

CHAPTER 2

THEORY

This chapter aims to review the background of theories for the experiment designs and discussions under previous researches. It mainly consists of:

2.1 Types of carbon nanotubes (CNTs)

Carbon nanotubes (CNTs) have been the subject of a growing research effort since they were first observed by Iijima [1], especially once their potential for use across a wide variety of applications was realised. Research to date has revealed that CNTs possess exceptional physical and thermal conductivity properties and this has resulted in further research [2-3]. There are two main types of CNTs, these being, the single walled nanotubes (SWNTs) and the multi walled nanotubes (MWNTs) [4]. The thermal conductivity of CNTs has been measured at 3,000W/mK for MWNTs and 6,000 for SWNTs..

Figure 2.1 shows the shape and structure of SWNTs which are produced using carbon. Their diameter is measured on the nanometre scale and they can be many micrometres in length. The SWNT is in effect, a graphene sheet that is rolled up to form a minute tube shape. Graphene is a hexagonal lattice at an atomic scale made of carbon atoms utilising a covalent bond. The properties of the SWNT are determined by the way the graphene is rolled. SWNTs characteristics are defined by the chiral vector, $c_h = na_1 + ma_2 \equiv (n, m)$, where a_1 and a_2 are lattice vectors and n and m are integers multiples of the unit vector, relating to the number of carbon hexagon structures. Changing the axis of rotation will produce a different SWNT with the three variants being, armchair ($n = m$), zigzag ($m = 0$), or chiral type ($m \neq 0$ and $m \neq n$).

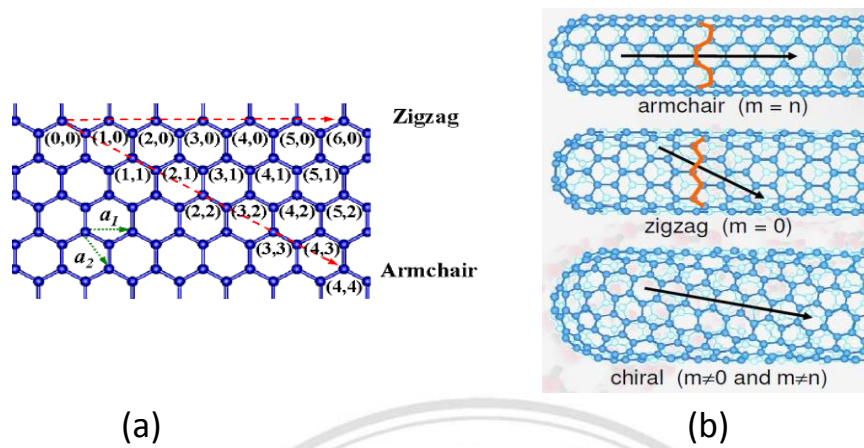


Figure 2.1 (a) Flat hexagon lattices of a graphene sheet, (b) Structure of SWNTs [5]

As the name implies, MWNTs are made up of concentric tubes of multiple rolled layers of graphite (see figure 2.2 below). MWNT wall structure can be correlated, semi correlated or independent while the spacing between walls can regular or random.

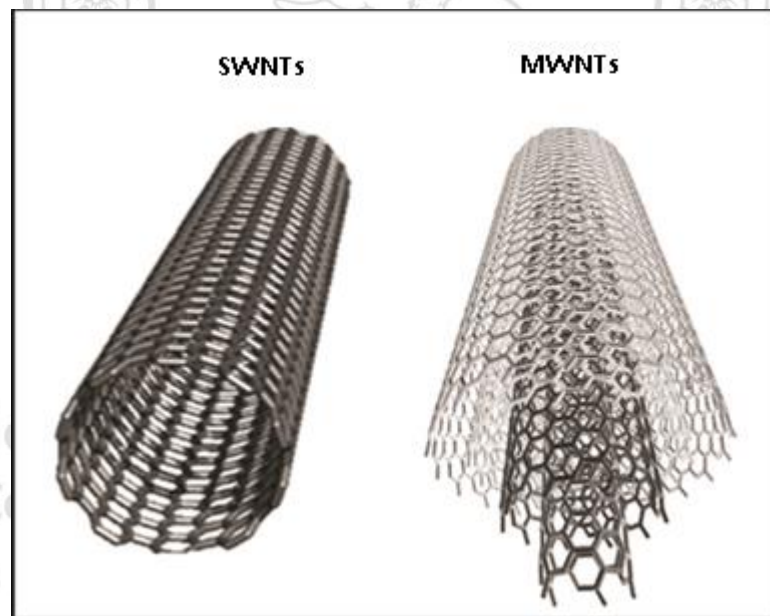


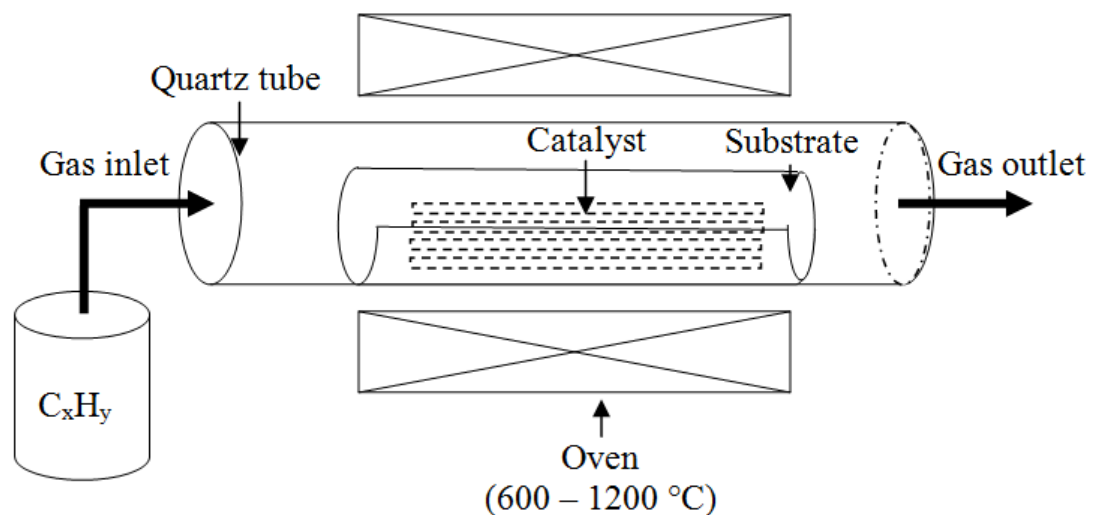
Figure 2.2 Schematic diagrams of SWNTs and MWNTs [6]

