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Investigations to conduct a study about possibilities to use small scale solar dish Stirling engine system in Thailand

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Abstract

This research studies the possibilities of generating electricity by using small scale solar dish Stirling engine system in Thailand. A solar dish Stirling engine system was evaluated and designed as prototypes for Thailand**.** The performance of system for electricity generation was also simulated under Thai climate condition. The results of the study can be structured in two parts. First is testing the existing Stirling engine and second is simulation the electricity generation by solar dish Stirling engine system prototype in Thailand. The existing Stirling engine at the Komplexlabor of the FH – Stralsund University, Germany was tested to understand the characteristics of the operating system. Stirling engine was operated at temperature of about 800 ^{o} C in the combustion chamber, being its nominal rotational speed 1,517 rpm. Finally, the average Stirling engine efficiency was established in 22 %. The results of simulation on solar dish Stirling engine were that the main components for a prototype of a solar dish Stirling engine system in Thailand shall consist of a Stirling engine with a nominal power of 25 kW, and a 131 m^2 dish concentrator. It can generate electricity about 27,946 kWh/year of electricity under Thai climate condition. During the working process, the heat lost on dish concentrator was 22 % and heat lost within the Stirling engine was 60.84 %. The system efficiency of this solar dish Stirling engine system was 17 %.

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Keywords: Solar dish Stiring engine, Performance of Stiring engine, System efficiency of Stiring engine.

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1. Introduction

Presently, an energy crisis affects the world economy badly, with social and environmental consequences. The main problems come from fossil fuels, such as oil, gas and coal, which will deplete in the near future, especially petroleum that will be exhausted within 30 years [1].

The reserved energy from fossils has rapidly decreased, while the energy demand has increased due to population growth, economic growth, industrial growth and technology advance, which affect the environment with greenhouse-effect gases (mainly CO_2) [2]. 1,500 million ton of CO_2 were emitted in year 1971, and this figure increased to 20,000 million ton in 1990. By prediction, it will reach 30,000 million ton in 2010 if there is no procedure to reduce CO_2 emission, the climate change will cause disasters throughout the world in the near future. Solar radiation is the original source of almost all the energy that is consumed in the daily life. Petroleum comes from the rests of animals and plants. But animals and plants cannot live without the sun. Thus, 99.98 % of world useful energy comes from the sun, and other 0.02% is geothermal energy. The amount of solar energy available on the earth is a million times greater than our current energy demands. The solar thermal power plants are applications of solar energy that should be more encouragement, for helping to solve the mentioned problems. The goal of this study is to analyze new possibilities to generate electricity by solar thermal power plants, which are clean and based on an unlimited resource. This research emphasizes on a solar dish Stirling Engine system which was studied and simulated in electricity generation under Thai climate conditions.

Nomenclature

Q_u	The useful heat (Heat at the receiver)
Q_{chem}	Chemical Energy
Q_{solar}	Solar Radiation Energy
ρ_c	The refractivity
I_d	The direct radiation
A_r	The aperture area of dish concentrator
f_c	The cleanness factor
$\partial\psi_1\psi_2$	The fraction of rays reflected from a real mirror surface which are in intercepted by the absorber for preface tracking.
$(F\psi_3)$	The fraction of rays intercepted by the absorber for perfect optics and point of sun for mirror tracking error.
f_t	The factor on shading of mirror
η_{sys}	System efficiency
Pel	Electricity Power

2. Solar dish Stirling engine system

The Stirling engine was patented in 1816 by Robert Stirling (1790-1878), a minister of the Church of Scotland. At that time, steam engines had a rather low efficiency (2-10 %), and were quite unsafe. Boilers exploded often, and the high pressure steam that was released had scalding effects. Most Stirling engines of the 19th century delivered only a small power output (a few or fractional horsepower), and were used in rural areas (mostly Scotland) to drive farm machines, pumps etc. before electricity became abundant. After that the Stirling engine was revealed in 1930 by Philips Company and it has been developed until now. The Stirling engine is a heat engine. It has high efficiency rather than gasoline engine and diesel engine. When Stirling engine is operating, makes little sound. Nowadays, Stirling engines have been developed for generating electricity whit heat supplied by renewable energy sources, particularly solar energy. A so-called Dish Stirling engine system, which can convert solar energy into electricity, is illustrated in Fig. 1. [3],[4],[5]

