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Parametrična analiza Stirlingove soproizvodne enote na biomaso za uporabo v hišni tehniki

A parametrical Analysis of a Biomass Stirling Cogeneration Unit for Use in Housing

Uroš Stritih - Gregor Zupan - Vincenc Butala
(Fakulteta za strojništvo, Ljubljana)

Pričujoči prispevek predstavlja enoto za soproizvodnjo toplotne in električne energije (STE) na lesno biomaso za preskrbo z energijo v stanovanjskih hišah. Stirlingov motor je uporabljen kot sredstvo za soproizvodnjo toplotne in električne energije, za katero je bila narejena termodinamična analiza. Termodinamične vrednosti so izračunane matematično, za simulacijo pa je napisan računalniški program. Izdelana je parametrična analiza termodinamičnih vrednosti glede na učinkovitost Stirlingovega motorja. Moč motorja se lahko spreminja s količino delovnega plina, kar zahteva zbiralnik. Ker je učinkovitost motorja odvisna samo od zgornje in spodnje temperature v motorju, bi bila v primeru popolne regeneracije izohorne toplote, električna učinkovitost Stirlingovega motorja enaka učinkovitosti Carnotovega postopka.

(Ključne besede: Stirlingov motor, biomasa, parametrične analize, učinkovitost)

This paper presents a combined heat and power (CHP) unit using wood biomass to provide an energy supply for housing. The Stirling engine is used as a CHP-producing technology for which a thermodynamic analysis was carried out. The thermodynamic values were mathematically calculated and a computer program for the CHP simulation was written. A parametrical analysis of different combinations of thermodynamic values with respect to the efficiency of the Stirling engine was made. The power of the engine can be changed by the quantity of the working gas, which requires a reservoir. We concluded that if all the isochoric heat were regenerated, the electrical efficiency would be equal to Carnot's efficiency, since it depends only on the upper and lower temperatures in the engine.

(Keywords: Stirling engines, biomass, parametrical analysis, efficiency)

0 UVOD

Energetska oskrba v gospodinjstvih in industriji se običajno zagotavlja z nakupom električne energije iz javnega elektroenergetskega sistema in lastnim pridobivanjem toplote iz goriva, nabavljenega pri dobavitelju goriva. V zadnjem času se pa kot izbirna možnost pokrivanja energetskih potreb pojavlja soproizvodnja toplotne in električne energije. Z rastjo cen fosilnih goriv na svetovnih trgih, povečevanjem okoljevarstvene zavesti ter uvajanjem novih tehnologij zgorevanja goriv postaja lesna biomasa pomemben vir za pridobivanje tako toplotne kakor tudi električne energije. Soproizvodnja z uporabo biomase je torej izbirna možnost za

0 INTRODUCTION

The energy supply for households and industry is usually ensured by buying electrical energy from the public electrical energy system, while purchasing fuels from fuel suppliers provides one's heating. Recently, an alternative method for covering energy needs has appeared, called combined heat and power (CHP) generation. With the rise in the prices of fossil fuels on world markets, increased environmental consciousness, and the introduction of new fuel-combustion technologies, wood biomass is becoming an important means of acquiring both thermal and electrical energy. CHP using biomass is therefore an alternative option for soproizvodnjo toplotne in električne energije. Biomasa kot gorivo je sestavljena iz različnih prvinskih virov in je lahko uporabljena neposredno, ali pa je spremenjena v drugotno gorivo skozi različne tehnološke postopke. Lesna biomasa je po navadi uporabljena samo za proizvodnjo toplote, pri čemer je smotrno kurilni napravi prigraditi hranilnik toplote [1].

Soproizvodnja toplotne in električne energije na mikro ravni je eden od glavnih načinov za doseganje razpršene proizvodnje. Znotraj mikro soproizvodnega sistema ločimo hišno in nehišno skupino. Prva skupina, s 3 kW_e ali manj, je oblikovana tako, da se prilagaja potrebam stanovanja, druga skupina pa je lahko uporabljena za večstanovanjske stavbe, manjše hotele ali za manjše plavalne bazene.

Prednosti hišne soproizvodnje (HSE) pred ločeno proizvodnjo energije so: večja energijska učinkovitost, približanje proizvodnje uporabniku, zmanjšanje negativnih vplivov na okolje in povečanje zanesljivosti energijske oskrbe stavbe. Hišna soproizvodna enota se običajno izbere na pokrivanje toplotnih potreb stanovanjske hiše. Odvisno od vrste gradnje in velikosti stavbe običajno zadošča HSE moči med 5 in 15kW_t. Ker je hišna soproizvodnja blizu uporabniku, ni izgub energije med prenosom.

Stirlingovi motorji v primeru soproizvodnje toplotne in električne energije so bili tema številnih študij. Ö Ercan Ataer [2] je v svoji študiji predstavil razporeditev temperature plina vzdolž regeneratorskega bata in stene valja za kompresijski in ekspanzijski polovični krog. L. Berrin Erbay in Hasbi Yavuz [3] sta analizirala Stirlingov toplotni stroj pri največji moči; njuna analiza je vključevala politropno ekspanzijo in politropno kompresijo. Erich Podeser [4] je predstavil proizvodnjo električne energije iz biomase z uporabo Stirlingovega motorja; motor je bil konstruiran za razpršeno proizvodnjo električne energije za podeželske vasi, kjer električna omrežja niso dobro razvita. Ö. Ercan Ataer in H. Karabulut [5] sta analizirala hladilnik, ki deluje po Stirlingovem načelu. Analiza je vključevala termodinamično analizo motorja s kotom 90° med regeneratorskim in delovnim batom. Evgueniy Entchev in ostali [6] so v letu 2003, za dva različna sistema, analizirali delovanje mikrosistema Stirlingovega motorja za soproizvodnjo toplotne in električne energije.

1 STIRLINGOV KROŽNI POSTOPEK

Stirlingov motor (sl. 1) temelji na zaprtem krožnem postopku, pri katrem je delovni plin

heat and power production. Biomass is made up of various primary sources, either used directly or converted into secondary fuels via various technological processes. Wood biomass is usually used for heat production only, in which case a thermal storage unit should be combined with a biomass boiler [1].

