Sets for Measuring Linear Thermal Expansion Coefficient of Metal Using Digital Video-Based Single Slit Diffraction Method

Yuri Yogaswara[1,a)], Fourier Dzar Eljabbar Latief[2,b)]

[1]*Magister Pengajaran Fisika, Departemen Fisika, FMIPA ITB, Jl. Ganesha No.10 Bandung 40132*
[2]*Fisika Bumi dan Sistem Kompleks, Departemen Fisika, FMIPA ITB, Jl. Ganesha No.10 Bandung 40132*

✉: [a)]yogaswarayuri@gmail.com, [b)]fourier@fi.itb.ac.id

Abstract

The development of an apparatus for the measurement of linear thermal expansion coefficient of metal by a single diffraction method has been developed. The development was made based on several ideas from previous researchers, as well as to overcome several limitations which yields insignificant results. The development includes the redesign of the primary holder module, the temperature measurement module (using a thermocouple sensor connected to the PC), and the measurement approach of the diffraction pattern distance by means of digital video analysis techniques using Tracker software. The development of the modules as well as the measurement approach that has been done yields very good experimental results. The measured linear thermal expansion coefficient of aluminum has a high level of accuracy and precision. The result is $(23.100 \pm 0.2186)\times10^{-6}$/°C, and compared from a reference, i.e., 23.000 $\times$ 10^{-6}/°C, the relative error of is 0.95% and the relative standard deviation is 0.43%.

Keywords: development tools, linear expansion, single slit diffraction, digital video analysis

INTRODUCTION

Measurement of linear thermal expansion coefficient are generally carried out through experiments using *Musschenbroek* apparatus, which are commonly used in high schools. There are many other tools and methods currently available which have been developed for the measurement, one of which is the single slit diffraction method. The experimental apparatus for the measurement of linear thermal expansion coefficient by a single slit diffraction method has been previously developed by several researchers, e.g., Pujayanto, et al., (2016), Wulandari & Radiyono (2015) and Ferawati & Okimustava (2012). Based on the results of these researches, there are several limitations which still need to be resolved to produce more accurate results. The development to overcome the previous limitations includes the improvement of the design and the size of the measured metal object, the redesign of the primary module, how to measure the rapid temperature change (which was previously undetected due to the limitations of the measuring instrument), and how to measure the generated diffraction pattern. Based on these considerations, an experimental apparatus to measure the linear thermal expansion coefficient of metal was developed, by using a single slit diffraction method with data acquisition using digital video recording. The accuracy of the results from the measurements is analyzed by a comparison with the result from a reference, while the precision of the apparatus is evaluated by means of standard deviations analysis from repeated measurements.

RESEARCH METHODS

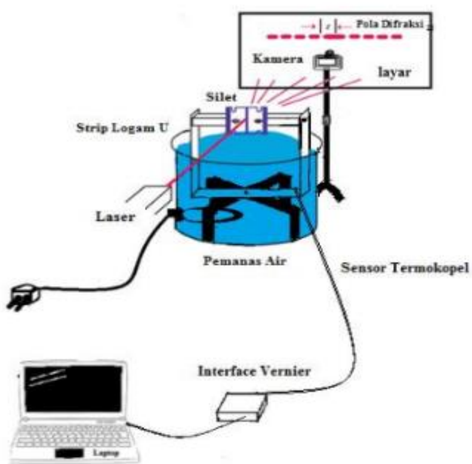
This research started with re-designing the apparatus, manufacturing the modules and constructing the experimental set, and concluded with evaluating the apparatus by analyzing the experimental results. The design and manufacture of the apparatus was carried out in the Department of Physics workshop, Institut Teknologi Bandung. The evaluation was carried out in the Basic Physics Laboratory of the Basic Science Center - A ITB building. All of the stages of this research are carried out in the period of January – June, 2018.