Fig. 1. Solar dish Stirling engine system [6]

Dish Stirling engine systems that use solar energy as the primary energy supply, and then convert it into electricity. Different dish Stirling engines have been built and operated during the past 15 years. Efficiencies of dish Stirling engine systems have been reported to be about 25 % for the net solar energy to electrical energy conversion efficiency.

3. Research methodology

A partial part of this study consists in a practical work on the Stirling engine unit Solo STIRING 161 micro CHP-Module at the Komplaxlabor of Stralsund University, Germany. Its nominal power is 25 kW. This Stirling engine is fed by natural gas, as primary energy supply. The Stirling engine at the Stralsund University is used as laboratory station, for study and research, in combination with a biomass boiler. The Stirling engine 161 is a single acting 90 ^{o} V type, with two cylinders and two pistons. This type of Stirling engine can be also called α type. The results from the practical work can be used for a simulation of electricity generation by solar dish Stirling engine in Thailand. The study of the electricity production by solar dish Stirling engine in Thailand relationships between the required heat for driving the Stirling engine and the electrical energy output are needed. After testing the Stirling engine at the laboratory station, the characteristics concerning to the performance of the Stirling engine are used for simulation of electricity generation under Thai climate condition. Research methodologies of solar dish Stirling engine system are shown in Fig. 2.

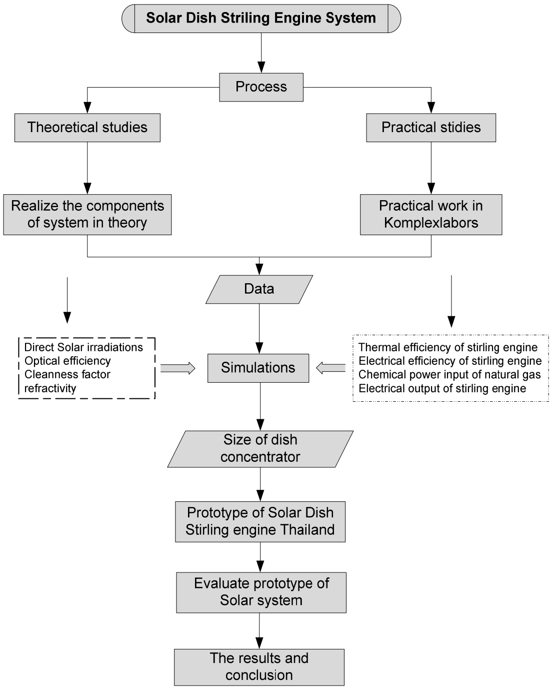

Fig.2. Research methodology

Not only the results from testing a Stirling engine are used for simulation, but also direct radiation potential values in Thailand. In this research, values of the direct solar radiation potential from "A research report of Potentials of Concentrating Solar Power Technologies in Thailand by the Department of Alternative Energy Development and Efficiency, Ministry of Energy and Solar Energy Research Laboratory, Department of Physics, Faculty of Science, Silapakorn University" were used. The direct radiation is shown in Fig. 3.