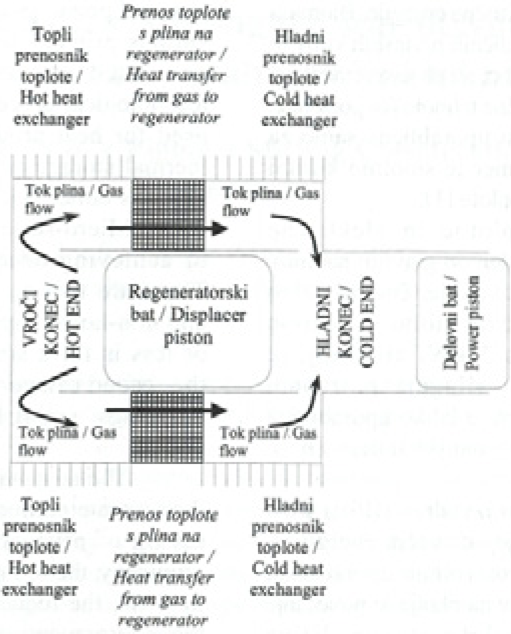
Micro-scale CHP is one of the main ways of achieving decentralized power production. There are two categories of micro-CHP: house and non-house uses. The first category of 3 kW_e or less is for a single household's needs, while the second category is for multi-story residential buildings, small hotels, and small swimming pools.

The advantages of house CHP compared to the separate production of heat and power are: the saving of primary energy, the higher electrical efficiency, the bringing of energy production closer to users, the reduction of the negative impact on the environment, and the increase in the certainty of energy supply. The house CHP unit is usually dimensioned to cover the heat needs. A CHP unit of heat power between 5 and 15 kW is usually enough for the house category. Because house CHP brings energy production closer to the users, there is no energy loss during the transmission.

Stirling engines, as an example of a heat and power production unit, have been the subject of a number of studies. Ö Ercan Ataer [2] presented the gas temperature distribution along the displacer and cylinder wall for a compression and expansion half-cycle. L. Berrin Erbay and Hasbi Yavuz [3] analyzed a Stirling heat engine under maximum power conditions; their analysis included polytropic expansion and polytropic compression. Erich Podeser [4] presented electricity production from a biomass Stirling engine; the engine was designed for decentralized electricity production in rural villages, where the electricity network is not well developed. Ö Ercan Ataer and H. Karabulut [5] analyzed a refrigerator that operates on the Stirling-cycle, including a thermodynamic analysis of the engine with an angle of 90° between the displacer and the power piston. Evgueniy Entchev et al. [6] estimated the operation of a micro-system for CHP production for two different systems in 2003.

1 STIRLING CYCLE

The Stirling engine (Fig. 1) is based on a closed circular process, where the working gas is alternately



Sl. 1. *Beta izvedba Stirlingovega motorja [7]*
Fig. 1. *Beta configuration of a Stirling engine [7]*

izmenično komprimiran v hladnem valju in ekspandiran v vročem valju. Prednost Stirlingovega motorja v primerjavi z motorji z notranjim zgorevanjem je v tem, da toplota ni dovedena krožnemu postopku z zgorevanjem goriva znotraj valja, ampak je prenesena skozi prenosnik toplote. Toplota, ki nastane z zgorevanjem goriva, se prenese delovnemu plinu skozi topli prenosnik toplote. Toplota, ki se ne spremeni v delo, se prenese ohlajevalni vodi skozi hladni prenosnik toplote. Ker je Stirlingov motor zaprt sistem, se kot delovno sredstvo lahko uporabi bolj primeren plin od zraka. Najbolj uporabljeni plini so helij, vodik in dušik.

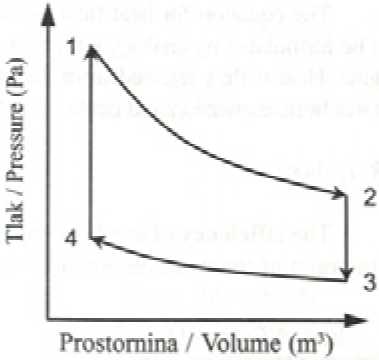
Motorji, ki delujejo na način Stirlingovega postopka, so najbolj učinkoviti toplotni stroji, ki so se kadarkoli zgradili [7]. Kot motor lahko deluje na katerikoli toplotni vir, vključno na sončno ogrevanje. Glede na lego valjev ločimo naslednje tri tipe Stirlingovih motorjev: alfa, beta in gama.

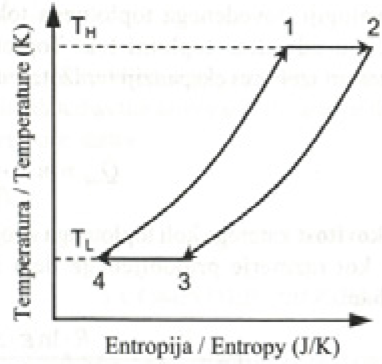
V idealnem Stirlingovem motorju se odvijajo štirje ločeni termodinamični postopki. Ti postopki so prikazani v diagramu tlaka v odvisnosti od prostornine ter temperature v odvisnosti od entropije (sl. 2). V idealnem Stirlingovem motorju se vpliv prostornine prenosnikov toplote, regeneratorja in prenosnih poti zanemari.

compressed in a cold cylinder and expanded in a hot cylinder. The advantage of a Stirling engine compared to an internal combustion engine is that heat is not supplied to the circular process with fuel combustion taking place inside cylinder, rather it is transferred from outside through the heat exchanger, like a steam boiler. Heat originating from the fuel combustion is transmitted to the working gas through a hot heat exchanger. Any heat not transformed into work on the engine shaft is delivered to cooling water in the cold heat exchanger. Because it is a closed system, more a appropriate working gas than air can be utilized in the Stirling engine. The most utilized gases are: helium, hydrogen, and nitrogen.

Engines working on the Stirling-cycle principle are the most effective heat engines that have ever been built [7]. As engines they can operate on any kind of heat source including solar. There are three different types of Stirling engines, depending on the position of the cylinders: alpha, beta, and gamma.

