Study on Penetration of 4-MeV Electron Beam in Natural Rubber Latex

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Abstract. Vulcanization with electron beam irradiation provides unique and high efficient processing for natural rubber latex. It is one of very interesting and effective industrial applications of particle accelerators. A radio-frequency (RF) linear accelerator (linac) and electron beam irradiation system have been developed for natural rubber vulcanization at the PBP-CMU Electron Linac Laboratory of the Plasma and Beam Physics (PBP) Research Facility, Chiang Mai University (CMU). This accelerator will be able to produce electron beams with maximum energy up to about 4 MeV. In this research, we used a Monte Carlo simulation program called GEANT4 to study transportation of 4-MeV electron beam with Gaussian transverse distribution through a vacuum window, an air gap and natural rubber latex. The vacuum window is made of 50-micron titanium foil and the natural rubber was placed 18 cm downstream the foil exit. Simulations of electron depth dose and transverse distribution in these media were conducted. In addition, calculation on the irradiation throughput was performed. The study results revealed that for the electron beam with Gaussian transverse distribution and an average energy of 4.06 MeV, the irradiation area should be 2.8 mm×2.8 mm with the depth of 8 mm. With this condition, the irradiation time of 0.02 second will provide the dose of at least 50 kGy per irradiated point, which is enough for the rubber vulcanization process. The overall irradiation throughput rate is 6.865 kg/hr.

1. Introduction
The electron beam irradiation on materials provides unique effects that cannot be obtained by other methods. One of good examples, which is of our interest, is the electron beam irradiation for natural rubber vulcanization. The natural rubber, which is the hydro-carbon material call polysisoprene (C5H8)n, is used in many applications and products. However, the field natural rubber has low mechanical properties, which are low tensile strength and abrasion resistance. Thus, it has to be vulcanization to improve their properties before the usage. This is the process that defined by the cross-linking between individual polymer chains. In conventional way, vulcanization process can be done by adding sulphur or peroxide to the field natural rubber.
Accelerated electron beam irradiation is an alternative option of rubber vulcanization. It can be used to improve both chemical and physical properties of the natural rubber [1]. Energetic electrons penetrating through the medium and interacting with atomic electrons of rubber are result in energy transfer. The electron beam processing is an ionizing process, which is based on the Coulomb interaction. Secondary electrons are generated due to this interaction and excite the rubber molecules. As a result, free ions and radicals are produced. The cross-linking process is occurred when the bonds between these free radicals in the polymer chains are formed. The electron beam dose is an important parameter, which is defined by energy that irradiated material received per its mass. It is used to determine the effect of the irradiation such as cross-linking, scission, or curing. The absorbed dose that is required for cross-linking in polymer materials is in the range of 50-150 kGy [2].

2. Methodology
The RF linac for natural rubber vulcanization is under commissioning at the PBP-CMU Electron Linac Laboratory. In this accelerator system, electrons are emitted from the thermionic cathode and are first accelerated in the direct-current (DC) electron gun. The electrons with average kinetic energy of about 17 keV are then further accelerated in the RF linac structure to reach the maximum average kinetic energy of about 4 MeV. Lower beam energies can be obtained by adjusting the power of the input RF wave. The accelerated electron beam exits the accelerator system at the vacuum exit window made of a titanium foil. This material was chosen due to its low density and mechanical properties that can handle the large different pressure between the vacuum and air.

In this work, Monte Carlo simulations of electron beam transportation and interaction in the titanium window, air gap and the natural rubber latex were performed by using the program called Geometry ANd Tracking or GEANT4 [3]. This program is a non-commercial toolkit, which is widely used to study the charged particle beam transportation through matter. The GEANT4 simulations were conducted with the electron beam irradiation system as presented in figure 1 (a). The simulation is started in a vacuum tube at the position 6 cm prior the vacuum exit window. This tube is made of stainless steel with an inner and outer radius of 3.25 and 4.45 cm, respectively. The electron beam distribution used in this study has the energy in a range of 3.94 to 4.17 MeV (as shown in figure 1 (b)), which provides the mean energy of 4.06 MeV. This beam has a Gaussian transverse distribution with an rms size of 1.05 mm. Then, the beam passes through the 50-micron titanium foil to air. The distance from the titanium window to the surface of the rubber latex is 18 cm. Finally, the accelerated electrons penetrate in the natural rubber latex. The densities of the titanium foil and air used in this study are 4.5 and 1.225 x10^{-3} g/cm^3, respectively. Normally, the density of the natural rubber latex is 0.92 g/cm^3. However, the rubber latex that is used to form the product by molding technique has about 60% of rubber. Thus, we performed the Monte Carlo simulation with this condition.

Figure 1. (a) Layout of electron beam irradiation system that was built in the GEANT4 program. (b) The initial energy distribution for the electron beam with mean energy of 4.06 MeV.
3. Simulation results

The simulations were done in order to investigate the electron beam penetration depth and dose distribution in the natural rubber latex. The results of this study were used to estimate the electron beam irradiation throughput. In this study we considered that the RF linac can produce electron pulses with the average energy of 4.06 MeV and the electron current of 100 mA for 4 µs pulse width, which equivalents to $1.873 \times 10^9$ electrons per pulse. Based on the tests of the RF system for the accelerator, the machine could run with stable condition at the pulse repetition rate in a range of 25-200 pulses per second. Therefore, the maximum number of electrons per second can reach $3.8 \times 10^{11}$ electrons.

