THE SELECTION OF STIRLING ENGINES APPLIED TO COGENERATION SYSTEMS

Piotr Drogosz, Szymon Nitkiewicz, Andrzej Piętak

University of Warmia and Mazury,
Technical Sciences Faculty, Department of Mechatronics
Sloneczna Street 46A, 10-710 Olsztyn, Poland
tel.: +48 89 5245101, fax: +48 89 5245150
e-mail: piotr.drogosz@uwm.edu.pl, szymon.nitkiewicz@uwm.edu.pl,
apietak@uwm.edu.pl

Abstract

The cogeneration systems of energy production are built and developed to achieve the highest economic and ecologic efficiency. These two aims can be realized by increasing energetic efficiency of transforming different sources of energy into technical systems and optimizing usage of own energy. These can be achieved by the usage of different equipment. The search for new constructions, structure and systems is still developing. This article describes the basic principles for use of Stirling engines in micro immobility cogeneration systems. This attempt is made because the Stirling engines seem to be a convenient equipment of optimizing usage of own energy in micro agropower plants. Especially we try to determine which type of the Stirling engine seems to be the best to fulfil the demands in practice. For this purpose a procedure of selection and adjustment of Stirling engines was formulated. In the described procedure many steps ought to be taken for correct choice of all technical arrangements. In this paper the following topics were considered: energetic demands of small houses, maximum instantaneous electric power, consumption of electric energy throughout a year, maximum instantaneous heating power, consumption of heat energy of the year, selection and choice of construction of Stirling engines, selection and choice of pressure of working gas.

Keywords: combustion engines, Stirling engines, heating power, cogeneration systems, hydrogen

1. Introduction

New forms and technology of tools enable an increase in efficiency of technical, technological, economic, energetic and methodological aspects of agropower plants and micro cogeneration systems. Economic efficiency depends on policy and law. Independent of local policy and law regulations, the technical, technological and organization efficiency decides about available energy derived from available energy sources. Generally the most important is to obtain and effectively use owned energy in opposition to accessible energy of energy source. It needs an optimization of organization. But optimization depends on deep comprehension of technology. Eventually, optimization leads to technological changes. This paper describes step by step basic procedure of selection and adjustment of Stirling engines designed to micro immobility cogeneration systems. We assume that technology and consumption of electric and thermal energy are known. The construction and technical parameters of Stirling engines are also known from market offers. And Polish local policy and legal system determine the commonly used organization aspects of micro heat and power cogeneration systems.

2. Energetic demands of small houses – step one

Technology law determines energetic demands of buildings. In huge buildings transparency of installations is important. For that reason independent installations are usually used. Independent installations are easier to manage than combined but combined installations are more economical not only in small houses [4]. Each system of installation of a building ought to respect the same physical criteria, especially: maximum instantaneous electric power consumption, consumption of electric energy of the year, maximum instantaneous heating power consumption, and consumption of heat energy of the year. Values of the main criteria decide about selections and choices of all technical arrangements. A system of technical norms is useful in selection of dimensions but generally a structure ought to be chosen by a consumer or advisory body pointed by him. After the decision that combined heat and power (CHP) ought to be used, energetic demands of buildings should be taken into account. For that reason regulations of government law acts and norms should be fulfilled. However, with respect to housing in Poland only special instruction of society of electric engineers determines energetic demand of maximum instantaneous electric power consumption of small houses and flats [2].

3. Maximum instantaneous electric power – step two

Maximum instantaneous electric power consumption must be provided by Stirling engines as well. This is the main criterion of selection and choice of Stirling engine with a generator of electric power. In the market year by year we can find more offers of Stirling electric power generators. It gives the hope that gradually the selection and choice of Stirling engines will be easier and more convenient.

In small houses the usage of Stirling engines is necessary because it works very quietly. However, different sources of thermal energy can be used. It enables to burn many ecological renewable fuels. If we take a small autonomic living house into consideration, then at the moment in Poland, the price of energy wood combusted throughout a year is lower than fixed costs of gas and power subscription (actual consumption excluded). The whole consumption of energy cost of wood (15% watered) is usually five times lower than gas and power billings. What is more, in some places we do not have to pay for the wood or other renewable fuels that can be used. Thus the only cost is the purchase and installation of a Stirling engine, which is relatively high.