The research is based on a concept of linear thermal expansion where a metal rod expands as it undergoes a temperature increment. The linear expansion (change in length) experienced by a particular metal depends on a constant known as the linear thermal expansion coefficient. Various measurements are available to determine the constant, one of which is based on the analysis of diffraction pattern. Diffraction refers to various phenomena that occur when a wave (in this case, light) passes through a narrow barrier or gap where the wave will be diffracted (spread-out) where the spread out will generate a dark-bright pattern on a screen. In this research, a metal rod is designed so that the two ends will form a narrow gap, where a beam of light is passed through the gap thus generates a diffraction pattern on a screen.

The experiment was carried out using a set of apparatus which employs a method of measuring changes of width of the single narrow gap as the metal undergoes a thermal expansion. Furthermore, the apparatus should also be able to measure the rapid temperature change, as well as the corresponding rapid expansion. In this research, the developed apparatus uses laser as the beam of light which is passed through the single narrow gap to obtain a single slit diffraction pattern. The increase in the gap width that is proportional to the linear expansion of metal length can be measured by analyzing the generated diffraction pattern, in which, the linear thermal expansion coefficient of the metal can then be determined.

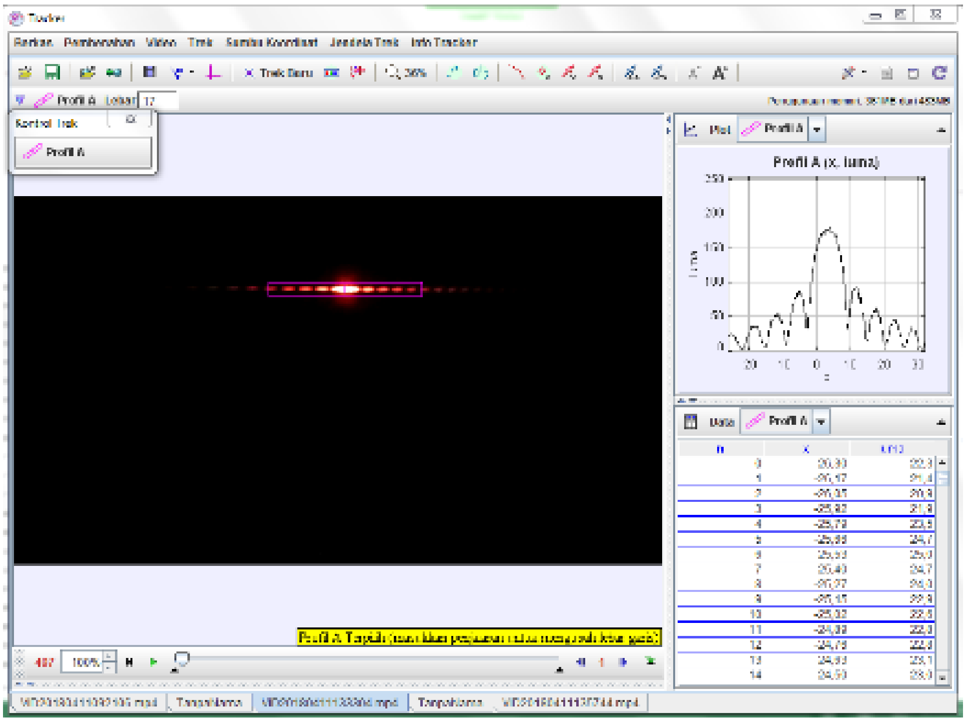
Analysis of the generated diffraction pattern mainly focused on measuring the distance of the pattern. The measurement was carried out by means of video analysis using Tracker: a software for analyzing and modeling various type of motion as well as optical phenomena. Tracker is a free software developed by Open Source Physics (OSP) using a Java framework (Wee & Lee, 2012). As for the temperature change, a thermocouple temperature sensor is used where the module is connected to the PC through Logger Pro software. This module is used to overcome rapid temperature change.