CNTs are prepared using a variety of methods such as laser ablation, arc discharge and chemical vapour deposition (CVD) [4]. These processes occur either within a vacuum or with gases that support the production of CNTs. Large numbers of high quality CNTs can be synthesised using such methods either within a vacuum or at atmospheric pressure.

The most popular method is CVD due to its low set up cost, high yield and it is easy to scale up [5-7]. When compared to laser ablation or arc discharge methods, the CVD technique is simple and economical for the synthesis of CNTs at relatively low pressure and temperature [6]. The purity of the yield from CVD is superior to that of both arc discharge and laser ablation.

In addition to advantages, the versatility of CVD is also a feature. It allows the harnessing of good quantities of hydrocarbons in their solid, liquid or gaseous states, various substrates can be utilised and it enables CNT growth in thick or thin films, aligned or entangled, straight or coiled or as a designed nanotube on a patterned substrate [7-9].

In the CVD process, a hydrocarbon process is passed through a tubular reactor, for about approximately 15 minutes, where a catalyst material is present at temperatures ranging between 600 and 1200 degrees Celcius which is enough to decompose the hydrocarbons. The CNTs the form on the catalyst within the reactor. Once the system cools to room temperature, the CNTs can be collected [10-11].



Scheme 2.1 diagram of CVD method

Nanometer sized particles are required for the synthesis of CNTs, to enable the decomposition of the hydrocarbon at a lower temperature would be required for its spontaneous decomposition. The most commonly used metals are Nickel, Iron and Cobalt. These are preferred because of the high solubility of carbon within these metals and the high carbon diffusion rate throughout the metal [12].

When the hydrocarbon vapour comes into contact with the hot metal nanoparticles, it decomposes into hydrogen and carbon atoms. The hydrogen then disperses and the carbon gets dissolved into the metal. Once the carbon solubility limit is reached in the metal, the dissolved carbon precipitates out and crystallises into a cylindrical network that is energetically stable. Some heat is released to the metal's surface during the decomposition of the hydrocarbon while the crystallising carbon absorbs some heat from the precipitation zone [12].

2.2 Growth Mechanism of CNTs

2.2.1 Tip growth model

Where the interaction between the catalyst and the substrate is weak, the hydrocarbon decomposes on the top surface of the metal. Carbon then diffuses down through the metal particle and CNTs precipitate out through the bottom of the metal causing it to be pushed up from the substrate. While the top of the metal remains open, the decomposition of fresh hydrocarbon will continue allowing continued diffusion of carbon causing the CNTs to grow in length. Once the top of the metal is covered, the catalytic process ceases and the growth of the CNTs stops [13-15].

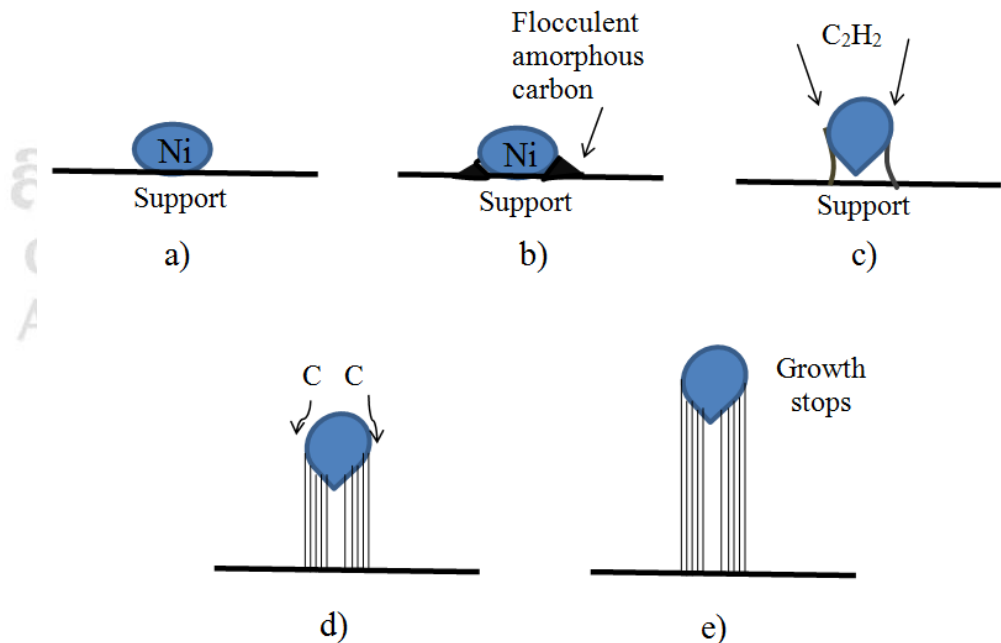


Figure 2.3 Tip growth model of CNT [16]

2.2.2 Base-growth/ Root-growth model

In the base growth model, the hydrocarbon decomposition and the carbon diffusion occur in a similar manner to that found in the tip growth model. The difference is that the CNT does not push the metal particle up. As a result, the CNT precipitation is forced out through the top of the metal where it crystallizes out as a hemispherical dome. This then extends up in the form of a seamless CNT. As the hydrocarbon continues decomposing around the outer surface of the metal and the dissolved carbon diffuses upwards, the CNT grows upwards with the catalytic particle fixed at its base [11-13]. In the third diagram in figure 2.5 below, it can be seen that this method produces a long tail [13-15].

