

**Wilhelm SERVIS<sup>1</sup>**  
**Vladimir MEDICA<sup>2</sup>**  
**Andrej KORBAR<sup>3</sup>**

**Authors' addresses:**

<sup>1</sup> servis@hispeed.ch  
 Gutstrasse 51  
 8400 Winterthur, Switzerland  
<sup>2</sup> medica@rijeka.riteh.hr  
 Vukovarska 58  
 51000 Rijeka, Hrvatska  
<sup>3</sup> andrej.korbar@zg.htnet.hr  
 Sortina 1b  
 10020 Zagreb, Hrvatska

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# New Stirling Engine Concept (NSC-Engine) with Application of Direct Heat Introduction

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*Authors*

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*Zahvaljujemo se profesoru dr.sc. Ivi Kolinu, hrvatskom znanstveniku, koji je dao znan dan doprinos razvoju toplinskih izotermalnih motora Stirlingova tipa, a koji je od samoga početka podržao znanstvenu obradu ove teme i time razvoj NKS-motora.*

*Autori*

## Review paper

The efficiency of thermal engines is directly dependent on the temperatures and temperature differences of their heat reservoirs (heater and cooler). Up to now the improvements of the Stirling engine's efficiency have been exclusively achieved through the increase of the engine hot-side temperatures, whereas the possible improvements of the engine thermal efficiency by lowering their cold-side temperatures, have not been thoroughly researched.

In the research work of Wilhelm Servis the influence of lowering the engine cold-side temperature down to the deep, cryogenic temperature range on the Stirling engine performance was investigated. The research work results show a regular, very perceptible increase of thermal efficiency and brake power by lowering the cold-side temperatures of the investigated engines down to the cryogenic temperature ranges. On the basis of this investigation it was possible to define a list of measures to be taken to achieve improvements of the classic Stirling engine. These improvements were achieved through the application of the principle of the direct heat input and output from the engine process, the realisation of engine cooling through the injection and additional evaporation of liquefied working medium in the engine cylinder, and the engine cooling down to the cryogenic temperature range.

The application of the mentioned measures has led to the development of the "New Stirling Engine Concept (NSC-engine = NKS-motor)". These are the engine types PROFIT<sub>0</sub>, PROFIT<sub>1</sub> and PROFIT<sub>2</sub>, covered by pending and obtained patents. The NSC-engines, realised on the basis of this "New Concept" have the highest possible achievable thermal efficiency and power production, substantially higher than the presently used thermal engines. These engines, will be able to use nearly any energy source (also porter of heat and cold) and also will be able to operate as real "class zero" or "class ultra low emission" engines (no or very low CO<sub>2</sub>- and NOx-emissions).

**Keywords:** *aerothermal engine, NSC-engine, Stirling isothermal engine, thermal efficiency.*

## Novi koncept Stirlingova motora (NKS-motora) s primjenom izravne izmjene toplina

## Pregledni rad

Korisnost toplinskih motora izravno je ovisna o temperaturi i o razlici temperatura njihovih toplinskih spremnika (zagrijača i hladnjaka).

Dosadašnja poboljšanja termičke korisnosti Stirlingovih motora postizavana su isključivo povišenjem temperature njihovih zagrijača, a mogućnosti poboljšanja korisnosti tih motora sniženjem temperature njihovih hladnjaka nisu bile ispitivane u dostatnoj mjeri.

Znanstvenim radom Servisa ispitivan je utjecaj sniženja rashladnih spremnika topline do kriogeničkih temperatura na značajke Stirlingovih motora. Rezultati tih znanstvenih istraživanja pokazuju ujednačen, vrlo zamjetan porast korisnosti i snage ispitivanih motora do dubokoga, kriogeničkog područja temperatura hladnjaka motora. Na osnovi tog istraživanja bilo je moguće napraviti popis mjera za postizanje poboljšanja klasičnoga Stirlingova motora. Ta poboljšanja su postiziva primjenom načela izravnog dovodenja i odvođenja topline od procesa motora, realizacijom hlađenja motora ubrizgavanjem i naknadnim isparavanjem radnog medija u cilindru motora i hlađenjem motora do kriogeničkih temperatura.

Primjena navedenih mjera rezultirala je razvojem "Novoga koncepta Stirlingovih motora (NKS-motor = NSC-engine)". To su motori tipa PROFIT<sub>0</sub>, PROFIT<sub>1</sub> i PROFIT<sub>2</sub>, koji su zaštićeni patentima. NKS-motori, izvedeni po tom "Novom konceptu", mogu postizati najviše moguće termičke korisnosti i snage, bitno veće nego današnji toplinski motori. Ti motori će, skoro neograničeno, moći koristiti razne izvore energije (kao i nositelje topline i hladnoće) i funkcionirati s "nultim" ili s "vrlo malim zagadivanjem" okoliša (bez ili s vrlo sniženim CO<sub>2</sub>- i NOx-emisijama).

**Ključne riječi:** *aerotermalni strojevi, NKS-motor, Stirlingov izotermalni motor, termička korisnost.*

## 1 Introduction

This topic was thoroughly analysed in the PhD Thesis of Servis [1], and it was reported in several scientific papers during the past eight years, and in an introductory paper published in *Brodogradnja* [2 to 7].

The authors' intention is to continue with this concluding paper the reporting on the topic initiated earlier in *Brodogradnja* journal, and to:

- a) give the introduction to globally important reasons for performing this scientific research,
- b) confront the achieved research results and possible extrapolations of the results with the research intentions.

From the matters reported here evident is connection between the fast world population growth and its consequences on environmental pollution problems, world weather changes and problems in energy supplies and resources.

Today we do not doubt the necessity of finding proper solutions for the removal or partial removal of the before mentioned problems.

The results of the presented research are undoubted, and proposed solutions indicate a way to possible solution regarding the mentioned problems.

## 2 Actual world environmental and energy situation

From the actual analysis of the world situation and perspectives, performed by the scientific group of "Club of Rome" [8] and [1] follows that the world population and energy consumption grow exponentially, Figure 1.

That problem and its effects have become of global importance, which reflects in:

- 1) Globally exhausted world reserves of natural wealth and energy,
- 2) Environmental impacts and difficulties in world environment and biosphere pollution, and increase in the Earth's atmosphere medium temperature, and in
- 3) Sociological impacts in lowering the life standard and population impoverishment, evident not only in developing countries (due to higher energy prices and related impact).

The before mentioned consequences, the already evidenced and the expected ones, are of enormous concern. Thus, for the sake of illustration in the text that follows given are only few of unfavourable world prognoses for the current 21st century.

### In the environmental sector

a) Increase of the average global temperature is expected to be up to 10 °C [10], regardless the evidence of global dimming of the Earth's atmosphere [9] due to the increased share of particulate matters and aerosols. It at the same time diminishes the global warming and reduces globally the agriculture yield.

b) The expected world sea level rise (roughly up to 1 m in the Adriatic Sea) will cause floods of the coasts and some most populated world ports and cities.

c) There are expected changes in sea stream flow directions and intensities, which could have fatal impact on the most developed parts of the Earth (an example is Europe and the importance of the Gulf stream).

## 1. Uvod

O ovoj temi, opširno obrađenoj doktorskim radom Servisa [1], znanstveno je izvještavano u nekoliko navrata tijekom proteklih osam godina, a uvodno i u *Brodogradnji* [2 do 7].

Želja autora je s ovim zaključnim radom nastaviti započeto informiranje u ovom stručnom časopisu i pri tome:

- a) dati pregled globalno važnih razloga za obavljanje ovog znanstvenog istraživanja i
- b) konfrontirati postignute rezultate istraživanja i predviđene moguće ekstrapolacije tih rezultata s navedenim razlozima ovog istraživanja.

Iz iznesenog u ovom radu može se vidjeti zastrašujuća povezanost već dulje vremena uočenog, eksponencijalnog porasta stanovništva Zemlje s u proteklo vrijeme dobro uočljivim posljedicama toga porasta izraženih s ekološkim problemima, sa sve intenzivnijim meteorološkim ekscesima i s tim pojavama izravno povezanim energetske resursnim problemima.

Nužna potrebitost nalaženja rješenja za potpuno uklanjanje ili bar ublaženje tih problema danas više nije upitna.

Rezultati ovih istraživanja su nedvojbena, a predložena rješenja pokazuju jedan put k mogućim rješenjima navedenih problema.

## 2. Aktualna ekološka i energetska situacija Zemlje

Iz aktualne analize stanja i perspektive Zemlje načinjene od znanstvene ekipe "Club of Rome" [8] i [1], proizlazi između ostaloga, da stanovništvo Zemlje i cjelokupna svjetska potrošnja energije stalno rastu i da taj porast ima eksponencijalni karakter, slika 1.

Taj problem i njegove uočene posljedice poprimaju globalne, svjetske razmjere koji se očituju:

- 1) u općem iscrpljenju zaliha prirodnih, osobito energetske bogatstva Zemlje,
- 2) u ekološkim problemima i teškoćama, odraženim zagađenjem i oštećenjem okoliša i biosfere i rastom srednje temperature atmosfere Zemlje i
- 3) u sociološkim teškoćama, odraženim padom životnoga standarda i osiromašenjem, uočljivim ne samo u nerazvijenim zemljama (osobito zbog sve viših cijena energenata i popratnih pojava).

Gore spomenute, uočene i dalje očekivane posljedice su enormne, pa se na ovome mjestu, ilustracije radi želi istaknuti samo nekoliko od najneugodnijih prognoza za aktualno, 21. stoljeće:

### Na ekološkom sektoru

a) Srednji porast temperature atmosfere Zemlje bi mogao biti do oko 10 °C, [10]. Taj rast se očekuje usprkos djelovanja u novije vrijeme uočenoga globalnog zamračenja atmosfere (*global dimming*) [9], koje nastaje zbog sve većeg udjela čestica čađe i aerosola u atmosferi i svojim djelovanjem ublažava globalno zatopljenje atmosfere i istodobno, između ostaloga, globalno reducira agrarne prinose Zemlje.

b) Očekivani rast razine svih mora Zemlje (na Jadranu za oko 1m) uzrokovat će preplavlivanje većeg dijela današnjih svjetskih luka i priobalnih gradova.

c) Očekivane globalne promjene intenziteta i smjerova tokova strujanja u oceanima i morima (za Europu osobito fatalan bi mogao biti utjecaj promjene toka i intenziteta Golfske struje).

These changes could change or completely perturb climatic and meteorological configurations with unforeseen impact on world population and world flora and fauna.

### In the energy sector

d) Expected complete exhaustion of the world reserves in crude oil, according to all prognoses (including the SHELL based Hubbert's prognosis [10]) which is to be expected already at the end of the 21st century, Figure 2.

Te promjene morskih struja bi mogle poremetiti ili potpuno promijeniti klimatsku i meteorološku konfiguraciju s nedoglednim posljedicama za floru, faunu i stanovništvo Zemlje.

### Na energetsom sektoru

d) Očekivano potpuno iscrpljenje zaliha nafte (zemnog ulja) po svim će prognozama (od kojih ovdje eksplicitno navodimo po SHELL-u provjerenu Hubbertovu prognozu [10]) pri aktualnoj potrošnji uslijediti do kraja 21. stoljeća, slika 2.

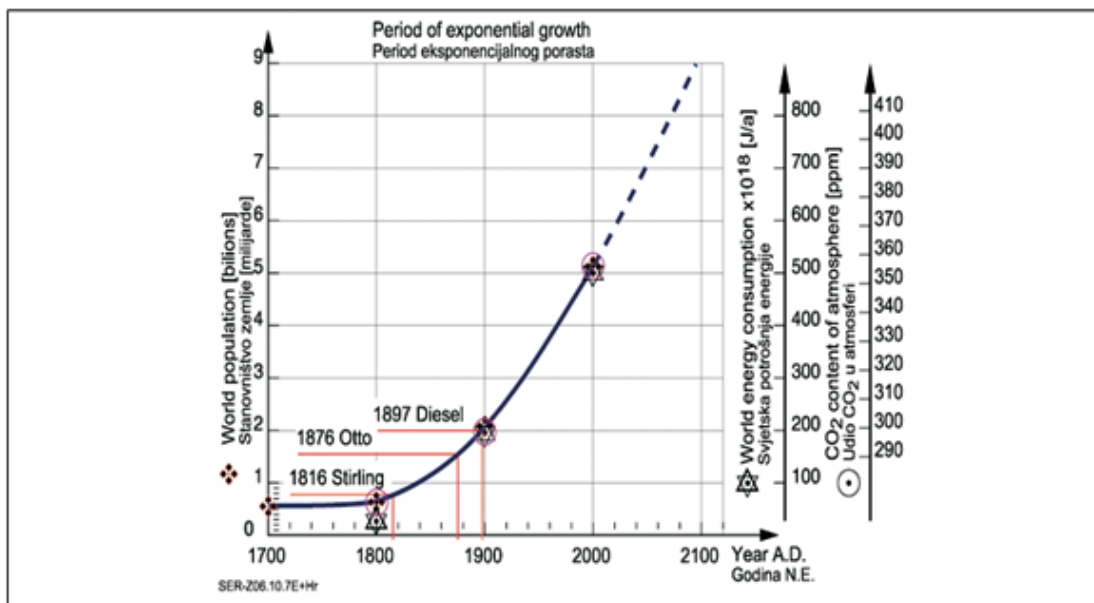


Figure 1 World population growth and its influence on world energy consumption with its effects (CO<sub>2</sub>) [1]  
Slika 1 Pregled razvoja stanovništva Zemlje i utjecaj na svjetsku potrošnju energije i posljedice (CO<sub>2</sub>) [1]

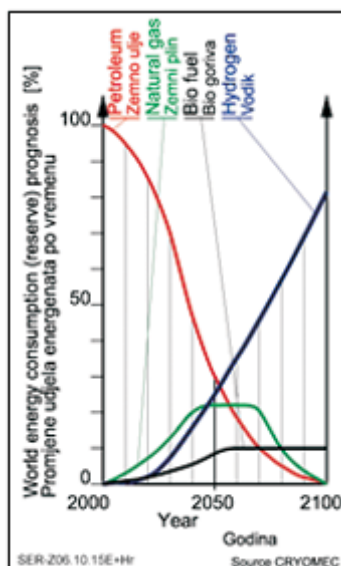
It can be seen from Figure 2 that the exhaustion of crude oil reserves in close future must be covered by higher consumption in natural gas, bio fuels, hydrogen and from alternative energy sources (wind, water, waves and sunlight) or from nuclear power plants.

e) It is also evident from Figure 2 that the future global energy supply is based on hydrogen.

