

INVESTIGATING THE CHARACTERISTICS OF LARGE-VOLUME PVT SCINTILLATION DETECTORS IN THE RADIATION PORTAL MONITORS USING MONTE CARLO SIMULATIONS

Cao Van Hiep*, Dinh Kim Chien, Dinh Tien Hung, Nguyen Thi Thoa

Abstract: This paper presents the characteristics determination process of the large-size Polyvinyl Toluene (PVT) scintillation detectors using MCNP5 simulation code. The energy spectra using a ^{137}Cs calibration source, absolute efficiency in the energy range of $50 \div 3000$ keV, and the angular response of the EJ-200 $50 \times 50 \times 5$ cm³ and $25 \times 25 \times 5$ cm³ are investigated. The simulated energy spectra are in good agreement with the experimental spectra. The results of determining the absolute efficiency show that the EJ-200 $50 \times 50 \times 5$ cm³ and $25 \times 25 \times 5$ cm³ plastic detectors have detection efficiencies of 16,3% and 9,2%, respectively, at 10cm source-to-detector distance, and down to 0,6% and 0,17% at 100 cm source-to-detector distance. The angular responses of the detectors show that the detection efficiency value reached $\geq 90\%$ of the maximum value with the incident angle less than $5\pi/6$. The results can be applied in the process of design optimization of plastic-based radiation portal monitors.

Keywords: Radiation portal monitors (RPMs); Scintillation detectors; Monte Carlo simulation method.

1. INTRODUCTION

Plastic scintillator is a scintillating material in which the primary fluorescent emitter, called a flour, is suspended in the base, a solid polymer matrix. While this combination is typically accomplished through the dissolution of the flour prior to bulk polymerization, the flour is sometimes associated with the polymer directly. Plastic scintillators are produced in a wide variety of shapes and sizes. Plastic scintillation detectors with polystyrene and polymethylmethacrylate substrates have been experimentally studied, but these types of materials are not commonly used in the commercial system due to the physical properties of the scintillator. Polyvinyl Toluene (PVT)-based scintillation detectors have the best light transmission among plastic detectors and are commonly used in radiation measurement systems which require high sensitivity (radiation portal monitors, surface contamination measuring systems, etc.).

Radiation Portal Monitors (RPMs) are passive radiation detection devices used for the screening of individuals, vehicles, cargo or other vectors for detection of illicit sources such as at borders or secure facilities [1, 2]. RPM is often equipped with large gamma and neutron detectors that increase the ability to detect radioactive sources with low activity. First generation RPMs often rely on PVT scintillators for gamma counting. They provide limited information on energy of detected photons, and as a result, they were criticized for their inability to distinguish gamma rays originating from nuclear sources from gamma rays originating from a large variety of benign cargo types that naturally emit radioactivity. However, the most commonly installed gamma detector on RPMs is a scintillation detector using PVT scintillators due to its low-cost, large crystal size, and durability [3]. Due to their low average atomic mass and density, PVT scintillators tend to have low energy resolution when compared to other commonly used detectors such as High Purity Germanium (HPGe), NaI(Tl),... Detector characteristics such as absolute efficiency, angular dependences can help researchers calculate the sensitivity, effective working area of RPM, thereby giving the optimal design for the

system. The optimally designed RPM system needs to meet the following criteria: stable operation, high detection sensitivity, low false alarm rate.

This study presents the large-sized PVT scintillation detector characteristics determination process using MCNP5 by (i) simulating the energy spectrum obtained from the detector using ^{137}Cs standard radiation source; (ii) calculate absolute detection efficiency according to source-to-detector distance and incident gamma energy; (3) Investigate the dependence of absolute recording efficiency on the source angle.

2. MATERIALS AND METHOD

2.1. Gamma spectrometer using EJ-200 plastic scintillation detector

The EJ-200 PVT scintillation de investigated in this study includes: (1) Detector R500*50A500/2M-HV-E2-P with the crystal size of $500 \times 500 \times 50 \text{ mm}^3$ and (2) R250*50A250/ 2M-HV-E2-P the with crystal size $250 \times 250 \times 50 \text{ mm}^3$ (SCIONIX, Inc.). The three-dimension structure of the two detectors is illustrated in figure 1.