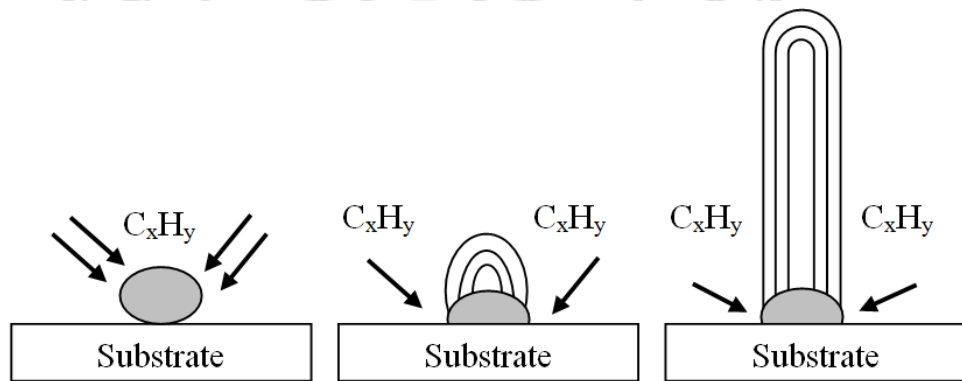


Figure 2.4 Base-growth/root growth model [16]

2.3 Composite materials [17]

Composite materials can be a combination of two or materials with resulting in the composite possessing better properties than those of the individual materials. Composites differ from multi phase materials that form naturally from reactions, phased transformations or other phenomena. Carbon fiber reinforced polymer is one example. Composite materials differ from alloys. While alloys are made of two or more components, an alloy can be produced naturally through processes such as casting [17]. Composite materials are noted for their ability to produce the desired characteristics through careful design and manufacture, and are widely used across many industries, including the aerospace, energy, biomedical, automotive and electronic industries. An example of a composite material is asphaltic concrete which uses bitumen as its matrix

and is possibly the most widely used of all composite materials [18]. In the third diagram in Figure 2.4, we can see along tail or ability, composite materials can be designed to satisfy the needs of technologies relating to the biomedical, automobile, aerospace, electronics, energy, and other industries. As a result, composite materials constitute most commercial materials. Continuous carbon fibre composites are often produced through a laminating process that involves placing single sheets of continuous carbon fibre one on top of another with the orientation of each sheet changed to achieve the design strength and stiffness. Carbon fibre polymer-matrix composites have the following attractive properties:

- Low density (lower than aluminium)
- High strength (as strong as high-strength steels)
- High stiffness (stiffer than titanium, yet much lower in density)
- Good fatigue resistance
- Good creep resistance
- Low friction coefficient and good wear resistance
- Toughness and damage tolerance (as enabled by using appropriate fiber orientations)
- Chemical resistance (chemical resistance controlled by the polymer matrix)
- Corrosion resistance
- Dimensional stability
- Vibration damping ability
- Low electrical resistivity
- High electromagnetic interference shielding effectiveness
- High thermal conductivity

2.4 Processing of Composite Materials [18]

The ability of the components to be joined into a cohesive, composite material has a direct bearing on the technology and the process costs. In many cases, the process involves high temperatures or pressures which are normally dictated by the matrix material, as is the time needed for the process.

The difference in the thermal contraction rates of the matrix and filler during cooling can result in a weakening of the bond or a total failure of the bond, where high temperatures are needed for the process. The weakening of the bond results in the filler being less effective as reinforcement which in turn diminishes the mechanical properties of the composite. Metal-matrix composites are seriously affected by this problem because of the high processing temperatures needed.

Fiber composites are normally made by impregnating a fiber preform with the matrix or matrix precursor in a liquid state. The fiber preform may be in the form of a woven fabric. Where composites take the shape of tubes, the fibers can be impregnated in the form of a tow which is wound from a spool to a mandrel.

Alternatively, reinforcing fibers and matrix fibers can also be intermixed in a solid state. In addition to the above processes, the fibers and matrix material can be mixed by coating the reinforcing fibers with the matrix material, by sandwiching reinforcing fibers with foils of the matrix material, and in other ways. After impregnation or intermixing, consolidation is carried out, often under heat and pressure [18].

There is a range of other processes that can be used to produce composite materials, with some examples provided below;

2.4.1 Polymer-Matrix Composites (PMC) [17, 19]

Polymer-Matrix composites are classified by the matrix which is either a thermoset or a thermoplastic polymer. Thermoset matrix polymers have been far more common until recently while thermoplastic matrix polymers have been undergoing rapid development. The advantages of thermoplastic-matrix composites compared to thermoset-matrix composites include the following:

Lower manufacturing costs:

- No cure
- Unlimited shelf-life
- Reprocessing possible (for repair and recycling)
- Fewer health risks due to chemicals during processing
- Low moisture content
- Thermal shaping possible
- Weldability (fusion bonding possible).

Better performance:

- High toughness (damage tolerance)
- Good hot/wet properties
- High environmental tolerance.

The disadvantages of thermoplastic-matrix composites include the following:

- Limitations in relation to processing methods
- High processing temperatures
- High viscosities
- Prepreg (collection of continuous fibers aligned to form a sheet that has been impregnated with the polymer or polymer precursor) is stiff and dry when a solvent is not used (i.e., not drapeable or tacky)
- Fiber surface treatments less developed.

