CHAPTER II

REVIEW OF RELATED LITERATURE AND RESEARCH

Review of Related Literature

From the previous chapter, we will find that the application of heat insulated paint on the roof surface and on the wall surface is another alternative to reduce the energy loss in cooling the building. From the previous study, at present there are many researches and development about the energy saving technology by coating the surface of materials or buildings with the insulators for example, [4] testing the heat performance in the small building which is coated by the heat insulated paint that has the ceramic atom as a main composition compare with the small building with conventional paint coating and without paint coating as well as compare the solar reflectance and heat emission of the gypsum board coated with heat insulated paint which has ceramic atom as a main composition, conventional paint and uncoated. This research found that the gypsum coated with heat insulated paint can increase solar reflectance and heat emission up to 94.7% and 89% respectively and solar reflectance can also increase about 7.4% and 55.2% as compared with the gypsum board coated by conventional paint and uncoated respectively. Moreover, the effect can reduce the electric energy consumption about 21% and 43% correlated with coated by conventional paint and uncoated one.

A. Synnefa, et al. [5] tested of heated absorption, sun light, infrared reflection and the temperature on the surface of tested materials was compared with various insulated paint shades and with conventional paint. The test had been done 24 hours per day for 5 consecutive months (Aug – Dec). They found that the insulated paints can reduce heat absorption and reflect sunlight and infrared ray very well, while the surface temperatures are considered low when comparing with the other coating. Therefore, applying on top of the roof and walls is recommended.

K. Uemoto, et al. [6] investigated the thermal performance of cool colored acrylic paints which contain infrared reflective pigments in order to compare with the conventional one in similar colors. The result shows that, under the same conditions,

the paints with so call cool pigment can produce higher near infrared reflectance and also, the surface temperatures are 10°C less than the conventional coating. From result, they could conclude that the cool colored paints can reduce energy consumption.

In 2007, A. Synnefa [8] simulated the potential on 5 shades of cool colored with thin layer asphalt and compared to a sample of conventional black asphalt in order to analyze the solar spectral by Computational Fluid Dynamics (CFD). From the spectrophotometric measurements, the result shown higher values of solar reflectance on the layer of asphalt samples. In case of off-white shade, the highest of temperature difference of about 12°C was achieved, and the CFD showed that surface and air temperatures are decreased when applying the color thin layer sample.

The impact from using cool roof coating, which increases the solar reflectance, on energy loads by investigating energy consumption of air conditioner as the cooling and heating loads under various climates was studied in A. Synnefa's research [8]. His result showed that the cooling loads were reduced about 18-93% with decreasing 11-27% of the peak cooling demand of air conditioner and the hour of discomfort was improved by 9-100%. This application is useful in non-insulated buildings because it can reduce the cooling load about 9-48 kWh /m²/ year dominating the heating penalty (only 0.2-17 kWh /m²).

In M. Santameris's research [9], 14 types of different reflective coatings were investigated in order to study the thermal performance and reduce the heat island effect. It was shown that the usage of reflective coatings can reduce a white concrete temperature about 4°C and 2 °C for day and night, respectively. It was warmer by 2°C and cooler by 5.9 °C over the ambient air during the day and night respectively. Moreover, his research could recommend the suitable coating for building and other surfaces of the urban environment in order to avoid the effect of urban heat island as well as the reduction of cooling loads and electricity consumption of buildings.

R. Levinson [10] created the solar reflective non-white surfaces, such as metal, clay tile, concrete tile, wood and asphalt shingle. The result showed that reflectance was maximized especially in the near infrared (NIR) spectrum (0.7-2.5 nm) by pigment coated as topcoat which had weak absorption and strong backscatter NIR radiation. In gray-cement concrete tiles case, the NIR reflectance was about 0.6 with NIR scattering pigment coating color but it could be up to 0.85 with overlaid by

white primer and covered by NIR-transparent organic pigments as topcoat. And granule-surfaced asphalt shingles coated by a white primer and a cool color topcoat had about 0.45 of NIR reflectance.

G.B. Smith, A., et al. [11] study the coated surface of material with iron oxide and silicon oxide coated flakes of alumina as the dominant pigment and comparing the result with materials without any heat insulator coating. The reflection, distribution and absorption of the sun light were recorded. The result shown that the iron oxide and silicon oxide coated flakes of alumina will help reducing the heat radiant from sun light and reflect the infrared ray and can reduce energy lost by over 50%.

