DEVELOPMENT OF DISH-STIRLING CONCENTRATING SOLAR THERMAL-ELECTRIC ENERGY CONVERSION SYSTEM

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ABSTRACT

Sunlight is the world's largest renewable energy source. Using the existing technologies, this energy can provide the needs of all the people on Earth. By increasing the solar-to-electric energy conversion efficiency while maintaining the cost and lifespan of a machine, conventional photovoltaic technology is being progressively challenged by concentrated solar thermal engine technology especially in large scale power plant. For local research, the limitation of technological development between technical potential and practical utilisation of solar energy becomes one of the reasons behind the minimum growth of solar energy field. Owning a local renewable energy conversion system means decrease fossil fuel dependability, secure near to long term power supply chain and hence enhances economic development. In order to develop local expertise with low production cost, full scaled dish-Stirling CST based on DNI solar flux modules were prototyped. The development of the research began with a preliminary assessment on a 2m diameter manual operated ideal paraboloid concentrating dish prototype. Based on the important design parameters and followed by rigorous system design principles, an 8m diameter combined paraboloid-Fresnel concentrating dish with low focus height, low dish height and minimal wind resistance was designed and constructed. Using the hydraulic-electric two-axis solar tracking system, the proposed system was able to move 0-90° in Azimuth axis and +/-180° in elevation axis for the full day solar tracking with the consideration of yearly solar path variation. For the thermal-to-mechanical energy conversion, a compact and superior combination of square configuration, four cylinders rhombic drive beta drive mechanism Stirling engine system was integrated with the concentrating dish and tracking mechanism. Throughout the research and development, detailed investigations were conducted to achieve correct operation of the actual prototype. Referring to the 3D model, these studies, including a 3D ray trace analysis on the dish's focal region solar flux concentration pattern, influent of Azimuth angle offset on the thermal receiver performance, air flow simulation on +/- 0 to 28m/s wind load, coefficient of drag comparison and stress distribution due to wind and structural loads. From the computational and operating analysis, the paraboloid-Fresnel dish showed 34.9 to 38.3% of wind load reduction compared with ideal paraboloid design, low C_D in between 0.077 to 0.76 depends on wind flow direction and rotating angle. Together with structural mass, stress simulation indicated maximum stress of 320.6MN/m^2 and was validated with six components failure. Meanwhile, practical model showed 51% of structural stress reduction after continuous design improvement. Next, focal region temperature readings were recorded under various circumferences, and maximum concentrated temperature of 357°C had agreed the research hypothesis that specific thermal receiver design can store the solar flux at higher intensity. After several cranking tests, the prototype Stirling engine was unable to start as designed due to scattered solar thermal distribution. Based on Schmidt's analysis, the predicted engine output power was 6.03kW. Considering the total energy consumption for PLC, electric motor, hydraulic system and auxiliary system, the net power output was predicted at 5.759kW. Based on 1000W/m^2 solar DNI, the energy conversion efficiency for 8m diameter concentrating dish was predicted at 11.52%.