Polymer-matrix composites are much easier to fabricate than metal-matrix, carbon-matrix, and ceramic-matrix composites, whether the polymer is a thermoset or a thermoplastic. This is because of the relatively low processing temperatures required to fabricate polymer-

matrix composites. For thermosets, such as epoxy, phenolic, and furfuryl resin, the processing temperature typically ranges from room temperature to about 200 °C; for thermoplastic polymers, such as polyimide (PI), polyethersulfone (PES), polyetheretherketone (PEEK), polyetherimide (PEI), and polyphenyl sulfide (PPS), the processing temperature typically ranges from 300 to 400 °C.

2.4.2 Metal-Matrix Composites (MMC) [17, 20]

Metal matrix composites are generally far more expensive to produce than polymer matrix composites because of the high temperatures needed for the process. The fabrication of metal-matrix composites often involves the use of an intermediate, called a preform, in the form of sheets, wires, cylinders, or near-net shapes. The size and shape of the preform are the same as those of the composite article to be made. The preform contains the reinforcement, which is usually held together by a binder that can be a polymer (e.g., acrylic, styrene), a ceramic (e.g., silica, aluminium meta phosphate), or the matrix metal itself. For example, continuous fibers are wound around a drum and bound with a resin, and subsequently the wound fiber cylinder is cut off the drum and stretched out to form a sheet. During subsequent composite fabrication, the organic binder evaporates. As another example, short fibers are combined with a ceramic or polymeric binder and a liquid carrier to form a slurry; this is then filtered under pressure or wet pressed to form a wet “cake,” which is subsequently dried to form a preform. When the matrix metal is used as the binder, a continuous fiber bundle is immersed in the molten matrix metal so as to be infiltrated with it, thus forming a wire preform; alternately, fibers placed on a matrix metal foil are covered and fixed in place with a sprayed matrix metal, thus forming a sprayed preform.

2.4.3 Ceramic-Matrix Composites (CMC) [17]

A ceramic-matrix composite (CMC) is commonly made by converting a polymer matrix to a ceramic. The process often involves thermal

composition known as pyrolysis. For example, polycarbosilane (a polymer that has both carbon and silicon atoms) is often used as the precursor of silicon carbide. The fibers can be short or continuous. In both cases, the composites can be formed by viscous glass consolidation, i.e., either hot pressing a mixture of fibers and glass powder, or by winding glass-impregnated continuous fiber under tension above the annealing temperature of the glass.

Short fiber ($\leq 3\text{mm}$) borosilicate glass composites are prepared by hot pressing, in a vacuum or in argon gas, using an isopropyl alcohol slurry of fibers and Pyrex powder ($< 50\ \mu\text{m}$ particle size) at $700\text{--}1,000\ \text{°C}$ (depending on the fiber content, which ranges from 10 to 40 vol.%) and 6.9 MPa. Fibers longer than 3mm are more difficult to disperse in the slurry. The resulting composite has fibers that are randomized two-dimensionally, as some alignment occurs during pressing.

Continuous fibre composites are made by allowing fibres from a spool to pass through a glass powder slurry (containing water and a water-soluble acrylic binder), winding the slurry-impregnated fibres onto the sides of a hexagonal prism (mandrel or take-up drum), cutting up the flat unidirectional tapes from the mandrel, stacking the pieces (plies) in a proper orientation, burning out the stack to remove the binder, and then hot pressing the stack at a temperature above the working temperature of the glass.

This process is known as slurry infiltration or viscous glass consolidation. During hot pressing, the glass must flow into the space between adjacent fibres. Since glass does not coat carbon, sufficient pressure is necessary. Viscous glass consolidation can also be carried out without hot pressing. In this case, a glass powder-impregnated continuous fiber tow is wound under tension (e.g., about 15kPsi or 100 MPa) onto a collection mandrel at a temperature above the annealing temperature of the glass.

2.4.4 Carbon-Matrix Composites [18]

Carbon-matrix composites are also made through the pyrolysis process that carbonizes the matrix of a polymer-matrix composite. Pyrolysis is akin to charring, which involves a chemical reaction that removes essentially all atoms that are not carbon from the polymer (the carbon precursor) [18]. The carbonization process is typically conducted in an inert atmosphere at around 650–1,200 °C. The atmosphere is usually nitrogen at temperatures up to 1,000 °C and in argon at temperatures above 1,000 °C. Argon at high temperatures is used because carbon tends to react with nitrogen to form poisonous cyanide compounds above 1,000 °C. One common carbon precursor is bitumen (a polyaromatic hydrocarbon material derived from petroleum or coal), which is a mixture of thermoplastic polymers. Bitumen (also called pitch) is attractive because of its relatively high char yield (i.e., the mass of the resulting carbon divided by the mass of the carbon precursor). A high char yield means a smaller amount of porosity in the resulting carbon-matrix composite. There are many grades of pitch. Those with higher molecular weights tend to give higher char yields.

Due to the porosity, which is detrimental to the mechanical properties of the composite, the carbon-matrix composite is commonly subjected to impregnation of the carbon precursor and then another round of carbonization. In order to achieve a sufficiently low porosity, multiple cycles of impregnation–carbonization are conducted, thus resulting in a high processing cost. In order to decrease the required number of cycles, the last cycle is commonly followed by a process known as chemical vapor infiltration (CVI), in which the remaining pores are filled with carbon that is deposited from the thermal decomposition of a carbonaceous gas that infiltrates the composite.