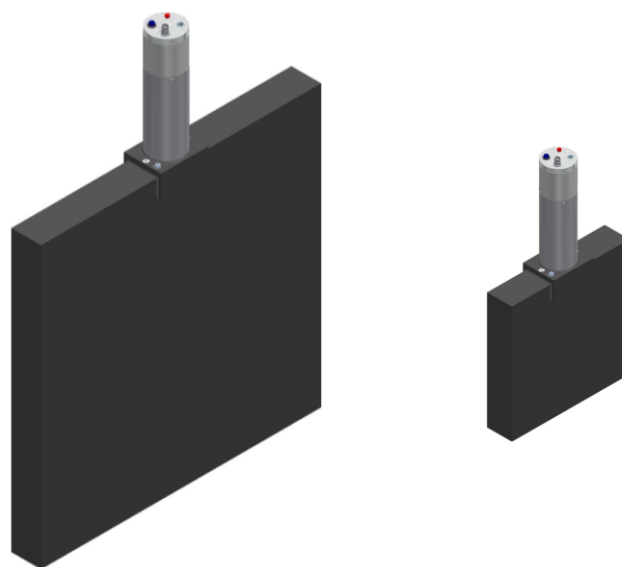


Figure 1. (a) Plastic detector EJ-200 size $50 \times 50 \times 5 \text{ cm}^3$ and (b) $25 \times 25 \times 5 \text{ cm}^3$.

The main component of the scintillator is Polyvinyl Toluene compound - a synthetic polymer of Alkylbenzenes with the linear chemical formula of $[\text{CH}_2\text{CH}(\text{C}_6\text{H}_4\text{CH}_3)]_n$. The general characteristics of the two detectors are presented in table 1.

Table 1. General characteristics of the EJ-200 PVT scintillation detector.

Specification	Unit	Value
Polymer base		Polyvinyl Toluene
Light output in % relative to anthracene	% Anthracene	64
Scintillation efficiency, photons per 1 MeV e^-	Photon/1 MeV e^-	10000
Wavelength of max emission	nm	425
Rise time	ns	0,9
Decay time constant	ns	2,1
Number of H atoms per cm^3	$\times 10^{22}$	5,17

Number of C atoms per cm ³	$\times 10^{22}$	4,69
Number of electron per cm ³	$\times 10^{23}$	3,33
Density	g/cm ³	1,023
Refractive index		1,58
Photomultiplier tube		Ø51mm, ETL 9266
Dimension	mm	250×250×50 500×500×50

The signal from the detector preamplifier was amplified by CANBERRA 2022 spectroscopic amplifier (CANBERRA, Inc. USA) with a shaping time constant of 1 μ s. The shaped signal was analyzed on a digital multichannel analyzer APG7300A (TechnoAP, Japan). The gamma spectrum is transmitted to the computer for storage, display and analysis. The experiment setup of the measuring system is presented in figure 2.

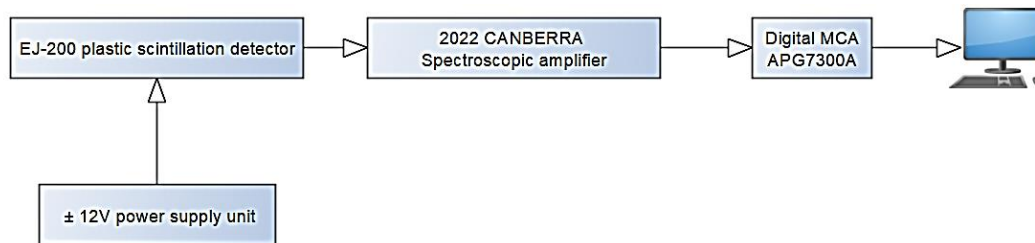


Figure 2. Experimental setup of the measuring system.

In this study, the experimental gamma spectra were obtained using ^{137}Cs calibration with a source-to-detector distance of 30 cm and the acquisition interval of 10 minutes. The radioactive source is disc-shaped with a diameter of 20 mm, the outer shell of the source is covered with a 1mm thickness of pure aluminum. The source has an activity of 135,9 kBq (± 1.36 kBq) at the time of measurement. The experimental gamma spectra were used to provide resolution correction parameter for the simulated energy spectra obtained from the MCNP5.