ABSTRAK

Cahaya matahari adalah sumber tenaga boleh diperbaharui yang terbesar di dunia. Dengan menggunakan teknologi yang sedia ada, tenaga ini boleh menyediakan keperluan semua manusia di Bumi. Dengan meningkatkan kecekapan penukaran tenaga solar untuk elektrik sementara mengekalkan kos dan jangka hayat mesin, teknologi photovoltaic konvensional sedang beransur-ansur dicabar oleh tertumpu solar enjin teknologi haba terutama di loji kuasa secara besar-besaran. Bagi penyelidikan tempatan, had pembangunan teknologi antara potensi teknikal dan praktikal penggunaan tenaga solar menjadi salah satu daripada sebab-sebab di sebalik pertumbuhan bertakung bidang tenaga solar. Memiliki sistem penukaran tenaga tempatan yang boleh diperbaharui ertinya mengurangkan pergantungan pada bahan api fosil, kekalkan rantaian bekalan kuasa jangka panjang dan dengan itu meningkatkan pembangunan ekonomi. Dalam usaha untuk membangunkan kepakaran tempatan dengan kos pengeluaran yang rendah, piring/Stirling CST berskala penuh berdasarkan modul fluks solar DNI telah dibangunkan. Pembangunan penyelidikan bermula dengan penilaian awal mengenai piring paraboloid diameter 2m. Berdasarkan parameter reka bentuk yang penting dan diikuti dengan prinsip-prinsip reka bentuk sistem ketat, piring diameter 8m hasil gabungan paraboloid-Fresnel dengan ketinggian tumpuan dan tinggi piring yang rendah, serta rintangan angin minimum telah ditakrifkan dan dibina. Menggunakan hidraulik elektrik dua paksi Penjejakan sistem solar, sistem yang dicadangkan mampu untuk bergerak 0-90° dalam Azimut paksi dan +/-180° dalam paksi ketinggian untuk Penjejakan hari solar penuh dengan mengambil kira perubahan laluan solar tahunan. Untuk penukaran tenaga terma kepada mekanikal, kombinasi yang padat dan atasan konfigurasi persegi, empat silinder berbentuk *rhombic drive* enjin *Stirling* jenis beta bersepadu dengan piring penggumpulan cahaya matahari serta mekanisme pengesan. Sepanjang penyelidikan dan pembangunan, siasatan terperinci dijalankan untuk mencapai pengendalian yang betul bagi prototaip sebenar. Merujuk kepada model 3D, kajian termasuk ray 3D surih analisis di rantau tumpuan pring kepekatan corak fluks, kesan sudut Azimut diimbangi prestasi penerima haba, udara simulasi aliran dari 0-28m/s angin beban, pekali perbandingan seret dan agihan tegasan yang disebabkan oleh angin dan beban struktur. Dari analisis pengiraan dan operasi, piring paraboloid-Fresnel menunjukkan 34.9-38.3% pengurangan beban angin berbanding dengan reka bentuk paraboloid yang ideal, C_D rendah di antara 0.077-0.76 bergantung kepada arah aliran angin dan sudut berputar. Bersama-sama dengan jisim struktur, simulasi tekanan menunjukkan tegasan maksimum 320.6MN/m^2 dan disahkan dengan enam komponen kegagalan. Sementara itu, model praktikal menunjukkan 51% daripada pengurangan tekanan struktur selepas peningkatan reka bentuk yang berterusan. Seterusnya, fokus rantau bacaan suhu dicatatkan di bawah keadaan pelbagai, dan suhu maksimum pekat 357°C telah bersetuju hipotesis penyelidikan bahawa penerima reka bentuk haba tertentu boleh menyimpan fluks solar pada intensiti yang lebih tinggi. Selepas beberapa ujian cuba hidupkan enjin, prototaip Stirling enjin tidak dapat beroperasi seperti yang direka bentuk kerana rata berselerak panas matahari. Berdasarkan analisis Schmidt, kuasa enjin yang diramalkan adalah 6.03kW. Dengan mengambil kira jumlah penggunaan tenaga untuk PLC, motor elektrik, sistem hidraulik dan sistem bantu, kuasa keluaran bersih diramalkan pada 5.759kW. Berdasarkan 1000W/m^2 solar DNI, kecekapan penukaran tenaga bagi piring diameter 8m telah diramalkan pada 11.52%.

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LIST OF ABBREVIATIONS

Capital Letters

A_a	Reflector area
A_r	Receiver area
A_w	Cavity internal area of receiver
A_c	Entrance aperture area of receiver
BDC	Bottom Dead Centre
CSP	Concentrating solar power
CST	Concentrating solar thermal
C_D	Coefficient of drag
C_p	Specific heat capacity at constant pressure
C_v	Specific heat capacity at constant volume
CR	Geometric concentration ratio
CR_o	concentration ratio
DNI	Direct Normal Irradiation
E	Total emissive power
E_b	Total emissive power of a blackbody
F	Force
FOS	Factor of safety
H_f	Focus height
H_d	Dish height
I_a	Reflector solar flux
I_r	Receiver solar flux
L_0	Distance between the Sun and the Earth = 1.496×10^{11} m
M	Moment
Mtoe	Million Tonnes of Oil Equivalent
P	Working gas pressure
PLC	Programmable logic control
P_{min}	Minimum working pressure
P_{max}	Maximum working pressure