A thermoplastic polymer such as bitumen melts upon heating. The melting of the matrix is undesirable for the conversion of a polymer-matrix composite to a carbon-matrix composite. Furthermore, during

carbonization, pitch tends to bloat due to the evolution of gases generated by pyrolysis. The bloating can cause the expulsion of pitch from the carbon fiber preform during carbonization. Thus, the carbonization process is usually preceded by a process known as stabilization, which involves heating at 200–300.C in the presence of oxygen. In stabilization, oxygen diffuses into the carbon precursor and reacts with it, thus converting it chemically to a form that does not melt. Hence, the stabilization process is also known as infusebilization.

The fabrication of carbon–carbon composites is carried out using four main methods, namely:

1. liquid phase impregnation
2. hot isostatic pressure impregnation carbonization
3. hot pressing, and;
4. chemical vapor infiltration

2.5 Theory of hybrid composite materials [21]

Hybrid composite materials are containing of continuous fiber reinforced ply and metal layers. To form an adhere bond between the composite and metal laminate structures during the curing process, the temperature must be more than 120 °C. Therefore, very high residual stresses could build up because of the difference in coefficients of thermal expansion (CTE) for different materials. For example, the CTE of aluminum is about $2.36 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$ and for polymers it is higher than $1.05 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$ [21]. This thermal mismatch results in delamination of hybrid composite materials, which can result in fatigue crack growth in the polymer/metal interface. Figure 2.5 shows the result of delamination or debonding of polymer/metal interface due to this thermal mismatch.

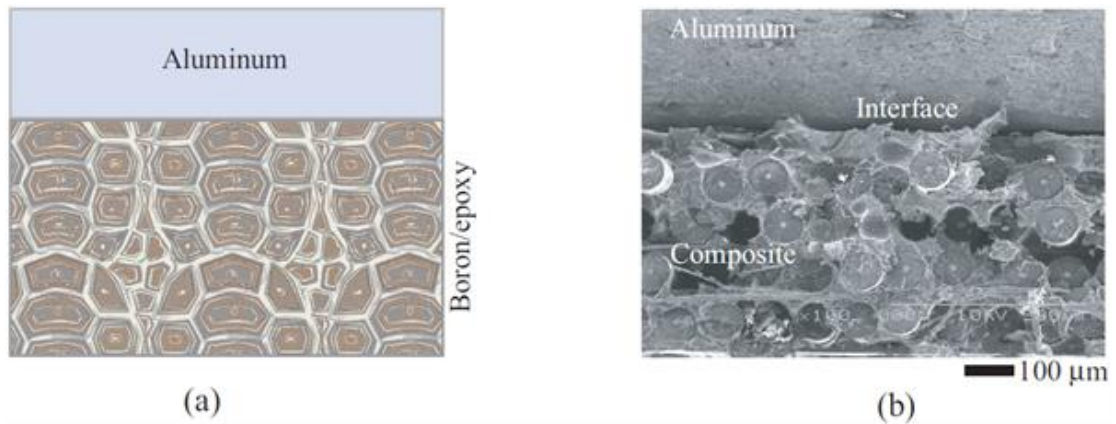


Figure 2.5 Interface Composite/metal: (a) schematic of a boron/epoxy bonded to aluminum substrate to form a hybrid composite structure; (b) SEM image showing the interface debonding feature [22].

The important step in the bonding procedure to reduce the thermal residual stresses in the structure is the substrate surface preparation. The substrate surface preparation method for increasing of polymer/metal interface bonding includes alkaline etching and acid pickling [23], plasma processing [24–26], ion beam irradiation [27–29], and coupling agent treatment [30].

2.5.1 Mechanism of heat transfer [31]

Conduction in a metallic solid is largely due to the random movement of electrons through the metal. The electron in the hot portion of the solid have a higher kinetic energy than those in the cold section and transfer some of this kinetic energy to the cold atom, thus resulting in a transfer of heat from the hot surface to the cold. Since the free electrons are also responsible for the conduction of an electrical current through a metal, there is a qualitative similarity between the ability of a metal to conduct heat and to conduct electricity. In addition, some heat is transferred by interatomic vibrations.

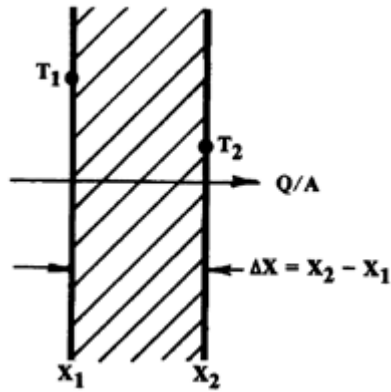


Figure 2.6 Diagram of conduction through a plane wall.

The details of conduction are quite complicated, but for engineering purposes may be handled by a simple equation, usually called Fourier's equation. For the steady flow of heat across a plane wall (Figure 2.6) with the surfaces at temperatures of T_1 and T_2 where T_1 is greater than T_2 the heat flow Q per unit area of surface A (the heat flux) is:

$$\frac{Q}{A} = q = k \left(\frac{T_1 - T_2}{X_1 - X_2} \right) = k \frac{\Delta T}{\Delta X} \quad (2.1)$$

The quantity k is called the thermal conductivity and is an experimentally measured value for any material. Equation (2.1) can be written in a more general form if the temperature gradient term is written as a differential:

$$\frac{Q}{A} = -k \frac{dT}{dx} \quad (2.2)$$

The negative sign in the equation is introduced to account for the fact that heat is conducted from a high temperature to a low temperature, so that (dT/dx) is inherently negative; therefore the double negative indicates a positive flow of heat in the direction of decreasing temperature.