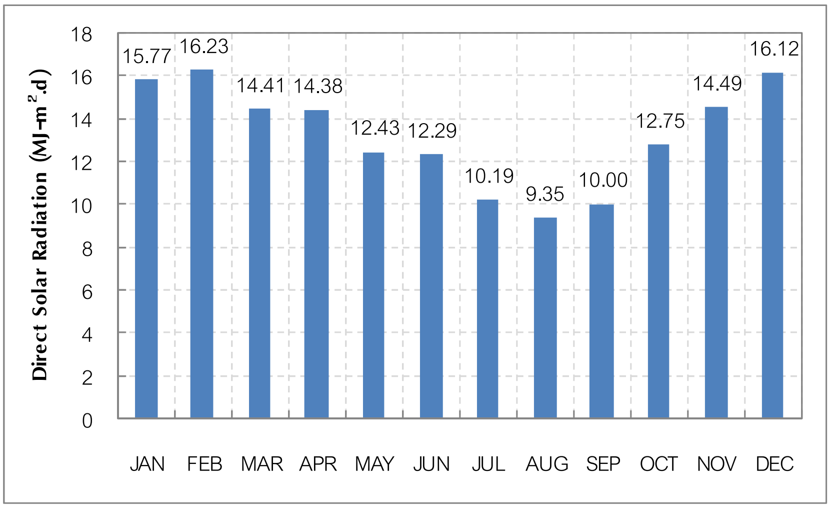

Fig.3. Average direct solar radiation in Thailand [7]

Solar dish concentrator concentrates the direct solar radiation to the focal point. The useful heat can be defined as the following equation [3],[6],[8]

$$Q_u = (\rho_c f_t).(\partial\psi_1\psi_2)(F\psi_3)(f_c)I_d A_r \quad (1)$$

In this research, the assumption is that the useful heat (Q_u) is equal to the chemical energy content of the natural gas (Q_{chem}) used to power the Stirling engine because the Stirling engine was tested to get the relationship between chemical energy and electrical energy output. For this reason, the amount of solar energy refracted to the receiver by dish concentrator should be the same as the chemical energy. The idea is shown in Fig. 4.

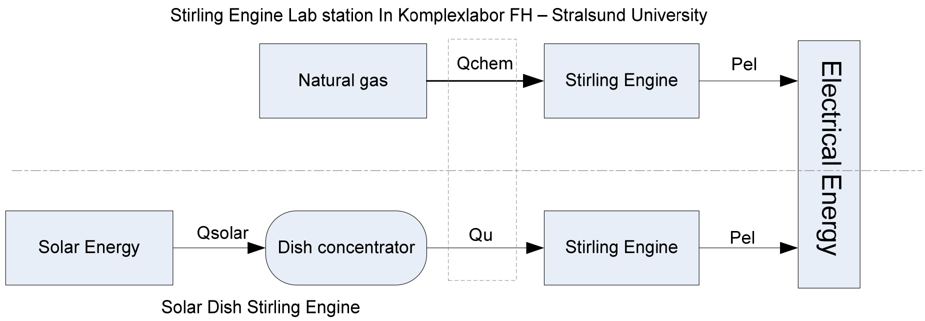

Fig. 4. The model of an idea solar dish Stirling engine

Referring to the above figure, the relationships of both systems can be written as follows.

$$Q_{chem} = Q_u \quad (2)$$

The value for the chemical energy (Q_{chem}) can be found at the testing results of the Stirling engine. Also referred to the discussion above, the Dish concentrating area (A_r) of dish concentrator can be calculated, as showed in the following equation.[3],[6],[9],[10]

$$A_r = \frac{Q_{chem}}{I_D \rho_c f_t f_c (\partial\psi_1\psi_2)(F\psi_3)} \quad (3)$$

The system efficiency (η_{sys}) of a dish Stirling engine can be found as:

$$\eta_{sys} = \frac{P_e}{I_D A_r} \quad (4)$$

All of important parameters which were used to calculate the dish concentrating area, and to study the generation of electricity with solar dish Stirling engine systems under Thai climate condition, are shown in the Table 1.

