SUPERVISOR DECLARATION

"I hereby declare that I have read this thesis and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Thermal-Fluids)"

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Date:	28 JUNE 2013

THE HEAT TRANSFER PHENOMENON WITHIN VOLUMETRIC RECEIVER OF CONCENTRATED SOLAR TOWER USING DIAMOND LIKE CARBON (DLC) MATERIAL

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DECLARATION

"I hereby declare that the work in this report is my own except for summaries and quotations which have been duly acknowledged."

Signature:	____________________
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Date:	28 JUNE 2013

Special for my beloved

Father and Mother,

Zahari Bin Abdul Rahman and Siti Habsah Bt Zahari,

Family and Friends

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ABSTRACT

This project aimed to investigate the effectiveness of using Diamond Like Carbon (DLC) as volumetric receiver of Concentrated Solar Tower. Volumetric receiver, the type of solar absorber that is mostly studied which able to operate at high temperature, above 900K, the material therefore should be one that is durable to high temperature, have high absorptivity and high thermal conductivity for efficient heat transfer rate. Therefore the current system used non-oxide ceramics; Silicon Carbide (SiC) as the material. However, some problem have been identified while using SiC, which sometimes the occurrence of hot spots have melted the front surface eventhough the air outlet temperature has not yet reached the material melting temperature. Some had stated that this may due to the instabilities of flow and the inability of the material to spread the peak heat because of low effective thermal conductivity. Hence, in this project the applicability of DLC as the receiver material has been investigate whether DLC receiver able to overcome this problem. In this project, the study was conducted by performing 3D simulation using ANSYS Fluent platform towards heat transfer within DLC receiver module with several characteristics in order to observe the temperature distribution on the surface, the outlet temperature and analyzing the ability of DLC module to reduce hot spot. In the simulation, a small area is concentrated with higher heat flux to initiate hot spot. After that calculation continued with homogenous 1MW/m^2 heat flux and the result at the end of calculation was observed whether hot spot reduced and vanish. All receivers with 1.35mm, 1.55mm and 3.5mm mean cell size for 3000W/m.K thermal conductivity of DLC are able to overcome the hot spot phenomena while producing high outlet air temperature of 2300K. This concludes that with very high thermal conductivity of material, the hot spot phenomena are able to be overcome regardless of the porous characteristic of the receiver. Hence, DLC of 130W/m.K to 3000W/m.K thermal conductivity is the suitable candidate for volumetric receiver.

ABSTRAK

Penerima berisipadu adalah sebahagian daripada komponen Menara Suria Tertumpu yang beroperasi pada suhu yang sangat tinggi iaitu 900K. Oleh itu, penerima berisipadu mestilah diperbuat daripada bahan yang tahan terhadap suhu tinggi dan mempunyai kebolehserapan dan kekonduksian terma yang tinggi untuk pemindahan haba yang efektif. Sistem yang sekarang kebanyakannya menggunakan seramik tidak oksida, 'Silicon Carbide' (SiC). Akan tetapi, dengan menggunakan SiC beberapa masalah telah dikenalpasti iaitu pembentukan bintik panas telah melebur pemukaan modul penerima SiC walaupun suhu udara pada keluaran belum mencapai takat lebur. Merujuk kepada beberapa sumber, ini mungkin disebabkan ketidakstabilan aliran udara dan kekonduksian efektif terma yang rendah menyebabkan haba tertumpu pada sesetengah kawasan pada modul penerima. Oleh itu, di dalam kajian ini keupayaan 'Diamond Like Carbon' (DLC) sebagai bahan penerima sama ada ia mampu mengatasi masalah ini telah dikaji. Kajian ini telah dilakukan dengan mengsimulasi pemindahan haba secara 3D terhadap beberapa model penerima DLC yang berbeza-beza saiz keliangan menggunakan pelantar ANSYS Fluent. Ini adalah untuk mengetahui taburan suhu pada permukaan dan suhu keluaran serta menganalisa keupayaan DLC untuk mengurangkan bintik panas. Hasil analisa menunjukkan bahawa bagi ketiga-tiga model dengan saiz sel minima 1.35mm, 1.55mm dan 3.5mm untuk kekonduksian terma DLC 3000W/m.K fenomena bintik panas dapat dikurangkan disamping menghasilkan suhu udara keluaran yang tinggi iaitu 2300K. Dengan itu dapat disimpulkan bahawa dengan kekonduksian terma bahan yang sangat tinggi, fenomena bintik panas dapat diatasi tanpa mengambil kira saiz keliangan. Oleh itu, DLC yang memiliki kekondusian terma dalam lingkungan 130W/m.K ke 3000W/m.K adalah calon yang sesuai untuk penerima berisipadu.