Four separate thermodynamic processes are performed in an ideal Stirling engine. Those processes are shown in graphs of pressure versus volume and temperature versus entropy (Fig. 2). In an ideal Stirling-cycle, the influence of the volume of heat exchangers, regenerators, and transport is ignored.





Sl. 2. *Termodinamični postopki v idealnem Stirlingovem motorju*
Fig. 2. *Thermodynamic processes in an ideal Stirling engine*

2 MATEMATIČNI MODEL

Čisto delo Stirlingovega motorja se določi z uporabo krožnega integrala tlaka po prostornini. Ker je neto delo, delo enega kroga, ki ga opravi motor, moramo za določitev električne moči integral tlaka glede na prostornino pomnožiti še s frekvenco gibanja delovnega bata v motorju:

2 MATHEMATICAL MODEL

The **net work output** of a Stirling engine can be evaluated by considering the cyclic integral of pressure with respect to volume. Because the net work output is the work output of one cycle made by the engine, the integral of the pressure with respect to volume should be multiplied by the frequency of the power piston motion in the engine:

$$P = \nu \cdot \int p \cdot dV \quad (1).$$

Za izračun integrala upoštevamo delo, ki se opravi med izotermno ekspanzijo in porabi med izotermno kompresijo. Med izohornima preobrazbama se ne opravi in ne porabi nič dela. Na ta način lahko oblikujemo končno enačbo za moč:

To evaluate the integral we need only consider the work done during the isothermal expansion and used during the isothermal compression, since there is no work done or used during the isochoric processes. Thus, the final equation for power can be formulated as:

$$P = m \cdot R \cdot \ln \varepsilon \cdot \Delta T \cdot \nu \quad (2),$$

kjer sta ε kompresijsko razmerje (V_2/V_1 in V_3/V_4), ΔT pa temperaturna razlika med zgornjo T_H in spodnjo T_L temperaturo.

Toplotni tokovi v Stirlingov motor in iz njega se izračunajo z upoštevanjem integrala temperature glede na entropijo:

where ε corresponds to the compression ratios (V_2/V_1 and V_3/V_4) and ΔT is the temperature difference between T_H and T_L.

Heat flows into and out of the Stirling engine can be evaluated by considering the integral of the temperature with respect to entropy:

$$\dot{Q} = \nu \cdot \int T \cdot dS \quad (3).$$

Toplotni tok prehaja v motor pri izohorni kompresiji ter izotermni ekspanziji. Z uporabo prvega glavnega zakona termodinamike se lahko zapiše končna enačba za toplotni tok v motor:

Heat flow passes into the engine during the isochoric compression and isothermal expansion. Using the laws of thermodynamics, the final equation for heat flow into the engine can be formulated as:

$$\dot{Q}_{in} = m \cdot \nu \cdot \left(c_v \cdot \Delta T + R \cdot T_H \cdot \ln \varepsilon \right) \quad (4).$$

Po analogiji dovedenega toplotnega toka lahko določimo odvedeni toplotni tok. Toplota zapušča motor pri izohorni ekspanziji ter izotermni kompresiji:

The equation for heat flow out of the engine can be formulated by analogy with heat flow into the engine. Heat is thus rejected from the engine during the isochoric expansion and isothermal compression:

$$\dot{Q}_{out} = m \cdot \nu \cdot \left(c_v \cdot \Delta T + R \cdot T_L \cdot \ln \varepsilon \right) \qquad (5).$$

Učinkovitost katerega koli toplotnega stroja je določena kot razmerje pridobljenega dela in vložene toplote:

The **efficiency** of any heat engine is defined as the ratio of the work output and the heat input:

$$\eta = \frac{P}{\dot{Q}_{in}} = \frac{R \cdot \ln \varepsilon \cdot \Delta T}{c_v \cdot \Delta T + R \cdot T_H \cdot \ln \varepsilon} = \frac{\ln \varepsilon \cdot \Delta T \cdot (\kappa - 1)}{\Delta T + T_H \cdot \ln \varepsilon \cdot (\kappa - 1)} \qquad (6).$$

Eksergija toplotnih tokov je odvisna od temperature pri kateri toplota prehaja meje sistema. Višja ko je temperatura prehajanja toplote, večja je njena eksergija:

The **exergy of heat the flows** depends on the temperature that the heat passes at a boundary of the system. The higher the temperature, the higher its exergy:

$$E_{\dot{Q}} = \nu \cdot \int_A^B \left(1 - \frac{T_e}{T} \right) \cdot dQ \qquad (7).$$

Eksergija dovedenih toplotnih tokov je sestavljena iz eksergije toplotnega toka med izohorno kompresijo ter izotermno ekspanzijo:

The exergy of the supplied heat flow consists of the exergy of the heat flow during the isochoric compression and isothermal expansion:

$$E_{\dot{Q}_{in}} = m \cdot \nu \cdot \left\{ c_v \cdot \left[\Delta T - T_e \cdot \ln\left(\frac{T_H}{T_L} \right) \right] + \left[R \cdot T_H \cdot \ln \varepsilon \cdot \left(1 - \frac{T_e}{T_H} \right) \right] \right\} \qquad (8).$$

Eksergija odvedenih toplotnih tokov je sestavljena iz eksergije toplotnega toka med izohorno ekspanzijo in izotermno kompresijo:

The exergy of the heat flow out of the engine consists of the exergy of heat flow during the isochoric expansion and isothermal compression:

$$E_{\dot{Q}_{out}} = m \cdot \nu \cdot \left\{ c_v \cdot \left[-\Delta T - T_e \cdot \ln\left(\frac{T_L}{T_H} \right) \right] + \left[R \cdot T_L \cdot \ln\left(\frac{1}{\varepsilon} \right) \cdot \left(1 - \frac{T_e}{T_L} \right) \right] \right\} \qquad (9).$$

Eksergija masnega toka biomase je odvisna od količine vlage v gorivu, ker je kurilnost biomase enaka kurilnosti gorljivih snovi samo v primeru, ko je gorivo absolutno suho. Za vse preostale vrednosti količine vlage v gorivu je kurilnost biomase manjša od kurilnosti gorljivih snovi za uparjalno toploto vode:

The **exergy of the mass flow of biomass** depends on the moisture content of the fuel since the net caloric value of the biomass is equal to the net caloric value of combustible substances only in the case where the fuel is absolutely dry. For all the remaining values for the moisture content of the fuel, the net caloric value of biomass is less than the net caloric value of the combustible substances by an amount equal to the heat of vaporization of water:

$$E_{\dot{m}_b} = \dot{m}_b \cdot H_{cs} = \dot{m}_b \cdot (H + r \cdot w) \qquad (10).$$

Eksergijska učinkovitost je določena kot količnik med eksergijo, dobljeno iz sistema, ter med eksergijo, ki je dovedena sistemu:

The **exergy efficiency** is defined as the quotient of exergy obtained from the system and the exergy that is supplied to the engine:

$$\xi = \frac{E_{out}}{E_{in}} = \frac{E_{\dot{Q}_{out}} + P}{E_b} \qquad (11).$$

Tlačna stanja v Stirlingovem motorju so določena za vsako stanje posebej z naslednjo enačbo:

The **pressure conditions** of the Stirling engine are defined for each state by the following equation:

$$p_i = \frac{m \cdot R \cdot T_i}{V_i} \quad (12).$$

Srednji tlak v motorju pa se izračuna kot aritmetično povprečje posameznih tlačnih stanj:

The medium pressure in the engine is calculated as the arithmetical mean of the individual pressure states:

$$p_m = \frac{\sum_{i=1}^{n} p_i}{n} \quad (13).$$

3 RAČUNALNIŠKI PROGRAM

Simulacija STE je sestavljena iz treh delov in je narejena z uporabo računalniškega programa Microsoft Excel. Podatki so vstavljeni v program v prvem delu. Ti podatki vsebujejo lastnosti delovnega plina in ohlajevalnega sredstva oz. sredstva za ogrevanje hranilnika toplote. Poleg tega ti podatki vsebujejo tudi parametre Stirlingovega motorja, to so delovna prostornina motorja, kompresijsko razmerje, zgornja in spodnja temperatura v motorju, masa delovnega plina in kurilnost biomase.

Rezultati simulacije, dobljeni iz matematičnega modela, so predstavljeni v drugem delu računalniškega programa. Izračunan je toplotni tok v motor pri izohornem in izotermnem postopku. To je zahtevani toplotni tok za doseganje zgornje temperature v motorju. Glede na ta toplotni tok je izračunan masni pretok biomase za doseganje zahtevanega toplotnega toka v motor oz. za doseganje zgornje temperature v motorju. Izgube pri zgorevanju in prenosu toplote skozi topli prenosnik toplote so upoštevane pri učinkovitosti kurilne naprave. Izračunan je tudi toplotni tok iz motorja pri izohornem in izotermnem postopku za ogrevanje sredstva hranilnika toplote. Predpostavljen je 100-odstotni prenos toplote na sredstvo za ogrevanje hranilnika toplote. To pomeni, da je predpostavljen toplotni tok na sredstvo za ogrevanje hranilnika toplote brez izgub. Eksergiji toplotnih tokov v Stirlingov motor in iz njega sta izračunani za izohorni in izotermni postopek. Preostali rezultati, kakor so električna energija, dobljena iz sistema, električna učinkovitost motorja za primer brez regeneracije toplote kakor tudi za primer popolne regeneracije toplote in toplotna ter eksergijska učinkovitost motorja, so prav tako podani v tem delu računalniškega programa.

Tlačna stanja so izračunana v tretjem delu računalniškega programa in temeljijo na enačbi

3 COMPUTER PROGRAM

A simulation of the CHP unit consists of three parts and was made using the computer program Microsoft Excel. The data are entered into the program in the first part. These data concern the properties of the working gas and the cooling fluid or the fluid for heating the thermal storage, in addition to the Stirling engine's parameters, such as the working volume of the engine, the compression ratio, and the highest and the lowest temperature in the engine. The mass of the working gas and the net caloric value of the biomass are also given in this part.

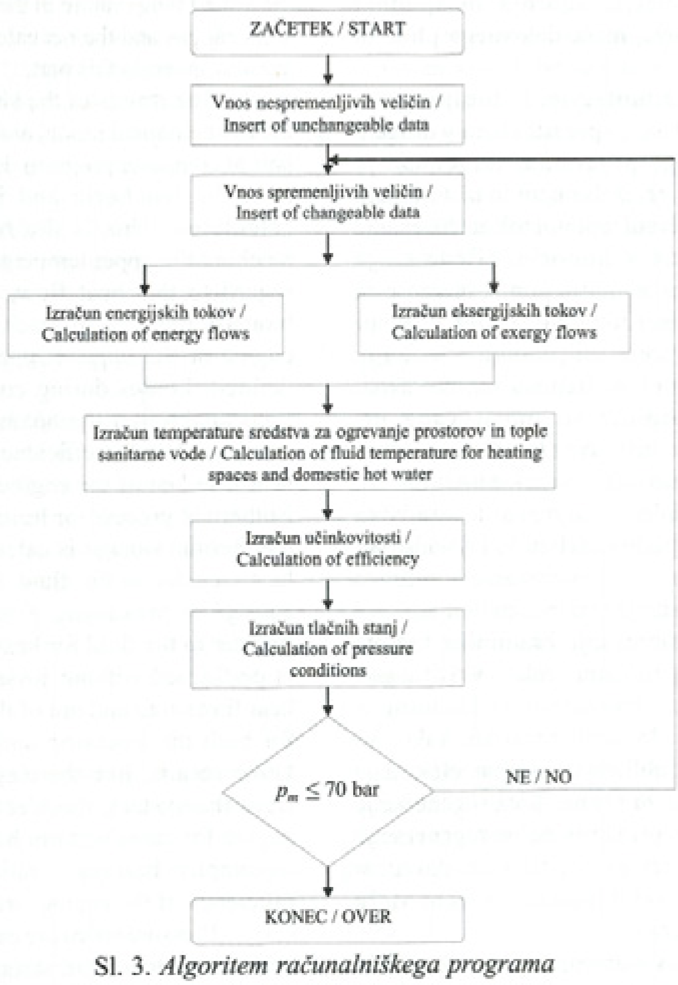
The results of the simulation obtained from the mathematical model are presented in the second part of computer program. Heat flow into the engine over the isochoric and isothermal process is calculated. This is the required heat flow for reaching the upper temperature in the engine. With regard to this heat flow, the mass flow rate of biomass required to reach the heat flow into the engine or the upper temperature in the engine is defined. Losses during combustion and the heat transfer through the hot heat exchanger are also considered in the efficiency of the boiler. Further heat flow out of the engine over the isochoric and isothermal process for heating the fluid for heating the thermal storage is calculated. A total of 100% heat transfer to the fluid for heating the thermal storage is presumed. This means that the heat transfer to the fluid for heating the thermal storage is performed without losses. The exergies of the heat flows into and out of the engine are calculated for both the isochoric and isothermal processes. Other results, like the electrical energy obtained from the system, the electrical efficiency of the engine for cases without heat regeneration as well as complete heat regeneration, and heat and exergy efficiency of the engine, are also given in this part.