Calculation of the linear thermal expansion coefficient involves digital image processing method, i.e., image acquisition, image digitization, image quality improvement, and graph plotting. Linear regression is applied to analyze the relationship between $1/y$ (y = the distance of the first order of dark diffraction pattern to center pattern) and T (temperature), the gradient/slope of the curve is used to calculate the linear thermal expansion coefficient of the metal. The design and arrangement of the experimental apparatus is shown in FIGURE 1.



a)

b)



c)

FIGURE 1. (a) trial set scheme; (b) experimental device arrangement in data collection; and (c) sample video frames analyzed using Tracker.

RESULT AND DISCUSSION

Development of Experiment Apparatus

In the previous studies, analysis of the diffraction pattern was done manually, where the distance of the first order of dark diffraction pattern to center pattern generated on a screen is measured using a ruler. Likewise, data acquisition of temperature change was based on a manual reading of the analog thermometer scale. The rapid expansion process which occur as the temperature increases rapidly, makes it difficult to record the temperature data accurately. Therefore, the use of digital-automated data acquisition devices in this study is employed to overcome the difficulty. Digital-data acquisition includes the video recording of the diffraction pattern and recording of temperature data using thermocouple temperature sensor which is connected to the PC through Logger Pro software. The limitations from previous studies are listed in TABLE 1, as well as the analysis of the causes and the corresponding applied development.

The size of the metal strip and the design of the primary module of the previous research (limitation number 1) can be seen in FIGURE 2(a). FIGURE 2(b) shows the design of the new primary module holder (development to resolve limitation number 2). To resolve the limitation number 3, the use of a digital-based thermocouple sensor temperature gauge is shown in FIGURE 2(d), which replaces the analog-based rod mercury thermometer temperature gauge shown in FIGURE 2(c) which is used in previous researches. Millimeter block which is used in the previous researches to measure the distance of the generated diffraction patterns is shown in FIGURE 2(e) (limitation number 4). FIGURE 2(f) shows the digital video analysis tool; the Tracker software. The use of Tracker software is based on research conducted by Brown & Cox (2009).

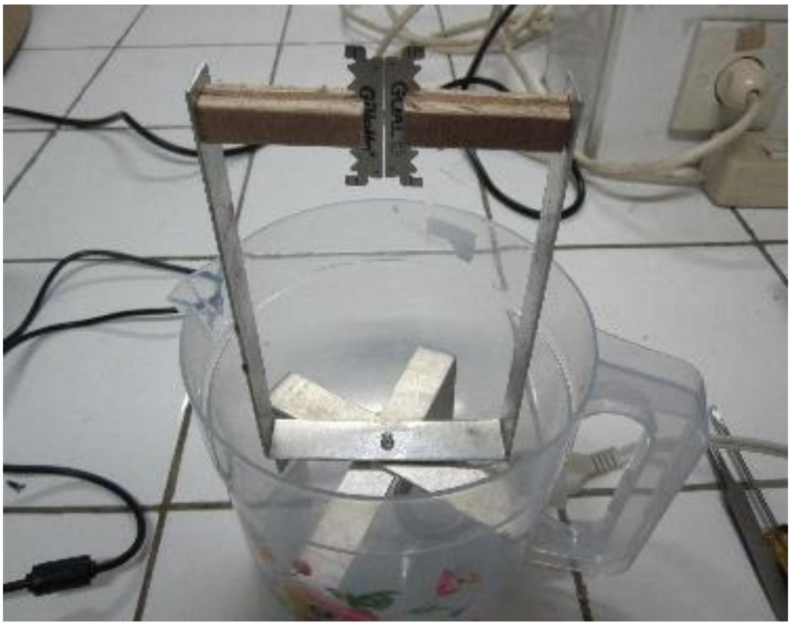
TABLE 1. Factor's constraints, analysis of causes, and development of experimental tools.

TABLE 1. Factor's contraints, analysis of cause and development tools.