At the same time evident is the lack of commercially proven technology for hydrogen production in large scale irrespective of the fossil fuels (exception from this are nuclear power plants). Today we have developed systems for hydrogen storage and distribution in liquid phase, and also gas catalytic heaters enabling the temperatures up to 1500 K. Fuel cells for direct conversion of hydrogen chemical energy to electrical energy are introduced widespread [11].

Figure 2 Prognosis of the world crude oil and natural gas reserves fall and growth in hydrogen consumption [17]

Slika 2 Prognoza smanjenja zaliha zemnog ulja i plina i porast udjela potrošnje vodika [17]



Iz slike 2 se vidi, da će se smanjenje postojećih svjetskih zaliha nafte već u najskorije vrijeme morati moći nadoknaditi zemnim plinom, bio-gorivima, vodikom kao i (ovdje nepokazanim) alternativnim izvorima energije (vjetar, vode, valovi i sunce) ili nuklearnim izvorima energije.

e) Iz slike 2 se ujedno vidi, da se predviđena, buduća globalna opskrba energijom većim dijelom oslanja na vodik.

Pritom se mora imati u vidu, da danas još ne postoji komercijalno razvijena tehnologija kojom bi se u potrebnim (golemim) količinama, vidi sliku 1, mogao neovisno od fosilnih goriva proizvoditi vodik (iznimka su nuklearne centrale), ali i, da su danas već dostatno razvijeni sustavi za masovno uskladištavanje i transport vodika u ukapljenom stanju, kao i plinski katalitički zagrijači s aktualnom mogućnošću postizanja temperatura do područja od oko 1500 K, kao i sustavi s gorivnim ćelijama za izravno generiranje električne struje od vodika [11].

An analysis of all aspects for the solution of the before mentioned problems is out of the scope of this paper. Regardless of this fact, here we can point the following:

e1) Steps to reduce the consumption of fuel, which leads to the increase of the efficiency of heat engines, which will be the topic in this paper, and

e2) Steps for the development of hydrogen production technologies [11] or other alternative energy sources, which will be out of the scope of this paper).

### 3 Current state of the art technology of Stirling engines

This paper pleads an opinion that one of possible solutions of the above mentioned problem must start from the facts that large part of actual energy consumption starts with energy conversion in thermal engines from source energy (e.g. energy of diesel fuel) into mechanical work, wherefrom it follows:

a) Energy saving and reduction of environmental pollution could be achieved by the application of more efficient thermal engines than internal combustion engines (like compression (Diesel) - or spark-ignition engines),

b) That more energy efficient engines with a potential for improvement include the engines performing Stirling isothermal process, which belongs to the most efficient processes for energy conversion from heat to mechanical work. With Stirling engines performing such process, mechanical power is produced from conversion of the heat energy flux (by using classical Stirling process) between two heat storages. Temperature difference between heater and cooler (or heat storages) is one of the crucial factors influencing the energy conversion efficiency and intensity. The engine efficiency increases proportionally with the temperature difference between heater and cooler.

Possibilities in increasing the already high classic Stirling engine efficiency by increasing the heater temperature are exhausted and limited by existing technology. Heater temperatures are as high as the material limits (technological limit). In classical Stirling engines these temperatures are at approx. 1000 K.

c) Essential improvements of the Stirling engine efficiency are possible only by:

c1) Imposing the lowering of the cooler temperature and increasing at the same time the temperature difference having the same heater temperature, and

c2) By introduction of improved thermodynamic processes and strategies for their performing.

In the PhD thesis by Servis [1] the current knowledge on classic Stirling engines is substantially extended to new areas. These new findings and the proposals given in the thesis for the improvements in the Stirling process and strategies for their performing in the so-called "New Stirling Engine Concept (NSC-concept)" need to be presented separately.

Therefore, in this 3rd chapter a short overview of "Classical Stirling Engines" will be presented, while the presentation of the "New Stirling Engine Concept (NSC-concept)" will be given in the 4th chapter.

Analiza svih mjera, kojima bi se gore spomenuti problemi riješili, prešla bi uvelike ciljeve i okvire ovog rada, ali je jasno, da tu generalno i sa sigurnošću možemo ubrojiti:

e1) mjere za smanjenje potroška pogonskoga goriva, odnosno za povišenje korisnosti toplinskih motora, o kojima će se u ovom radu pobliže informirati i

e2) mjere za razvoj tehnologija za proizvodnju vodika [11] ili nekih drugih alternativnih izvora energije, o kojima se u ovom radu neće informirati.

### 3. Aktualno stanje tehnike Stirlingovih motora

Ovim radom se zastupa mišljenje da jedno od mogućih rješenje prije spomenutoga problema treba polaziti od činjenice, da veliki dio pokazanog, aktualnog (enormno velikog, slika 1) potroška energije, započinje njezinom pretvorbom pomoću toplinskih motora od izvora energije (npr. dizelskoga goriva) u mehanički rad, iz čega slijedi:

a) da bi se boljim toplinskim motorima nego što su to toplinski motori s unutarnjim izgaranjem u današnjoj uporabi (to su dizelski i Ottovi motori) moglo energiju štedjeti i ujedno smanjiti zagađenje okoliša,

b) da u skupinu toplinskih motora s potencijalom za poboljšanja pripadaju u prvom redu izotermalni motori sa Stirlingovim procesom i to zato, jer se Stirlingov (izotermalni) proces nepobitno ubraja u skupinu najučinkovitijih načina pretvorbe energije u mehanički rad. S tim procesom i s po njemu izvedenim Stirlingovim motorima mehanički se rad dobiva pogodnom pretvorbom topline (tzv. klasičnim Stirlingovim procesom) između njihova dva toplinska spremnika. Temperaturne razine i diferencije temperatura spremnika topline (zagrijača i hladnjaka) Stirlingova motora pripadaju u čimbenike koji bitno utječu na njegovu korisnost i na količinu mehaničkog rada pretvorenog motorom od dovedene topline, pa korisnost Stirlingova motora raste proporcionalno s rastom razlike temperatura njihovih toplinskih spremnika.

Mogućnosti postizanja visoke korisnosti Stirlingovih motora s povišenjem temperature njihovih zagrijača danas su uglavnom iscrpljene, jer su temperature zagrijača toliko visoke koliko to raspoloživi materijali termički opterećenih dijelova motora dopuštaju (tehnološki limit). Za klasične Stirlingove motore te su temperature danas oko 1000 K i

c) da se bitna poboljšanja korisnosti Stirlingovih motora aktualno mogu postići još samo:

c1) markantnim sniženjem temperature njihovoga hladnjaka i time postizanjem veće razlike temperatura uz istu temperaturu zagrijača i

c2) poboljšanjem njihovoga termodinamičkog kružnog procesa i načina njegovog izvođenja.

Objavljuvanjem doktorskoga rada Servisa [1] se aktualno stanje znanja o Stirlingovim motorima bitno proširilo, pa stoga spoznaje dobivene tim radom, kao i u radu dani prijedlozi za poboljšanje njihovoga termodinamičkog procesa i načina njihovog izvođenja, po tzv. "Novom konceptu Stirlingovih motora (NKS-koncept)", zahtijevaju odvojeno iznošenje informacija.

Zato će se u ovom 3. poglavlju iznijeti kratki pregled tehnike "klasičnih Stirlingovih motora", a informacije o Stirlingovim motorima po "Novom konceptu Stirlingovih motora (NKS-koncept)" bit će iznesene u 4. poglavlju.

### 3.1 Classical Stirling Engine

Classical Stirling engine, named after its inventor Robert Stirling (1790-1878) [12] and [13] is a piston heat engine with external fuel combustion (heat addition and extraction are external), which performs isothermal Stirling process cycle. This thermal process is performed through two isothermal and two isochoric changes in a closed cycle with the same working fluid (which at the time was air). Part of the heat content is recovered in the process cycle by using the heat regenerator.

Figure 3 presents the classical Stirling engine from 1816, which is considered by authors as the representative for the class of classical Stirling engines. All main components and the principle of operation of these engines can be seen in the same figure.

In the time period from the first Stirling engine up to our days (almost 190 years) a large number of Stirling engines were patented and realised, different in their designs and operation modes, but always with the same idea of the isothermal Stirling cycle. To enable the differentiation between various engine designs Stirling engines are classified into different configuration types; the newest configuration type was presented by Servis's new Stirling engine typology [1].

### 3.1. Klasični Stirlingov motor

Klasični Stirlingov motor, nazvan po svome izumitelju Robertu Stirlingu (1790. do 1878. godine, [12] i [13]), toplinski je stapni motor s izvanjskim izgaranjem goriva (dovođenje i odvođenje topline je izvana), koji radi s tzv. izotermalnim Stirlingovim kružnim procesom, tvorenim od dvije izoterme i dvije izohore u zatvorenom termodinamičkom sustavu s uvijek istim radnim medijem (tada sa zrakom) i s iskorištavanjem topline sadržane u radnome mediju, tijekom kružnoga procesa pomoću tzv. regeneratora.

Na slici 3 vidimo prikaz klasičnoga Stirlingova motora iz 1816. godine, kojeg autori rada smatraju reprezentativnim za te motore. Iz te slike se mogu razaznati sve karakteristične sastavnice i uočiti način rada tih motora.

Tijekom vremena, od pojave Stirlingova motora pa do danas (skoro 190 godina!) bilo je i još uvijek biva patentirano i izvedeno mnogo novih Stirlingovih strojeva različitih po konstrukciji i načinu rada ali sa zajedničkom zamisli izotermalnoga Stirlingovog kružnog procesa. Da bi ih se moglo razlikovati razvijene su tipologije tih motora od kojih ovdje spominjemo najnoviju, prezentiranu doktorskim radom Servisa [1].

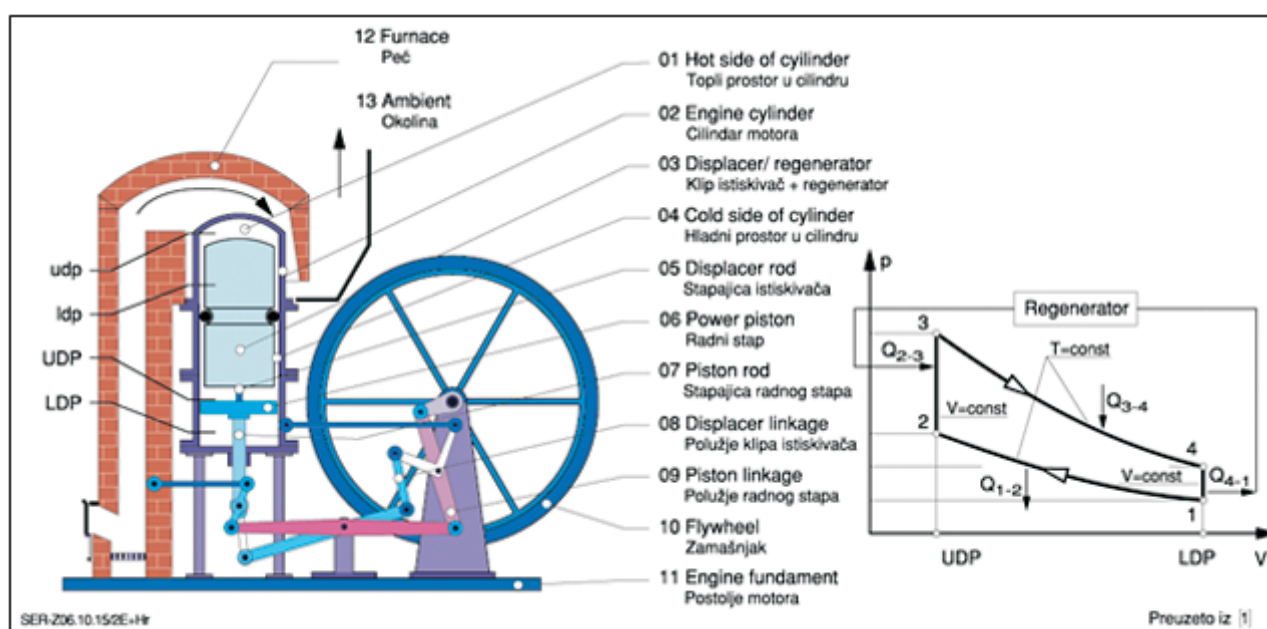


Figure 3 Cross-section of the Stirling engine from 1816, in the BETA(P) configuration, using the regenerator [1]  
Slika 3 Presjek Stirlingova motora iz 1816. godine, koji je izveden po BETA(P) konfiguraciji i s regeneratom [1]

The Stirling engine configurations can be classified into three basic designs: ALFA, BETA and GAMMA. These engines with additional design options may be further classified in more details than it was possible so far.

According to this new classification, the Stirling engine form 1816 (the first operating engine of that kind, Figure 3) may be classified as BETA(P), which is characterised by having a working piston (06) and a displacer piston (03) in the same engine cylinder (02), with the heat regenerator (03). Engine power was at 1.5 kW.