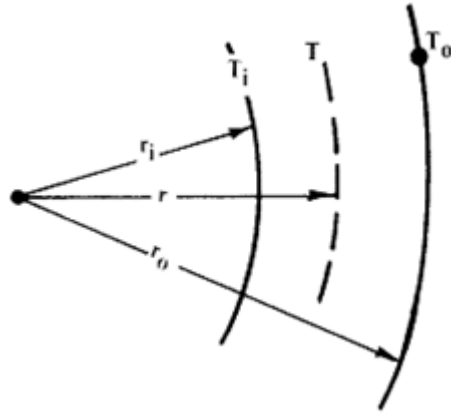


Figure 2.7 Diagram of conduction through a cylindrical wall.

For the conduction through a tube wall, the main advantage of equation 2.2 is that it can be integrated for those cases in which the cross sectional area for heat transfer changes along the conduction path. A section of tube wall is shown in Figure 2.7 Q is the total heat conducted through the tube wall per unit of time. At the radial position r in the tube wall ($r_i \leq r \leq r_o$), the area for heat transfer for a tube of length L is $A = 2\pi rL$. Putting these into equation 2.3 gives

$$\frac{Q}{2\pi rL} = -k \frac{dT}{dx} \quad (2.3)$$

which may be integrated into

$$Q = \frac{2\pi Lk(T_i - T_o)}{\ln(r_o / r_i)} \quad (2.4)$$

If $T_i < T_o$, Q comes out negative; this just means that the heat flow is inward, reversed from the sense in which we took it. For thin walled tubes, the ratio of the outer to the inner radius is close to unity, and we can use this simpler equation,

$$Q = \frac{2\pi r_o Lk(T_i - T_o)}{r_o - r_i} \quad (2.5)$$

with very small error.

2.6 Solar heat collectors [33]

2.6.1 Solar Energy

The nuclear fusion reactions in the sun yield a huge amount of energy which is estimated at 3.47×10^{24} kJ per unit time. Only a small part, about 5×10^{-11} kJ, of this energy is irradiated onto the earth's surface. Solar energy is clean and harmless to living organisms on the earth because the harmful short wavelength ultraviolet rays are absorbed before reaching the troposphere by the stratospheric ozone layers and weakened by the air composition and moisture in the troposphere. In order to separate the various forms of solar energy;

1. Heat from the sun's rays which are possible when there is little or no cloud cover. This type of energy is dependent on heat from the sun's rays and is dominated by the multiplicity of methods designed to heat water.
2. Power from the sun's light any time except at night, cloudy or clear.
3. Power from air or water movement (hydrological cycle), any time day, cloudy or clear.

The easiest way of using collected solar radiation is for low temperature heating purposes. Most of the low temperature solar heating systems depend on the use of glazing, because it has the ability to transmit visible light and to block infrared radiation. High temperature solar collectors employ mirrors and lenses. Solar thermal engines are an extension of active solar heating and help to produce high temperatures to drive steam turbines to produce electric power. A benefit from solar radiation is through passive solar heating devices which have different uses. The absorption of solar energy directly into a building to reduce the energy required for heating and lighting of the habitable space. Passive solar heating systems can be integral parts of the building and mostly use air to circulate the collected energy without pumps or fans. Passive solar heating means low energy building designs, which are effective in

reducing the heat demand to the point where small passive solar gains make a significant contribution in winter.

It is well known that black surfaces absorb solar radiation more than any other color when a surface is blackened, it will absorb most of the incident solar radiation. Continuous flow of solar radiation onto such a surface will increase its temperature. This will continue until the heat gain from the solar radiation is in equilibrium with the heat loss from the collector. Among the heat losses, there are two types, namely, naturally unavoidable losses and losses due to human uses. The heat can be transmitted to where it is needed through pipes soldered to the metal plate which is heated due to exposure to solar radiation. The heat balance of a collector will have two components in relation as follows [32]

Absorbed heat – Lost heat = Removed heat by coolant

$$\varepsilon = \frac{(A_h - L_h)}{I_s} \quad (2.6)$$

When ε is the efficiency coefficient, A_h is the absorbed heat L_h is the lost heat, and I_s is the incident solar radiation. For the design of the collectors to become the higher in efficiency, there are two methods. The reduction heat losses or the increase of the incident solar radiation. Therefore, the heat absorbed per unit area. It is possible to reduce heat loss by using transparent cover plates, by using specially treated absorber surfaces, and by evacuating the space between the cover plate and the absorber surface. In contrast, for high temperature solar collectors the efficiency must be increased by increasing the incident radiation through the use of concentrators. As a material is heated by solar radiation, it will reach equilibrium with its surroundings by conduction, convection, and radiation.

2.6.2 Conduction

When heat is transferred within a solid body there are at least two different heat areas (temperature difference). Heat transfer is possible by means of vibrations of the atomic lattice which forms the body of the material. The heat is also carried away by electrons, and this contribution is much greater than that due to lattice vibration. During conduction there is no mass transfer. Atoms move randomly under thermal stress in liquids and gases, and this also lead to heat conduction. The heat transfer is proportional to the temperature difference, dT , along a distance, dx (dT/dx being the temperature gradient) and, hence, the conduction heat flow can be defined as;

$$H_c = -k \frac{dT}{dx} \quad (2.7)$$

Where H_c is the heat flow per unit area of cross section (W/m^2), T is the temperature ($^{\circ}C$), x is the direction and distance (m), and k is the thermal conductivity of the material ($W/m^{\circ}C$).