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LIST OF SYMBOL

kW	=	kilowatt (10^3 Watt)
MW	=	megawatt (10^6 Watt)
EJ	=	Exa Joule (10^{18} Joule)
λ_{eff}	=	Effective Thermal Conductivity
λ_f	=	Fluid Thermal Conductivity
λ_s	=	Solid Thermal Conductivity
$\emptyset$	=	Porosity
K_1	=	Viscous coefficient
K_2	=	Inertial coefficient
μ	=	Fluid viscosity
ρ	=	Fluid density
v	=	Velocity
d	=	Mean cell size (m)
α	=	Heat transfer coefficient
T_s	=	Surface temperature
T_f	=	Fluid temperature
A_v	=	Interfacial area density (m^2/m^3)
Nu_{lv}	=	Local volumetric Nusselt Number
D_h	=	Hydraulic diameter
Q	=	Heat transfer rate
A_s	=	Surface area
ΔT	=	Temperature difference
K	=	Kelvin

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CHAPTER I

INTRODUCTION

1.1 BACKGROUND

Technology is advancing year by year and development is rapidly growing, resulting increased in energy demands. Nevertheless, current energy resources which is fossil fuels will soon depleted, in which making the development not sustainable anymore with this trending, there will be one point in which the power production would not be able to meet the energy demands. Therefore, alternatives resources aside from fossil fuels were researched extensively by scientists and researchers.

Alternative energy or also known as renewable energy is clean, renewable and of course sustainable such as solar radiation, geothermal, wave and tidal and also nuclear energy may be suitable to be the energy resources candidates to fulfill in the energy demand which cannot be supplied by current energy resources in the future. Among all the alternative energy, the most interesting is solar energy, which is clean, does not produce harmful emission and sustainable. Adding to that point, solar energy development also is a lucrative business since all the energy resources come from the heat of the sun.

Sun from solar system emits energy in the form of photon at a rate of $38x10^{23}$ kW. However, due to distance between Earth and Sun which is too far, only about $1.8x10^{14}$ kW will be seized by the Earth, but only 60% of the figure will reach the earth surface. Nevertheless, with only 0.1% of this energy would be enough to generate power which is 7500 times larger than the world total primary consumption of 450 EJ. The energy contained within solar radiation is very large that it succeeded even the combination of all the estimated non-renewable energy resources including fossil fuels and nuclear energy (Goswami, 2010).

The abundant energy within solar can be harness to generate electricity by either solar photovoltaic or solar thermal. Electricity generated by petrochemical effect in solar photovoltaic application. The energy contained within the photons of solar radiation absorbed by the p-n material of PV cells and electron released by the n materials in which the electron was carried to p-junction and thus produces electricity (Twidell and Weir, 2006).

Solar energy also harvested through the solar thermal electricity power plants in which the heat from irradiation will be used to run a heat engine and electricity will be produced by the generator coupled to turbine of heat engine. The key point in solar thermal power plant is to concentrate the irradiation in order to achieve high temperature, large enough to run a heat engine with reasonable efficiency. There are three types of solar thermal power plants namely parabolic trough, central receiver (solar tower) and parabolic dish (Steinhagen, 2008). Among these three types of solar thermal power plant, the concentrated solar tower with central receiver has advantage on the capability of handling higher temperature compared to parabolic trough which this is good from thermodynamic aspect (Steinhagen, 2008).

Solar tower absorber operating principles varies from each other, basically categorized into three; tube receiver, volumetric receiver and dual receiver (Kretzshmar, 2012). However volumetric receiver such as in Figure 1.2 is one that mostly studied for its potential of being able to absorb more radiation in the volume of material due to the porosity (Fend, 2010).