Pressure states are calculated in the third part of the program on the basis of the equation of state. The medium pressure in the engine is defined as stanja. Srednji tlak v motorju je določen kot aritmetično povprečje posameznih tlačnih stanj.

Podatke iz Joanneum Research [4] smo uporabili z namenom, da se preveri pravilnost delovanja simulacije. Namen njihovega projekta je bilo oblikovanje, konstruiranje in delovanje Stirlingovega motorja, ki je ogrevan z dimnimi plini, ki nastanejo pri zgorevanju biomase. Motor je bil oblikovan samo za laboratorijske raziskave. Uporabljen delovni plin je bil zrak, ker je cenejši od helija in povsod na voljo. Njihova 25-odstotna učinkovitost motorja je bila preverjena pri 3,2 kW moči in je malo manjša od naše. Vsi naši rezultati so bili dobljeni z uporabo njihovih podatkov. Spremembe parametrov so predstavljene v naslednjih diagramih. Eksperimentalno preverjena področja so označena s križcem, ali pa je kar cel stolpec označen drugače. Algoritem računalniškega programa je prikazan na sliki 3.

the arithmetical medium of the individual pressure states.

Data from Joanneum Research [4] is used in order to authenticate the correctness of the operation. The goals of their project were the design, construction and operation of the Stirling engine, which is heated by the flue gas of a biomass furnace. The engine was designed only for laboratory research. Air was used as the working gas because it is cheaper than helium and available everywhere. A shaft power of 3.2 kW at a coefficient of performance of 25 % was verified, which is a little bit lower than our findings. All our data were obtained using their data. The changes of the parameters are presented in the following diagrams. Experimentally verified areas are marked with a cross or the whole columns are marked differently. An algorithm of the computer program is shown in Fig. 3.



Sl. 3. *Algoritem računalniškega programa*
Fig. 3. *Algorithm of the computer program*

4 PARAMETRIČNA ANALIZA

Prva analiza, ki je bila za nas zanimiva, je, kako se električna učinkovitost spreminja od vrste plina v motorju (sl. 4). Vzeti plini za simulacijo so bili: zrak, acetilen, amoniak, helij in vodik. Plini na sliki so razporejeni v vrstnem redu od plina z najnižjo (zrak) do plina z najvišjo plinsko konstantno (vodik).

Po predvidevanjih naj bi se električna učinkovitost močno spreminjala v odvisnosti od plinske konstante; pri zraku najnižja, pri vodiku najvišja električna učinkovitost. S slike 4 pa je razvidno, da je najvišja električna učinkovitost pri heliju in ne pri vodiku ter da ni najnižja učinkovitost pri zraku temveč pri acetilenu. Razlog je v razmerju specifične toplote plina pri stalnem tlaku in specifične toplote plina pri nespremenljivi prostornini (κ), kar je lepo prikazano v enačbi (6).

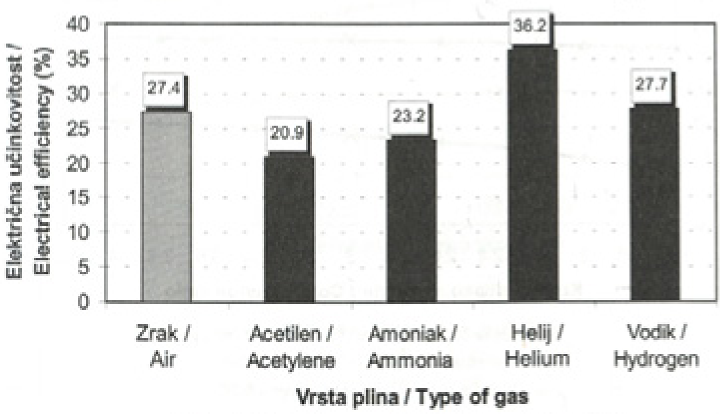
Po predvidevanjih pa se spreminja srednji tlak v motorju, ki je odvisen samo od specifične plinske konstante (sl. 5). Uporaba helija kot delovnega sredstva v motorju po sliki 4 daje najvišjo električno učinkovitost v enakih razmerah. S slike 5 pa je razvidno, da se pri uporabi helija srednji tlak povzpne prek 370 bar. Tega pa za ostale uporabljene parametre v naši simulaciji konstrukcija motorja ne bi zdržala. Pri uporabi vodika kot delovnega sredstva pa bi se srednji delovni tlak zvišal kar na prek 735 bar. To pomeni, da delovni plin ne more biti preprosto zamenjan s plinom z višjo učinkovitostjo. Potrebno je, da so tlačna stanja preračunana preden zamenjamo plin v motorju. Če izračun nakazuje, da so tlačna stanja nesmiselna, zamenjava delovnega plina ni mogoča.