Table 2.1 Thermal conductivity of some materials

Materials	k (W/m°C)
Metals:	
Copper	385
Aluminum	205
Steel	50
Non - metals:	
Glass	0.8
Concrete	0.8
Wood	0.14
Glass fiber	0.03
Polymers:	
Low density polyethylene (LDPE)	0.30
Linear low density polyethylene (LLDPE)	0.35
High density polyethylene (HDPE)	0.44
Polypropylene (PP)	0.11
Liquids:	
Water	0.61
Gases:	
Air	0.0239

2.6.3 Convection

Convection is the process by which heat from the hot surfaces is carried away by a fluid such as water. Fluid flowing across a surface is heated and then the heated volume is removed due to fluid flow with replacement by new, cooler fluid. This heat transfer is referred to as convective cooling or heating. The rate of heat removal will depend on both the temperature difference between the surface and the bulk fluid temperature, plus the velocity and characteristics of the fluid. Another example of heat convection can be found in building designs where the ridge of the roof and the caves are both vented. The hot air inside the roof space rises out the ridge vents and cooler air is drawn in the cave vents. In solar energy conversion both forced and natural convections may be accompanied by phase changes. Therefore, convection heat flow can be defined as;

$$H_f = c(T_s - T_f) = c\Delta T \quad (2.8)$$

Where H_f is the heat flow per unit area (W/m^2), c is the convective heat transfer coefficient ($\text{W}/\text{m}^2\text{C}$), T_s is the surface temperature ($^{\circ}\text{C}$), and T_f is the fluid temperature ($^{\circ}\text{C}$). The convective heat transfer coefficient is dependent on both the nature of the fluid and its flow velocity. The transference of heat to a fluid begins when energy is transferred to the molecules of the fluid. Then, physically move away, taking the energy with them. A warmed fluid expands and rises, creating a current known as natural convection, which is one of the principal processes of heat transfer through windows. It is possible to reduce the convection losses through double glazing windows by filling the space between the glazing with heavier, less mobile gas molecules, such as argon or carbon dioxide.

2.6.4 Radiation

A hot body of material may be losing heat by radiation through emission of electromagnetic waves. The maximum power which can be radiated from a body at a given temperature is called the black body radiation

corresponding to that temperature. The radiation power, P , from a black body increase to the fourth power of the absolute temperature, T , of the same body and it is given by Stefan's law as

$$P = \sigma T^4 \quad (2.9)$$

Where $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ is Stefan's constant. Heat flux in the case of radiation from a black body is presented in below table.

Table 2.2 Black body radiation

Surface temperature (K)	Heat flux (W/m ²)
6000	73.5×10^6
3000	4.6×10^6
2000	9.1×10^5
1073	75.0×10^3
873	32.9×10^3
673	11.6×10^3
473	2.84×10^3
353	1.10×10^3
333	880
300	459

2.7 Types of solar heat collectors

Solar heat collectors are devices which absorb the sun's light energy and converts it into heat, and transfers this heat to a fluid, either air or liquid. There are several types of solar heat collectors; flat-plate, evacuated-tube, and concentrating collectors.

2.7.1 Flat-Plate Collectors

Flat-plate collectors are the most common collector for residential water heating and space heating installations. A typical flat-plate collector is an insulated metal box with a glass or plastic cover (called the glazing) and a dark colored absorber plate. The absorber plate is usually black because the dark color absorbs more solar energy than lighter colors. When solar radiation passes through a transparent cover and strikes the absorber plate, a large portion of this energy is absorbed by the plate and then transferred to the air or liquid passing through the collector. The underside of the absorber plate and the side of casing are well insulated to reduce conduction losses.

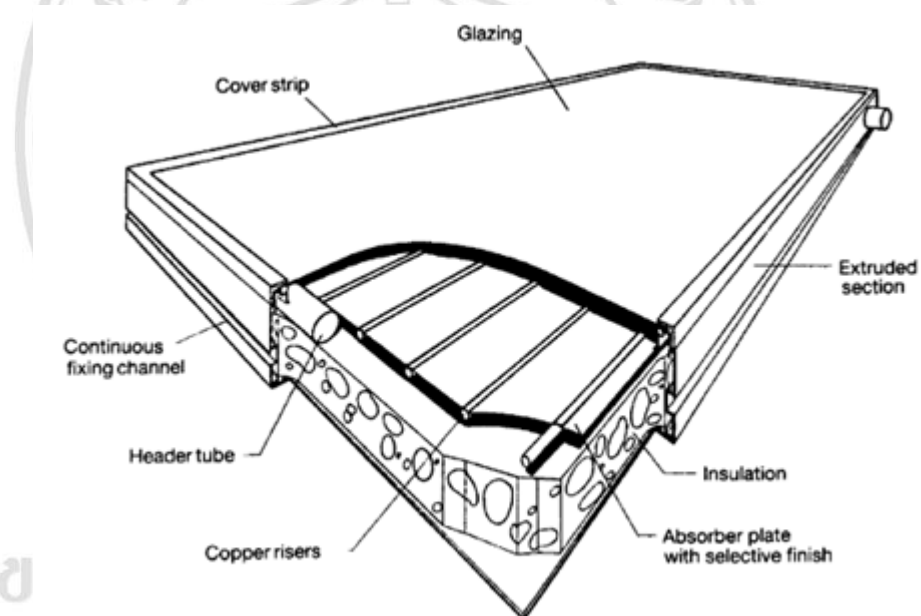


Figure 2.8 Flat-plate collector [32]

The transparent cover is used to reduce convection losses from the absorber plate through the restraint of the stagnant air layer between the absorber plate and the glass. Absorber plate is often made of metal, usually copper or aluminium, because they are good heat conductors. Copper is more expensive, but is a better conductor (~ 385 w/mK) and is less prone to corrosion than aluminium.

2.7.2 Evacuated-Tube Collectors

Evacuated-tube collectors heat water for residential applications that require higher temperatures. In an evacuated-tube collector, sunlight enters through the outer glass tube, strikes the absorber tube, and changes to heat. The heat is transferred to the liquid flowing through the absorber tube.