2.2. Monte Carlo simulation using MCNP-5

MCNP is a general-purpose Monte Carlo N-Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport. The program was originally developed by the Monte Carlo group and is now under the development of Transport Methods Group (XTM group) of Applied Theoretical & Computational Physics Division (X Division) at Los Alamos National Laboratory (LANL - USA). MCNP was distributed through RSICC (Radiation Safety Information Computational Center) at Oak Ridge National Laboratory, USA. Every two or three years they release a new version of the program. MCNP uses standard nuclear data libraries to simulate particle transportation processes. The MCNP program controls this process by seeding pseudo random numbers between 0-1 according to a given statistical rule, and the model is performed on a computer with the required number of trials often being very large.

In this study, the geometry of the detector in MCNP5 was constructed based on the dimensions described in the technical documentation which provided by the manufacturer. The gamma pulse height distribution from the scintillator was obtained using Tally F8 – Pulse height tally.

2.3. Gamma spectra simulation

The distribution of gamma energy deposited in the sensitive volume of scintillator was obtained using Tally F8 with a separation of 10 keV/bin. The Gaussian energy broadening parameters (GEB parameters) were selected in the FT8 GEB card to homogenize the simulated spectral with the experimental spectrum. The energy resolution at the deposited energy E on the spectrum is modified according to equation (1):

$$FWHM = a + b\sqrt{E + cE^2} \quad (1)$$

where a (MeV), b ($MeV^{\frac{1}{2}}$) and c are the correction coefficients investigated from the experimental spectrum. The energy resolution correction parameter for the EJ-200 plastic scintillation detector in this study is $a = -0,00198$ (MeV) ; $b = 0,1636$ ($MeV^{\frac{1}{2}}$) and $c = 0,8471$.

The region outside the detector is assumed to be air at standard conditions with a density $\mu_a = 1,2754.10^{-3} g.cm^{-3}$. The Compton scattering background on the experimental spectra is always higher than the simulated spectrum due to the contribution of scattering gamma ray from surrounding materials. Therefore, to minimize this discriminant, a 30mm thick layer of aluminum was placed behind the plastic scintillator to simulate the scattering contribution.

2.4. The dependence of absolute detection efficiency on sour-to-detector distance and incident gamma energy

2.4.1. Simulation of absolute detection efficiency

The absolute efficiency is defined as the percentage of detected event in the detector sensitive volume. The detection mechanism of the detector is based on the interaction of radiation with the detector material. The detection efficiency of radiation detector includes: absolute efficiency, intrinsic efficiency, total efficiency, and full-peak efficiency. Since the primary interaction of radiation with plastic scintillator is Compton scattering, the full- peak efficiency is not of interest on these types of detectors. In this study, the absolute efficiency of two plastic detectors was investigated through the ^{137}Cs gamma spectrum obtained on MCNP5 simulation code. The energy spectrum using Tally F8 was normalized to unity per particle history, so the simulated absolute efficiency is calculated as follows:

$$\varepsilon_p(E) = \sum_{E'=E_{min}}^{E'=E_{max}} P(E') \quad (2)$$

where $\varepsilon_p(E)$ is the absolute efficiency corresponding to the deposited photon energy E , $P(E')$ is the tally F8 value at the energy bin E' , E_{min} , E_{max} are the lower and the upper threshold energy of the simulated gamma spectra, respectively. In this study E_{min} set at 20 keV.

2.4.2. The dependence of absolute detection efficiency on the source-to-detector distance and incident gamma energy

The dependence of absolute efficiency on the source-to-detector distance was investigated by changing the source position on the simulated configuration. In this study, the gamma emitter is located at 5 locations with the following distances to the

detector surface: 10, 20, 30, 50, and 100 cm. The number of particle history during the simulation is set from $1 \times 10^6 - 1 \times 10^8$ and is proportional to the square of the source-to-detector distance to minimize the statistical error of the simulation results.

The dependence of absolute detection efficiency on gamma ray energy was investigated through simulation with various emission gamma energy. In this study, the gamma emission energies were set at the following values: 50, 100, 200, 400, 600, 800, 1000, 1200, 1400, 2000, and 3000 keV. The gamma emitter is located at a distance of 50 cm from the detector surface.