Table 1. Parameters for calculating the solar Dish Stirling Engine system [11]

Parameter	symbol	value
Refractivity of concentrator	ρ_c	0.931
Cleanness factor	f_c	0.98
Factor of fraction of rays refracted from real mirror which are intercepted by absorber	$\partial\psi_1\psi_2$	0.95
Factor of tracking error	$(F\psi_3)$	0.95
Factor of shading of mirror	f_t	0.95

4. Analysis and discussion on solar dish Stirling engine system

The test procedure was completed with a performance test of the Stirling engine. The electrical load was charged from a minimum point up to a maximum point (different load testing points), starting with 8 kW, and up to 22 kW, even when this last value was not the nominal electricity output. The most important parameters for operating system were measured and controlled by a computer program at the Stirling engine system during the testing time. The results are shown, in Table 2.

Table 2. Results of testing the Stirling Engine

Parameter	Testing Point								
	Unit	8 kW	10 kW	12 kW	14 kW	16 kW	18 kW	20 kW	22 kW
Thermal power	kW	7.82	9.74	11.89	13.91	15.96	17.74	20.07	20.00
Electrical power	kW	1.34	2.86	4.21	5.41	6.63	7.75	8.87	8.93
RPM	rpm	1503	1510	1512	1515	1519	1524	1529	1529
Cylinder pressure	bar	28.00	46.00	62.00	79.00	96.00	113.00	131.00	132.00
He pressure	bar	223.00	211.00	204.00	197.00	190.00	184.00	178.00	178.00
Ambient temperature	^{o} C	17.50	19.90	22.90	25.90	28.80	32.00	35.00	35.60
Stirling temperature	^{o} C	699.20	699.70	700.00	700.00	699.70	700.00	699.40	700.20
Gas temperature 1	^{o} C	739.70	765.40	784.50	808.30	822.60	830.70	836.20	832.50
Gas temperature 2	^{o} C	742.70	761.90	787.90	808.50	825.90	830.80	838.70	833.40
Water out temperature	^{o} C	17.00	18.10	20.90	23.60	26.10	29.30	31.60	32.80
Water in temperature	^{o} C	8.90	8.70	8.90	8.90	8.90	8.90	9.10	9.10
Water flow Rate	m^3\h	0.77	0.78	0.78	0.78	0.78	0.79	0.78	0.78
Natural gas flow rate	m^3\h	0.95	1.41	1.84	2.31	2.75	3.27	3.63	3.70
Electricity efficiency	%	16.97%	20.43%	23.20%	23.51%	23.94%	23.39%	23.45%	23.30%
Thermal efficiency	%	73.34%	58.11%	56.92%	55.34%	54.42%	54.98%	53.95%	55.69%

From the measurements, the average temperature inside the combustion chamber was 803 °C. Generally, after the receiver has absorbed the heat, the heat is transferred to a working fluid. In this case, the working fluid was Helium (H_e). After Helium had absorbed the heat from the receiver, the temperature and pressure become high enough to move the piston inside the constant-volume cylinder. The temperature and pressure of the working fluid were rising in the meantime, reaching average values of 699 °C and 195.63 bars respectively. The working fluid begins to expand in the cylinder to move the piston, which generates mechanical energy. The average rotational speed at testing was 1,518 rpm. The mechanical energy is used to generate electrical energy. From the results, the average electricity output was 5.94 kW, and the total efficiency in electricity production was 22 %, being the average thermal efficiency of 58 %. The temperature in the combustion chamber varied in a range between 740 °C – 838 °C for the different testing points, those belonging to the 8 kW and 22 kW output power values, respectively. The pressure at the helium storage tank was decreasing between 223 bar and 178 bar, when the pressure inside the Stirling cylinders increased between 28 bar and –137 bar. The result described above is shown in Fig. 5.

