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STEM

20 December 2017

Review of Literature

Introduction

For the past hundred thousand years, the Earth's climate has been changing slowly, but recently, the Earth has been heating up at an unprecedented rate (National Aeronautics and Space Administration [NASA], 2017a). Since the Industrial Revolution in the 1700s, humans have radically changed the Earth by consuming fossil fuels for energy and by clearing land for agriculture and cities (Environmental Protection Agency [EPA], 2016). The main cause for the increase in global temperatures is the increase in greenhouse gas emissions in the atmosphere. When the rays of the sun reach Earth, some of the rays are absorbed by the surface of the Earth, while others are reflected back into space. However, greenhouse gases in the atmosphere such as carbon dioxide, methane, nitrous oxide, and water vapor absorb some of the energy, thereby preventing the sun's heat from escaping into space. As the amount of carbon dioxide increased from 280 to 400 parts per million (ppm) in the last 150 years (see Figure 1), the Earth's

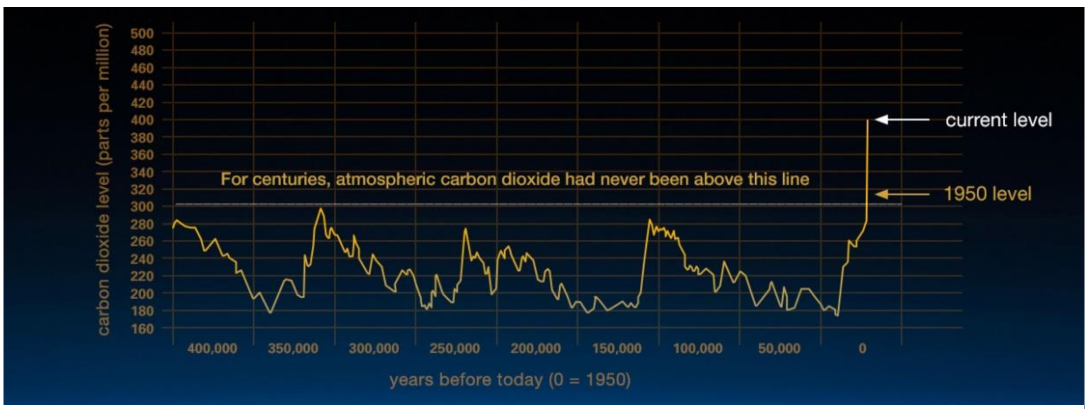

Figure 1. The graph shows the amount of carbon dioxide in the atmosphere for the past hundred thousand years (National Aeronautics and Space Administration, 2017b).

temperature has increased as well (NASA, 2017a). An increase in Earth's temperature can lead to more severe droughts, heat waves, coastal flooding, wildfires, hurricanes, and other natural disasters (NASA, 2017c).

Current Carbon Capture Methods

One potential solution to the increase in atmospheric carbon dioxide is carbon capture and storage (CCS), which attempts to capture, isolate, and store carbon dioxide. The carbon dioxide can either be captured directly from the atmosphere or before it is released from the power plants. Currently, there are several different methods to capture carbon dioxide (Goeppert, Czaun, Prakash, and Olah, 2012, p. 7833).

Biomass

One renewable method to capture carbon dioxide is through photosynthesis; plants already use solar energy to capture carbon dioxide from the air. However, photosynthesis is rather inefficient as only 0.5-2% of the energy from sunlight is converted into biomass, which means that vast amounts of land and water must be utilized to capture large amounts of carbon dioxide. As available real estate decreases, deforestation, which is already an immense problem, would increase to make more space for additional plants, which would contribute to an increase in carbon emissions (Goeppert, Czaun, Prakash, and Olah, 2012, pp. 7837-7838).

Na/Ca cycle

Chemical cycles are another way to capture carbon dioxide. In general, chemical cycles utilize a sorbent, which is capable of reacting with carbon dioxide to form a different substance. The new substance is then moved to a closed system where another reaction takes place to release the carbon dioxide and regenerate the sorbent. The carbon dioxide is stored, and the regenerated sorbent can be used to capture more carbon dioxide. There are a variety of chemical cycles that can be used to capture and store carbon dioxide (Zeman, 2007, 7559).