Constraints Factors	Analyze Factor	Tool Development
a. The primary module is not sturdy which causes the module not to be in an upright or steady position.	The metal strip is too thin, causing it to be curved due to the weight of the wood support so that the position of the primary module is not steady.	The size of the metal strip is replaced by a thicker one (20 mm wide and 1.0 mm thick).
b. Uneven expansion on both sides of the metal.	The primary module holder is designed on one side, made by clamping the top of the side. This causes expansion to only occur in one direction (not balanced).	The holder's design and position of the primary module are re-designed. The primary module holder is replaced by using a screw attached to the bottom of the metal, thus the expansion is balanced on both sides of the metal.
c. The temperature rise is too rapid so that it cannot be observed carefully on the scale of the increase in 1°C.	Accuracy of analog temperature gauges used and limitations of the observer's vision. The temperature of the water (which conducts the heat to the metal) rises rapidly, which cause the observation to be inaccurate if measured using analog device.	The temperature gauge is replaced with a digital temperature measuring device, i.e., a thermocouple sensor that is connected directly to the PC via a Vernier connection interface.
d. Inaccuracy in measur-ing the width of the diffraction pattern on the screen.	The width of the pattern is measured using ruler which is highly inaccurate, especially in the case of rapid change of the pattern due to rapid temperature rise.	A digital video camera is used to record the generated diffraction patterns, where the produced video is then analyz-ed using *Tracker* software.

e. A slight-repeated movement in the diffraction pattern on the screen when the water reaches the boiling point.	When observations are carried out for a long time, at the boiling point, the water will undergo a phase change. During this phase change, the water vapor affects the path of the laser beam, which causes a change in the generated diffraction pattern.	The water container is enclosed with a cover which is adjusted accordingly to fit the design of the primary module.

a)



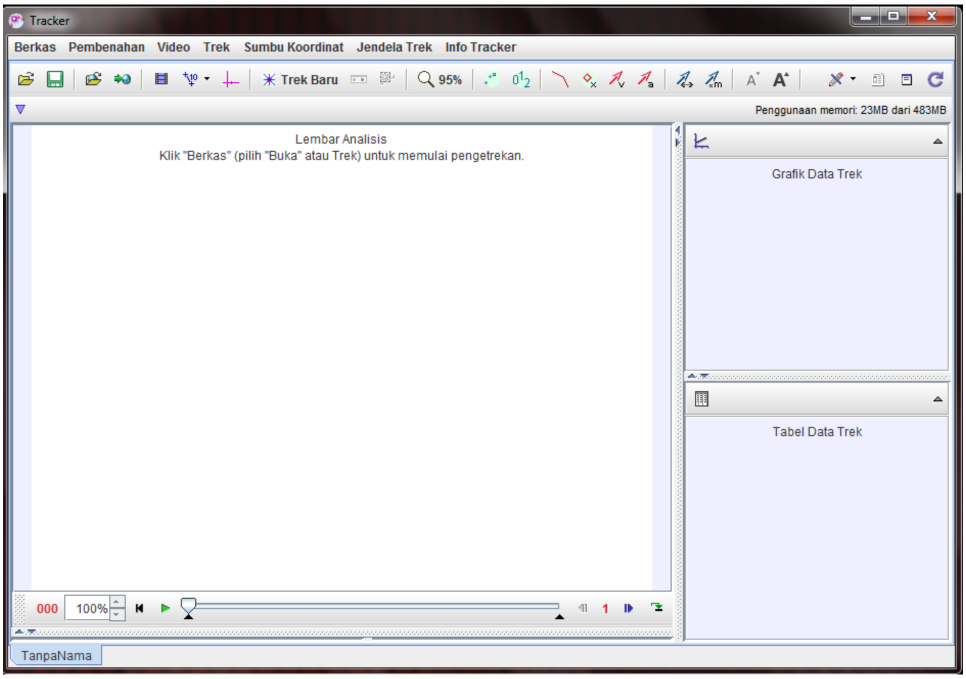
b)

c)