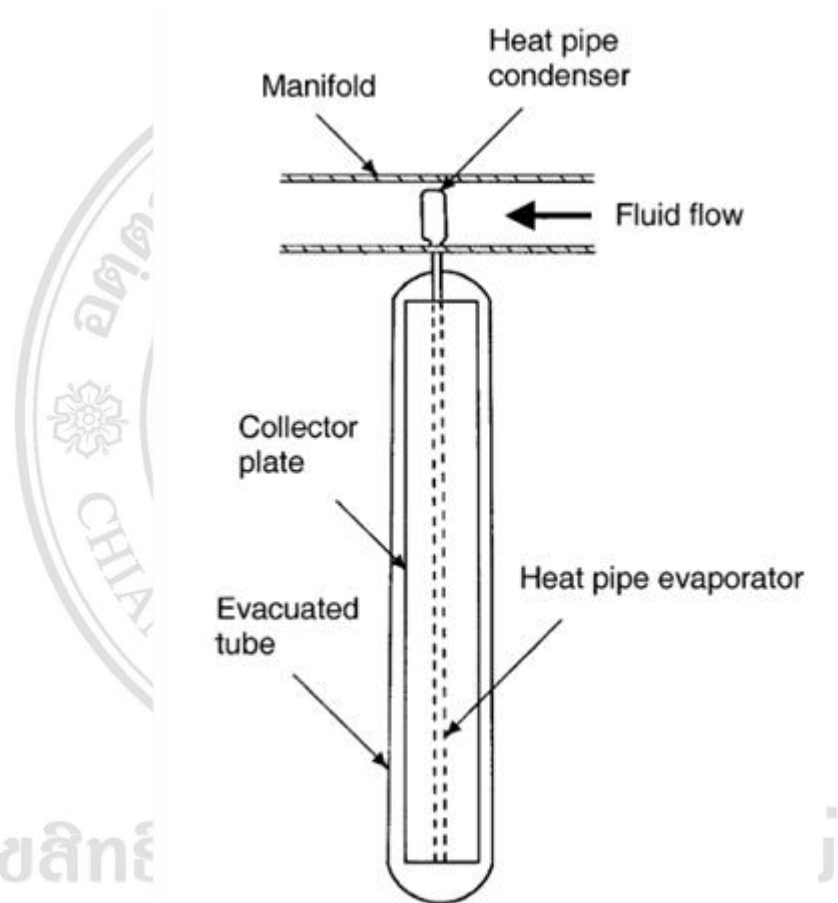


Figure 2.9 Evacuated-Tube Collectors [33]

2.7.3 Concentrating Collectors

Concentrating Collectors use mirrored surfaces that concentrate the sun's energy onto an absorber called a receiver. Concentrating Collectors also achieve high temperatures, but unlike evacuated-tube collectors, they can do so only when direct sunlight is available. The mirrored surface focuses sunlight collected over a large area on to a smaller absorber area to achieve high temperatures. Concentrators can only focus direct solar

radiation, with the result being that their performance is poor on hazy or cloudy days.

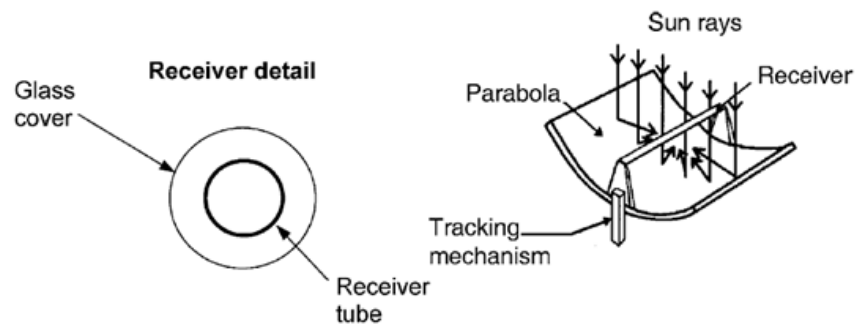
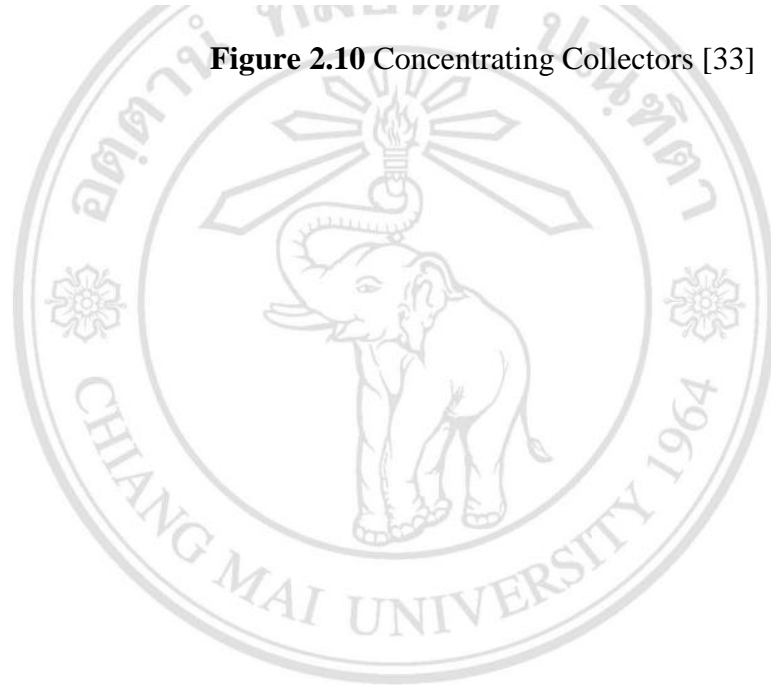


Figure 2.10 Concentrating Collectors [33]



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