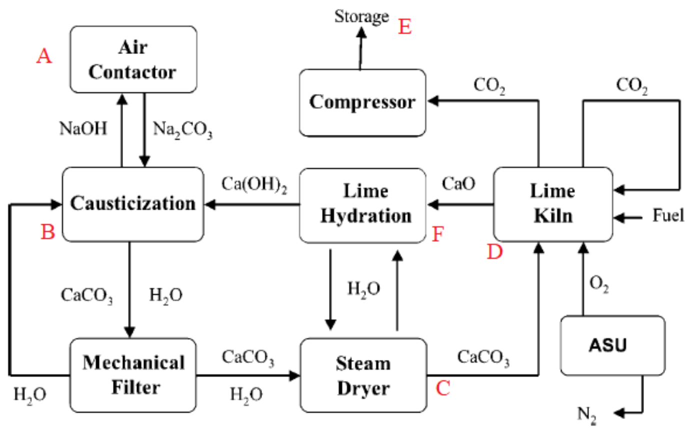

Figure 2. An overview of the Na/Ca cycle (Zeman, 2007, Figure 2, p. 7559)

One of these chemical cycles include the Na/Ca cycle (see Figure 2), which can be summarized in the following four equations:

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \tag{1}$$

$$Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3 \tag{2}$$

$$CaCO_3 \rightarrow CaO + CO_2 \tag{3}$$

$$CaO + H_2O \rightarrow Ca(OH)_2 \tag{4}$$

In this method, carbon dioxide is captured by reacting a sodium hydroxide solution with carbon dioxide gas (“A” in Figure 2). There are many ways to perform this reaction, one of which includes dripping the sodium hydroxide solution through the top of a packed column and flowing the carbon dioxide through the column’s bottom. As the carbon dioxide passes by the sodium hydroxide, the sodium hydroxide solution absorbs the carbon dioxide to produce sodium carbonate and water (eq. 1), and the sodium carbonate is then sent to a causticizer (B) where it reacts with calcium carbonate to form sodium hydroxide and calcium carbonate (eq. 2). The sodium hydroxide is sent back to the packed column (A), while the calcium carbonate is dried

(C) and sent to the calciner (D) where it is heated in a lime kiln to 900°C and separated into calcium oxide and carbon dioxide (eq. 3). The separated carbon dioxide can then be stored (E), and the calcium oxide is reacted with water (F) to form calcium hydroxide (eq. 4), which is sent back to the causticizer (B). While the decomposition of calcium carbonate into calcium oxide and carbon dioxide (D) is the only step that requires energy input, the amount that is needed is quite high (Zeman, 2007, 7558-60).

Potassium Carbonate Cycle

One cycle that does not require as much energy as other cycles is the potassium carbonate cycle. This cycle is also much simpler as it only requires one reversible reaction:

$$K_2CO_3 + H_2O + CO_2 \rightleftharpoons 2KHCO_3 \tag{5}$$

Solid potassium carbonate and water are combined to form a potassium carbonate solution. The solution can then be reacted with carbon dioxide gas, using a packed column or another method, to form a potassium bicarbonate precipitate. The potassium bicarbonate is moved to a closed system. Between 100°C and 200°C of heat is added to the potassium bicarbonate to regenerate carbon dioxide gas, water vapor, and solid potassium carbonate. The potassium carbonate can then be used again to capture more carbon dioxide (Polak & Steinberg, 2012, p. 6).

There are many advantages to the potassium carbon cycle. In water, the solubility of potassium carbonate is 112 g/100 mL while the solubility of potassium bicarbonate is 22.4 g/100 mL, so potassium carbonate will be more likely to precipitate than stay in solution. This trait is particularly useful because less thermal energy is needed to decompose the potassium bicarbonate while it is a precipitate rather than in solution (Polak & Steinberg, 2012, p. 6). The method is also quite simple as it only requires two reactions which can be described as $A + CO_2 \rightarrow ACO_2$, followed by $ACO_2 \rightarrow A + CO_2$, where A is a sorbent. In these types of reactions, only an apparatus to capture carbon dioxide and an apparatus to heat the product are needed to perform the cycle (Goeppert, Czaun, Prakash, and Olah, 2012, p. 7843). Other alkali metals can be used in place of potassium, such as lithium or sodium. However, not all of these elements are as efficient as potassium.

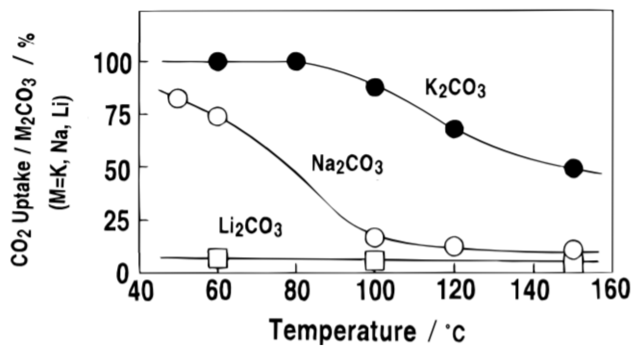

Figure 3. This graph shows the effect of temperature on the amount of carbon dioxide captured for potassium carbonate, sodium carbonate, and lithium carbonate (Hayashi et al., 1998, Figure 7, p. 188).