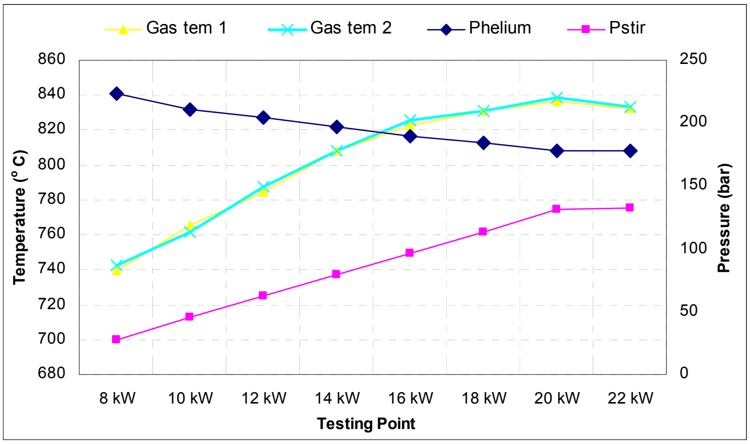

Fig.5. Relationship of temperatures and pressures of Stirling engine

4.1 Calculation of the dish concentrating area

This part of research aims to optimize the size of dish concentrating area. The main assumption for calculation, based on the result of the Stirling engine at the laboratory station in Komplexlabor at FH-Stralsund University, was the input energy (chemical energy of natural gas), that was considered as equal to the solar energy refracted by the dish concentrator. The results of the size of dish concentrator calculation in different testing points are shown in Fig 6.

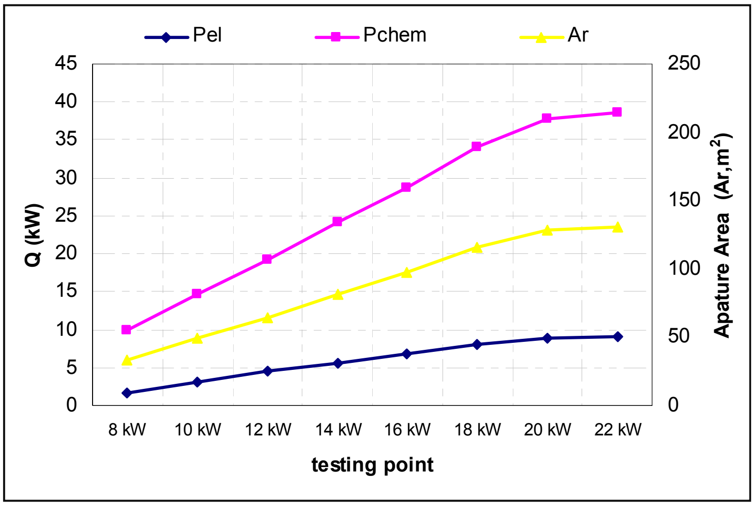

Fig.6. Relation of dish concentrator size with the input and output energies

The dish concentrating area was defined by the required heat of the Stirling engine, and by the potential of direct solar radiation. There were, at the 8 kW testing point, 9.90 kW for the required heat and 1.68 kW for electrical output, respectively. In this case, the required solar dish concentrator area was 33 m^2. At the testing point of 22 kW, the required heat value was 38.63 kW, and the electrical output was 9 kW. For these values, the required solar dish concentrator area was 131 m^2. This value was calculated for the prototype simulation in Thailand because it is maximum value for electricity generation.

4.2 Design of a prototype of solar dish Stirling engine system for Thailand

This part of the research consists solar dish Stirling engine system design of Thailand by using both direct solar radiation values from Thailand (yearly average daily of direct radiation) and the testing results of the Stirling engine laboratory station. According to the testing results in table 2, at the highest testing point, the required heat was 38.6 kW and the electricity output was 9.00 kW. Based on these values, the concentrating area of dish concentrator could be designed. The area of the dish concentrator was then 131 m^2. A drawing of the prototype of solar dish Stirling engine for Thailand is in Fig. 7.