The roof of small building is coated by white reflecting paint to study the effect of solar ray on energy saving of air conditioner and reflection the solar ray of building [12]. The experiment period was one and a half months and the result will be compared with green roof on building. The result found that the roof of building that coated with white can reflect sun light about 72% which is higher than non-coated roof, about 26%. The white reflecting paint building can save the energy about 125 kWh per year.

A. Dombrovsky, et al. [13] investigated the effect of infrared property of coating with 6-66% of hollow micro spheres in surface of material on the reflection, transfer, and radiant under wave range of $2.6 - 18$ μm. It is found that hollow micro spheres can help to reflect the solar ray and reduce the heat transfer under the tested wave range at $8-13$ μm. Therefore, it can reduce the heat load, if the roof and wall of buildings are coated with hollow micro spheres.

From the study of previous researches, application of the insulation techniques by coated surface of material with insulating paint namely white reflecting paint, iron oxide and silicon oxide coated flakes of alumina help to reflect the incident solar ray causing to reduce the heat load, if the roof and wall of buildings are coated with insulating paint. But there is so little information available on the application of coated color that consisted of TiO_2, microsphere ceramic, and infrared reflective Pigment altogether which contribute high reflectivity on the surface of building material. They are well known as high solar reflective pigment. Therefore, the objective of this research will focus on developing the optimal paint formula (Beger Cool UV Shield) with high solar reflective pigments to reduce heat transfers and

minimize the cooling energy consumption of a small coated building. Also, the paint system will be experimented to find out the most appropriate primer and topcoat that enhance the solar reflectivity performance. The actual measurement of reflectivity, conductivity and emissivity will be tested by standard test certified body. The test result will show the different of heat performance and energy consumption of three buildings, which are uncoated, coated with conventional paints (colors), and coated with high solar reflective paint (Beger Cool UV Shield). Finally, a mathematical model will be derived to link paint's solar reflective value and conductivity to predict the temperature, which will lead to energy saving calculation.

Heat transfer [14]

Heat transfer is the behavior that normally occurs in everywhere if only it has the temperature difference in the medium between 2 points. The energy called "HEAT" will be moved from high temperature into low temperature area. There are 3 types of heat transfer, conduction, convection and radiation, as shown in figure 3. Conduction, the thermal energy will directly transfer through the medium which its molecules are in contact from higher temperature area to lower temperature area. Conduction will be considered only in the medium without a flow. Convection is the thermal transfer behavior that the hot particles can be moved into lower temperature area in the medium. Thus, it will occur only in moving medium molecules. Radiation can be happened without medium. The heat energy will be transferred in form of electromagnetic radiation into the surround. For instance, the energy from the Sun travels through the vacuum and warming the Earth without the medium.
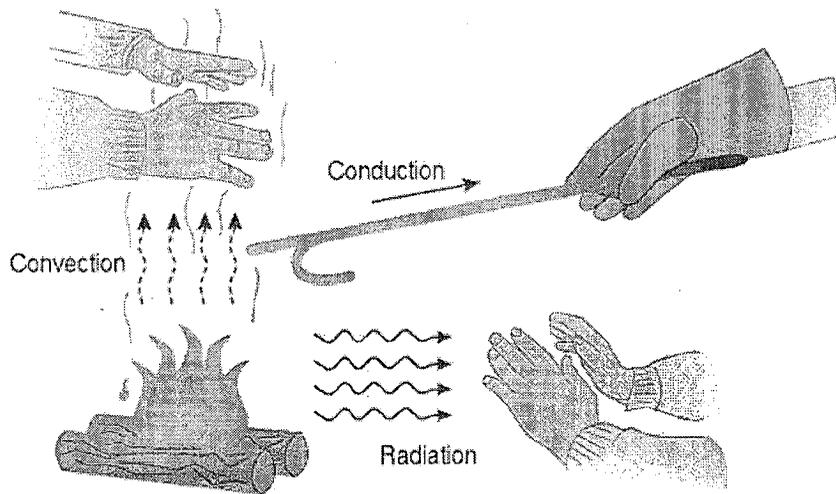
Figure 3 The transfer of thermal energy occurs only through conduction, convection, radiation or any combination of these [14]