P_{mean}	Mean working pressure
PV	Photovoltaic
Q	Heat transfer
Q_H	Heat source or sink per unit volume
Q_s	Solar energy incident on the concentrating dish
Q_r	Radiant solar energy falling on the receiver
Q_l	Heat losses from the receiver to the surroundings
Q_u	Useful energy collected
Q_{lo}	Optical loss from the collector
Q_{lk}	Conductive heat loss from receiver
Q_{lc}	Convective heat loss through the receiver aperture
Q_{lr}	Radiative heat loss through the receiver aperture the focusing device
R	Gas constant
$R_{s\,n}$	Dish front radius for mirror in section n
$R_{c\,n}$	Dish centre radius for mirror in section n
$R_{e\,n}$	Dish end radius for mirror in section n
S_i	Mass distributed external force per unit mass
T	Working gas temperature
TDC	Top Dead Centre
TW	Terawatts
TWh	Terawatts hour
T_{min}	Working fluid minimum temperature
T_{max}	Working fluid maximum temperature
T_w	Average operating wall temperature in the cavity
T_a	Ambient temperature
V	Working gas volume
W	Work done
W_c	Compression work done
W_e	Expansion work done
W_{net}	Net-work done

Small Letters

d_r	Concentrating dish diameter
d_f	Focus area diameter
d_{sun}	Diameter of the Sun= 1.392 x 10^9 m
d_{earth}	Diameter of the Earth= $d_{sun}/10^9$
h	Thermal enthalpy
h_c	Convective heat transfer coefficient
l_n	Reflected sun ray length
l_m	Faceted mirror length
m	Mass of working gas
n	Mirror section
p_f	Paraboloid focus point
q_i	Diffusive heat flux
r_i	Sun ray incoming vector
r_t	Sun ray refraction vector
rpm	revolution per minute
r_v	Compression ratio
s	Entropy
x	X-axis coordinate
y	Y-axis coordinate
$y_{s\,n}$	Front height for mirror in section n
$y_{c\,n}$	Centre height for mirror in section n
$y_{e\,n}$	End height for mirror in section n
$y'_{s\,n}$	Front height for ideal parabolic in section n
$y'_{c\,n}$	Centre height for ideal parabolic in section n
$y'_{e\,n}$	End height for ideal parabolic in section n

Greek Symbols

α	Absorptivity
α_t	Thermal diffusivity
γ	Ratio of the energy intercepted by the receiver to the energy reflected by
ε	Emissivity
ε_c	Cavity surface emittance

ε_{eff}	Effective infrared emittance of cavity
η_t	Thermal efficiency
η_{plant}	Plant efficiency
η_{col}	Solar collector efficiency
η_{ref}	Reflector efficiency
η_{eng}	Engine efficiency
η_o	Optical efficiency
n_i	Sun ray incoming ratio
n_t	Sun ray refraction ratio
θ	Solar incidence angle
θ_n	Faceted mirror angle
θ_i	Sun ray incoming angle
θ_r	Sun ray reflecting angle
θ_t	Sun ray refraction angle
θ_a	Sun's radiation cone maximum half angle
θ_α	Solar altitude angle
θ_β	Solar azimuth angle
θ_δ	X-axis angle
θ_L	Y-axis angle
θ_H	Z-axis angle
θ_{rim}	Half angle subtended by the arc of the parabola
k	Thermal diffusivity
λ	Factor of un-shading
σ	Stress
$\sigma_{vonMises}$	Von misses stress
σ_{limit}	Maximum stress
σ_S	Stefan-Boltzmann constant, 5.67 x 10^{-8} W/(m^2K^4)
ρ	Fluid density
ρ_r	Reflectivity
ρ_{gas}	Working gas density
τ	Transmissivity
τ_{ik}	Viscous shear stress tensor

τ_t	Temperature ratio
Ω	Angular velocity.