Just for illustration, a few typical designs of the classical Stirling engines will be presented here:

Iz spomenute tipologije može se vidjeti, da se Stirlingovi motori mogu svrstati u 3 osnovne konfiguracije (to su ALFA, BETA i GAMA konfiguracija) i da se ti motori mogu s dodatnim opcijama još iscrpnije specificirati nego je to do sada bilo moguće.

Po toj novoj, opće vrijedećoj tipologiji je Stirlingov motor iz 1816. godine (prvi funkcionirajući motor te vrste, pokazan slikom 3), izveden po BETA(P) konfiguraciji, koju karakterizira ugradnja radnoga stapa (06) i klipa istiskivača (03) u istom cilindru motora (02), koji koristi, isto tako po prvi put, regenerator topline (03) i sa snagom oko 1,5 kW.

Ovdje će se, ilustracije radi, pokazati još nekoliko tipičnih klasičnih Stirlingovih motora:

1) Figure 4 presents the photograph of the Lehmann engine from 1866 in BETA(P) design, without the heat regenerator. Engine power was at 745 W. This engine is specific because of the similarity with the Stirling engine from 1816, but it is without the heat regenerator, resulting in a lower efficiency. This, horizontal engine was realised 50 years after the Stirling patent, and it was the basis for the first numerical analysis of such engines by Schmidt [1] and [16].

2) Figure 5 presents the photograph of the modern Stirling engine "SES" in the ALFA(P) design, powered by high temperature solar energy. The engine has the heat regenerator and develops a power of 25 kW. This engine was used in the pilot project to research the possible applications of the solar energy.

3) Figure 6 presents the photograph of the modern Stirling engine produced by Kockums in the ALFA(P) design with the heat regenerator. The engine has a power of 130 kW. Such engines of higher power are used in submerged submarine propulsion (AIP=Air Independent Propulsion), while for the propulsion on the sea surface diesel engines are applied.

Using the numerical analysis of the processes in actual classical Stirling engines and modern diesel engines (presented by the Sabathé cycle), the comparison between various idealised thermal cyclic processes was performed.

Figure 7 presents the results of such comparison by using the "Elementary numerical analysis of the zeroed order". From the results is evident that there is a large potential of the classical Stirling engines when compared with the diesel engines. The advantage of such analysis of idealised thermal cycles is in the remedy of the influence of design details in the resulting analysis.

It is evident from Figure 7:

- in typical conditions of the classical Stirling engine (K1, 348 K/ 900 K) and the diesel engine (D, 348 K/ 2200 K), the thermal efficiency and power of the diesel engine are higher, but also

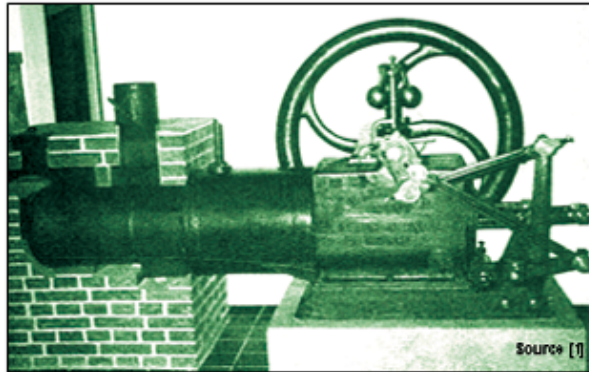
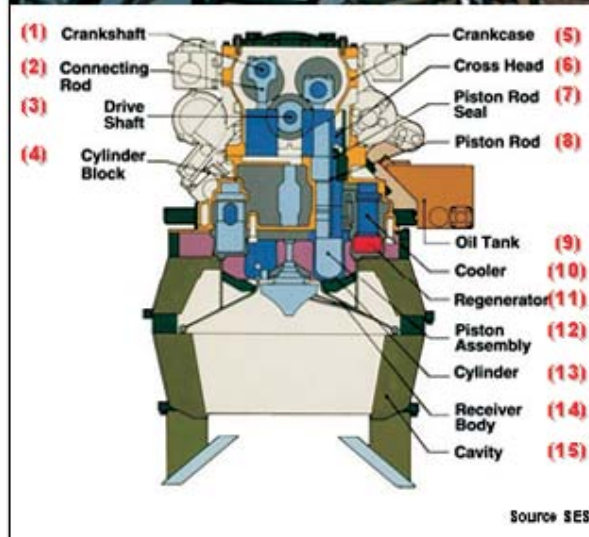


Figure 4 Lehmann engine from 1866, in the BETA(P) configuration, displayed at Deutsches Museum, Munich, Germany) [1]

Slika 4 Lehmannov motor 1866., BETA(P), izložen u Njemačkom tehničkom muzeju u Münchenu [1]

Figure 5 Solar Stirling engine "SES", (Stirling Energy Systems, ALFA (P), 25 kW/ 1900 rpm)

Slika 5 Solarni Stirlingov motor "SES", (Stirling Energy Systems, ALFA(P), 25 kW/ 1900 1/min)



1) Na slici 4 vidimo fotografiju Lehmannovog motora iz 1866. godine, koji je BETA(P) konfiguracije bez regeneratora i sa snagom od oko 745 W, a koji je zanimljiv zbog činjenice da je on praktički identičan sa Stirlingovim motorom 1816. godine, ali koji nema regenerator (manja korisnost!). Taj, horizontalno položeni motor građen je 50 godina nakon Stirlingova patenta. Na njegovoj osnovi izvedena je prva numerička analiza tih motora po Schmidt, [1] i [16].

2) Na slici 5 vidi se fotografija suvremenoga solarnog visokotemperaturnog Stirlingova motora "SES", ALFA(P) konfiguracije, s regeneratorom i sa snagom 25 kW. S tim eksperimentalnim motorom srednje snage se između ostalog ispituju mogućnosti korištenja sunčeve energije.

3) Na slici 6 vidi se fotografija suvremenoga Stirlingova motora tvrtke Kockums ALFA(P) konfiguracije, s regeneratorom i sa snagom od oko 130 kW. Ti motori veće snage služe za podvodni (AIP= Air Independent Propulsion) pogon podmornica, dok za površinsku plovidbu služe dizelski motori.

Numeričkom analizom procesa aktualno građenih klasičnih Stirlingovih i suvremenih dizelskih motora (Sabathé), koji ovdje reprezentiraju suvremene visokovrijedne toplinske motore, u radu se usporedilo njihove idealizirane termodinamičke kružne procese.

Na slici 7 vidimo rezultat te usporedbe s u radu razvijenom "Elementarnom numeričkom analizom nultog reda", iz koje se vidi još uvijek golem potencijal klasičnoga Stirlingova u odnosu prema dizelskom procesu. Prednost je tako obavljenih analiza idealiziranih kružnih procesa da se na taj način izbjegava uzimanje u obzir izvedbenih pojedinosti pripadajućih motora.

Iz slike 7 vidimo:

- da su uz tipične uvjete rada klasičnoga Stirlingova (K1, 348 K/ 900 K) i dizelskog (D, 348 K/ 2200 K) motora, termička korisnost kao i proizvedeni rad dizelskoga procesa veći, ali i

- at the same operation conditions (K2, 348 K/ 2200 K) the efficiency and the power of the classical Stirling engines could be even better than that of the diesel engine.

From Figure 7 it is evident that by lowering the cooler temperature (K3, 80 K/ 2200 K), significant improvement of the efficiency and power of the classical Stirling engines is achieved. Servis [1] has presented the reasons why the realised Stirling engines, despite the application of the best isothermal cycle, have not achieved the efficiency of the diesel engines. Reasons for this are:

- Maximum temperatures for heat addition in Stirling engines are lower than and limited to approx. 1000 K (technology limit) and

- The compression ratios (up to  $\epsilon = 2$ ) and pressures in Stirling engines are low (due to the problems in sealing), which reduces the engine efficiency.

In further discussion Servis [1] stresses that the classical Stirling engines, besides the advantages (the most important of which are higher efficiency and low ecological impact), and besides the already existing technical and technological possibilities for the improvement and competitiveness of such engines, have not achieved the favourable market position. It is now the time to achieve this position.

Based on these considerations Servis [1] presents the following list of intentions aimed at realising the goal of improving the competitiveness of Stirling engines:

- Simplification of the engine kinematics,
- Increase of the compression ratio in the engine,
- Possibility to increase the maximum pressure and temperature by introducing the heat into the engine cylinder,
- Application of cryogenic temperatures on engine coolers,
- Simplification of the heat transfer by direct heat transfer,



Figure 6 Stirling engine "Kockums", ALFA(P) [26]  
Slika 6 Stirlingov motor "Kockums", ALFA(P) [26]

- da bi uz iste uvjete rada (K2, 348 K/ 2200 K) korisnost i proizvedeni rad klasičnoga Stirlingova procesa mogli bili znatno veći od dizelskog (D).

Iz slike 7 se ujedno može vidjeti, da se sniženjem temperature odvođenja topline od klasičnoga Stirlingova procesa (K3, 80 K/ 2200 K) postiže znatno poboljšanje korisnosti i proizvedenog rada. S raspravom se u radu Servisa [1] nadalje ukazuje na razloge zašto izvedeni Stirlingovi motori usprkos korištenja najafektivnijeg mogućeg, tzv. izotermalnoga kružnog procesa, postižu niže korisnosti nego dizelski motori. Do toga dolazi između ostalog:

- jer su temperature dovođenja topline u Stirlingov motor ograničene do oko 1000 K (tehnološki limit) i

- jer su postizivi stupnjevi kompresije (do  $\epsilon = 2$ ) i radni tlakovi Stirlingova motora, zbog problema brtvljenja preniski, što bitno snižuje korisnost motora.

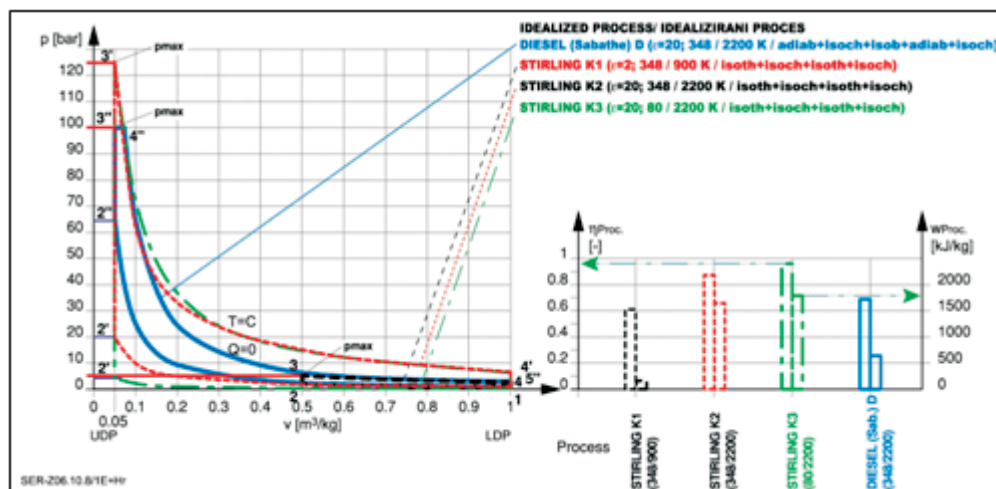
Nadalje se raspravom u radu Servisa [1] ističe da klasični Stirlingovi motori i pored njihovih uočenih prednosti (od kojih se posebno ističe visoku korisnost njihovog idealiziranog procesa i ekološku podobnost izvedenih motora), kao i pored danas već postojećih tehničkih i tehnoloških mogućnosti za postizanje poboljšanja i konkurentnosti motora, do danas nisu preuzeli tu i te kako poželjnu ulogu, pa da je krajnje vrijeme da se to učini.

Na osnovi tih razmatranja se u radu dalo ovdje pokazani (skraćeni) popis mjera, kojima bi se taj cilj, postizanje konkurentnosti Stirlingovih motora mogao postići, tj. ako bi se postiglo:

- pojednostavljenje kinematike motora,
- moćnost postizanja visoke kompresije motora,
- moćnost postizanja visokih radnih tlakova i visokih temperatura dovođenja topline u motor,
- korištenje niskih temperatura hlađenja motora,
- pojednostavljenje načina prijenosa topline iz i u motor (izravna izmjena toplina),

Figure 7 p,v and  $\eta$ -w diagram for the classical Stirling (K1, K2, K3) and diesel (Sabathé, D) cycles [1]

Slika 7 p,v i  $\eta$ -w dijagram za Stirlingov klasični (K1, K2, K3) i dizelski (Sabathé, D) kružni proces [1]



f) Creation of the improved isothermal cycle (NSC-process cycle) to achieve the pre-set goal,

g) Development of the NSC-Engine performing the improved isothermal cycle (NSC-process cycle),

h) Enlargement of the list of possible fuels, and the possibilities of application of alternative or other energy sources (such as application of the waste cryofluids etc.).

### 3.2 Results of the investigation of the influence of the engine cooler temperature of the classical Stirling engines

Based on the results of numerical analyses of idealised thermal cycles in the classical Stirling engines Servis [1] has examined the influence of the lowering of the engine cooler temperature through experimental research (3c1).

Based on the experimental results he has confirmed the "list of intentions" to be performed in achieving the pre-set goal (from 3.1a to 3.1h). Former research on the influence of the cooler temperature lowering was performed on three classical Stirling engines (PROBA1, PROBA2 and PROBA2B). The engine PROBA2B is presented in the Figure 8 (which is based on Prof. Kolin's engine [16]). This engine was adapted for the application of the engine cooler down to the temperature of 80 K [4 and 5]. This engine was examined at the end of preparatory research.