1. Conduction heat transfer

Conduction heat transfer phenomena are found throughout the physical world which was recognized that by invoking certain minor simplifications, mathematical solutions resulted directly. It can be determined from differential equations and will be used for calculation in order to find the heat energy which was transferred per unit time. This equation is called Fourier's law, as shown in figure 4. From this equation, the temperature contributes to the distance, for example, the temperature T(x) will vary only with the distance along X axis.

$$\text{The Fourier's equation: } q''_x = -k\frac{\partial T}{\partial x} \qquad (2.1)$$

Whereas q''_x (unit :W/m^2) which is called " heat flux " means the rate of heat transfer in direction X per area unit which is perpendicular to the transferred direction. Whereas, k is a coefficient value depended on kind of material which is the transport property, called thermal conductivity (W/m K).
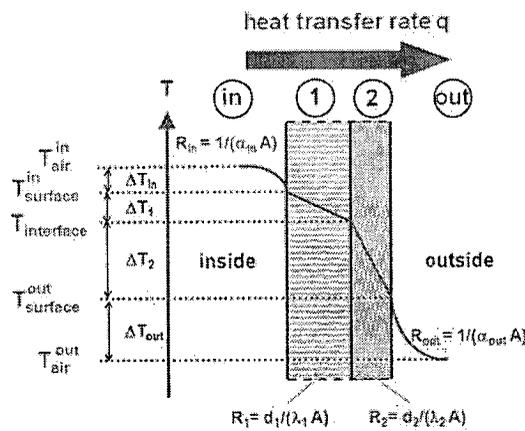
Figure 4 The heat transfer – one dimension plane wall [14]

For steady state, the equation (1.) can be integrated to equation (2.). It is calculated under plane wall with L thickness, constant thermal conductivity k and temperature T_1 on one side and T_2 on the other. This can be used to determine the steady-state heat transfer through slabs as follow.

$$q_k = \frac{kA}{L}(T_1 - T_2) \qquad (2.2)$$

In order to simplify the conduction behavior as the electrical circuit analog, the temperature difference is analyzed to be voltage difference and heat flux to be like a current flow. Therefore, from equation (2.2), thermal resistance, as the resistance in the circuit, can be calculated as following:

$$R_k = \frac{L}{kA} \qquad (2.3)$$

From this equation, heat transfer through the layers walls with different types of materials can be easily calculated by summing thermal resistances in series or parallel form.

2. Convection heat transfer [15]

There are 2 types of convection; natural convection and forced convection. For natural convection, surrounding fluid receives the heat from heat source, becomes less dense and rises. When the hot fluid float, the cooler moves to replace, heated by heat source again and then the process continues, forming convection current. Result from different density of fluid, buoyancy force is presented as the driving force of natural convection. The simple example of the natural convection is the heat transfer between the very hot road's surface and air above the road. The air in the layer -area attached to the road's surface will have less density than the air in the above level. It means the hot air will flow up and the cold air will move in to replace it, resulted in the movement of air current as shown in figure 5. In contrast, forced convection is occurred when fluids are forced by others equipment such as pumps, fans or whatever are used to propel the fluid to make the convection current. In some heat transfer systems, both natural and forced convection contribute significantly to the rate of heat transfer. In order to calculate the rate of convection between object and surrounding fluid, the heat transfer coefficient, h, is presented. It is not a material property. Equation (2.4) is used for calculation of heat transfer, both of natural and forced convection, in which T_s represents the temperature of object and T_α represents the temperature of surrounding such as ambient air.

$$q'' = h(T_s - T_\infty) \qquad (2.4)$$
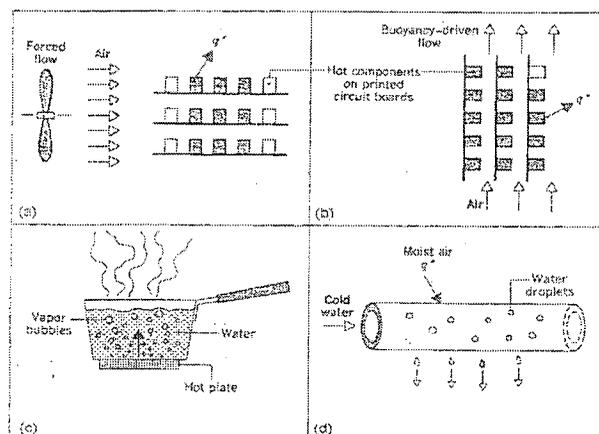
Figure 5 The convection a) Forced convection b) Natural convection c) Boiling   d) Condensation [16]

3. Radiation heat transfer [16, 17]

Radiation can be separated into various types depending on the properties of the emitted, types of emission source, etc. It will be occurred when the electron format in the atom of material is changed, result of producing the energy in form of electromagnetic waves. Radiation does not need medium any more, while conduction and convection do. In actually, the best radiation efficiency is available in the vacuum.