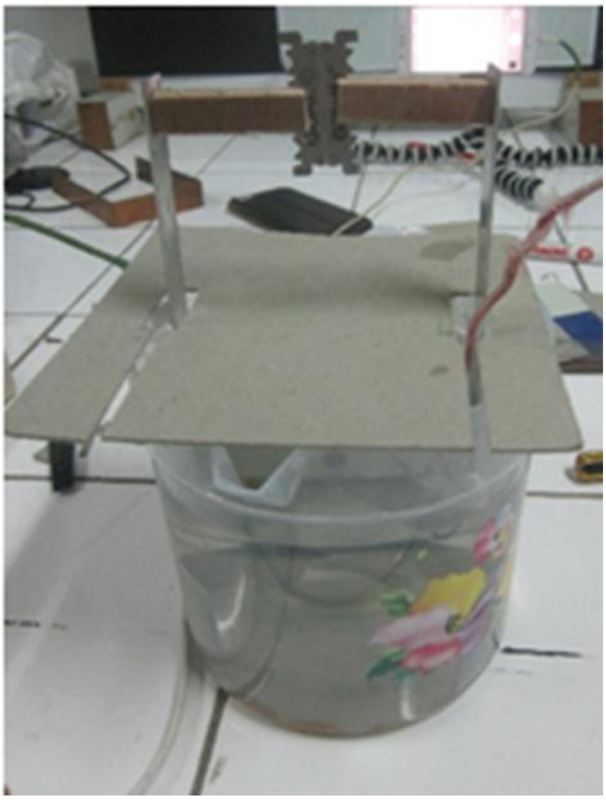

Thermocouple
Vernier
ORDER CODE TCA-BTA
VERNIER SOFTWARE & TECHNOLOGY
LABQUEST
MINI
Vernier

d)

e)


Tracker
Berkas
Pembenahan
Video
Trek
Sumbu Koordinat
Jendela Trek
Info Tracker
Trek Baru
95%
Penggunaan memori: 23MB dari 483MB
Lembar Analisis
Klik "Berkas" (pilih "Buka" atau Trek) untuk memulai pengetrekan.
Grafik Data Trek
Tabel Data Trek
000
100%
TanpaNama

f)

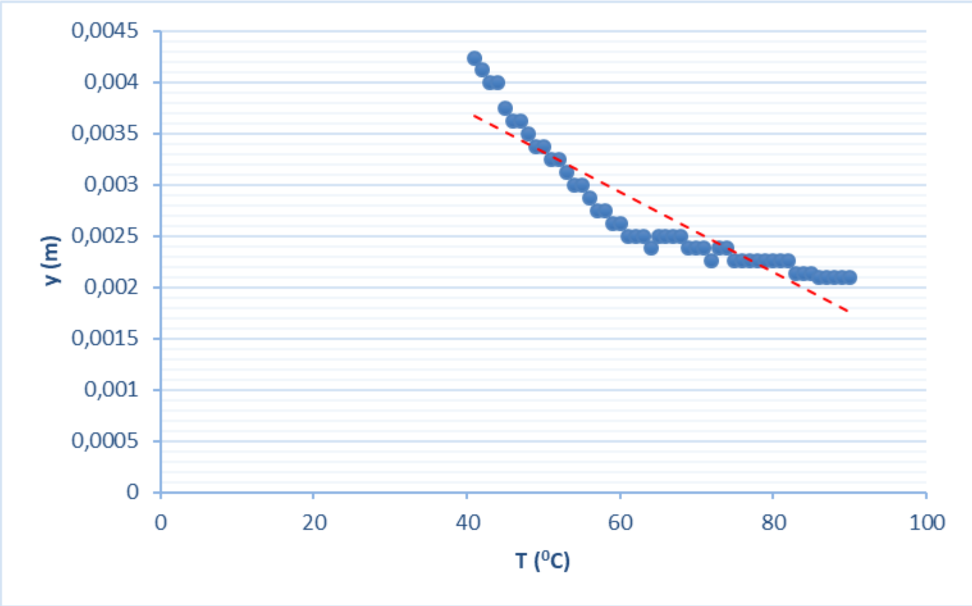


g)