Figure 9 presents the photography of the PROBA2B engine on the test bed. The engine cooling was performed by using liquefied nitrogen, while the engine heating was realised by using DC electric heater. The engine braking was performed by dynamo brake and high precision balance.

Figure 10 presents the results of the experimental research performed on the three mentioned

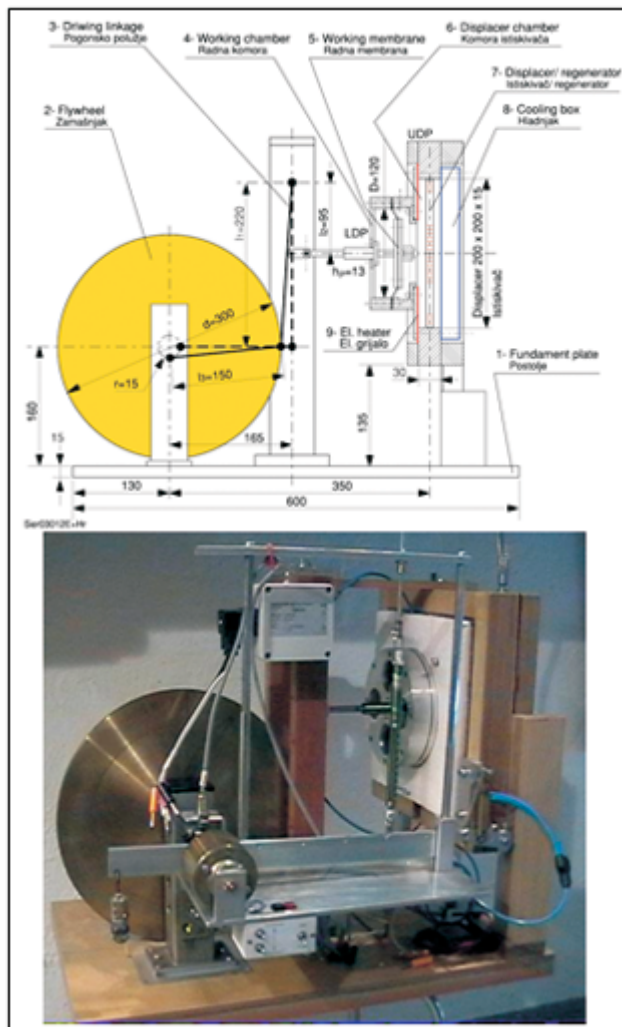


Figure 8 Simplified drawing and photography of the PROBA2B engine in the BETA(M) configuration [1]  
Slika 8 Pojednostavljeni crtež i fotografija motora PROBA2B, BETA(M) [1]

Figure 9 Photography of the PROBA2B engine on the test bed [1]  
Slika 9 Fotografija motora PROBA2B na probnom stolu [1]



f) kreiranje jednog novog, boljeg izotermalnog termodinamičkog kružnog procesa (NKS-proces) kojim bi se gore navedene mjere mogle postići,

g) razvoj NKS-motora s kojima se gore navedeni izotermalni termodinamički kružni proces (NKS-proces) može realizirati i

h) proširenje vrsta pogonskih goriva i mogućnosti korištenja alternativnih i drugih pogonskih energija (npr. izvora hladnoće i topline itd.).

### 3.2. Ispitivanje i rezultati ispitivanja utjecaja temperature hlađenja klasičnih Stirlingovih motora

Na osnovi spoznaja dobivenih numeričkim analizama idealiziranih procesa klasičnih Stirlingovih motora se u radu Servisa eksperimentalnim putem ispitaio utjecaj sniženja temperature odvođenja topline od motora (3c1) i na osnovi rezultata eksperimentalnih ispitivanja utvrdilo i provjerilo "mjere" s kojima se očekuje postizanje poboljšanja motora (od 3.1a do 3.1h).

Prethodna ispitivanja utjecaja sniženja temperature rashladnoga spremnika su u radu obavljena s tri klasična Stirlingova motora (to su motori PROBA1, PROBA2 i PROBA2B), od kojih se na slici 8 vidi motor PROBA2B; to je plosnata (tzv. Kolinova [16]) inačica klasičnoga Stirlingova motora, konstruiranog i izvedenog posebno za potrebe ispitivanja s temperaturom rashladnoga spremnika do 80 K, [4 i 5], koji je bio ispitan na kraju prethodnih ispitivanja u radu.

Na slici 9 vidi se fotografija motora PROBA2B na probnom stolu. Hlađenje motora izvedeno je pomoću ukapljenog dušika, a grijanje je bilo s istosmjernom električnom strujom. Kočenje motora izvedeno je s dinamo kočnicom i preciznom vagom.

Na slici 10 vide se rezultati prethodnih ispitivanja tri promatrana klasična Stirlingova motora



classical Stirling engines (PROBA1, PROBA2 and PROBA2B) and the results of the mentioned numerical analyses. For the sake of comparison, the figure also presents experimentally derived efficiencies of the classical Stirling engines, published in two papers [14]. The presented diagram is designed according to the method of "General presentation of the influence of lowering the temperature of engine cooler on the performances of Stirling engines" developed by Servis [1]. This presentation is characterised by the common presentation of the Carnot cycle efficiency and measured brake efficiencies of the analysed engines in dependence on the engine heater and cooler temperatures and their difference. This presentation has general character. From Figure 10 evident is mutual agreement of change trends in measured brake efficiencies and the Carnot cycle efficiencies. This agreement is also same for the measured data published in [14], showing the same character. Further we can see the influence of the Carnot cycle efficiencies on the measured brake efficiencies.

It is not possible to present the evident similarity in change trends of the measured brake efficiencies on the Stirling engines with those for the Carnot cycle without such diagram based on the method "General presentation ...". The application of this method has contributed to the understanding of the basic knowledge and its application.

The same is also valid for a Stirling engine working in various temperature areas. This method is helpful in understanding and explanation of gradients in measured values of brake efficiencies, depending on engine heater and cooler temperatures.

In establishing the mentioned gradients of measured efficiencies, dependent on the engine heater and cooler temperatures, Carnot's sentence about the "influence of engine cooler temperature range on efficiency" \*) was confirmed for the very first time. Confirmed was the "reflection of the coldness on the Stirling engine efficiency", which had not been experimentally confirmed before.

(PROBA1, PROBA2 i PROBA2B) i rezultati gore navedenih numeričkih analiza. Usporedbe radi su u tom prikazu pokazane i mjerene korisnosti klasičnih motora iz dva strana izvora [14]. Pri izvedbi dijagrama koristila se metoda "Općega prikaza utjecaja sniženja temperature hladnjaka na značajke Stirlingovih motora", razvijena u radu Servisa [1], koju karakterizira istodobni prikaz i usporedba Carnotove i mjerene (kočene) korisnosti promatranih motora u ovisnosti o temperaturi dovođenja i odvođenja topline i o razlici tih dviju temperatura. Taj prikaz ima opći karakter. Iz slike 10 vidimo nadalje međusobno podudaranje rasta i karaktera mjerenih korisnosti s Carnotovim korisnostima. To podudaranje se zapaža i za podatke mjerenja i ispitivanja motora uzetih iz literature [14] i ima također opći karakter. Nadalje se tu zapaža bitan utjecaj pripadajućih Carnotovih korisnosti (odnosno parametara koji ih tvore) na kočene korisnosti.

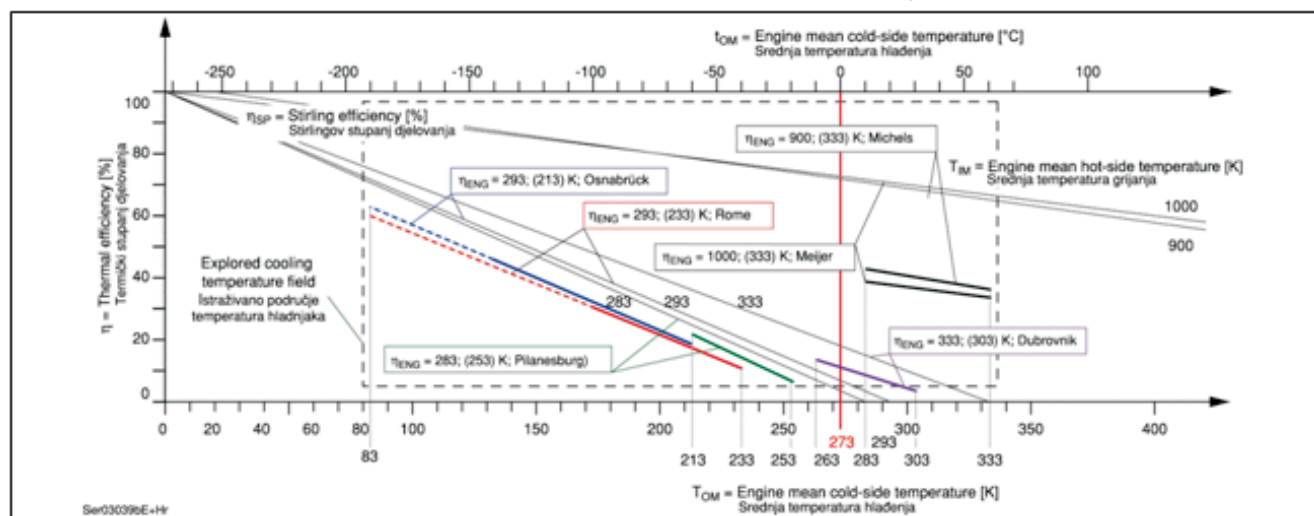
Spomenuta se srodnost tokova mjerenih korisnosti Stirlingovih motora s pripadajućim Carnotovim korisnostima bez korištenja ovdje pokazanog "Općeg prikaza..." ne bi mogla tako jednostavno zapaziti, pa je konzekventno korištenje te metode pri obradi rezultata ispitivanja znatno pridonijelo sagledavanju biti dobivenih spoznaja i olakšalo obradu i primjenu istih.

Isto tako se za neki Stirlingov motor s različitim temperaturnim područjima rada bez tog načina prikazivanja ne bi mogli uočiti i objasniti mjerenjima utvrđeni različiti a ipak srodni, od temperatura dovođenja i odvođenja topline ovisni, gradijenti mjerenih korisnosti.

Utvrđivanjem spomenutih, od temperatura dovođenja i odvođenja topline ovisnih gradijenta mjerenih korisnosti, se (po prvi put!) meritorno potvrdila valjanost Carnotove izjave\*) "o povoljnom utjecaju niže u odnosu na višu razinu temperaturnoga područja rada toplinskog motora", odnosno ovdje istaknuta refleksija hladnoće na korisnost Stirlingovih motora a koja dosad u kontekstu sa Stirlingovim motorima nije bila eksperimentalno dokazana.

\* [15, Fox, R. / Sadi Carnot: "REFLECTIONS ON THE MOTIVE POWER OF FIRE", p. 93]:  
"... the fall of calorific yields more motive power at lower temperatures than it does at higher ones..."

Figure 10 Results of the former experiments and numerical simulations of classical Stirling engines [1]  
Slika 10 Rezultati prethodnih mjerenja i numeričkih analiza promatranih klasičnih Stirlingovih motora [1]



Further, it is evident from Figure 10 that the change characters of the efficiency and power are not dependent on the Stirling engine types, but are dependent on their design.

In the end, it is to be pointed out here that the measured engine power is increased at the lowered engine cooler temperature too, which was also evident from the numerical analyses.

It can be generally stated that the performed experiments have confirmed in quantitative manner the increase of the engine efficiency and power by lowering the engine cooler temperature of the classical Stirling engines (which has been confirmed experimentally up to the engine cooler temperature of 132 K [1]). This influence is more pronounced as we are approaching the absolute temperature of zero [15].

#### 4 New Stirling Engines Concept (NSC-concept)

Observations and results of experiments on classical Stirling engines have lead to the definition named here “New Stirling engine Concept (NSC-concept)”, which comprises:

a) Instructions for performing the NSC thermodynamic cycle (Idealised NSC-process cycle that consists of: isothermal compression + isochoric heat addition + isobaric heat addition + isothermal expansion + isochoric heat removal, and

b) Instructions for the NSC-engine realisation and realisation of the NSC-process cycle.

In the NSC-concept all evidenced positive influences are included from the former experiments with lowered engine cooler temperature, as well as all other initiatives to reach higher competitiveness of the Stirling engines [1], part of which is “listed” in chapter (3.1). Here we will point some of them:

- initiatives in performing the NSC-process cycle,
- initiatives for better heat transfer to and from the cycle, -initiatives in “Carnotising” the NSC-process cycle, - engine design with hybrid displacer, - application of the simplified standard

Nadalje se iz slike 10 zapaža neovisnost karaktera tokova korisnosti i snaga od tipa Stirlingovih motora, ali i da su postignuti iznosi korisnosti i snaga vrlo ovisni o izvedbi promatranog motora.

Na kraju, ovdje se želi istaknuti, da i mjerene snage motora rastu bez iznimke ako se temperatura hladnjaka snizuje (što je jednoznačno potvrđeno i numeričkim analizama).

Generalno se može ustvrditi da su prethodna mjerenja motora kvantitativno potvrdila, da su i pokazala kako se, sa sniženjem temperature rashladnoga spremnika povisuju korisnost i dobiveni rad klasičnih Stirlingovih motora (što je utvrđeno do temperature hlađenja od oko 132 K, [1]) i da je taj utjecaj to povoljniji što se temperaturno područje rada motora više približava apsolutnoj temperaturnoj nuli [15].