It has been shown that in an environment with 13.8 percent carbon dioxide and ten percent water vapor, potassium carbonate captures 100 percent of the carbon dioxide below 80°C (see figure 3). As the temperature increases above 80° C, it slowly becomes less efficient. Sodium carbonate could replace potassium carbonate (sodium carbonate cycle); sodium carbonate is similar but less efficient than potassium carbonate at lower temperatures. Lithium carbonate, on the other hand, is ineffective at capturing carbon dioxide by 60°C (Hayashi et al., 1998, p. 188). It is also interesting to note that in 2015, the average price of sodium carbonate, $140.88 per ton, was much lower than the average price of potassium carbonate, $595 per ton (United States Geological Survey [USGS], 2016, p. 70.2; USGS, 2017, p. 58.2).

Solar Concentrators

While the sodium carbonate cycle requires less heat energy than other cycles to remove carbon dioxide from the air, 100-200°C of thermal energy is still required to perform the regeneration reaction. There are many methods of producing this heat, including the use of solar concentrators. Solar concentrators, unlike regular ovens, utilize solar energy, a renewable source of energy, to focus a large area of sunlight into a smaller area to increase the temperature of a surface. The amount of energy that can be collected depends on the type of concentrator and its location in the world (Kaplan, 1985, p. 1).

Standard convex lens

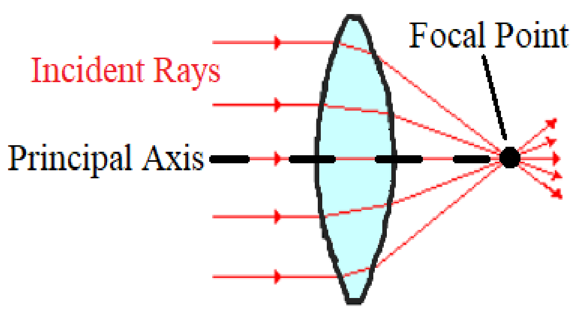

Figure 4a. Light rays parallel to the principal axis of a standard convex lens converge at the focal point (The Physics Classroom, n.d.).

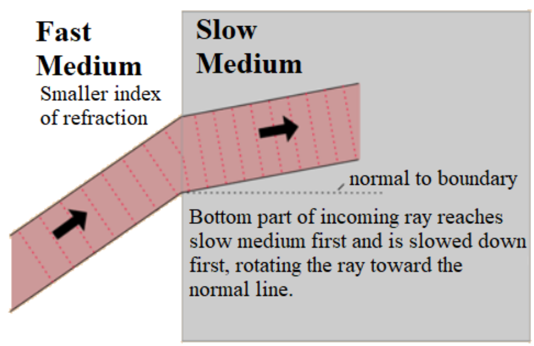

Figure 4b. When light travels through a different medium, the light ray bends due to a change in density of the material (Nave, n.d.).

Solar energy can be collected using standard convex lenses (Kaplan, 1985, p. 6). The convex lens uses refraction to concentrate incoming light rays, called incident rays, onto one point, called the focal point. The light ray must be parallel to the principal axis, which is the axis that runs horizontally through a lens, in order to converge at the focal point (see Figure 4a). Fortunately, the rays of the sun hitting the Earth's surface are considered parallel to each other (Khan, 2010a). The lens, which is denser than the air, causes the light to travel at a slower speed (Khan, 2010b). As a light ray enters the "slow medium," or the medium of higher density, one side of the ray hits the new medium before the other side, causing the first side to begin moving at a slower speed before the second side, which bends the light ray (see Figure 4b). The shape of the lens allows for all of the individual light rays hitting the lens to bend such that they converge at the focal point, allowing the energy in all the rays to concentrate in one place (Nave, n.d.).

Unfortunately, in order to collect and concentrate more energy, the surface area available for light collection must increase. To accommodate the surface area requirements of the sodium carbonate cycle, the size of the lens needs to increase, which means the thickness of a standard convex lens must increase as well. As a lens increases in width, the rays of the sun have to travel through the lens for a longer duration, and energy is lost. Most standard convex lenses are made of glass, which makes larger lenses heavier and impractical (Kaplan, 1985, p. 6).