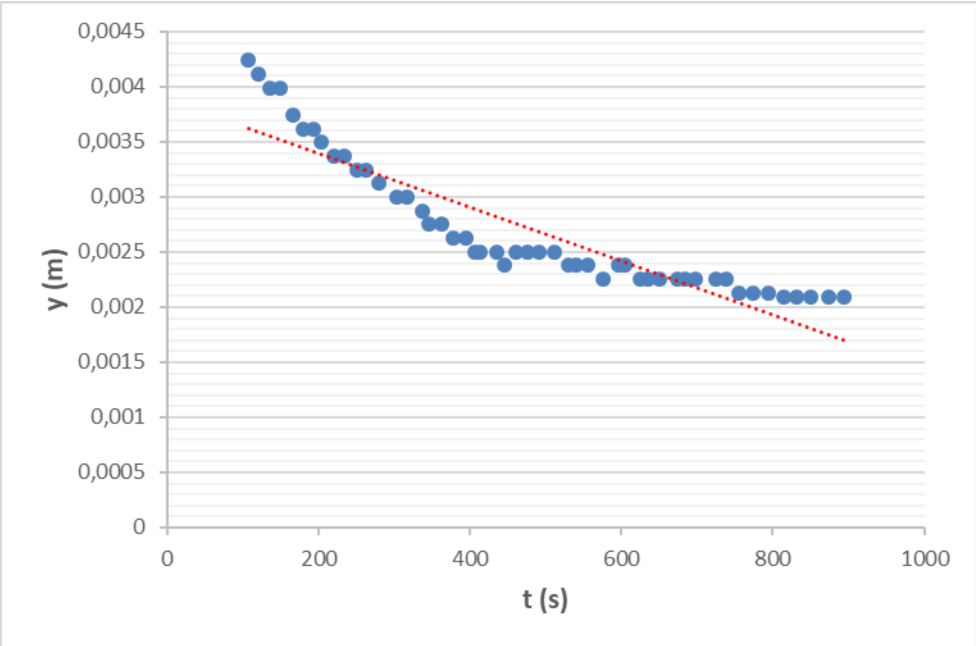
FIGURE 2. (a) Design of the primary module used in previous researches, (b) the re-design of the primary module, (c) mercury thermometer used in previous researches, (d) thermocouple sensors (digital) used to measure temperature, (e) millimeter blocks used for measuring the distance of diffraction patterns in previous researches, (f) Tracker software to analyze the distance of diffraction patterns, (g) Heater cover to minimize water vapor.

Evaluation of the Experiment Results

Evaluation of the developed experimental apparatus was conducted through analysis of several physical parameters that can be measured, i.e., temperature (*T*), time (*t*) and the distance of the first order of dark diffraction pattern to center pattern (*y*). FIGURE 4 (a) shows the graph obtained from plotting the *y* and *T*, which qualitatively show the relationship between *y* and *T*. FIGURE 4 (b) shows the relationship between *y* and *t*.



a)



b)

FIGURE 4. (a) Plot of *y* (the distance of the first order of dark diffraction pattern to center pattern) vs. *T* (temperature), (b) Plot of *y* (the distance of the first order of dark diffraction pattern to center pattern) vs. *t* (time).

As seen in FIGURE 4 (a), when the temperature increases the distance of the first order of dark diffraction pattern to center pattern decreases (the generated diffraction pattern narrows down). The rapid temperature rise over time causes the distance of the first order of dark diffraction pattern to center pattern decreases, as seen in FIGURE 4 (b). This shows that the width of the metal gap increases due to thermal expansion of the metal. From the results of the experiment, the relationship between the temperature rise of each 1°C and 1/*y* is shown in FIGURE 5.