4 PARAMETRICAL ANALYSIS

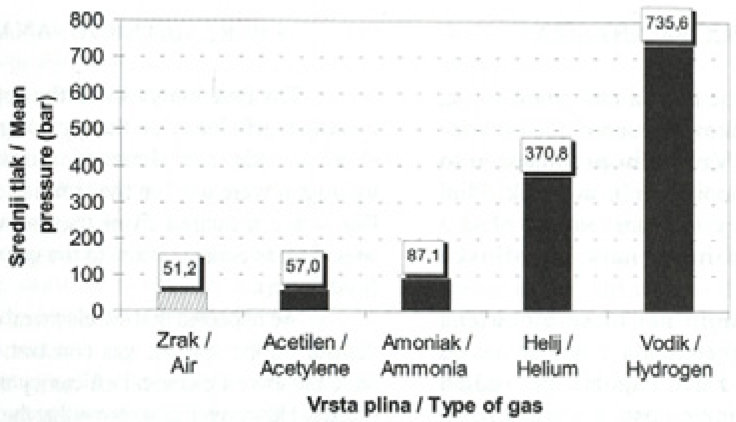
The first analysis was the dependence of the electrical efficiency on the type of gas in the engine (Fig. 4). Air, acetylene, ammonia, helium, and hydrogen were used in the simulation. The gases in Fig. 4 are arranged from the gas with the lowest specific gas constant (air) to the gas with the highest (hydrogen).

We expected that the electrical efficiency would depend on the specific gas constant: thus, air should have the lowest electrical efficiency and hydrogen the highest. However, Fig. 4 shows that the highest electrical efficiency is actually found with helium and not with hydrogen, while the lowest efficiency is not with air but with acetylene. This is due to the ratio of the specific heat capacity of the gas at constant pressure with the specific heat capacity of the gas at constant volume (κ), which is seen from Equation 6.

The medium pressure in the engine changed according to our expectations, since it depends only on the specific gas constant (Fig. 5). Using helium as the working gas in the engine gives the highest electrical efficiency under equal conditions according to Fig. 4. However, Fig. 5 shows that when using helium the medium pressure in the engine exceeds 370 bar and at that pressure the engine would collapse. If we were to use hydrogen as the working gas in the engine, the medium pressure in the engine would exceed 735 bar. This means that the working gas cannot be simply replaced with a gas that has a higher efficiency. It is necessary to calculate the pressure conditions before the gas is replaced in the engine. If the calculation indicates that the pressure conditions are not reasonable, a replacement of working gas in not possible.



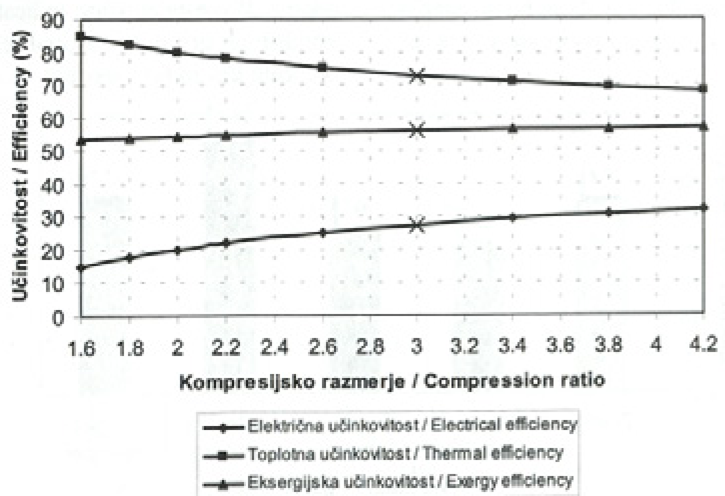
Sl. 4. *Vpliv plina na električno učinkovitost*
Fig. 4. *Influence of gases on the electrical efficiency*



Sl. 5. *Vpliv plina na srednji tlak v motorju*
Fig. 5. *Influence of gases on the mean pressure*

Pri spreminjanju kompresijskega razmerja se v naši simulaciji spreminja samo zgornja mrtva prostornina in s tem gib bata, večja prostornina pa ostaja ves čas stalna. Ker se torej pri višanju kompresijskega razmerja delovna prostornina motorja veča, zgornja mrtva prostornina motorja pa manjša, dosežemo tudi višje tlačno stanje po koncu izotermne kompresije. Pri višjem tlaku pa je za vzdrževanje stalne temperature v motorju potreben večji toplotni tok. Ker je pri izotermni kompresiji nižja temperatura kakor pri izotermni ekspanziji, je pri enaki spremembi kompresijskega razmerja potreben manjši odvedeni toplotni tok, kakor je dovedeni. Ker je torej sprememba pri dovedenem toplotnem toku večja kakor pri odvedenem toplotnem toku, iz sistema pridobimo več dela in s tem večjo moč

Changing the compression ratio changes only the upper non-zero volume and the movement of the piston; however, the larger volume remains constant at all times. With a rise in the values of the compression ratio, the working volume of the engine increases and the upper non-zero volume decreases. Thus, a higher pressure condition is reached at the end of the isothermal compression. Keeping a constant temperature in the engine at a higher pressure requires a higher heat flow into the engine. Because there is a lower temperature during the isothermal compression than during the isothermal expansion, a lower heat flow out of the engine than into the engine is required when there is a constant change in the compression ratio. Since there is a greater increase of heat flow into the engine than heat flow out of the engine, more work and, consequently, more power comes out of



Sl. 6. *Sprememba učinkovitosti v odvisnosti od kompresijskega razmerja*
Fig. 6. *Efficiency change as dependent on compression ratio*

motorja. S slike 6 je lepo razvidno, da se z večanjem kompresijskega razmerja električna učinkovitost povečuje, toplotna pa zmanjšuje. Za čim večjo električno učinkovitost je torej treba imeti čim višje kompresijsko razmerje, ki pa je zaradi konstrukcijskih lastnosti materialov navzgor omejeno.

Slika 7 prikazuje odvisnost posameznih učinkovitosti od zgornje temperature v motorju. Črta s kvadratki pomeni idealno električno učinkovitost, ki bi bila dosežena v primeru popolne regeneracije toplote. Pri naših podatkih, s temperaturo 1273 K, bi imeli s popolno regeneracijo toplote, električno učinkovitost prek 72 odstotkov. Najnižja črta na sliki pomeni električno učinkovitost brez regeneracije toplote. Vse električne učinkovitosti se z višanjem temperature dvigajo, toplotna učinkovitost pa se z višanjem temperature zniža.