#### 4. Novi koncept Stirlingovih motora (NKS-koncept)

Zapažanja i rezultati mjerenja klasičnih Stirlingovih motora iz prethodnih ispitivanja rezultirali su definiranjem u radu nazvanog “Novog koncepta Stirlingovih motora (NKS-koncept)”, koji obuhvaća:

a) Upute za izvođenje kružnoga termodinamičkog NKS-procesa (Idealizirani NKS-proces tvori se od: izotermne kompresije + izohornog dovođenja topline + izobarnog dovođenja topline + izotermne ekspanzije + izohornog odvođenja topline) i

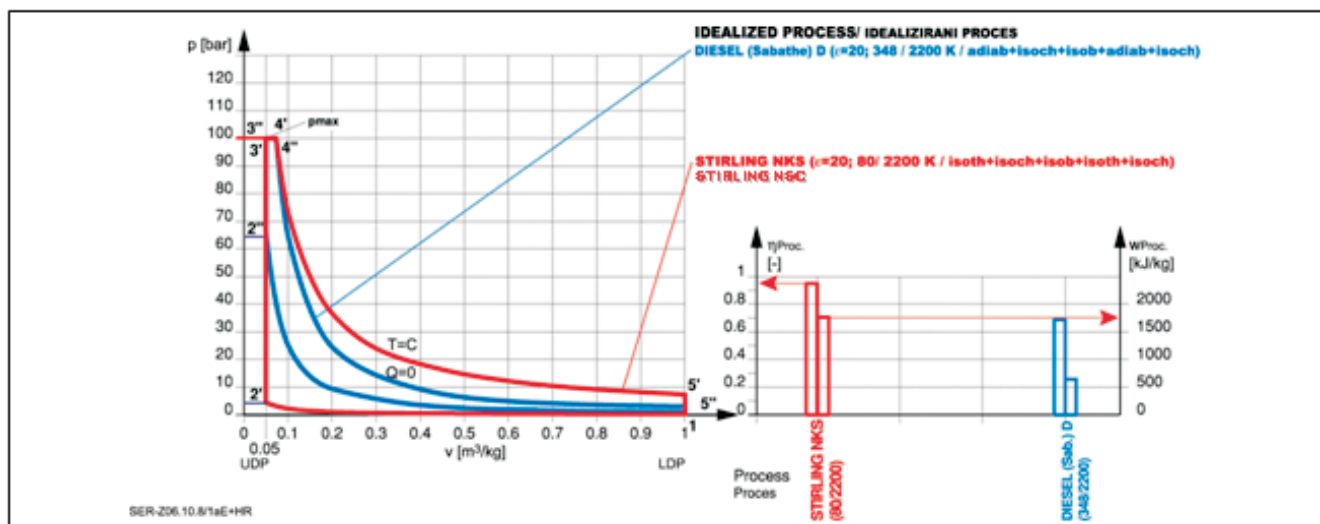
b) Upute za izvedbu NKS-motora i time za realiziranje NKS-procesa s tim motorima.

S NKS-konceptom uzeti su u obzir svi zapaženi pozitivni utjecaji dobiveni prethodnim ispitivanjima pri sniženju temperature hlađenja kao i sve otud utvrđene “mjere” za postizanje konkurentnosti Stirlingova motora [1], navedene u popisu mjera (3.1), od kojih se ovdje skraćeno navode:

- mjere za postizanje “NKS-procesa”, -mjere za poboljšano dovođenje i odvođenje topline od procesa, -mjere za karnotiziranje NKS-procesa u motoru, -izvedba motora s hibridnim istiskivačem,

Figure 11 p,v- and  $\eta$ ,w-diagram for Diesel (Sabathé, D) process and for the New Stirling engine Concept based process (NSC-process) [1]

Slika 11 p,v- i  $\eta$ ,w-dijagram za dizelski (Sabathé, D) i za termodinamički kružni proces po Novom konceptu Stirlingovih motora (NKS-proces) [1]



engine kinematics, - recommendations for NSC-engine design and - patents for the NSC-engines [18 to 25].

The analysis of the potentials of the developed idealised thermodynamic cycle (NSC-process cycle) was performed with the earlier mentioned elementary numerical analysis, like for the classical Stirling engines and diesel engine idealised cycle.

Comparison of the results of the analysis is presented in Figure 11. It is evident that there is a large potential of the NSC-process, when compared with the diesel process (D) or other process cycles (Figure 7). From Figure 11 is also evident that with the engine operation parameters, typical for actual diesel engines, the achieved efficiency and power of the NSC-process are much higher.

Expected benefits of the presented, but experimentally actually not completely confirmed NSC-engines are in the possibility to apply cryogenic temperatures of the engine cooler and in possible direct cooling of the working fluid (by injection of the cryogenic evaporating liquid directly to the engine cylinder), and in the possibility to apply much higher maximum temperatures (than the ones encountered in diesel engines), with all positive consequences.

#### 4.1 NSC-engine PROBA3D: First engine design according the NSC-concept

Based on the above-mentioned initiatives and numerical analysis of the idealised NSC-process cycle, the first experimental and demonstration engine based on the NSC-concept, the NSC-engine PROBA3D [1], was realised. This engine is of the PROFIT0 type and in BETA(M) configuration with the regenerator. This engine was made from the basic necessity for the experimental confirmation of the change trends in engine efficiency and power from the former research (see "list of intentions"). This new engine enabled the experimental evidence on one hand, and it was the first example of a completely new family of Stirling NSC-engines on the other hand. In this sense, the PROBA3D engine was the first demonstration engine of this concept.

In the design of this engine all listed initiatives were respected, while at the same time a robust, simple and inexpensive engine was realised. This engine was therefore of the PROFIT0 type, applying the elastic membrane as the working piston.

A photograph, simplified drawing and the indicated p-v diagram of the PROBA3D engine are presented in Figure 12. From the indicated p-v diagram it is evident that the realised engine cycle consisting of isothermal compression 1-2, isochoric heat addition 2-3, isobaric heat addition 3-4, isothermal expansion 4-5 and isochoric heat removal 5-1 is performed in this demonstration engine.

#### 4.2 Results of the experimental examination of the PROBA3D engine and comparison with former experiments

From the above presentations it is evident that the NSC-engine PROBA3D was developed on the basis of information and experience sampled in the former experiments on classical Stirling engines, as presented by Servis [1]. The same engine was used for further research:

- a) to confirm the influence of lowering the engine cooler temperature, and
- b) to confirm the initiatives ("list of intentions") for further improvements intended with the NSC-concept.

-korištenje standardne stapne, pojednostavljene kinematike motora, -upute za izvedbu NKS-motora i -patenti za izvedbu NKS-motora [18 do 25].

Analiza potencijala toga, u radu razvijenog idealiziranog termodinamičkog kružnog NKS-procesa, obavljena je na isti način kao i za inačice klasičnoga Stirlingova i dizelskog procesa s u radu razvijenom elementarnom numeričkom analizom.

Na slici 11 vidi se usporedba rezultata tih analiza, iz koje zapažamo golem potencijal NKS-procesa u odnosu na dizelski (D) i druge procese (slika 7). Iz te slike jasno se vidi, da su uz tipične uvjete rada dizelskog motora postignuta korisnost i rad idealiziranog NKS-procesa znatno veći od idealiziranog dizelskog procesa.

Očekivane prednosti ovdje pokazanog, ali u praksi (mjerenjima s NKS-motorima) još ne za sve inačice i pojedinosti potvrđenog NKS-procesa, se osim toga očituju u činjenici da će se zbog mogućnosti korištenja znatno nižih temperatura odvođenja topline iz procesa kao i zbog načina izvođenja hlađenja (izravno, s ubrizgavanjem ukapljenog radnog medija u prostor motora) moći koristiti znatno više temperature dovođenja topline od uobičajenih u dizelskim motorima, sa svim zbog toga izazvanim pozitivnim posljedicama.

#### 4.1. NKS-motor PROBA3D: prvi motor izveden po "NKS-konceptu"

Na osnovi gore navedenih predviđenih mjera i numeričkih analiza idealiziranog NKS-procesa izveden je prvi eksperimentalni i demonstracijski motor po NKS-konceptu, NKS-motor PROBA3D [1], koji je tipa PROFIT0 u BETA(M) konfiguraciji i s regeneratorom. Taj motor je s jedne strane nastao iz nužne potrebe provjere spoznaja (vidi "mjere") dobivenih prethodnim ispitivanjima u radu, s kojim se omogućilo mjerenje i eksperimentiranje i s druge strane, s kojim se dobio prvi predstavnik jedne cijele obitelji novih motora po NKS-konceptu, pa je motor PROBA3D ujedno i demonstracijski motor toga koncepta.

Pri izvedbi tog motora se u prvom redu nastojalo slijediti predviđene "mjere" i dobiti solidan i što jednostavniji (jeftiniji) eksperimentalni objekt, pa je on iz tih razloga izveden kao tip PROFIT0 s radnom membranom.

Na slici 12 vide se fotografija, pojednostavljeni crtež i indicirani p,v-dijagram motora PROBA3D.

Iz indiciranoga p,v-dijagrama motora vidi se da je postignuti tijek kružnoga procesa (izotermna kompresija, 1-2 + izohorno dovođenje topline, 2-3 + izobarno dovođenje topline, 3-4 + izotermna ekspanzija, 4-5 + izohorno odvođenje topline, 5-1) već i s ovim, demonstracijskim motorom ostvaren.

#### 4.2. Ispitivanje i rezultati ispitivanja NKS-motora PROBA3D i usporedba s prethodnim ispitivanjima

Iz gornjih izlaganja vidi se da je NKS-motor PROBA3D bio razvijen na osnovi informacija i iskustava dobivenih prethodnim ispitivanjima u radu [1] i zatim eksperimentalno ispitan s ciljem da se:

- a) potvrdi utjecaj sniženja temperature odvođenja topline (hlađenja) motora i
- b) provjeri "mjere" s kojima se očekuje postizanje poboljšanja predviđenih konceptom NKS-motora.

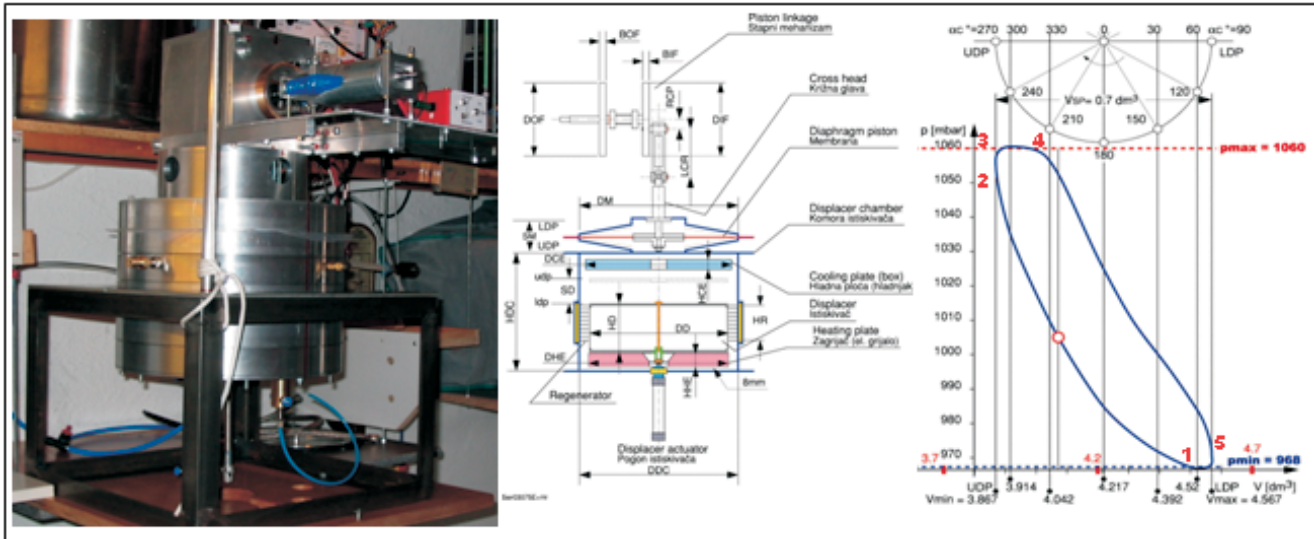


Figure 12 Photography, simplified drawing and the p,v diagram of the PROBA3D engine [1]  
 Slika 12 Fotografija, pojednostavljeni crtež i p,v-dijagram motora PROBA3D [1]

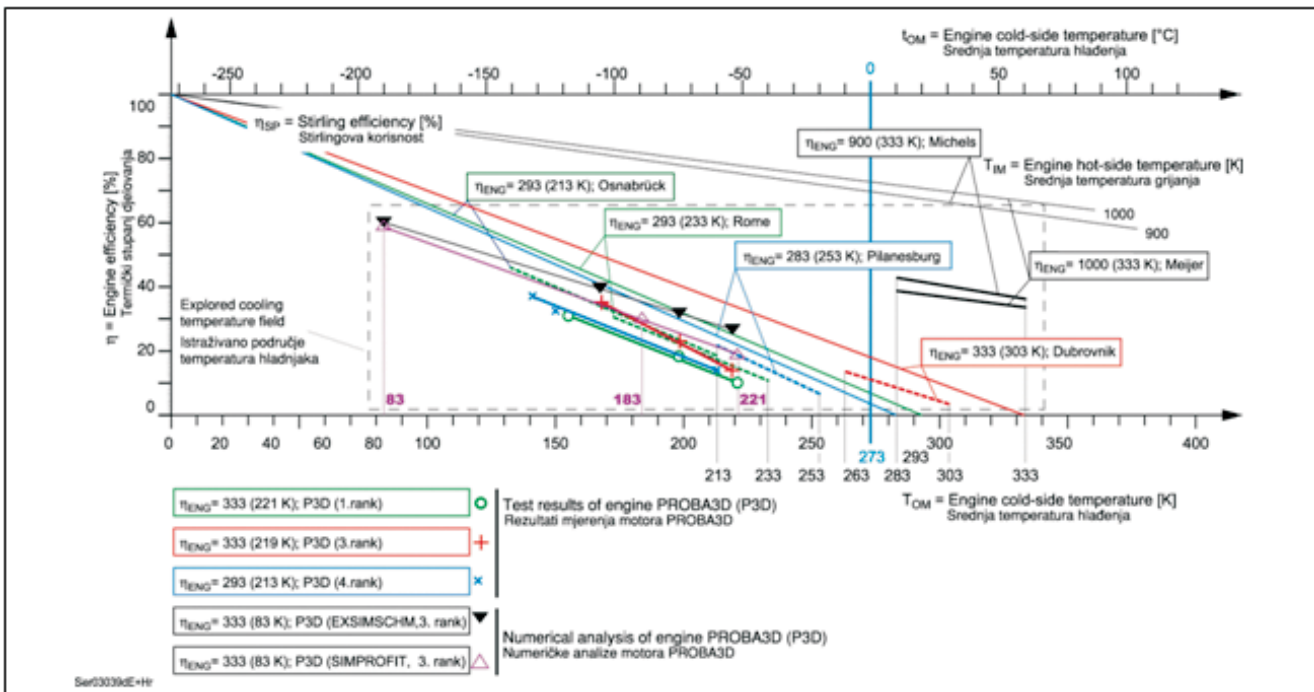


Figure 13 Results of experimental measurements and numerical simulations in presented Stirling engines [1]  
 Slika 13 Rezultati mjerenja i numeričkih analiza svih u radu promatranih Stirlingovih motora [1]

Figure 13 presents all published experimental results:  
 - for three classical Stirling engines PROBA1, PROBA2 and PROBA2B (former research),  
 - for experimental engine PROBA3D, and  
 - for the before mentioned published results of numerical simulations of the first, second and third order of the presented engines.  
 For the sake of comparison, the measured efficiency values for classical Stirling engines from two foreign publications are presented here too [14].