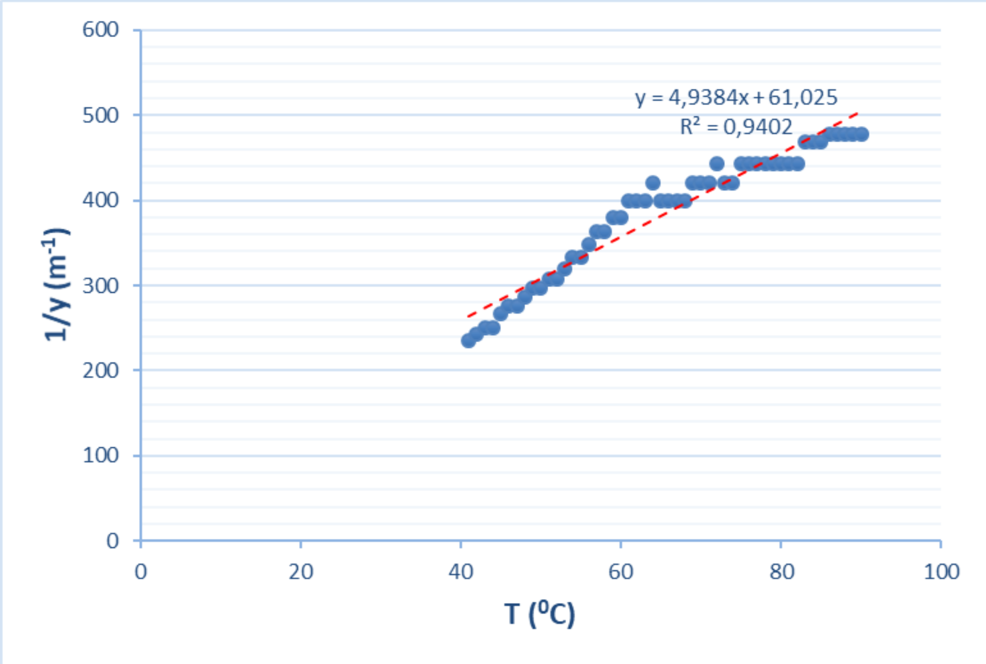


FIGURE 5. (a) Graph 1/*y* (*y* = first order dark distance) with respect to *T* (temperature).

The curve in FIGURE 5 is obtained by regression analysis between data 1/*y* (*y* = distance of diffraction pattern) to T (temperature) obtained by a linear relationship. From the graph obtained a gradient or slope graph value which is then used to calculate the value of aluminum metal expansion coefficient using Equation (1).

$$\frac{1}{y} = \frac{\alpha L_0}{D\lambda} T + \left(\frac{1}{y_0} - \frac{\alpha L_0 T_0}{D\lambda}\right) \quad (1)$$

From the plot in FIGURE 5, the relationship between 1/*y* and *T* is obtained by a linear regression analysis, which is also consistent with the results of a study by Bharmanee, et al., (2008) and Fakhruddin (2006). The experimental data shows the increase of temperature causes the width of the metal gap to increase, which causes the distance the diffraction pattern to narrow. Thus it can be concluded that the temperature rise is inversely proportional to the distance of the diffraction pattern. Experimental data from the analysis of measurements of aluminum metal long expansion coefficients are shown in TABLE 2. Analysis carried out included accuracy analysis by calculating relative error through Equation (2) and precision analysis carried out by calculating standard deviation using Equation (3) and relative standard deviation from repetitive measurement using Equation (4).

$$\text{Relatif Error} = \left|\frac{\alpha_{eksperimen} - \alpha_{referensi}}{\alpha_{referensi}}\right| \times 100\% \quad (2)$$

$$\text{SD} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad (3)$$

$$\text{SDR} = \frac{SD}{\bar{x}} \times 100\% \quad (4)$$

TABLE 2. The results of data analysis of linear thermal expansion coefficient of aluminum

Coefficient of Linear Expansion Reference (/°C)	Coefficient of Linear Expansion Experiment (/°C)	Standard Deviation (SD)	SD Relatively
$23.000 \times 10^{-6}/^{0}C$	22.972×10^{-6} 23.173×10^{-6} 23.438×10^{-6} 22.871×10^{-6} 23.047×10^{-6}	2.186×10^{-7}	0.95%
$x = (23.100 \pm 0.2186)\times10^{-6}/^{0}C$ with relative error 0.43%			

TABLE 2 provide an illustration of the quality of the produced data. Accuracy, which describes the similarity of the experimental data compared to a reference, is analyzed based on the comparisons which was made based on a relative error (the smaller the error, the greater the accuracy). The relatively small error value indicates that the measurement has a high level of accuracy. From the five measurements, the data that is fairly constant, which indicates that the measurement has a high level of consistency, as evidenced by the relatively small standard deviation and standard deviation. Standard deviation is a benchmark that shows the level of precision in measurement, the smaller the standard deviation, the higher the precision.