2.5. Angular dependence of absolute detection efficiency

The absolute recording efficiency values of 02 detectors were also investigated in 2 directions with 9 measuring positions corresponding to the angle of incidence from 0 to $\pi/2$ (radians). An angle of incidence of 0 radians corresponds to a position perpendicular to the detector surface center. The investigated positions of angular response are shown in figure 3 with the incident angle varying from 0 to $\pi/2$ with the increment of $\pi/16$. The absolute detection efficiency for different values of incidence angle was normalized by the formula:

$$\varepsilon_{p-normalized}(E, \theta) = \frac{\varepsilon_p(E, \theta)}{\varepsilon_p(E, 0)} \quad (3)$$

where $\varepsilon_p(E, \theta)$ is the absolute efficiency at incident angle θ , $\varepsilon_p(E, 0)$ is the absolute recording efficiency for the incident angle 0.

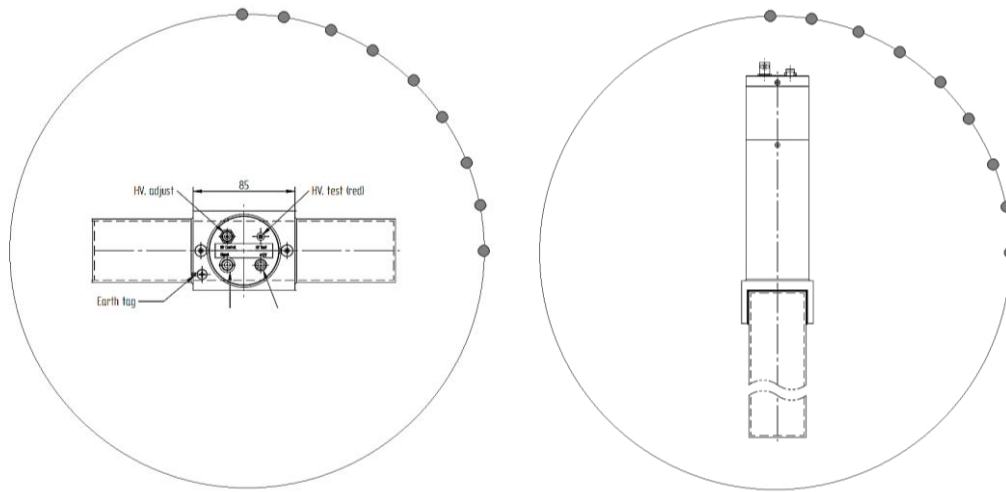


Figure 3. Investigated positions for angular response of plastic detector EJ-200 in the (a) horizontal and (b) in the vertical direction.

3. RESULTS AND DISCUSSION

The normalized experimental energy spectrum and simulated spectrum are presented in figure 4. The simulated spectrum on MCNP has similar shape to the experimental measurement spectrum. In the energy region greater than 800 keV, on the experimentally measured energy spectrum, there are counts due to the pulse pile-up and non-subtracted background radiation, these phenomena do not occur during the simulation process in MCNP, therefore, there is a difference between the two spectrums in this energy region. In

the energy range of 70 – 800 keV, the relative ratio between the simulated energy spectra and the experimental energy spectrum is $0,98 \pm 0,03$. This proves that the detector model, source description and the energy resolution correction parameters are built and selected in accordance with the practical measurement system. The absolute efficiency, the dependence of the detection efficiency on gamma ray energy, source-to-detector distance and angular dependence are also investigated based on this simulation configuration.

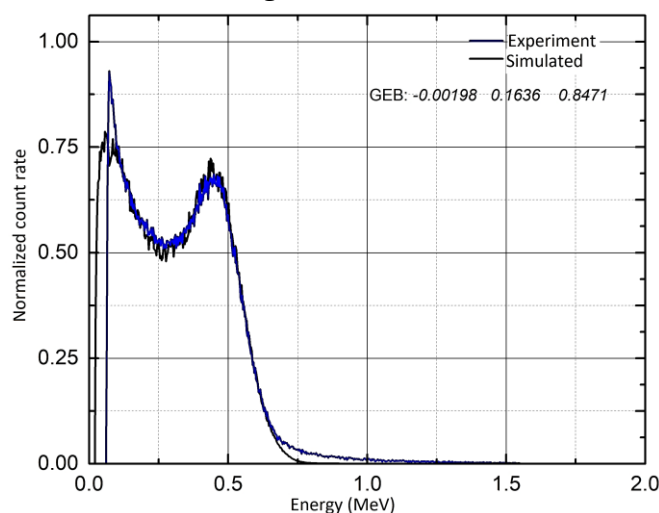


Figure 4. Experimental and simulated spectra for detector EJ-200 using ^{137}Cs calibration source.