Na slici 13 vide se svi rezultati obavljenih ispitivanja:  
 - za tri promatrana klasična Stirlingova motora PROBA1, PROBA2 i PROBA2B (prethodna ispitivanja),  
 - za eksperimentalni NKS-motor PROBA3D i  
 - za prije spomenute obavljene numeričke analize, prvog, drugog i trećeg reda tih motora.  
 Usporedbe radi su i ovdje pokazane mjerene korisnosti klasičnih Stirlingovih motora iz dva strana izvora [14].

As already noticed, from Figure 13 the following can be seen:

- Mutual agreement of the increase and character of the measured engine efficiencies of all engines in research,
- The essential influence of Carnot's efficiency, together with parameters determining it, is confirmed, and
- Carnot's sentence on the convenient influence of the lower engine temperature range compared to the higher engine temperature range is confirmed.

Based on these facts, it can be summarised that the results of experiments performed on all the here presented Stirling engines indicate the possibilities for the improvement of the efficiency and design features of NSC-engines (protected by pending patents [18 to 25]) through:

- a) Enabling lower energy consumption (through better engine efficiency by performing better process cycle),
- b) Increase of engine power (by performing better process cycle),
- c) Enabling simpler and adapted engine design (through innovations),
- d) Lower ecological impact of the new NSC-engines when compared to the internal combustion engines. This will apply even better by using hydrogen, solar energy or waste heat/ waste cold.

## 5 Methods applied in numerical analysis of the NSC-process cycles

In presented research four methods were applied for numerical analysis and calculations of Stirling engine process cycles. These are models of the first, second and third order.

The goal of these methods is to achieve adequate models for numerical simulations of the engine cycle parameters. Obtained results have to be validated by comparing the results with the measured data from engine tests. Such validated numerical models could be used for further numerical simulations of the selected Stirling engine or other similar engines.

Servis [1] has presented originally developed and applied three methods of numerical analysis:

- analysis of the zeroed order ("Elementary analysis", used for idealised process cycles of the engines),
- analysis of the first order ("Schmidt's isothermal analysis", used for the analysis of the real engine processes cycles), and
- analysis of the third order by Medica and Richard (developed specially for Stirling engines of the PROFITQ type, used for the analysis of the real engine process cycle).

In the framework of the research, developed was also "General mathematical model of NSC-engine" by Medica and Servis [1]. It will be the basis for the development of the numerical analysis of the third order used for the analysis of all three Stirling engine types based on the NSC-concept.

The very good agreement between measured and numerically derived efficiencies (and other parameters) of the engines in research, presented in Figure 13, could be even more improved or matched by comparing data with the measured values.

## 6 Application possibilities of the New Stirling Engine Concept (NSC-concept)

From the presented data the following could be concluded regarding the engines based on the NSC-concept:

Iz slike 13 vidi se već prije zapaženo:

- Međusobno podudaranje rasta i karaktera mjerenih korisnosti svih promatranih motora;
- Potvrđuje se bitan utjecaj pripadajućih Carnotovih korisnosti odnosno parametara koji ih tvore i
- Potvrđuje se valjanost Carnotove izjave o povoljnom utjecaju niže u odnosu na višu razinu temperaturnoga područja rada motora.

Na osnovi toga može se zaključno ustvrditi da rezultati objavljenih mjerenja svih Stirlingovih motora u radu, rezultati analiza njihovih idealiziranih kružnih procesa, uočene mogućnosti poboljšanja tih procesa kao i izvedbe izotermalnih motora formuliranih "NKS-konceptom" i zaštićenih patentnim prijavama za predviđene i pokazane izvedbe NKS-motora [18 do 25]:

- a) omogućavaju štednju pogonske energije (zbog postizanja viših korisnosti),
- b) povećavaju iznos proizvedenog rada motorom (zbog korištenja boljeg procesa),
- c) omogućavaju jednostavniju i pogodniju konstrukciju motora (zbog inovativnih mjera) i
- d) da će ti motori pri radu, kroz korištenje NKS-koncepta, uzrokovati manje zagađenje okoliša od toplinskih motora u današnjoj uporabi. Pri korištenju vodika, sunčeve energije ili otpadne topline kao izvora topline ti motori ne zagađuju okolinu.

## 5. Korištene metode numeričkih analiza NKS-procesa

U današnjoj se praksi upotrebljavaju četiri metode numeričke analize i proračuna kružnoga procesa Stirlingova motora; to su analize nultoga, prvog, drugog i trećeg reda.

Cilj tih metoda analiza je dobivanje podobnog analitičkog rješenja za procesne parametre promatranog motora. Takvo rješenje se onda uspoređuje s mjerenjima motora na probnom stolu (validiranje) da bi se na kraju dobila mogućnost kvalitetnog, isključivo numeričkog proračuna i simulacije rada promatranoga Stirlingova motora. Jednom verificirani, ti modeli olakšavaju razvoj novih inačica ispitivanih motora.

U radu Servisa [1] razvijene su i korištene tri metode numeričke analize, to su:

- analiza nultog reda (elementarna analiza, kojom se analiziraju idealizirani kružni procesi promatranih motora),
- analiza prvog reda (Schmidtova izotermalna analiza, kojom se analiziraju stvarni kružni procesi promatranih motora) i
- analiza trećeg reda po Medici i Richardu (razvijena posebno za Stirlingove motore tipa PROFITQ, kojom se analiziraju stvarni kružni procesi promatranih motora).

Osim toga u okviru rada razvijen je opći matematički model NKS-motora, po Medici i Servisu [1], koji će biti podloga za definitivni razvoj numeričke analize trećeg reda za modeliranje sva tri tipa Stirlingovih motora po Novom konceptu.

Vrlo dobro podudaranje mjerenih korisnosti i analiza utvrđenih korisnosti (i drugih parametara) promatranih motora, pokazanih slikom 13, može se odgovarajućim mjerama tijekom validiranja programa analiza još bolje uskladiti odnosno po potrebi poboljšati.

## 6. Mogućnosti primjene "Novoga koncepta Stirlingovih motora (NKS-koncepta)"

Iz dosadašnjih izlaganja može se uočiti sljedeće o motorima po NKS-konceptu:

- Application of the direct heat addition to and removal from the engine cycle;
- Carnotising of the engine cycle was achieved through the application of the heat regenerator (e.g. of the needle brush type [1]);
- Application of a hybrid displacer. Displacing of the working fluid between the hot and cold part of the engine cylinder is performed by the electronically controlled, hybrid driven displacer or by the developed hybrid “dynamic displacer”;
- Transmission of the work done to piston by pressure forces to crankshaft is performed through the normal cranking mechanism with a crosshead and flywheel;
- Engines are fully described (and protected) by 8 international patents [18 to 25].

Typical engine heater and cooler temperatures in NSC-engines are presented in Figure 14. They are:

a) for the engine heater temperatures range from ambient temperature to high temperatures of combustion (or for concentrated solar radiation) at  $\sim 10^3$  K.

b) for the engine cooler temperatures are in the range from ambient temperature to deep cryogenic temperatures of  $\sim 10^1$  K.

- Dovođenje i odvođenje topline od procesa motora izvodi se izravno.
- Obvezno karnotiziranje motora izvodi se tako da oni imaju regenerator (npr. igličasti regenerator [1]).
- Korišten je hibridni istiskivač (istiskivanje radnog medija tijekom procesa u motoru izvodi se elektronički nadziranom hibridnim pogonom istiskivača ili s u radu razvijenim hibridnim “dinamičkim istiskivačem” [1]).
- Prijenos rada od radnoga stapa na koljenasto vratilo motora izvodi se pomoću klasičnoga stapnog mehanizma s križnom glavom i zamašnjakom.
- Motori su opisani (i zaštićeni) s 8 internacionalnih patentnih prijava [18 do 25].

Tipične temperature zagrijača i hladnjaka motora po NKS-konceptu pokazane su na slici 14; one se kreću:

a) za dovođenje topline: od temperature okoliša pa do visokih temperatura pri izgaranju radnog medija (ili npr. koncentrirano solarno grijanje) u području  $\sim 10^3$  K.

b) za odvođenje topline: od temperature okoliša pa do dubokih kriogeničkih temperatura u području  $\sim 10^1$  K.

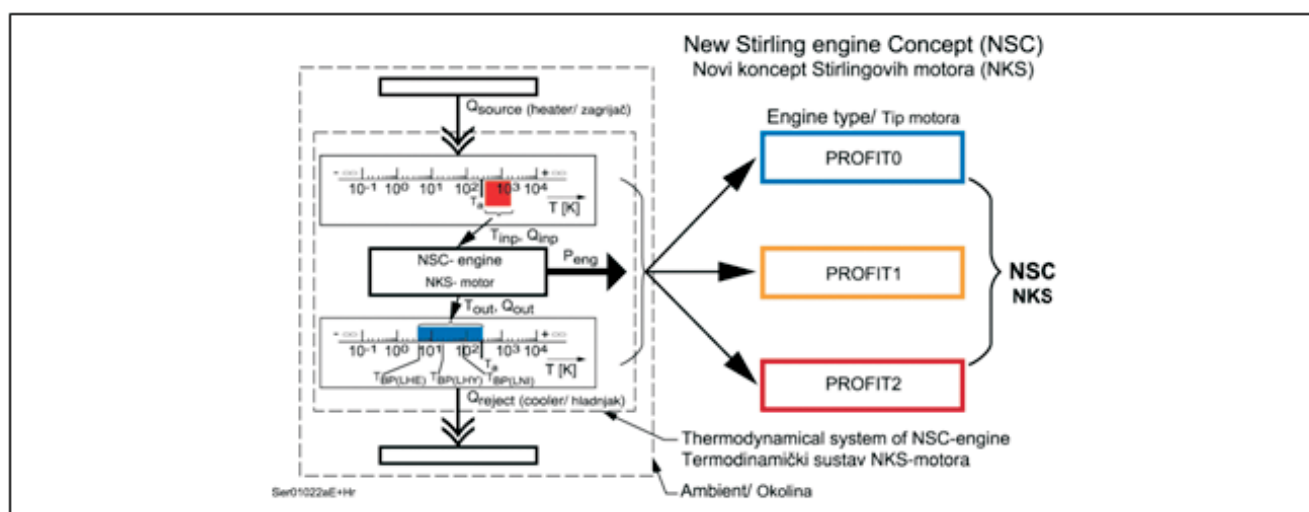


Figure 14 Typical temperatures of heaters and coolers of the New Stirling Engine Concept based engines (NSC-Engines) [1]  
Slika 14 Tipične temperature zagrijača i hladnjaka Stirlingovih motora po Novom konceptu (NKS-motor) [1]

## 6.1 PROFIT<sub>0</sub> type cycles of NSC-engines

This cycle process is based on the “idealised classical Stirling process cycle” (closed cycle consisting of isothermal compression, isochoric heat addition, isothermal expansion and isochoric heat removal of the working fluid and with the above cited characteristics of the NSC-concept).

Direct heat addition in these engines is achieved by special high- or low-temperature heaters in the engine cylinder or by catalytic fuel combustion, solar heating etc.

Direct cooling of the working fluid during isothermal compression (or heat removal from engine cycle) is performed using the in-cylinder cooler, cooled by some cooling fluid. It is important to point out here that the working fluid and the cooling fluid are not in direct contact, so they do not mix together. This is favourable when some aggressive cooling fluids are applied.

## 6.1. Kružni procesi NKS-motora tipa PROFIT<sub>0</sub>

Taj proces odvija se po “idealiziranom klasičnom Stirlingovom procesu” (zatvoreni sustav s izotermnom kompresijom, izohornim grijanjem, izotermnom ekspanzijom i izohornim hlađenjem uvijek istog radnog medija i uz to s gore navedenim značajkama NKS-koncepta).

Izravno dovođenje topline tih motora izvodi se sa posebnim visoko- ili nisko-temperaturnim zagrijačima u motoru (npr. katalitičko izgaranje goriva, solarno grijanje, itd.).