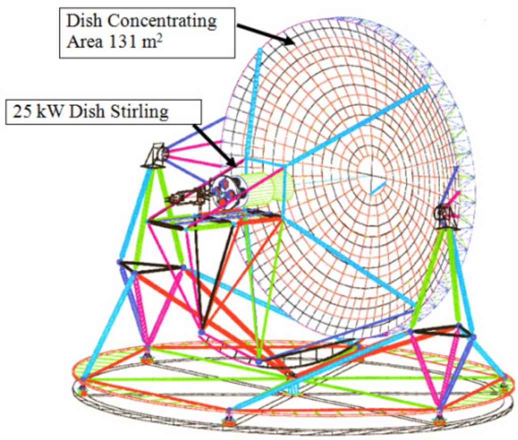

Fig.7. The 25 kW Dish Stiring Engine desingn for Thailand

This research concentrate only on two of the main components of Dish Stirling engine system, that were the Stirling engine and the dish concentrator, a solar dish Stirling engine system has several other components, such as tracking system, supporting structures, and others.

4.3 Simulation result of electricity generation by solar dish Stirling engine system in Thailand

The assessment of a dish Stirling engine prototype in Thailand by using relationship between required heat (Chemical energy of natural gas) and electrical energy output at the Stirling engine was tested. The energy input and energy output of Stirling engine related by the equation that converts heat to electricity of Stirling engine. The method of evaluation, using the input values of direct solar radiation from Thailand, which strike on the concentrating surface, where the direct solar energy is refracted into the receiver of the Stirling engine, being converted into heat and then into electricity, is shown in figure below.

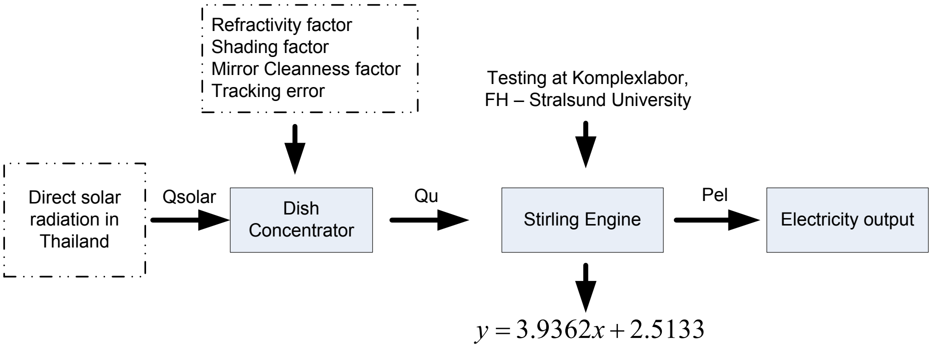

Fig. 8. Model of evaluation for the dish Stirling engine system in Thailand

Fig.8. shows the simulating method of the electrical output of a dish Stirling engine system. The results of the simulation could be divided in two different parts, the first being the yearly variation of the daily average of the electrical output, and the second yearly variation of the monthly average of the electrical output, as are shown below.