Slika 8 prikazuje odvisnost učinkovitosti od spodnje temperature v motorju. Črta s kvadratki pomeni idealno učinkovitost, ki pa se z višanjem temperature znižuje.

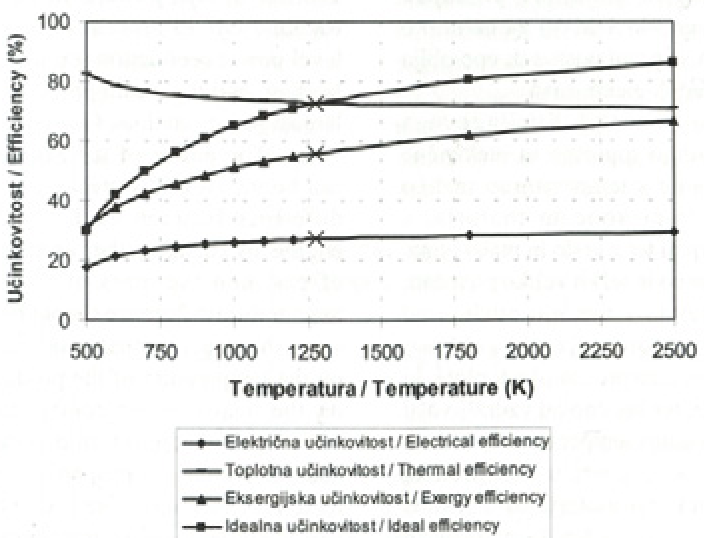
S slik 7 in 8 lahko ugotovimo, da dobimo višjo učinkovitost, če imamo spodnjo temperaturo v motorju čim nižjo, zgornjo temperaturo pa čim višjo. Vendar pa je to zaradi omejitev težko doseči. Navzgor smo omejeni z vzdržljivostjo materialov ter z možnostjo dovoda toplote v sistem; imeti moramo dovolj vroče ostanke zgorevanja ter veliko vrednost prehoda

the system. Fig. 6 shows an increase in the electrical efficiency and a decrease in the thermal efficiency with increasing compression ratios. A higher electrical efficiency requires a higher compression ratio, although the upper limit of the compression ratio is constrained due to the constructional properties of the materials.

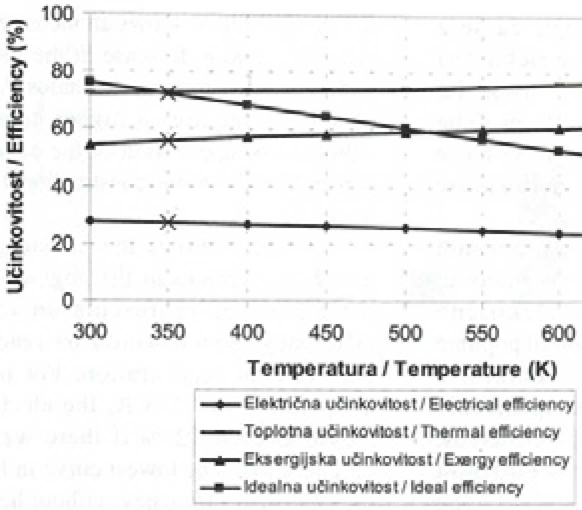
Fig. 7 shows the efficiencies versus the upper temperature in the engine. The curve with little squares represents an ideal electrical efficiency, which would be reached if we had perfect heat regeneration. For our data with a temperature of 1273 K, the electrical efficiency would exceed 72 % if there were perfect heat regeneration. The lowest curve in Fig. 7 represents the electrical efficiency without heat regeneration. All the electrical efficiencies increase with the rising temperature, while the thermal efficiency falls with the rising temperature.

Fig. 8 shows the dependence of the efficiencies on lower temperatures in the engine. The curve with little squares represents an ideal efficiency, which falls with rising temperature.

Figs. 7 and 8 show that a higher efficiency is obtained if the lower temperature in the engine is as low as possible and the upper temperature in the engine is as high as possible. This is difficult to achieve, for a number of reasons. There are upper temperature limits imposed by the constructional properties of materials and the potential heat supply, e.g., the products of combustion should be hot enough, the heat transfer



Sl. 7. *Učinkovitost v odvisnosti od zgornje temperature v motorju*
Fig. 7. *Efficiencies as dependent on the upper temperature*



Sl. 8. *Učinkovitost v odvisnosti od spodnje temperature v motorju*
Fig. 8. *Efficiencies as dependent on the lower temperature*

toplote in veliko površino prenosnika toplote. Omejeni pa smo tudi navzdol. Pri prenizki temperaturi je prenos toplote na ogrevalno sredstvo nemogoč zaradi prenizke temperaturne razlike med spodnjo temperaturo v motorju in temperaturo sredstva za ogrevanje hranilnika toplote.

5 SKLEP

Ugotovili smo, da je za hišno tehniko (do 100 kW toplotne moči) zelo primerna izvedba Stirlingov motor, saj se Rankinov postopek uporablja za višjo raven (do 1 MW) za daljinsko ogrevanje, medtem ko se parni postopek uporablja za nekaj več MW v večjih elektrarnah.

Ugotovili smo, da moč Stirlingovega motorja za soproizvodnjo toplotne in električne energije lahko povečamo s temperaturno razliko med vročim in hladnim koncem motorja, s kompresijskim razmerjem ter z vrsto in maso plina. Temperaturno spremembo je težko veliko povečati, ker je zgornja temperatura v motorju odvisna od temperature ostankov zgorevanja, od velikosti toplotne prehodnosti toplega prenosnika toplote, ki je odvisna od materiala, ter končno od vzdržljivosti materialov (tesnila). Spodnja temperatura v motorju pa je precej odvisna od temperature in pretoka sredstva, ki hladi hladni konec motorja. Sprememba kompresijskega razmerja ni mogoča. Kompresijsko razmerje je treba določiti pri konstruiranju motorja, ker je odvisno od geometrijske oblike motorja

coefficient should be large enough, and the size of the heat exchanger big enough. There are also lower temperature limits. At too low a temperature the heat transfer to the fluid for heating the thermal storage may become impossible due to a too low temperature difference between the lower temperature in the engine and the temperature of the fluid for heating.