Izravno hlađenje radnog medija, tijekom izotermne kompresije (odvođenje topline od procesa motora), izvodi se s hladnjakom hlađenim nekim medijem. Pritom je ovdje važno istaknuti da se radni medij i rashladni medij toga tipa motora međusobno ne miješaju, što ima veliku prednost pri korištenju eksergije agresivnih (ili opasnih npr. O<sub>2</sub>) pothlađenih medija.

## 6.2 PROFIT<sub>1</sub> type cycles of NSC-engines

This engine cycle is performed as an “idealized NSC-process cycle” (open engine process, presented in Figure 11, with isothermal compression, isochoric and isobaric heat addition, isothermal expansion and isochoric heat removal of the injected and additionally evaporated liquid working fluid and with the above cited characteristics of the NSC-concept.

Direct heat addition in the engine cycle (heating) is performed similarly as in the engines of the PROFIT<sub>0</sub> type (e.g. with high temperature solar heating, high temperature catalytic combustion heating etc.).

Direct cooling of the working fluid during the isothermal compression (heat removal) is performed by injection and evaporation of the liquefied working fluid in the engine cylinder (combustible or non combustible).

The excess of the working fluid is exhausted from the engine during the isochoric heat removal part at the end of each engine process cycle.

## 6.3 PROFIT<sub>2</sub> type cycles of NSC-engines

This engine cycle is performed as an “idealized NSC-process cycle” (open engine process, presented in Figure 11, with isothermal compression, isochoric and isobaric heat addition, isothermal expansion and isochoric heat removal of the injected and additionally evaporated liquid working fluid and with the above cited characteristics of the NSC-concept.

Direct cooling in the engine cycle is performed (like in the PROFIT<sub>1</sub> engine cycle) by direct injection and evaporation of the liquefied and combustible working fluid in the engine cylinder.

The direct heat addition to the NSC-process of these engines will be performed in the way that the injected, evaporated and compressed combustible working fluid is combusted through controlled liquid oxygen injection.

The excess of the working fluid is exhausted from the engine during the isochoric heat removal part at the end of each engine process cycle.

The here presented idealised NSC-process cycles (as presented in Figures 7 and 11), are due to their isothermal compression and expansion parts better than those of modern diesel engines (Sabathé) and are also for the identical temperature range the best among the actually used heat engines.

The efficiency and power of the real NSC-process cycle in engines of the PROFIT<sub>1</sub> and PROFIT<sub>2</sub> types will be improved due to the increased mass of the working fluid, which is injected in the engine cylinder during the engine cycle.

## 7 Description of the NSC-engines of PROFIT<sub>1</sub> type

Based on the above-presented performances, by applying the animations (in property of Servis), Figure 15, it is possible to present and describe the general example of the NSC-engine of the PROFIT<sub>1</sub> type (single acting/ multiphase/ non-resonant/ BETA (CR+CH+DHI/O+P+R+I)/ rigid [26]).

In Figure 15 it can be seen that the engine consists of:

1) the base engine, here with a crosshead and a cranking mechanism, and

## 6.2. Kružni procesi NKS-motora tipa PROFIT<sub>1</sub>

Taj kružni proces odvija se po “idealiziranom NKS-procesu” (otvoreni sustav, slika 11, s izotermnom kompresijom, izohornim grijanjem, izobarnim grijanjem, izotermnom ekspanzijom i izohornim hlađenjem uvijek iznova dovedenog (ubrizganog) radnog medija i uz to s gore navedenim značajkama NKS-koncepta).

Izravno dovođenje topline (grijanje) u proces tih motora izvodi se na slični način kao i kod PROFIT<sub>0</sub> motora (npr. sa solarnim visoko-temperaturnim zagrijačima, katalitičkim visoko-temperaturnim zagrijačima itd.).

Izravno hlađenje radnog medija, tijekom izotermne kompresije (odvođenje topline od procesa motora), postiže se ubrizgavanjem i isparavanjem ukapljenog (zapaljivog ili ne zapaljivog) radnog medija u motoru.

Višak radnog medija se na kraju svakoga kružnog procesa ispušta iz motora.

## 6.3. Kružni procesi NKS-motora tipa PROFIT<sub>2</sub>

Taj kružni proces odvija se po “idealiziranom NKS-procesu” (otvoreni sustav, slika 11, s izotermnom kompresijom, izohornim grijanjem, izobarnim grijanjem, izotermnom ekspanzijom i izohornim hlađenjem uvijek iznova dovedenog (ubrizganog) radnog medija i uz to s gore navedenim značajkama NKS-koncepta).

Izravno odvođenje topline od procesa motora postiže se ubrizgavanjem i isparavanjem ukapljenog, ali ovdje zapaljivog, radnog medija u prostor motora (kao i kod PROFIT<sub>1</sub> procesa).

Izravno dovođenje topline u proces tih motora postiže se tako, da se tijekom prvoga takta kružnoga procesa ukapljeni, zapaljivi radni medij nakon ubrizgavanja, isparavanja i izotermne kompresije u cilindru motora s izohornim dovođenjem topline zagrijava do temperature zapaljenja i zatim, pretežito tijekom drugoga takta, s nadziranom ubrizgavanjem ukapljenoga kisika dovodi do izgaranja (izohorno + izobarno dovođenje topline), iza čega slijedi izotermna ekspanzija i izohorno odvođenje topline. Višak radnog medija na kraju svakoga kružnog procesa ispušta se iz motora.

Ovdje opisani idealizirani NKS-procesi su, kako se na slikama 7 i 11 pokazalo, već zbog svog izotermalnog dijela procesa termodinamički povoljniji od suvremenih Diesellovih (dizelski, Sabathé), odnosno uz iste uvjete najpovoljniji.

Korisnosti i proizvedeni rad stvarnog NKS-procesa motora tipa PROFIT<sub>1</sub> i PROFIT<sub>2</sub> će zbog povećanja mase radnog medija, koja ubrizgavanjem ulazi u kružni proces motora, biti dodatno poboljšani.

## 7. Opis NKS-motora konfiguracije tipa PROFIT<sub>1</sub>

Na osnovi gore navedenih svojstava se korištenjem animacije (u vlasništvu Servisa, na engleskom), slika 15, može zorno pokazati i ukratko opisati opći primjer izvedbe jednog NKS-motora, koji je konfiguracije tipa PROFIT<sub>1</sub> (jednoradni/ višefazni/ nerezonantni/ BETA (CR+CH+DHI/O+P+R+I)/ kruti prijenos s klasičnim stapnim mehanizmom).

Iz slike 15 vidi se, da se NKS-motor sastoji od:

1) osnove motora (*Base Engine*, ovdje s križnom glavom i sa stapnim mehanizmom) i

2) the additional part to engine, called the PROFIT<sub>1</sub>-device, enabling the NSC-process cycle to be performed in the engine.

The PROFIT<sub>1</sub>-device consists of a casing with an exhaust valve and exhausts system, a dynamic displacer, an engine heater (catalytic combustor) with the fuel and oxidiser input and exhaust system, a heat regenerator (here of needle brush type). The working fluid may be here of combustible or non-combustible type.

Figure 16 presents the catalytic combustor for gaseous fuel in commercially available execution for surface temperatures up to approx. 1500 K.

Figures 17, 18 and 19 present the PROFIT<sub>1</sub> engine type during the idealised NSC-process cycle (presented in Figure 11) in the following positions of the working piston:

- Figure 17: at the start of injection of the liquefied working fluid in the cylinder of the PROFIT<sub>1</sub>-device engine,
- Figure 18: at the end of the isothermal compression and start of the isochoric heat addition,
- Figure 19: at the end of the isobaric heat addition and start of the isothermal expansion of the working fluid.

At the end of the second stroke the excess of the working fluid is exhausted from the engine cylinder through the exhaust valve.

2) dogradnje motora, koja se u ovom slučaju naziva "PROFIT<sub>1</sub>-uređaj" a s kojim se omogućava izvođenje NKS-procesa u motoru.

PROFIT<sub>1</sub>-uređaj tvoren je od: kućišta s ispušnim ventilom i sustavom za odvođenje radnog medija (ispuh), dinamičkog istiskivača, zagrijača (npr. katalitičkoga) sa sustavom za dovod gorivoga plina i oksidanta i za odvod produkta oksidacije, regeneratora (ovdje u igličastoj izvedbi) i uređaja za ubrizgavanje ukapljenog radnog medija (koji za taj tip konfiguracije može ali ne mora biti sagoriv).

Na slici 16 vidi se katalitički plinski zagrijač, koji komercijalno izveden može aktualno postizati radnu temperaturu usijane površine od oko 1500 K.

Na slikama 17, 18 i 19 vidi se gore pokazani NKS-motor konfiguracije tipa PROFIT<sub>1</sub> tijekom rada po idealiziranom NKS-procesu (pokazanom slikom 11) u pozicijama radnoga stapa;

- slika 17: na početku ubrizgavanja ukapljenog radnog medija u prostor PROFIT<sub>1</sub>-uređaja motora,
- slika 18: na kraju izotermne kompresije i početku izohornog dovođenja topline tijekom prvoga takta kružnoga procesa,
- slika 19: na kraju izobarnog dovođenja topline i početku izotermne ekspanzije radnog medija u motoru tijekom drugoga takta.

Na kraju drugoga takta se otvaranjem ispušnog ventila ispuhuje radni medij iz prostora motora.

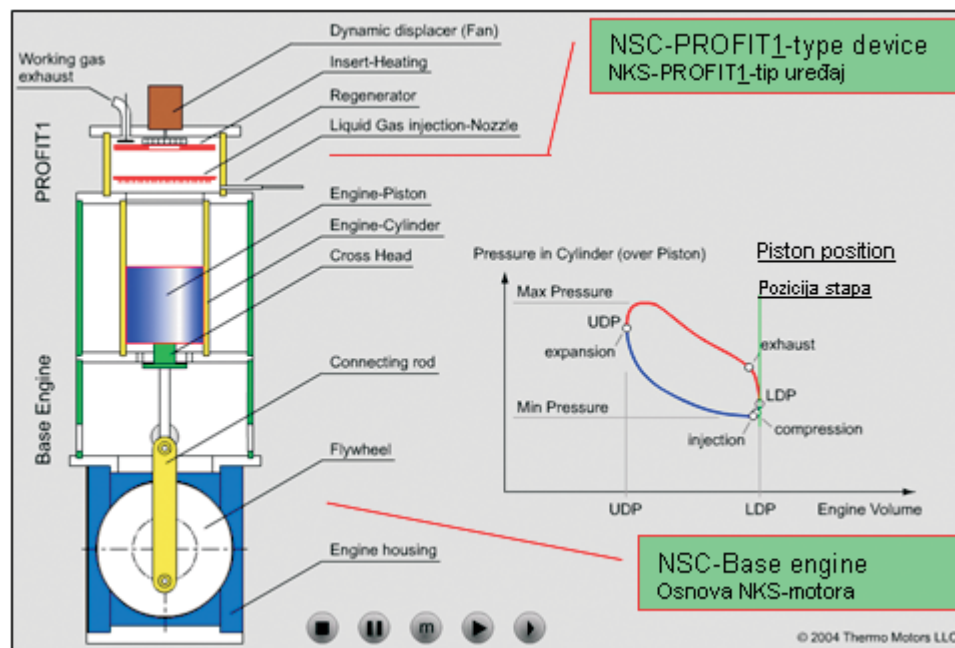
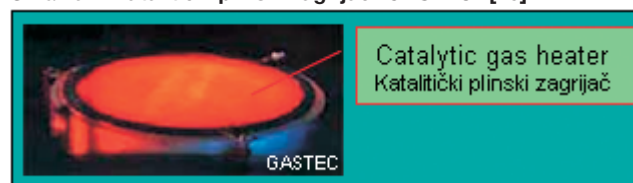


Figure 15 Components of the NSC-engine type PROFIT<sub>1</sub> with the working piston at lower dead point (LDP). Exhaust valve is open [26]  
Slika 15 Komponente NKS-motora tipa PROFIT<sub>1</sub> s radnim stapom u donjoj mrtvoj točki (LDP). Ispušni ventil je otvoren [26]

Figure 16 Catalytic combustor for gaseous fuel "GASTEC" [26]  
Slika 16 Katalitički plinski zagrijač "GASTEC" [26]





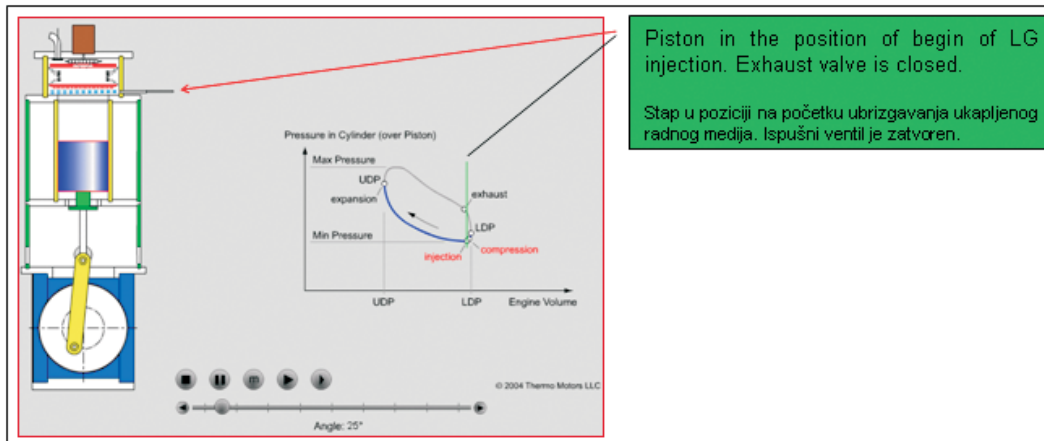


Figure 17 NSC-engine of configuration type PROFIT1 with the working piston at the start of working fluid injection (25 deg of crankshaft after LDP) [26]