Fresnel lens

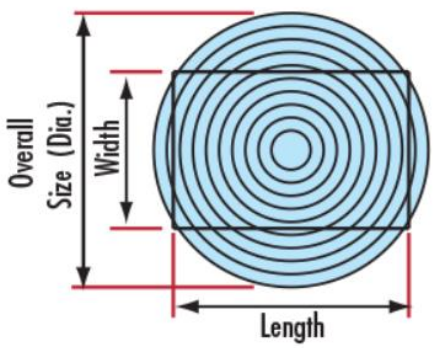

Figure 5a. The rings of a Fresnel lens (Edmund Optics, n.d., Figure 1).

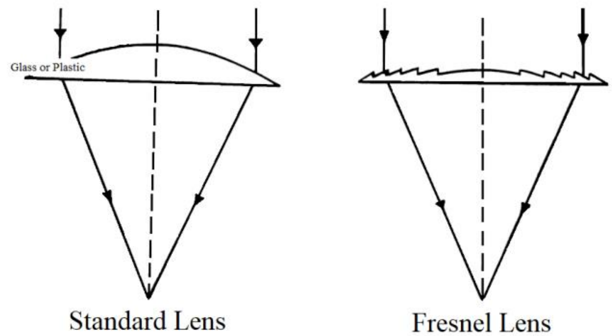

Figure 5b. The Fresnel lens is a flattened version of the standard lens (Kaplan, 1985, Figures 3 & 4, p. 6).

One solution to the problems of the standard convex lens is the Fresnel lens. The Fresnel lens is similar to the standard convex lens conceptually, but instead, it is a thin, flat sheet of glass or plastic filled with concentric grooves to imitate the standard lens (see Figures 5a & 5b). It is impossible to compress a curve onto a flat surface and not lose the angle of the curve, so Fresnel lenses utilize concentric grooves to recreate the effect of a standard lens. The angle of the grooves toward the center are lower, and the angle of the grooves toward the edge are higher to maintain the same curvature of a standard lens. Only the curvature of the surface of a medium affects the angle of refraction, not the volume of the medium. This property allows for a standard convex lens to be compressed into a flat sheet. As a result, Fresnel lenses are much lighter and therefore, can be much larger in surface area than a standard lens (Edmund Optics, n.d.).

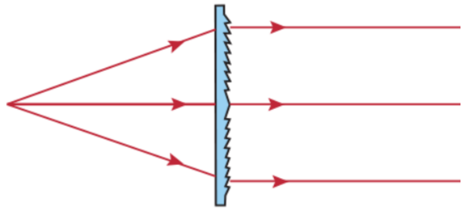

Figure 6a. Light collimation with a Fresnel lens (Edmund Optics, n.d., Figure 3)

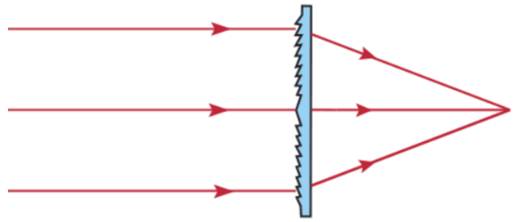

Figure 6b. Light collection with a Fresnel lens (Edmund Optics, n.d., Figure 4)

Fresnel lenses can be used for both light collimation and light collection (see figures 6a & 6b). If the source of light is coming from a single point, a Fresnel lens can refract the light rays to make them parallel. French physicist Augustin-Jean Fresnel (1788-1827) popularized the Fresnel lens by using this concept to improve the distance that the light of a lighthouse could travel. If the source of light were parallel rays, the Fresnel lens could be used to focus all the rays into a single point. (Edmund Optics, n.d.). A Fresnel lens can be used to concentrate the energy of the sun's rays into a single point to produce temperatures capable of reaching thousands of degrees Celsius (Kaplan, 1985, p. 17).

Parabolic dish

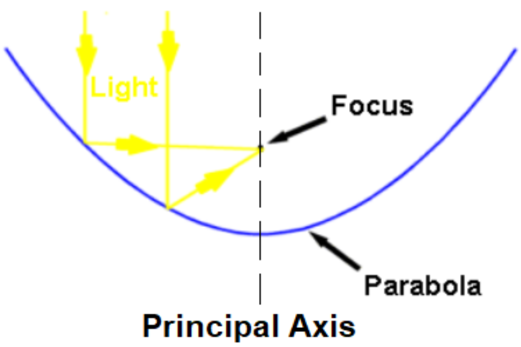

Figure 7a. Light rays parallel to the principal axis that are reflected off a parabola converge at the focus (Solar-Facts, n.d.).