The value of heat flux emitting from the real surface will be less than this and will be as per this equation.

$$q'' = \varepsilon \sigma T_s^4 \qquad\qquad (2.5)$$

Whereas T_s is the Absolute temperature (K) of the surface and σ is the Stefan Boltzmann constant ($\sigma = 5.67 \times 10^{-8}$ W/m^{2}K^4)

The parameter that indicate the radiation efficiency comparing to black material is called emissivity, ε. But in actually, the radiation is more complicated. When it occurs, some portion of energy will be absorbed, some will be reflected out and some will be transmitted, results in 3 added up parameters are presented in order to identify the efficiency of each phenomenon. Absorptivity (α) is defined as the ratio of energy that was absorbed against total energy radiated on the object, Reflectivity (ρ) as the ratio of energy that was reflected out against total energy radiated on the object and transmissivity.(τ) as the ratio of energy that penetrate through the object against total energy radiated on the object.

The total heat energy that radiate on object will be equal to the sum of absorbed energy plus reflected energy and transmitted energy.
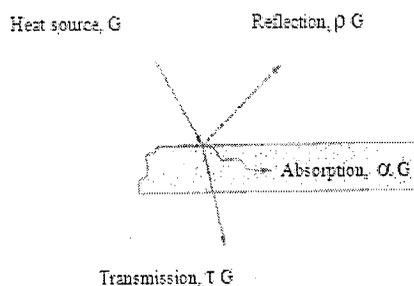
Figure 6 The total heat energy on the material [17]

In practical systems, the thickness of the surface layer over which absorption of irradiation from inside the enclosure occurs is very small compared with the overall dimension of an enclosure usually a few nanometers for metals and a few micrometers for most nonmetals. The same may be said about emission from within the walls that escapes into the enclosure. Thus, in the case of opaque walls it is customary to speak of absorption by and emission from a "surface," although a thin surface layer is implied. Four fundamental radiative properties are defined

Reflectivity, $\qquad \rho \equiv \dfrac{reflected\ part\ of\ incocoming\ radiation}{total\ incoming\ radiation}$ $\qquad$ (2.6)

Absorptivity, $\qquad \alpha \equiv \dfrac{absorbed\ part\ of\ incoming\ radiation}{total\ incoming\ radiation}$ $\qquad$ (2.7)

Transmissivity, $\qquad \tau \equiv \dfrac{transmitted\ part\ of\ incoming\ radiation}{total\ incoming\ radiation}$ $\qquad$ (2.8)

Emissivity, $\varepsilon \equiv \dfrac{energy\ emitted\ from\ a\ surface}{energy\ emitted\ by\ a\ black\ surface\ at\ same\ temperature}$ $\qquad$ (2.9)

Since all incoming radiation must be reflected, absorbed, or transmitted, it follows that

$$\rho + \alpha + \tau = 1 \qquad (2.10)$$

Electromagnetic spectrum [17]

The ranges of all possible frequencies of electromagnetic radiation are called electromagnetic spectrum, and it can characterize the distribution of electromagnetic radiation emitted and absorbed by that particular object, shown in figure 7. Electromagnetic spectrum range is divided by wavelength covering from short wavelength to very long one. The longest wavelength has the size equal to the universe, while the shortest one has the size as Plank length, although in principle the spectrum is infinite and continuous.