Simulation results reveal that after passing through the titanium window and 18 cm air gap the electron beam has remaining total energy of 99.98% of its initial value. Simulations of energy deposition in the natural rubber latex were then conducted. The simulated results in figure 2 show a typical characteristic of electron beam penetration curve. After the beam enters the rubber latex, the energy deposition increases before reaching the maximum value, which is caused by the collision of incident electrons with atomic electrons and nuclei of the rubber atoms. This process leads to ionization of rubber’s atoms that produces large amount of secondary electrons. These electrons have wide range of energy and angular distribution depending on energy and number of injected electrons as well as density and ionization energy of the irradiated material. They are emitted randomly and can collide to other atomic electrons and nuclei leading to more secondary electron production. This chain reaction will stop when injected electrons have not enough energy for ionizing the material atoms. At this point, the energy deposition curve reaches its maximum value. Then, the energy deposition starts to decrease until all electrons lose all their kinetic energies. As presented in figure 2 the beam can penetrate to about 2.5 cm in the rubber latex. The maximum energy deposition occurred at the position of 0.85 cm downstream the rubber surface. At this position, the electron beam energy deposition is about 16% higher than that at the surface. The optimum depth where the energy deposition is the same as at the rubber surface is 1.8 cm.

![Energy deposition of electron beam in the natural rubber latex.](image1)

![Transverse distributions of electron absorbed dose at the central axis for different depths.](image2)

At the rubber surface, the rms transverse size of the beam is 0.71 cm. The simulation results for transverse distribution of electron absorbed dose for different depths including the optimum depth of 1.8 cm at the central axis in this area are shown in figure 3. The beam with one pulse per second was used in this investigation. The results show that the absorbed dose decreases quickly at the depth deeper than 0.8 cm. The transverse distributions of the absorbed dose for different depths at the edge of this irradiation area were also studied. The simulated results in figure 4 show large differences of the dose values compared to those at the central axis. The electron beam provides extremely high dose at the central axis and decrease rapidly to the edge of the irradiation area, e.g. when consider at the surface of the rubber, the maximum dose at the central axis is about 15.5 times higher than the maximum dose at...
the edge. The electron beam irradiation in this considered area will result in a large difference of the vulcanized efficiency. The rubber molecules at the central axis will be over-vulcanized when the molecules at the edge received the proper dose.

![Figure 4. Transverse distributions of electron dose at the edge for different depths.](image1)

![Figure 5. Simulated transverse distributions of electron dose at the surface and at 0.8 cm.](image2)

The irradiation without any electron beam modification provides a large difference of the absorbed dose for different transverse positions. The high energetic electrons are accumulated at the central area around the beam axis and the low energy electrons from scattering and secondary electrons are located at the edges of the irradiated area. Thus, the irradiation area needs to be optimized and the result shows that for the irradiation area of 2.8 mm×2.8 mm, the maximum dose at the centre is around 27 kGy per pulse. Higher absorbed dose of only 2-5 times is needed to obtain the proper dose range for rubber vulcanization (50-150 kGy). When using the electron beam with the pulse repetition rate of 200 pulses per second, the required irradiation time is only 0.04 second. With this irradiation condition, the depth in the natural rubber latex where received at least 50 kGy electron absorbed dose is 0.8 cm. The transverse distributions of the absorbed dose on the surface and at the depth of 0.8 cm in the irradiation area of 2.8 mm×2.8 mm are compared in figure 5. The maximum dose on the surface is 185 kGy and at the depth of 0.8 cm is 78 kGy, which provides the ratio of the minimum and maximum dose of around 0.42. As a result, the rubber container should have the width and depth of 2.8 and 8 mm, respectively. The irradiation of the rubber latex in this suggested container will provide the proper rubber vulcanization for overall volume. The practical rubber container will have longer length than 2.8 mm as the it can be moved with the conveyer, which its moving step can be precisely controlled. Thus, the electron beam irradiation can be performed continuously. This optimal irradiation area and depth provide the irradiation throughput rate of 6.865 kg/hr.

4. Conclusion
The electron beam that is generated from the accelerator is passing through the 50-micron titanium window and 18 cm air gap before interacting with the natural rubber latex. Its total energy remains 99.98% with the rms transverse beam size of 0.71 cm at the rubber surface. With this area, electron beam dose at the edge and the center is very different. Thus, the irradiation area needs to be reduced to the optimal dimensions of 2.8 mm×2.8 mm×8 mm to receive the absorbed dose between 50-150 kGy and to provide the irradiation throughput of 6.865 kg/hr.

Acknowledgements
We would like to acknowledge the support from Chiang Mai University, the Thailand Center of Excellence in Physics, the Science and Technology Park Chiang Mai University (CMU STeP), the
Science Achievement Scholarship of Thailand (SAST) and the Development and Promotion of Science and Technology Talents projects (DPST).

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