Figure 1.1 is the Solar Two project, a concentrated solar tower with central receiver power plant which the major components consist of heliostat, solar tower absorber, and turbo machineries coupled with electric generator. The operating principle of major component of central concentrated power plant is:

1) Heliostats

   Heliostats are a field of mirrors that attached to tracking devices and able to move about two axes throughout the day in order to track sun and keep radiation reflected to the centre of receiver (Stine and Geyer, 2001).

2) Solar tower absorber

   Solar tower absorber functions by transferring energy from incoming reflected solar radiation to the working fluid that will run the turbine and generates electricity.

Figure 1.1: Central receiver system with a solar tower absorber

(Source: Steinhagen, 2008)

1.2 PROBLEM STATEMENT

Solar tower absorber operating principles varies from each other, basically categorized into three; tube receiver, volumetric receiver and dual receiver. However volumetric receiver is one that mostly studied for its potential of being able to absorb more radiation in the volume of material due to the porosity. Since the volumetric receiver principally absorbing the solar radiation reflected by heliostats, the material that builds the structure should have good absorptivity and conductivity while be able to withstand high operating temperature of above 800˚C. From literature, most plant used ceramics such as Silicon Carbide (SiC) as absorber. However, it was identified that there are few problems encounter using ceramic as an absorber, in which it tend to melt due to local overheating of material in the event of inhomogeneous flux distributions and flow instability which in some cases lead to formation of hot spots because of the material is unable to spread the heat to all volume in short period of time. Therefore the aim of this study is to replace the current absorber with Diamond Like Carbon (DLC) which has higher thermal conductivity and is more durable to high temperature condition.

1.2 OBJECTIVE

At the end of this project, following is the objective anticipated to be accomplished:

1) To investigate the effectiveness of using porous DLC as volumetric receiver on heat transfer phenomena.

1.3 SCOPES

This project is focusing on the absorber part of concentrated solar tower, which the absorber is volumetric receiver type. In this research, the applicability of DLC as the material of volumetric receiver was investigated and in order to accomplish this aim, the scope of study has been determined to focus on:

1) 3D Simulation of heat transfer between air and porous medium across the absorber using ANSYS Fluent.
2) Analyze the outlet temperature and temperature distribution across the absorber module.
3) Analyze formation of hot spots.

1.4 PROJECT FLOW

The first part of this final year project was conducted by reviewing on volumetric receiver and DLC related literatures. The literature that studied are related to numerical simulation of volumetric receivers, the formation of hot spots on volumetric receiver fronts, operating principle of the receivers and DLC properties. Literature review activity was conducted throughout the duration of final year project.

The first step to start the research is by studying the ANSYS Fluent software since the investigation of the applicability of DLC as volumetric receiver material was planned to be done through simulation. The modeling and analysis was performed on volumetric receiver model with DLC properties of certain porosity and cell size. Analysis of the result comprises of temperature distribution contour of the receiver front surface, outlet air temperature, and the heat transfer rate across the module. The analysis was further discussed whether heat transfer across a DLC volumetric receiver is effective and at the end of this project a conclusion will be developed to conclude this project objective achievement and some suggestion will be proposed.

Figure 1.2 is the project flow which started with problem statement and determining project objective. Based on the objective and work scope, literature review was performed and then the problem was setup and analyzed using ANSYS Fluent. The result from analysis was further discussed and conclusion will be made based on the achievement of this project objective. After that, all the project process, result and discussion documented and the report submitted signifying the end of final year project. The Gantt chart of project schedule was attached as Appendix 1 in appendix section.