The predominant interaction mechanism of gamma rays in the sensitive volume of the detector is Compton scattering, photons tend to leave a fraction of their energy in the material, resulting in no full-energy peaks on the obtained energy spectrum. The energy peak appearing on the spectrum corresponds to the maximum scattering energy ~ 425 keV.

3.2. The dependence of absolute efficiency on gamma energy and source-to-detector distance

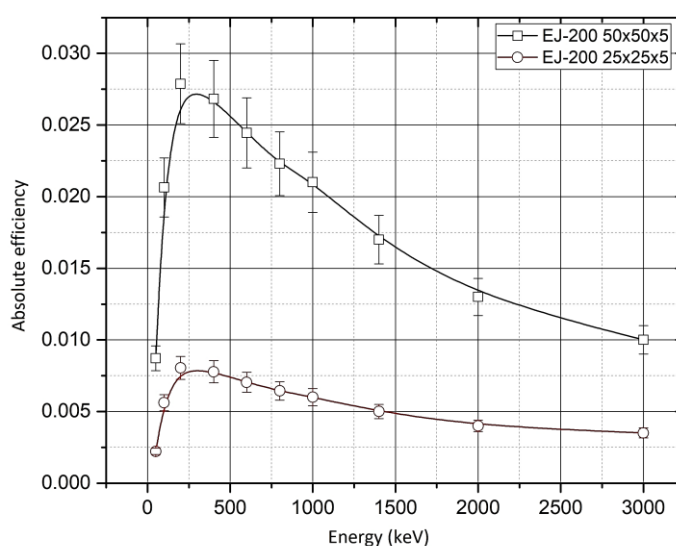


Figure 5. The dependence of the absolute efficiency to the incident gamma energy.

The dependence of the absolute efficiency of 02 detectors investigated according to incident gamma energy in the range of 50 keV $\div$ 3000 keV is shown in figure 5. Since both detectors have the same crystal thickness of 50 mm, these detectors have maximum recording efficiency at the same energy value ($\sim 150 \div 200$ keV). Gamma emission energy < 150 keV is strongly scattered and absorbed at the radiation source housing and the vinyl wrapping layer of the PVT detectors. The high-energy gamma ray has a probability of passing through the detector, not interacting in the sensitive volume, causing a decrease in recording efficiency. Detector size $50 \times 50 \times 5$ cm³ has a recording efficiency $1,7 \div 3,75$ times higher than detector $25 \times 25 \times 5$ cm³ in the investigated energy region.

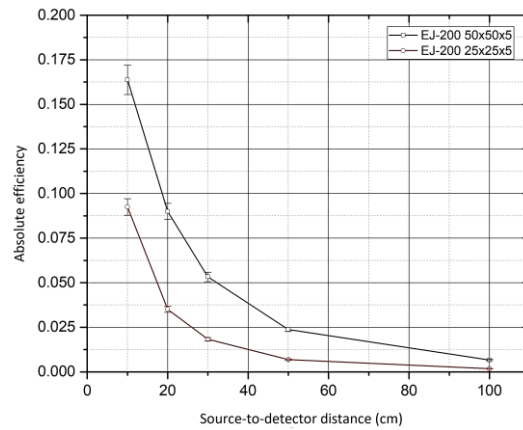


Figure 6. The dependence of the absolute efficiency on the source-to-detector distance (^{137}Cs calibration source).

3.3. Angular response of the absolute efficiency

Absolute detection efficiency for vertical and horizontal direction are shown in figure 7. This efficiency value is calculated for ^{137}Cs calibration source.