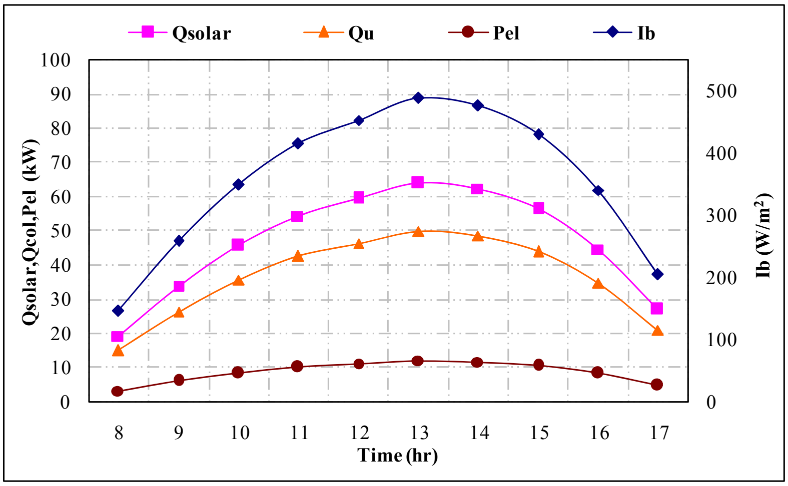

Fig.9. Yearly variation of the daily average of the electrical output

The simulation of the yearly variation of the daily average electrical output was performed by entering with yearly values of the daily average direct solar radiation in Thailand, and converting them to electricity values, by using the relationship between energy input and energy output of the tested Stirling engine. The electrical energy output of the prototype of solar dish Stirling engine in Thailand was 86 kWh/day. The direct solar radiation was 3.55 kWh/m^2day. The operating system was supposed to be in operation between 8.00 AM - 17.00 PM, and not out of this range. The system cannot operate only when the solar energy is not enough to power the Stirling engine. Maximum and minimum electricity outputs were 12.03 kW at 13.00 PM and 3.17 kW at 8.00 AM respectively. As per the results of simulation, the electrical output was increasing with increasing of solar direct radiation.

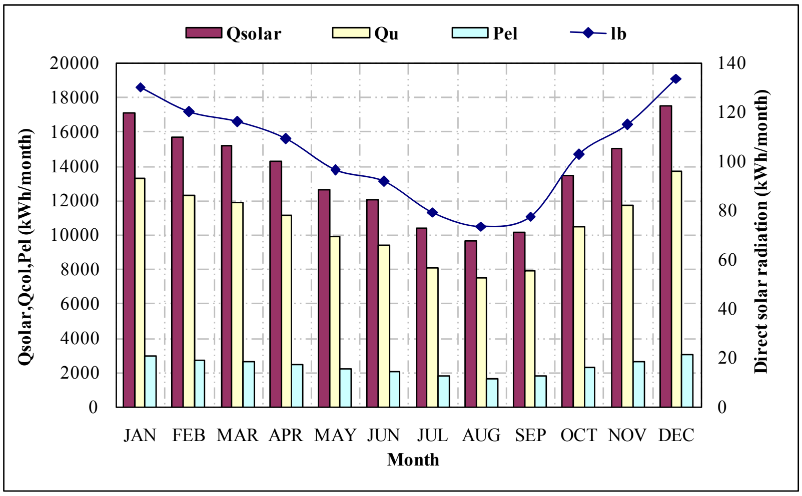

Fig.10. Yearly average monthly of electrical energy output

The results of simulating the yearly values of the monthly average of electrical energy output were following, the direct solar radiation energy in Thailand was 1,243 kWh/m^2.year, and the direct solar radiation energy striking on mirror surface of dish concentrator (131 m^2) was 162,857 kWh/year. The direct solar energy radiation is refracted by concentrator was 127,028 kWh/year. Finally, the electrical energy output was 27,946 kWh/year. The maximum electrical energy output was reached in December, during the winter time; when the sky above Thailand is very clear (Clear sky). On the opposite, during the raining season, that takes places in June, July, August and September, the sky is very cloudy, and so the electrical energy output was low.

During the working process of a solar dish Stirling engine, there are losses on each component of system, such as losses on dish concentrator and losses inside the Stirling engine. Overall losses of a solar dish Stirling engine, as analysed in this research, can be seen in fig 11. From the result of the simulation, the optical losses on the dish concentrator were 22 % and heat losses at the Stirling engine reached a 60.84 %. Finally, the result of simulation of the electric generation, under Thai climate conditions, by means of a solar dish Stirling engine system has a global efficiency of about 17 %.