CHAPTER 1

INTRODUCTION

1.1 Background Study on Solar Power

Due to environmental issues as well as increasing demand for renewable resource, the conversion of solar power into useful energy is receiving more and more attention in recent years. Sunlight is the world's largest energy source. The amount that can be readily accessed with existing technology greatly exceeds the world's primary energy consumption. Furthermore, sunlight is free, clean, renewable and technically exploitable in most part of the inhabited earth (Angkee and Chana, 2011).

Taking the Sun as the spectrum of a blackbody at 5800K, the amount of solar energy falling on a surface per unit area and per unit time is illustrated in Figure 1.1. Currently, the Sun radiates energy at 3.9×10^{26}W or 64×10^{6}W/m^2 but energy received by the Earth and its atmosphere is 1368W/m^2 or 1.7×10^{17}W of radiation yearly from the sun. This value varies in +/-1.7% due to changes in the Earth-Sun distance (Salsabila, Ab Kadir and Suhaidi, 2011). Assuming that the world population is 10 billion with a total power need per person of 10kW would require about 10^{11}kW of energy (Goswami, Frank and Jan, 2000). This is equal to 1000km x 1000km solar powered land area plotted in the middle of the Atlantic Ocean (Anton and Christian, 2009). Apparently, solar irradiance on only 1% of the earth's surface with 10% efficiency useful energy conversion could provide the needs of all the people on Earth (Goswami, Frank and Jan, 2000).

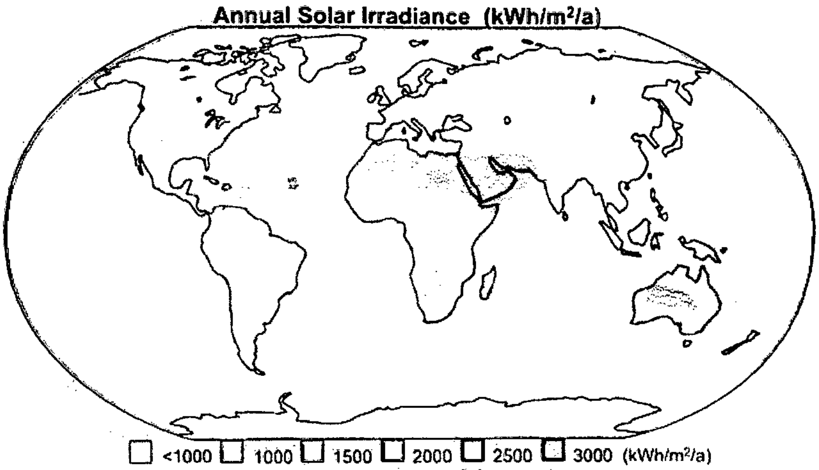

Figure 1.1 : Annual solar irradiance on Earth

Source : Anton and Christian (2009)

A tropical country such as Malaysia is generally hot all year-round and experiences its rainy season during the end of the year. Within an average of 12 hours of sunshine daily, the average solar energy received is between 1400 and 1900kWh/m^2 annually. The maximum radiation is received during a sunny day, where 90% of the extraterrestrial radiation becomes direct radiation while the rests are being deflected as diffuse radiation, while conversely, on a cloudy day, nearly all the solar radiation is diffused (Salsabila, Ab Kadir and Suhaidi, 2011). The weather condition in Malaysia is suitable for solar power implementation. This is because the weather condition is almost predictable and the availability of about 6h of direct sunlight with irradiation of between 800W/m^2 and 1000W/m^2 (Nowshad, Chin and Kamaruzzaman, 2009).

Today, two technologies are being actively developed to transform solar irradiation into electricity. One technology is photovoltaic or solar voltaic which uses photovoltaic materials to convert solar radiation directly into electricity. The other technology is solar thermal power or concentrating solar power converts the solar radiation into heat and then electricity through various thermodynamic cycles. For photovoltaic cells, efficiency up to 18% are reported while the efficiency of heat engine conversion systems can be as high as 33% depending on the quality of the technology used (Karabulut, Yucesu and Cinar, 2006). Restricted by the capital cost of solar panels and other issues, the photovoltaic technology is being increasingly challenged by solar thermal power technology. In recent years, some practical solar thermal power plants have been installed in countries such as the US, Europe, India and China (Wu, Xiao, Cao and Li, 2010).