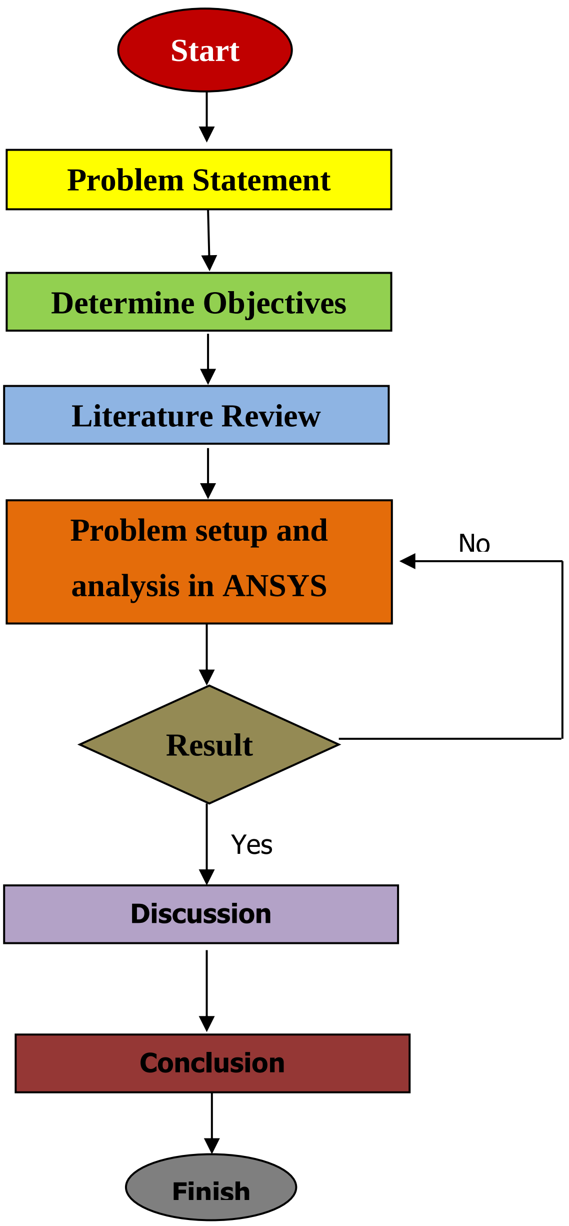

Figure 1.2: Flow chart of research activities

CHAPTER II

LITERATURE REVIEW

2.1 VOLUMETRIC RECEIVER

Avila-Marin (2011) discussed on three things regarding volumetric receiver; i) he grouped and divided the type of volumetric receiver into four; pressurized receivers with metal absorber, pressurized receiver with ceramic absorber, open receiver with metal absorber and open receiver with ceramic absorbers such as HITREC Project ii) absorber materials and iii) the operating principles.

Avila-Marin (2010) stated that generally the material used should be according to the working temperature of the system, for example the temperature lower that 800˚C shall be stainless steel and better if base-nickel alloys with high chrome content due to the oxides formed are black and very absorptive. While for operating temperature above 800˚C it was suggested in his paper that oxide ceramics such as aluminum oxides (Al_2O_3) that have good properties yet its whiteness is not good for optical performance. In order to improve the optical properties and absorptivity, non-oxide ceramics such as silicon carbide is the best candidate.

By referring to Figure 2.1, the operating principles of a volumetric receiver as according to Avila-Marin (Avila-Marin, 2011) are:-

1) Volumetric receiver is a combination of varying interlocking shapes, foam arrangement that made of metal, ceramic or other adequate materials with a specific porosity and installed in a volume inside the receiver so the solar radiation is absorbed in the depth of the structure.
2) The concentrated solar radiation heats the material in the volume and at the same time working fluid, usually air passes through the volume is heated up by forced convection transforming solar energy to thermal energy.
3) Heat is transferred to the working fluid at the surface which is heated up by the incoming radiation.
4) Finally, the volumetric effect causes the temperature of irradiated surface to become lower than the outlet temperature.

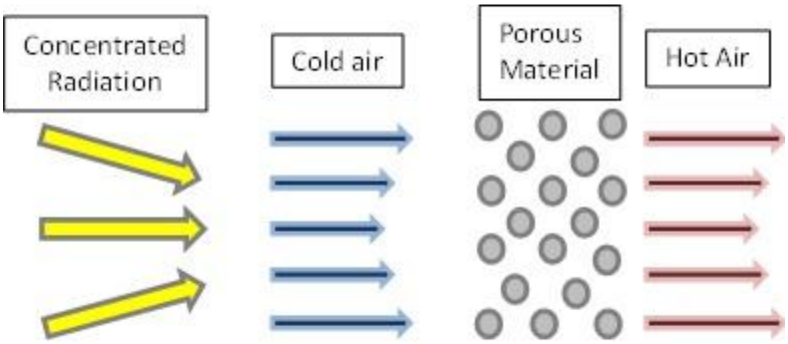

Figure 2.1: Cold air was heated by heat transfer between air and hot porous surface that irradiated