4. Consumption of electric energy throughout a year – step three

Maximum instantaneous electric power in small houses usually does not reach 11 kW (3~AC). Installations like that can be classified as micro autonomic cogeneration system. Irrespective of instantaneous electric power we ought to calculate consumption of electric energy throughout a year. It is possible by identification of the value of instantaneous electric power and time of its consumption. In commonly used calculations the average value of instantaneous electric power calculated throughout a year is considered as 10% of maximum accessible instantaneous electric power. But sometimes we can consider 10% of usage time of maximum instantaneous electric power. Usually in practice many different samples are between these limits. They depend on individual properties of a described building, but we should take it in to account.

5. Maximum instantaneous heating power – step four

Maximum instantaneous heating power consumption should be lower than generation. In autonomous micro cogenerations systems of heat and power the maximum instantaneous heat power depends on generation of electric power. Usually the generation of heat power exceeds maximum instantaneous consumption. However, relatively high values of heat time's constants of controlled systems suggest that high values of maximum instantaneous heating powers are usually not critical.

6. Consumption of heat energy of the year- step five

Measurements and calculations show that in any heat and power cogenerations system generates near three times more heat energy with low thermodynamic parameters than useful electric energy. This is an important property of any cogeneration system. This property suggests the usage of Stirling engines in cogeneration systems with higher production of heat than electric power. Electric demands as the main criteria of selection of a Sterling engine result in the necessity to manage relatively large quantity of heat with low thermodynamic parameters. Usually the quantity of heat is calculated within a year, but synchronization of the usage of electric and heat energy is very important. This should be considered in selection of a Stirling engine for any micro combined heat and power cogeneration system. However in small houses with autonomic cogeneration systems usually quantity of heat energy is too high. It means that in such places we ought to look for the possibility of usage of relatively large quantity of heat with low thermodynamic parameters. It suggests a necessity of joining some heat absorbing processes with autonomous micro cogeneration systems. It can be: swimming pools, green houses, cow sheds and drying-lofts for wood or other materials.

7. Selection and choice of construction of Stirling engines – step six

In step six the construction options of Stirling engines ought to be chosen. The weight and relatively low power density ratio are the main disadvantage of Stirling engines in comparison to commonly used combustion engines. In the past research many different constructions were examined. Eventually, the Stirling engines with double acting pistons seem to have the highest power density ratio. In double acting pistons both sides of pistons are active in work and power generation. In present constructions of Stirling engines four cylinders are usually used [5]. Fig. 1. shows main rules of work engines like that. Work of each of four double acting pistons should be displaced 90 angle degrees against each other.

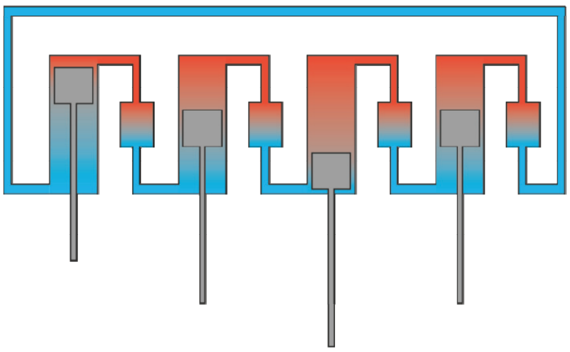

Fig. 1. The main principles of operation of the Stirling engine with four double acting pistons [7]

The mechanical structure connects the double acting pistons with crank shaft of the engine. Cisin Seiki Co. (Ltd.) from Japan builds the Stirling engine with oblique disk NS30A. This type of engine is showed in Fig. 2. Owing to the use of high pressure helium (14.5 MPa) and four double acting pistons this type of engine has relatively high power density ratio and ratio of energetic efficiency 37.5% [6].

In Table 1 the properties of different configurations of Stirling engines with four double acting pistons are compared. Power density ratio shows that any property of the same configuration can be different. However, we can see that the Stirling engine NS30A [6] with four double acting pistons built in oblique disk configuration is not the best. This configuration is only one of the most interesting. Thus we can see that the well know VR configurations can achieve relatively high power density ratio.