SUMMARY

The development of experimental apparatus for measuring the linear thermal expansion coefficient by means of digital video-based analysis if the diffraction pattern has been conducted. The development includes the re-design of the primary module holder, the use of temperature measurement with thermocouple sensors connected to the PC, and the distance measurement of diffraction patterns using digital video analysis techniques using Tracker software yielded a very good results, i.e., the ones with high degree of accuracy and precision. The linear thermal expansion coefficient of aluminum from the experiment is $(23.100 \pm 0.2186) \times 10^{-6}/^{0}C$ with an average of relative error of 0.43% and a relative standard deviation of 0.95%.

The experimental apparatus for measuring the linear thermal expansion coefficient is expected to contribute to the development of physical experiments regarding expansion and diffraction, primarily for the high school level. Future possible works includes the measurement of linear thermal expansion coefficient of other metals.

REFERENCES

Bharmanee, P 2008, 'Measurement of Thermal Expansion Coefficient for a Metal by Diffraction Patterns from a Narrow Slit', *Kasetsart J. (Nat. Sci.)*, vol. 42, no. 5, pp. 346-350.

Brown, D & Cox, AJ 2009, 'Innovative Uses of Video Analysis', *The Physics Teacher,* 47(10.1119/1.3081296), pp. 145 - 149.

Fakhrudin, H 2006, 'Quantitative Investigation of Thermal Expansion Using Singel-Slit Diffraction', *The Physics Teacher*, 2006, vol. 44, no. 2, pp.82-84, doi: https://doi.org/10.1119/1.2165434

Ferawati, R & O 2012, 'Penentuan Koefisien Pemuaian Panjang Alumunium (Al) Menggunakan Metode Difraksi Celah Tunggal', *Prosiding Seminar Nasional Quantum 2012, Pendidikan Fisika UAD,* Issue 978-979-19438-2-6, pp. 57-61.

Gonzales, RC, Woods, RE 2001, *Digital Image Fundamental in The Digital Image Processing, 2th ed*, Prentice-Hall, New Jersey, ch.2, pp. 34-70.

Halliday, D & Resnick, R 1997, 'Difraction. In: *Physics, 3rd* Edition', USA: Jhon Wiley & Sons, Inc., pp. 733 - 744.

Imai, H & Bates, W 1981, 'Measurements of The Linear Thermal Expansion Cofficient of Thin Specimens', *Journal of Physics : Scientific Instruments,* Volume 14, p. 7.

Inbanathan, S, Moorthy, K & Balasubramanian, G 2007, 'Measurements and Demonstration of Thermal Expansion Coefficient', *Journal of The Physics Teacher*, Volume 45, pp. 566 - 572.

Pujayanto, et al 2016, 'Pembuatan Alat Percobaan Pengukuran Koefisien Pemuaian Panjang Logam dengan Difraksi', *Prosiding Seminar Nasional Pendidikan Sains (SNPS)*, pp. 263-267.

Walker, J 2014, *Thermal Expansion: in the Fundamental of Physics Halliday & Resnick, 10th ed*, Jhon Wiley & Sons inc, USA, ch.18, sec.3, pp.520-522.

Wee, LK, Lee,TL 2011, 'Video Analysis and Modeling Tool for Physics Education, A workshop for Redesigning Pedagogy', *Workshop at the 4th Redesigning Pedagogy International Conf., Singapore*.

Wulandari, PS, Radiyono, Y 2015, 'Penggunaan Metode Difraksi Celah Tunggal pada Penentuan Koefisien Pemuaian Panjang Logam Alumunium (AL)', *Jurnal Materi dan Pembelajaran Fisika (JMPF)*, vol. 5, ISSN: 2089-6158.