Several paper have studied about pressure drop in the porous structure of volumetric receiver Wu et al. (Wu *et al.*, 2010, 2011), Incerra et al. (Incerra *et al.*, 2008) and Lacroix (Lacroix, 2007). Wu et al. (Wu *et al.*, 2010) in their paper had reported that they performed experimental and numerical studies of pressure drop in ceramic foams. In the paper, it had been investigated that the pressure drop decreases with increasing porosity (ε) and mean cell size (d).

Wu et al. (2010) performed the experimental studies on ceramic foams and ceramic foams with modified structure in which several holes with 2mm diameter were drilled uniformly in the foam specimen. At the end of the experiment, the modified foams have displayed good performance in the improvement of pressure drop and heat transfer. They conclude that it may due to the additional heat transfer provided by the mixing action of fluid in perpendicular direction, thanks to the pores drilled.

Fend et al. (2004a) and another researcher on the other hand in their paper mentioned about flow instabilities occurring in the porous structure of volumetric receiver. Fend et al. (2004a) have developed an experimental method to detect any occurrence of unstable flow which the experimental setup was as Figure 2.2. In the experiment, the front surface of sample recorded by an infrared camera. Referring to Figure 2.2, in the experiment the cylindrical sample was heated by tube heater while infrared camera installed in order to monitor the front surface temperature.

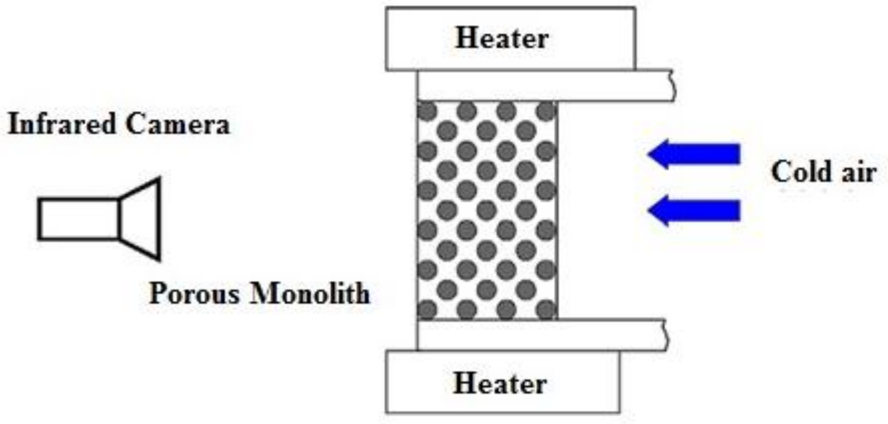

Figure 2.2: Experimental set up for investigating the flow instability by monitoring temperature distribution

(Source: Fend *et al.*, 2004a)

The flow instabilities occurrence sparks interest to be researched since the flow instabilities have potential to formed hot spots on the receiver's surface and cause material failure (Fend *et al.*, 2004a). In the recent study (Fend, 2010), Fend's experiment results had shown a relationship that as the cell density increases, the efficiency also increased. However, the porous structure may cause flow instabilities within receiver of certain material in which the permeability of the material does not tolerate high viscosity air that increased due to temperature increases. In this event, the absorber material may melts even though the outlet air temperature has yet to reach the material's melting point. Also suggested in his paper, this event may be avoided through a good effective thermal conductivity material applied, high inertial coefficient and the capability of material to mix the fluid throughout the structure.

The investigation of flow instability was explained in detail through Becker's theoretical and numerical study on this phenomenon (Becker *et al.*, 2006). The simulation result showed the relationship between hot spot occurrence and effective heat conductivity and permeability of material. The results were presented in the hot spot matrix such in Figure 2.3. The hot spot matrix in Figure 2.3 concludes that the hot spot occurrence reduced as the absorber as material's thermal conductivity increased and the hot spot occurrence is independent of the thermal conductivity if the inertial coefficient is $1x10^{-4}$.