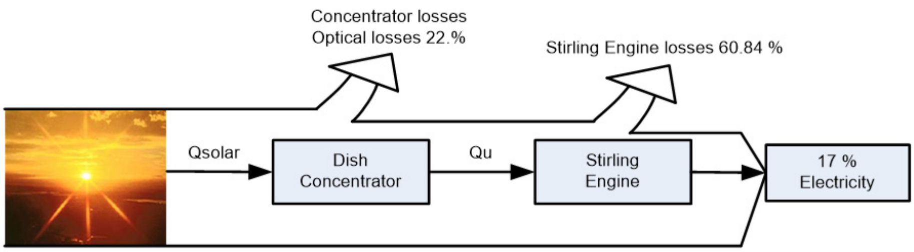

Fig.11. Losses in a solar dish Stirling engine system

5. Conclusion

A solar dish Stirling engine system is a kind of solar thermal power plants that can convert solar radiation into electrical energy. A Stirling engine laboratory station at the Komplexlabor of the FH Stralsund University was tested. The concluding results of testing were that the average electrical efficiency of Stirling engine was 22 %, but the maximum electrical efficiency was 24 %. The average thermal efficiency of the Stirling engine was 58 %, and the maximum efficiency of Stirling engine was 73 %. The average temperature in combustion chamber for operating the Stirling engine was 802 °C, and the pressure inside the Stirling cylinder to move the piston was 85 bar. The rotational speed of the Stirling engine was 1,517 rpm. All the values reported above are important to operate a Stirling engine. After knowing all the parameters to operate the Stirling engine, the next step was to find the suitable area of dish concentrator to concentrate direct solar radiation into the receiver of a solar dish Stirling engine. The size of the dish concentrating area was calculated to reflect sun light to the focusing point of the prototype of Stirling engine system in Thailand. The suitable size of the dish concentrating area was 131 m^2. With this value, the prototype of solar dish Stirling engine in Thailand could be designed. The prototype of Stirling engine in this research is 25 kW of Stirling engine nominal power and 131 m^2 of dish concentrating area. The concluding results of the simulation to define the amount of electric energy output that could be generated by the prototypes of dish Stirling engine systems under Thai climate condition were a daily electric energy output of 85.98 kWh/day, and a yearly electrical output of 27,946 kWh/year. Finally, the prototype of dish Stirling engine system in Thailand could convert solar energy to electrical energy with a 17 % of system efficiency, in terms of electricity. The electricity generation by solar dish Stirling engine system is a possibility to generate electricity by renewable energy which is clean and environmental friendly.

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References

[1] Franz K. Photovoltaic system technology. Kassel University: Germany; 2003.
[2] International energy outlook. Energy information administration office of integrated analysis and forecasting. U.S. Department of Energy: Washington; 2007.
[3] Robert Pitz-Paal. High temperature solar concentrators. Institute of technology thermodynamics: Germany Aerospace Center (DLR): Germany.
[4] Schlaich B, Partner. Euro dish – Stirling system description. MERO-Raumstruktur GmbH&Co: Germany; 2002.
[5] http://volumatri xgroup.com/2011/09/20/top-10-solar-technologies-to-watch-out-for/. 2013.
[6] Yogi G, Frank K., Jan F. Kreider. Principle of Solar Engineering. 2000.
[7] Serm J and Partner. Potentials of concentrating solar power technologies in Thailand. Department of Alternative Energy Development and Efficiency: Ministry of Energy and Solar Energy Research Laboratory Department of Physics: Faculty of science, Silpakorn university; 2006.
[8] Zhigang L, Dawei T, Jinglong D and Tie l. Study on the radiation flux and temperature distributions of the concentrator – receiver system in a solar dish/Stirling power facility. Applied Thermal Engineering; 2011. P. 1780-1789.
[9] Ramin S, Hoseyn S, Hadi H. Sizing a solar Stirling micro-CHP system for residential application in diverse climatic condition base on 3E analysis. Energy Conversion and Management 75; 2013. P. 348-365
[10] Mohammad A, Amir M, Saeed D, Marco B. Multi-objective thermodynamic –based optimization of output power of solar dish-Stirling engine by implementing an evolutionary algorithm. Energy conversion and Management 75; 201. P. 438 -445
[11] Keith L, Zawadski. Paraboloidel dish solar concentrators for Multi-Megawatt Power Generation. Solar World Congress: Bejjing; 2007.