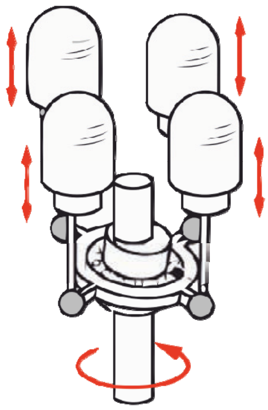

Fig. 2. Kinematic structure of Stirling engine NS30A [6] with four double acting pistons built in oblique disk configuration

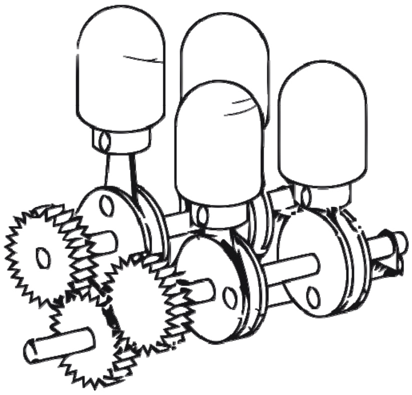

Fig. 3. Kinematic structure of Stirling engines NS30S [6] and Mod I [3] with four double acting pistons built in double row configuration

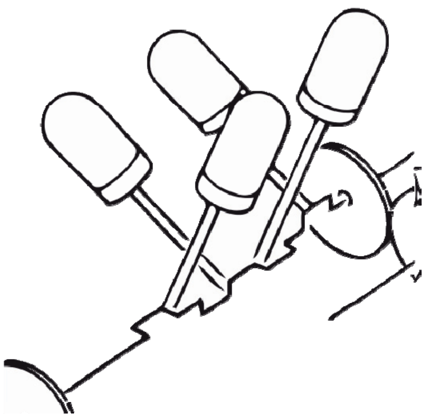

Fig. 4. Kinematic structure of Stirling engine Mod II [3] with four double acting pistons built in VR configuration

Tab. 1. A comparison of some properties of different configurations of Stirling engines with four double acting pistons

References	[5]	[5]	[1]	[1]
Code of type	NS30A	NS30S	Mod I	Mod II
Fig.	2.	3.	3.	4.
Mass [kg]	243	375	312	203
Working gas	Helium	Helium	Hydrogen	Hydrogen
Pressure of working gas [MPa]	14.5	15.4	10	10
Maximum power [kW]	30.4	45.6	54	60
Power density ratio [kW/kg]	0.1251	0.1216	0.173	0.296

8. Selection and choice of pressure of working gas – step seven

The thermodynamic properties of working gas of Stirling engines have the biggest influence of possibility to achieve high energetic efficiency. Fast exchange of heat is the main factor of working gas selection. Some construction options can increase or decrease speed of heat exchange. The special regenerators are built and used in Stirling engines to increase speed of heat exchange. Often they are built in special technology from special materials. The highest pressure of working gas increases the speed of heat exchange as well. But in every constructional option the properties of the working gas are of great importance. The gas heat capacity is the most important factor. From all the gases hydrogen has the highest heat capacity. But hydrogen is dangerous because the possibility of explosion and burning in the air is very high. Hydrogen makes a relatively wide range of explosion mixture in air between 4% and 74%. The mixture can explode by spark, heat or sunlight. The control of mixture of hydrogen in air is very difficult. Moreover, hydrogen is chemically active, embrittles many materials, mainly metals, can penetrate through any materials, metals included, and can decrease construction and fatigue properties of different materials including materials of seals. In spite of many difficulties hydrogen is used in cooling systems of generator of power plants. This shows possibility of effective usage of hydrogen.

The idea of the usage of hydrogen is controversial. Traditionally the USA, the largest supplier of helium in the world, promotes rejection of hydrogen. Helium is much more expensive than hydrogen, but helium has very low chemical reactivity and is included to the noble gases. It means that helium contributes to burning and explosive safety. From the noble gases helium is the cheapest. Moreover, helium has three time worse heat capacity than hydrogen and in that mater it is in the second place after hydrogen. In Stirling engines usually helium is used.