5 CONCLUSION

We have found that the Stirling engine is a suitable technology for power production in housing (up to 100 kW of heat power), while the ORC (Organic Rankine Cycle) process is better suited to higher level power production (up to 1 MW) as in district heating, and the steam process is best used for the largest power stations (more than 1 MW).

The power of the Stirling engine for CHP can be increased by creating a higher temperature difference between the hot and cold ends of the engine, by changing the compression ratio, the type of gas, and the mass of the working gas. The temperature difference cannot be changed infinitely since the upper temperature in the engine depends on the temperature of the products of combustion, on the heat-transfer coefficient of the hot heat exchanger, which in turn depends on the material, and finally on the properties of the construction material (packing). The lower temperature in the engine depends on the temperature and flow of the fluid that cools the cold end of the engine. Changing the compression ratio for a given engine is not (prostornina motorja, velikost batov, gibna prostornina). Večjo moč motorja si zagotovimo tudi z uporabo drugega plina, ki ima drugačno razmerje specifičnih toplot plina. Zelo primerna je uporaba helija, ker daje, v nasprotju z uporabo vodika, poleg večje moči motorja tudi veliko višjo električno učinkovitost. Motor pa mora biti, zaradi konstrukcijskih lastnosti materialov, izdelan za določen plin in zato sprememba plina v posameznih motorjih ni mogoča. Je pa med delovanjem mogoča sprememba količine plina. Sprememba količine plina ne vpliva na učinkovitost motorja, pač pa na njegovo moč oz. na pridobljeno delo iz motorja. S spreminjanjem količine plina v Stirlingovem motorju, kakor tudi pri temperaturni spremembi, se spreminjajo tudi tlačne razmere v motorju. Zato je treba že pri konstruiranju motorja določiti, kateri plin bo uporabljen, kakšni sta zgornja in spodnja temperaturna meja in za kakšne toplotne moči bo motor oz. soproizvodna enota namenjena.

Z upoštevanjem popolne regeneracije toplote daje po enačbah Stirlingov motor, teoretično učinkovitost enako učinkovitosti Carnotovemu postopku. Popolna regeneracija toplote ni mogoča, ker bi moral biti tok plina skozi regenerator zelo počasen, da bi tam oddal vso svojo toploto. Pridobljeno delo iz motorja je odvisno od njegove hitrosti; večja ko je hitrost, več dela pridobimo oz. večja je moč motorja pri enaki učinkovitosti. Prav tako pa zaradi mrtvih prostornin plin nikoli v celoti ne poteka skozi regenerator. Zato je popolna regeneracija mogoča samo teoretično, dejansko pa se regenerira le majhen del. Tudi gibanje batov ne more biti prekinjeno, zato ne dosegamo popolnih izotermnih in izohornih preobrazb. To in še mnogo drugih stvari daje dejansko električno učinkovitost veliko nižjo od idealne.

possible. The compression ratio is set at the time the engine is constructed, since it depends on the geometry of the engine (volume of the cylinders, size of pistons, bore times stroke). Higher power can be obtained by using different gases with different specific heat capacities. Using helium produces not only more power but also a higher electrical efficiency in comparison to hydrogen. Due to the constructional properties of materials, the engine must be made for a defined gas, so any change in gas for an individual engine is not possible. However, a change in the quantity of gas is possible during operation, which influences the power of the engine but not its efficiency. By varying the quantity of gas and the temperature, the pressure conditions in the engine are also changed. Because of this, the type of gas and the upper and lower temperature limits, as well as the heat needs of the engine or house CHP units, should be defined during the engine's construction.

By assuming complete (100%) heat regeneration, the Stirling engine has a theoretical efficiency equal to the Carnot efficiency. In reality, complete heat regeneration is not possible, since the gas flow rate through the regenerator would have to be very slow in order to release all of its heat. The work gained from the engine depends on its speed: the higher the speed, the more work is acquired or the higher the power of the engine at equal efficiency. However, the total volume of gas never goes through the regenerator due to non-zero volumes. Complete heat regeneration is, therefore, only possible theoretically, and only a small part is regenerated in reality. Finally, since the piston motion cannot be discontinuous, the isothermal and isochoric processes are never perfect. What this means is that the actual efficiency is much lower than the theoretical efficiency.

6 OZNAČBE
6 NOMENCLATURE

specifična toplota pri stalni prostornini	c_v	J/kg.K	specific heat capacity at constant volume
eksergija	E	J	exergy
kurilnost	H	J/kg	net caloric value
razmerje specifičnih toplot	κ		ratio of specific heat capacities
masa	m	kg	mass
masni tok	$\dot{m}$	kg/s	mass flow rate
moč	P	W	power
tlak	p	Pa	pressure
toplota	Q	J	heat

toplotni tok	$\dot{Q}$	W	heat flow
uparjalna toplota	r	J/kg	heat of vaporization
specifična plinska konstanta	R	J/kg.K	specific gas constant
entropija	S	J/K	entropy
temperatura	T	k	temperature
prostornina	V	m^3	volume
količina vlage v gorivu	w	kg/kg	moisture content of the fuel
Indeksi			**Subscripts**
biomasa	b		biomass
gorljive snovi	cs		combustible substances
okolje, elektrika	e		environment, electricity
visok	H		high
določeno stanje	i		certain state
doveden	in		supplied
nizek	L		low
srednji	m		medium
število stanj	n		number of states
izločen	out		extracted

7 LITERATURA
7 LITERATURE

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Naslov avtorjev: dr. Uroš Stritih
Gregor Zupan
prof. dr. Vincenc Butala
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
uros.stritih@fs.uni-lj.si
gregor.zupan@fs.uni-lj.si
vincenc.butala@fs.uni-lj.si

Naslov avtorjev: Dr. Uroš Stritih
Gregor Zupan
Prof. Dr. Vincenc Butala
University of Ljubljana
Faculty of Mechanical Engineering
Aškerčeva 6
1000 Ljubljana, Slovenia
uros.stritih@fs.uni-lj.si
gregor.zupan@fs.uni-lj.si
vincenc.butala@fs.uni-lj.si

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