1.2 Problem Statement

Compared with the heavily subsidised fossil fuel, renewable energy such as solar power often labeled as expensive and will never be price-competitive. In addition, solar technology has been always stereotyped as not technically feasible for electricity generation due to the high cost. Although solar power has an enormous potential to reduce the global emissions of greenhouse gasses, the current use of this energy resource represents less than 1% of the total electricity production from renewable sources (Goswami, Frank and Jan, 2000). Particularly in Malaysia, the present initiatives and efforts are lower than the country's actual potential. Currently, the solar status in Malaysia is 1MW, but its estimated potential can reach more than 6500MW (Salsabila, Ab Kadir and Suhaidi, 2011). The limitation of technological development between technical potential and practical utilisation of solar energy becomes one of the reasons behind the minimum growth of solar-energy field.

The total solar energy reaching the earth is made up of two parts; energy from direct irradiation and energy from diffused irradiation. Although power-plants can use direct and diffuse solar energy, most of the man-made solar-electric conversion system can convert only direct energy efficiently (Goswami, Frank and Jan, 2000). With the solar concentration system, high intensity solar thermal engine operation is much more efficient than the diffuse solar technology.

In the recent development, one of the most viable technologies is the concentrating solar thermal (CST) which is able to convert solar electric for both distributed and remote area applications. However, each energy conversion has efficiency, cost and an environmental footprint depending on the worthiness of the process. From a scientific and technical viewpoint, the development of new technologies with higher conversion efficiencies and low production costs become the key requirement for enabling the deployment of solar energy at a large scale (Goswami, Frank and Jan, 2000).

For the dish-Stirling CST technology as instance, it has good potential in power modulation and possess high concentration ratio. However, the solar-to-electric efficiency varies largely depending upon the solar flux density, concentration factor, the temperature of the thermal intermediary and the thermal cycle efficiency for the production of mechanical work and electricity. In order to maximise the solar fraction, intense search for effective and economic methods to capture, store and convert solar energy into useful energy should not be neglected (Mekhilef, Saidur and Safari, 2011).

In order to do that, one of the crucial steps is the introduction of specific solar thermal-electric energy conversion technology. In the case of dish-Stirling system, the technology development includes concentrator, receiver, absorber, thermodynamic cycle and tracking system. The technology must be further developed and proven to be technically and economically feasible with the consideration of environmental impact such as material degradation and climate constraints.

1.3 Objectives

Research objectives for the development of solar thermal energy conversion system are listed as follows:

i. To prototype 8m diameter innovative solar thermal concentrating dish with two-axis solar tracking system
ii. To develop compact multi cylinders solar Stirling engine with thermal receiver unit for concentrated solar flux operation
iii. To analyse the operation feasibility of integrated full scale solar dish-Stirling prototype model.

1.4 Work Scope

The work scope is specified as follows:

i. Development of solar thermal concentrator based on combined paraboloid-Fresnel principle
ii. Development of azimuth-elevation control unit, load supporting structures and direct normal irradiation tracking system
iii. Development of a square rhombic drive Stirling engine incorporated with the solar-thermal receiver
iv. Integration of working prototype dish-Stirling system
v. Installation of data acquisition and monitoring sensors
vi. Dish-Stirling working model operational analysis.

1.5 Hypothesis

Large concentrating dish development based on innovated paraboloid-Fresnel concept could minimise wind and rain load which indeed applicable for modular or distributed tropical application. Consistent solar tracking system could be developed using PLC principle and accumulation of high intensity solar direct normal irradiation. Consequently, it could increase the temperature of thermal flux in the specific receiver-absorber to drive the four-cylinder square type rhombic drive beta Stirling engine. For the solar power conversion, solar thermal is an alternate solution instead of the photo-chemical process.