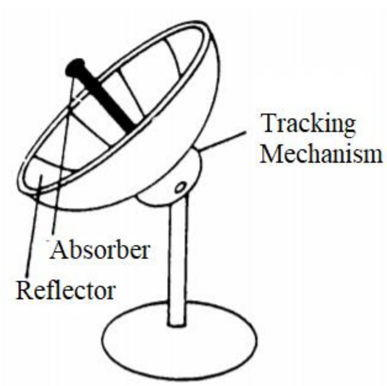

Figure 5. A parabolic dish utilizes a three-dimensional parabola to concentrate light on a focal point (Kaplan, 1985, Figure 7, p. 8).

In addition to lenses, which use refraction, curved mirrors can be used to capture the energy of the sun through reflection (see Figure 7a). One type of solar concentrator that utilizes reflection is the parabolic dish (see Figure 7b). The parabolic dish is a mirror in the shape of a three-dimensional parabola. When light rays parallel to the principal axis strikes the mirror, all of the light rays are reflected, and they converge at the focal point (Kaplan, 1985, p. 8). The mirrors of parabolic dishes are mainly made of one of two materials: silver or aluminum. Silver is highly reflective, yet it degrades easily, while aluminum is less reflective but can last longer than silver. To effectively concentrate sunlight, parabolic dishes need to be clean and smooth so that reflected sunlight can reach the focal point (Kaplan, 1985, p. 6).

Parabolic trough

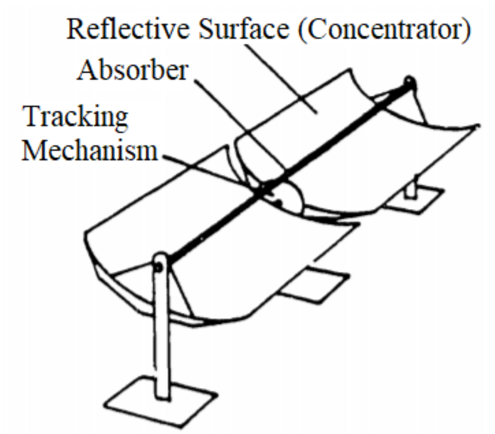

Figure 8. The parabolic trough uses a two-dimensional parabola to focus light along a line (Kaplan, 1985, Figure 9, p. 9).

A parabolic trough is like the parabolic dish, but instead of utilizing a three-dimensional parabola, it uses a two-dimensional one (see Figure 8). As a result, light is focused in a line, creating a channel for the sorbent to travel through. Just like the parabolic dish, the trough utilizes mirrors to reflect the sun (Kaplan, 1985, p. 9).

Problems with Solar Concentrators

The performance of solar concentrators is best on cloudless sunny days as direct radiation is needed. Clouds or fog reduce the intensity of the sunlight that reaches the concentrators and consequently, reduce the concentrators' effectiveness. The effectiveness of a concentrator also depends on its location in the world. Locations facing the sun directly receive more concentrated sunlight, and the sunlight travels less through the atmosphere, which allows for sunlight of higher intensity to reach the concentrators. However, places not directly facing the sun receive less concentrated sunlight and require the sunlight to travel through more atmosphere, causing the sunlight to be less intense by the time it reaches the concentrator (Kaplan, 1985, p. 4). The sun also moves from horizon to horizon throughout the day. If a concentrator does not move with the sun, the light rays will hit its surface at a less-than-ideal angle, changing the location and size of the area of concentrated light. Therefore, a solar concentrator needs a mechanism to track the sun throughout the day and the year to keep it aligned with the sun so that the light rays will always hit the same location. (Kaplan, 1985, p. 14).

Conclusion

With an increasing level of carbon dioxide in the atmosphere, it is necessary to lower its level before it causes too much damage to the environment. Carbon dioxide can be removed from the atmosphere through a variety of ways including through the use of biomass, the Na/Ca cycle, the potassium carbonate cycle, or the sodium carbonate cycle. However, biomass is inefficient, and the chemical cycles require a source of heat to regenerate the sorbent. The amount of heat energy needed for each chemical cycle differs, but the potassium carbonate and sodium carbonate cycles require only about 100-200°C of heat. Sodium carbonate, however, costs less than potassium carbonate. To reach temperatures of 100-200°C, solar concentrators, such as a Fresnel lens, can be used to concentrate and directly transfer energy from the sun into the sodium carbonate. Solar energy is also a renewable energy source, which will not contribute to the increase in carbon dioxide in the atmosphere. With this concept carbon dioxide removal, it could be possible to slow or reduce the amount of carbon dioxide in the atmosphere.

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