From figure 7, the heat from radiation emitted from surface of the object by the force of the temperature will have wave length at 10^{-7} to 10^{-4}m. And the details of the electromagnetic spectrum during heat radiation are shown in Figure 6.
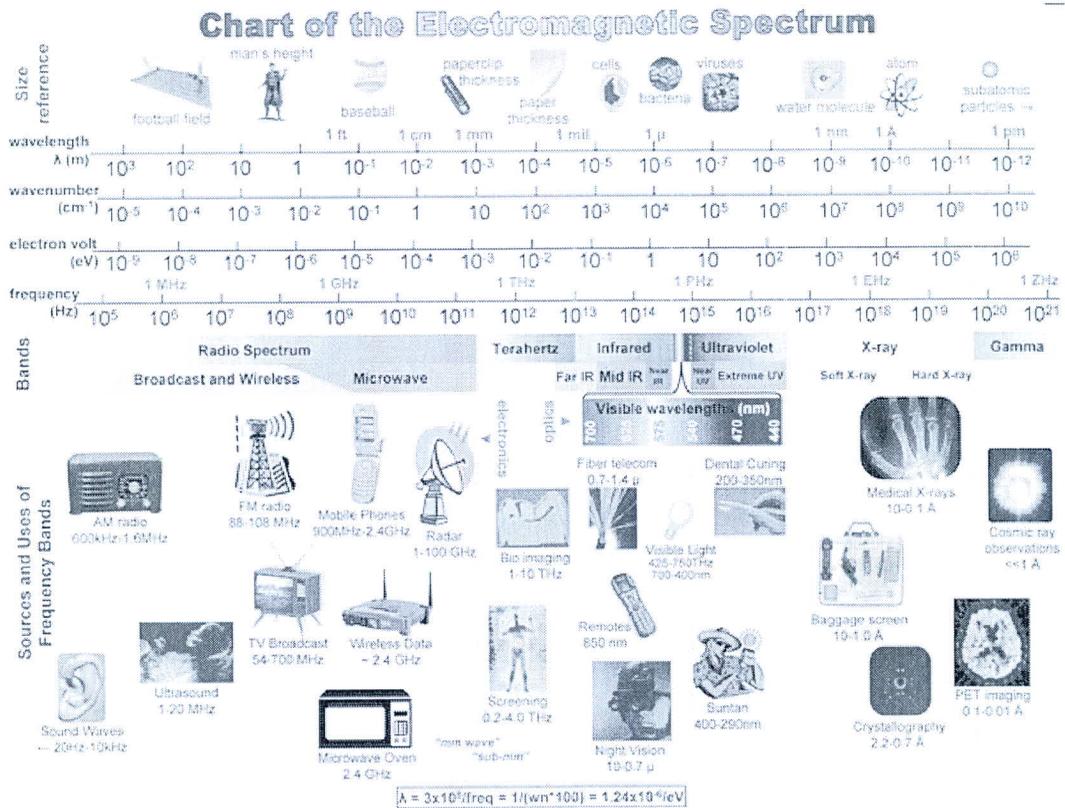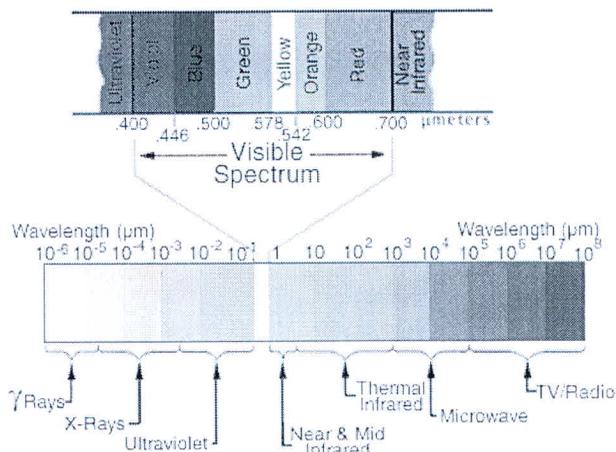
Figure 7 Electromagnetic spectrum [17]

Figure 8 Spectrum of magnetic waves, showing the heat ranges from radiation

Atmospheric and solar radiation [18]

Solar energy is the basic energy coming from the sun which is our primary source of energy. We can feel it in form of electromagnetic waves after experiencing considerable interactions with the atmosphere. When solar energy reaches the atmosphere, the atmospheric constituents will reflect it, cause of radiation energy emitted. From now on, we will discuss about the solar and atmospheric radiation corresponding to daily life in order to make it easy to understand.