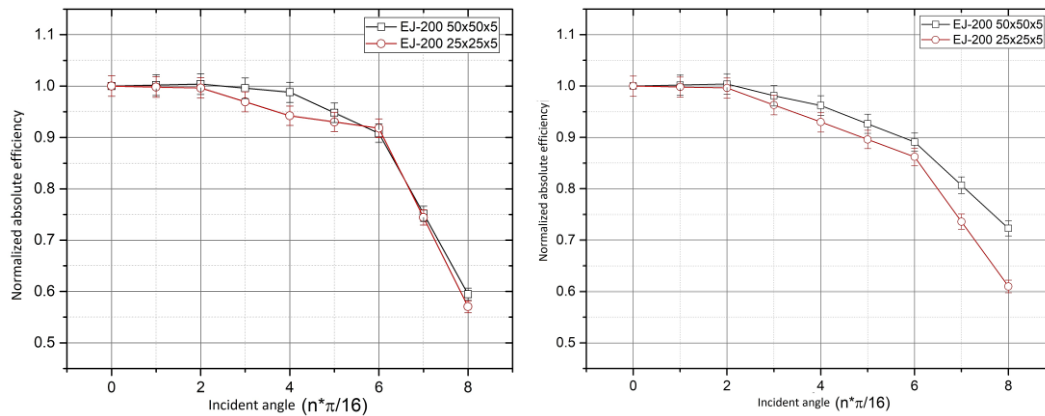


Figure 7. Variation of the absolute detection efficiency in the (a) vertical and in the (b) horizontal direction (normalized at 0 radians).

As shown in the figure 8, in both the vertical and horizontal directions, the angular response of both detectors still reaches $> 90\%$ with the incident angle of the source $< 5\pi/16$. However, with an incident angle greater than this value, the angular response of the detector decreases rapidly. At the incident angle of $\pi/2$, the angular response of both detectors reached $\sim 60 \div 70\%$ maximum value in the vertical and horizontal directions.

4. CONCLUSIONS

The study investigated the characteristics of 02 large-sized EJ-200 plastic scintillation detectors equipped on the radiation portal monitors using MCNP5 simulation code. The simulation model is verified by comparing experiment gamma spectra measured with ^{137}Cs calibration source. The source-to-detector distance and energy dependence of absolute detection efficiency are calculated from the simulated energy spectrum. In addition, angular response of the detector was also investigated in this study. The simulation results can be used in design optimization process of radiation portal monitors for pedestrians or vehicles.

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TÓM TẮT

KHẢO SÁT ĐẶC TÍNH CỦA ĐẦU DÒ NHẬP NHÁY PVT THỂ TÍCH LỚN LẮP ĐẶT TRÊN CÔNG GIÁM SÁT PHÓNG XẠ SỬ DỤNG MÔ PHỎNG MONTE CARLO

Bài báo này trình bày quá trình sử dụng mô phỏng Monte Carlo (MCNP5) nhằm xác định các đặc tính của đầu dò nhập nháy Polyvinyl Toluence (PVT) thể tích lớn thông việc xác định phổ năng lượng sử dụng nguồn đồng vị ^{137}Cs , hiệu suất ghi tuyệt đối trong dải năng lượng $50 \div 3000 \text{ keV}$ và xác định đáp ứng góc của detector PVT $50 \times 50 \times 5 \text{ cm}^3$ và $25 \times 25 \times 5 \text{ cm}^3$. Phổ năng lượng thu được từ quá trình mô phỏng phù hợp tốt với kết quả đo thực nghiệm. Kết quả xác định hiệu suất ghi tuyệt đối cho thấy detector PVT $50 \times 50 \times 5 \text{ cm}^3$ và $25 \times 25 \times 5 \text{ cm}^3$ có hiệu suất ghi lần lượt là 16,3% và 9,2% tại khoảng cách đặt nguồn 10 cm và giảm xuống 0,6% và 0,17% tại khoảng cách 100 cm. Kết quả khảo sát sự phụ thuộc của hiệu suất ghi theo góc cho thấy giá trị hiệu suất ghi đạt $\geq 90\%$ hiệu suất ghi cực đại với góc đặt nguồn $\leq 5\pi/6$. Các kết quả nghiên cứu có thể áp dụng trong quá trình tối ưu hóa thiết kế các công giám sát phóng xạ sử dụng detector plastic kích thước lớn.

Từ khóa: Công giám sát phóng xạ; Detector nhập nháy; Phương pháp mô phỏng Monte Carlo.

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Author affiliations:

Military Institute of Chemical and Environmental Engineering (MICEE).

*Corresponding author: caovanhiepl23@gmail.com.