Practical factors often decided about the usage of compressed air or nitrogen as the main working gas of Stirling engines. But compressed air has fourteen times worse heat capacity than hydrogen, five times worse than helium and about 30% worse than neon (which is more expensive than helium). Nitrogen is the cheapest incombustible gas. Compressed nitrogen has similar heat properties as compressed air because air contains 75% of nitrogen.

After the selection of a working gas for Stirling engines pressure ought to be chosen. High pressure is convenient from the thermodynamic point of view. The heat capacity rises proportionally to an increase in pressure of a working gas. The heat capacity rises two times when quantity decreases two times and pressure increases two times. But relation to the mass of working gas heat capacity rises only 0.8% of each MPa. It explains why high pressure of a working gas is often used in Stirling engines. Constructional difficulties limit the top value of working gas pressure. In relatively cheap constructions of Stirling engines, often compressed air or nitrogen with pressure below 1 MPa is used. In other units helium below 10 MPa is usually used. Hydrogen or highest pressures of any working gasses can be seen only in special cases.

9. Results

1) The majority of Stirling engines offered in the market can consume relativity small value of power. Thus, these engines are suitable for local, spread renewable energy sources.
2) Stirling engines are very quietl and can be used in small houses, which enables building scattered, autonomic micro power plants.
3) Power, cost and value of generated electric and heat power decided that Stirling engines should be used as high temperature main heat consumer unit. Only in special cases Stirling engines can be used as low temperature auxiliary heat consumer unit. The second possibility can be useful in places with high value of waste heat, for example in big commercial power plants.
4) Hydrogen is the best working gas of the Stirling engines from the thermodynamic point of view. Compressed air is the best working gas from the accessibility point of view. Compressed nitrogen is the best working gas from the economic and safety point of view.

5) All systems of combined heat and power cogeneration achieve high efficiency if heat with low thermodynamic parameters is effectively used and included in calculations. As far as Stirling engines are concerned, the same rule suggests that high efficiency can be obtained only if heat with low temperature is effectively used and included in calculations.
6) Stirling engines with four double acting cylinders are the most convenient. The mechanism of transforming mechanical energy does not have critical influence on the engine mass. From that point of view we can use row engines (type R), double row engines (type RR), V engines (type V), or VR engines (type VR). All these structures are relatively light and their weight changes in wide range.
7) The pressure of the working gas has the biggest influence on weight and efficiency of Stirling engines. Generally the value of the working gas pressure should be as high as possible.

Acknowledgement

The research financed by the National Centre for Research and Development, and an energy specialized company ENERGA S.A. This paper is part of strategic plan of scientific research and development named: “Advanced Technologies for Energy Generation”. The work is financed as part of budget of scientific task no. 4: “Elaboration of Integrated Technologies for the Production of Fuels and Energy from Biomass as well as from Agricultural and other Waste Materials”.

References

[1] Ernst, W. D., Shaltens, R. K., *Automotive Stirling Engine Development Project*, DOE/NASA/0032-34, NASA CR-190780, MTI Report 91TR15, USA 1997.
[2] Klajn, A., Markiewicz, H., *Prenorma SEP P SEP-E-0002*, Wytyczne, Komentarz, *Instalacje elektryczne w obiektach budowlanych. Instalacje elektryczne w budynkach mieszkalnych. Podstawy planowania*, Centralny Ośrodek Szkolenia i Wydawnictw SEP, Warszawa 2002.
[3] Nightingale, N. P., *Automotive Stirling Engine,* DOE/NASA/0032-28, NASA CR-175106, MTI 86ASE58SRI, USA 1986.
[4] Skorek, J., Kalina, J., *Gazowe układy kogeneracyjne*, WNT Warszawa 2005.
[5] Żmudzki, S., *Silniki Stirlinga,* WNT Warszawa 1993.
[6] http://www.nmri.go.jp/eng/khirata/stirling/index_e.html (03.01.2011).
[7] http://www.stirlingengine.fr (03.01.2011).