During sunrise and sunset times, we can see the sky fulfilled by reddish-orange color. It is due to at those times, the sun's rays pass through a greater thickness of the atmosphere than they do in midday, so, the violet and blue colors from the light confront with a greater number of molecules in atmosphere, results in greater fraction are scattered as shown in figure 9. Therefore, longer wavelengths, such as red, yellow and orange, are allowed reaching at the Earth surface. At sunset, the light travels through a thicker layer of atmosphere, which removes much of the blue from the natural light, allowing the red to dominate [18]
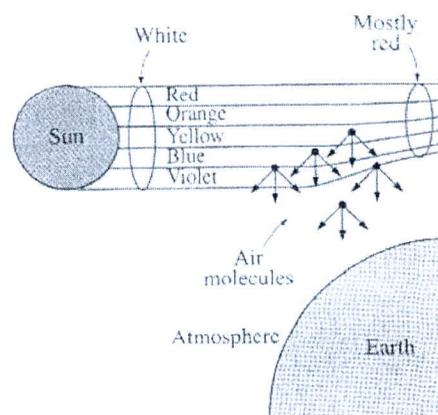
Figure 9 Air molecules scatter blue light much more than they do red light

Brewster's angle [19]

Considering incident light that crashes the surface of a non-conducting material and split into two parts called refracted ray and reflected ray. The reflected ray is the incident ray that reflected away from the surface and refracted ray is the remainder that transmitted into the surface of material. The proportion of the two parts depends on both incident angle and polarization direction of the incident light. The functions that describe the reflection of light polarized parallel and perpendicular to the plane of incidence are called the Fresnel Equations. Figure 10 shows a graph of the Fresnel equations for components of polarization parallel and perpendicular to the plane of incidence. From figure 10, we can see that the perpendicular ($\perp$) component of polarization is always almost reflected more strongly than the parallel ($\parallel$) component. Besides, the incident that is perpendicular with the surface, both components are reflected equally. And figure 11 also shows the Brewster's angle, which none of parallel component is reflected.
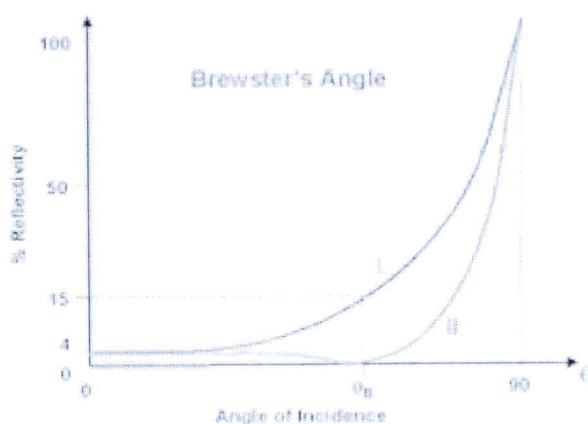

Figure 10 Graph of the Fresnel Equations showing the percent of incident light reflected for parallel and perpendicular polarizations [19]

Natural light is one of incidence that is non-polarized ray. Thus, it can be separated into two components. And the Fresnel equations can be used to describe the fraction of the reflected polarization. Thus, natural light is always at least partially polarized upon reflection.

$$\left(\frac{E_{ot}}{E_{oi}}\right) N = \frac{\frac{n_1}{\mu_{r1}}\cos\theta_i - \frac{n_2}{\mu_{r2}}\cos\theta_t}{\frac{n_1}{\mu_{r1}}\cos\theta_i + \frac{n_2}{\mu_{r2}}\cos\theta_t} \qquad (2.11)$$

$$\left(\frac{E_{ot}}{E_{oi}}\right) N = \frac{2\frac{n_1}{\mu_{r1}}\cos\theta_i}{\frac{n_1}{\theta_{r1}}\cos\theta_i + \frac{n_2}{\mu_{r2}}\cos\theta_t} \qquad (2.12)$$

Fresnel's equation shows the ratio between amplitude of incident ray and amplitude of reflected ray between two different media
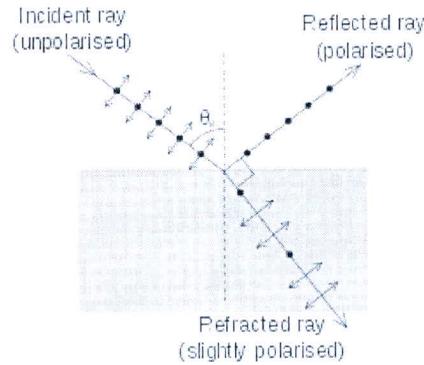
Figure 11 The Brewster's angle [20]

Brewster's angle is the angle that the reflected ray is completely perpendicular component, while the refracted ray is consisted of parallel component and 85% of perpendicular component. Brewster's angle can be found in relationship of the indices of refraction in the incident and reflecting medium, defined as n_1 and n_2 respectively and the Brewster's angle can be found according to Snell's law:

$$\theta_{iB} = \cot^{-1}\frac{n_1}{n_2}$$

$$(2.13)$$

Brewster's angle is often referred to as the "polarizing angle", because light that reflects from a surface at this angle is entirely polarized perpendicular to the incident plane ("*s*-polarized") A glass plate or a stack of plates placed at Brewster's angle in a light beam can thus be used as a polarizer. The concept of a polarizing angle can be extended to the concept of a Brewster wavenumber to cover planar interfaces between two linear bianisotropic materials.

IR-reflective pigments [20]

Although, the human's eye can't see all ranges of wavelength, just see only a small part of the electromagnetic, but pigment interaction can accept all and effects on coating properties. infrared (IR) is the one of invisible spectrum ranges that can affect usability and durability of coating. Thus the IR-reflective coatings are produced in order to avoid IR and keep cooling on objects. The easiest way to produce IR reflectivity is to use the coating that contains white pigment, like titanium dioxide (TiO_2) which can reflect both of the visible and infrared. The key to fight this "White Blight" and produce innovative, colored IR-reflective coatings is to use pigments that absorb in the visible to produce color and reflect in the IR for coolness.

There are three regions of solar energy that objects can reflect or absorb, namely, UV, the visible and infrared. Total solar reflectance (TSR) is the value that can explain how much of solar energy can be reflected by objects. The common instrument for determining TSR is the devices and services, more commonly known as the "D&S". The D&S returns a single number for the TSR, while a spectrophotometer reads individual wavelengths that can be used to make the spectral reflectance curves seen in this article. Selection of high-IR-reflective Arctic pigment to increase reflectivity is the key to produce the needed color.

In order to keep cooling in the objects, the highest reflective pigments should be selected. For availability, Carbon black, iron oxide black or copper chromite black is presented but it has very low infrared reflectivity and a TSR approximately 6%. Thus, in generally, IR-reflective formulations incorporate Arctic Black 10C909 to lower the L value in colors made with the other Arctic colors. Black 411 provides a higher TSR, but with a redder undertone. A complete listing of Arctic pigments

(Figure 12) provides a nearly full color gamut to use to help formulate high-IR-reflective coatings.

Pigment	Color Index	Color Shade	Total Solar Reflectance (TSR%)
Black 10C909	Pigment Green 17	Blue Shade Black	24
Black 411	Pigment Brown 29	Red Shade Black	30
Blue 385	Pigment Blue 28	Red Shade Blue	28
Blue 211	Pigment Blue 36	Green Shade Blue	30
Blue 424	Pigment Blue 28	Turquoise	39
Green 1878	Pigment Blue 36	Teal	29
Green 179	Pigment Green 26	Camouflage green	24
Green 223	Pigment Green 50	Yellow Shade Green	25
Brown 12	Pigment Green 33		30
Brown 157	Pigment 33	Red Shade Brown	3
Brown 8	Pigment Black 12	Medium Shade Brown	38
Brown 156	Pigment Black 12	Blue Shade Brown	51
Yellow 10C112	Pigment Yellow 53	Yellow Shade Brown	66
Yellow 10C272	Pigment Brown 24	Red Shade Yellow	71

Figure 12 Arctic reflective pigments [20]

From the study of previous researches, we found that if we use the materials with insulation property, has low heat absorption, can reflect the sun light or infrared ray well and has the hollow shape as the additive in the paint, we should have the paint that can distribute and reflect the heat well and if we use it to paint on the roof and walls of the building, we expect that it can help reducing the transfer of heat into the building and can reduce the energy loss in cooling the building. Therefore, this research will focus on developing the optimal paint formula (Beger Cool UV Shield) with color pigments to reduce the heat transfers and minimize the cooling energy consumption of a small building coated. The test result will show the different of heat performance and energy consumption of two building, which are coated with conventional paints (colors), and coated with high solar reflective paint (Beger Cool UV Shield).

None of these literatures had studied the integrative view of paint chemical ingredients that can improve both reflectivity and insulation properties in order to increase energy saving. As well as, the painting system are also play important role to boost up the energy saving if users carefully selected suitable primer and topcoat paint. One of the optimal paint formulations and paint system will be applied on a small

standard building to compare with uncoated and conventional paint in natural environment exposure. The actual temperature, and cooling energy consumption data will be collected to validate mathematical model that link solar reflectivity property of paint film with reduction in building temperature, and energy saving estimation.