Slika 17 NKS-motor konfiguracije tipa PROFIT1 s radnim stapom u poziciji na početku ubrizgavanja ukapljenog radnog medija (25° kolj. vratila poslije LDP) [26]

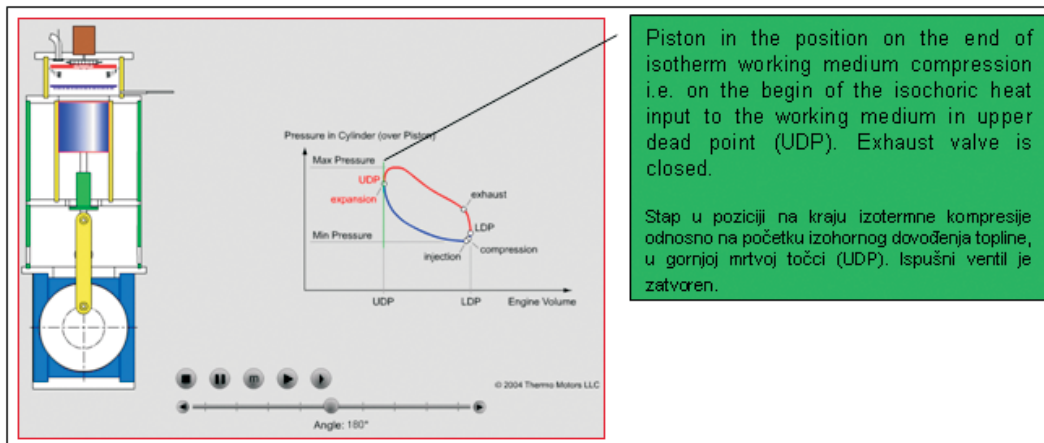
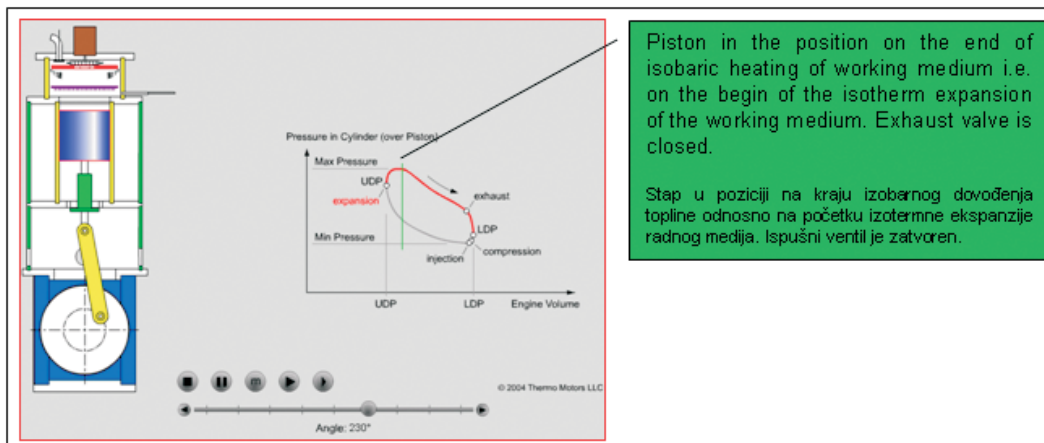


Figure 18 NSC-engine of configuration type PROFIT1 with the working piston at the end of the compression stroke (UDP) [26]

Slika 18 NKS-motor konfiguracije tipa PROFIT1 s radnim stapom u poziciji na kraju kompresije radnog medija u gornjoj mrtvoj točki (UDP) [26]

Figure 19 NSC-engine of configuration type PROFIT1 with the working piston at the end of the isobaric heat addition (50 deg of crankshaft after UDP) [26]

Slika 19 NKS-motor konfiguracije tipa PROFIT1 s radnim stapom u poziciji na kraju izobarnog dovođenja topline (50° kolj. vratila poslije UDP) [26]



NSC-Engines of the PROFIT<sub>2</sub> type have the PROFIT-device, as described previously (see chapter 6.3).

## 8 Some possible applications of the NSC-engines of the PROFIT<sub>1</sub> type

Already during the stage of performing the analyses and experiments of the engines (which were later named NSC-engines based on NSC-concept) the possibilities for their practically unbound applications were evident.

Here, some of the most interesting aspects and application possibilities of the PROFIT<sub>1</sub> type NSC-engines are presented in Figures 20 to 22 in the form of plant schematic drawing.

NSC-Engines, as presented in Figure 20, by schematic drawing of the plant, apply the exergy of liquefied gases in LNG pipeline terminals for direct cooling by liquid gas injection during the engine cycle (LNG=Liquid Natural Gas). For direct heat addition to the working fluid, catalytic combustor is placed in the engine cylinder (small part of combustible gas + air). Excess of the evaporated natural gas (bigger part of it) is exhausted directly to the gas distribution pipeline (under pressure).

Engines of such design may be used also for propulsion of LNG-tankers, where the gas provided for evaporative cooling may be combusted completely on catalytic combustor in the engine.

Engines of such design are able to reach the maximum power in the MW range (see Figure 23) in the design based on the existing large slow speed two-stroke diesel engines.

NSC-Engines, as presented in Figure 21, by schematic drawing of the plant, use injected water (H<sub>2</sub>O) as the working and cooling fluid for direct cooling during the engine process. For direct heat addition, a catalytic combustor using combustible gas (e.g. natural gas, hydrogen etc.), which may be stored in the liquid phase, is applied.

Such engines may be also applied for LNG tanker propulsion, where the evaporated gas is used as fuel gas.

Engines in such design are provided for small, medium or high power range (see Figure 23). Their design is also based on the existing diesel engines of the same power range.

NKS-motori konfiguracije tipa PROFIT<sub>2</sub> imaju PROFIT-uređaj opisan u poglavlju 6.3., koji ovdje neće biti iscrpnije razmatran.

## 8. Neke moguće primjene NKS-motora konfiguracije tipa PROFIT<sub>1</sub>

Već tijekom analiza i obrade eksperimentalnih ispitivanja uočena su svojstva motora (kasnije nazvanih NKS-motora po NKS-konceptu) ukazala na praktički neograničene mogućnosti i prednosti njihove primjene.

Ovdje će se, ukratko, skicirati neke zanimljive aspekte i mogućnosti primjene NKS-motora tipa PROFIT<sub>1</sub>, koji će biti pokazani u vidu shema postrojenja, slike 20 do 22.

NKS-motori pokazani shemom na slici 20 koriste eksergiju ukapljenih plinova u terminalima plinovoda zemnoga plina (LNG) za izravno hlađenje ubrizgavanjem tijekom procesa u motoru (LNG=Liquid Natural Gas=ukapljeni zemni plin). Za izravno dovođenje topline u motor, s katalitičkim zagrijačem (gorivi radni medij + zrak), koristi se jedan (mali) dio isparenog radnog medija (NG = Natural Gas=zemni plin). Preostali (veći) dio isparenog radnog medija (NG) ispušta se pod tlakom (koji je podesiv po potrebi) iz motora izravno u plinovod, pa tu kompresor nije potreban.

Tako izvedeni motori mogu se koristiti i za pogon LNG-tankera, u kojem slučaju se za hlađenje korišteni plin nakon isparavanja potpuno sagorijeva u katalitičkom zagrijaču.

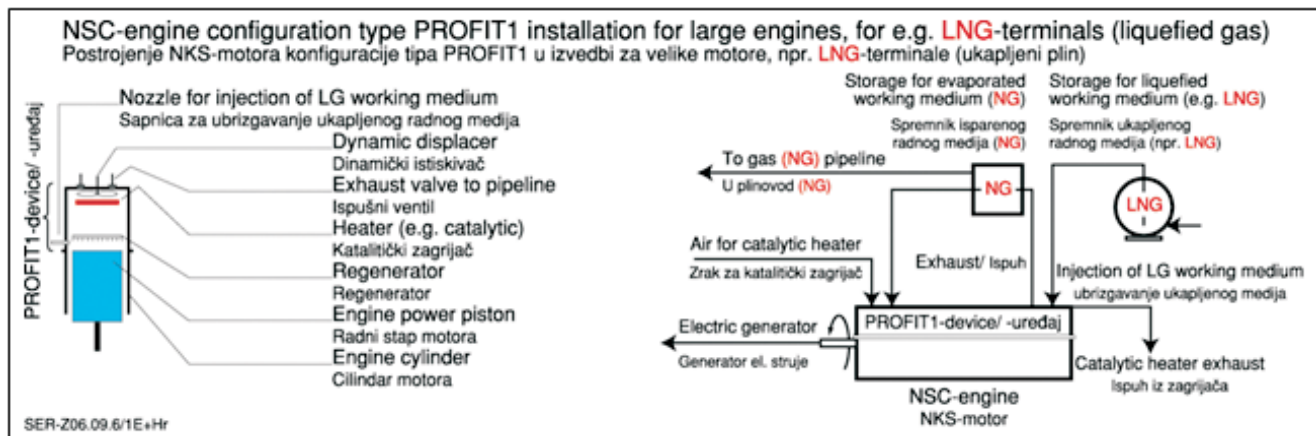
Motori u toj izvedbi predviđeni su za najveće snage (u gornjem MW-području snaga, vidi sliku 23), a izvode se na osnovama motora preuzetih od dizelskih motora toga područja snaga.

NKS-motori pokazani shemom na slici 21 koriste vodu (H<sub>2</sub>O) kao radni medij, s ubrizgavanjem koje se izvodi izravno hlađenjem tijekom procesa u motoru. Za izravno dovođenje topline u motor s katalitičkim zagrijačem koristi se neki gorivi plin (npr. NG, vodik itd.) koji može biti pohranjen i u ukapljenom stanju u spremniku goriva.

I ovi motori mogu služiti za pogon LNG-tankera, pri čemu se koristi ispareni dio LNG-tereta.

Motori u toj izvedbi predviđeni su za male, srednje, pa do najviših snaga, a mogu se isto tako izvoditi na osnovama motora preuzetih od dizelskih motora toga područja snaga (vidi sliku 23).

Figure 20 Schematic presentation of NSC-engine plant in configuration type PROFIT<sub>1</sub> in LNG-terminal plant for large engines [26]  
Slika 20 Shematski prikaz postrojenja NKS-motora konfiguracije tipa PROFIT<sub>1</sub> u izvedbi za LNG-plinske terminale u izvedbi za velike motore [26]



NSC-Engines, as presented in Figure 22, by schematic drawing of the plant, use water for cooling in the same manner as in Figure 21, with the difference that the water for direct cooling is produced by condensed vapour from hydrogen combustion products on the catalytic combustor used for direct heat addition (liquid hydrogen + oxygen).

Engines of such design are provided for small and middle power range. They may be of special execution for permanent propulsion of submarines in surface and submerged drive (for the so called AIP=Air Independent Propulsion).

NKS-motori pokazani shemom na slici 22 koriste vodu za hlađenje na isti način kao i motori pokazani shemom na slici 21 (s razlikom da se voda za izravno hlađenje ovdje dobiva kondenziranjem produkta izgaranja vodika u katalitičkom zagrijaču). Za izravno dovođenje topline u motor s katalitičkim zagrijačem koriste se vodik i kisik, koji su pohranjeni u ukapljenom stanju.

Motori u toj izvedbi predviđeni su za male i srednje snage, oni mogu biti posebne izvedbe predviđene za stalni (jedinstveni) pogon podmornica na površini i u podvodnoj plovidbi (AIP=Air Independent Propulsion).

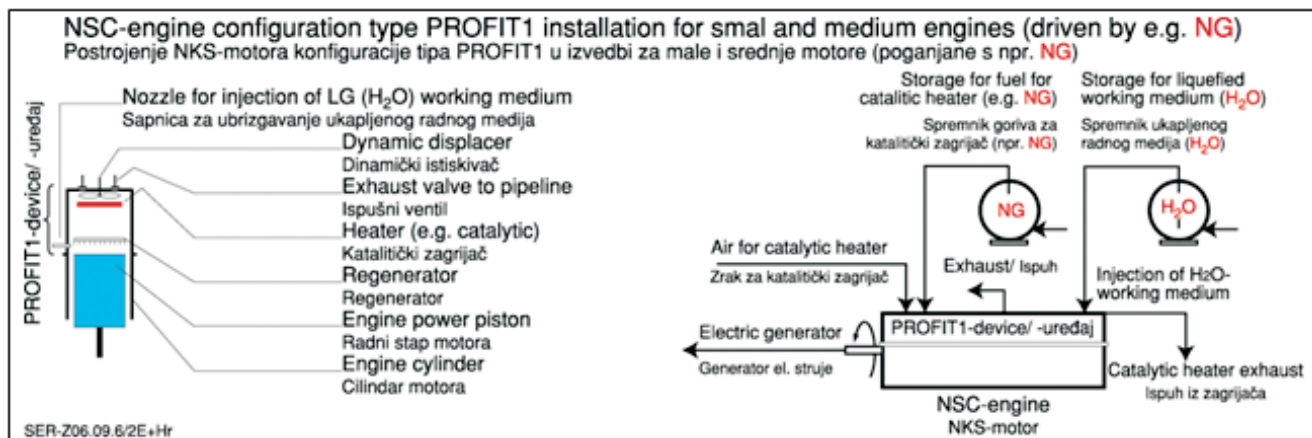


Figure 21 Schematic presentation of NSC-engine plant in configuration type PROFIT1 for small, medium and large engines [26]  
Slika 21 Shematski prikaz postrojenja NKS-motora konfiguracije tipa PROFIT1 u izvedbi za male, srednje i velike motore [26]

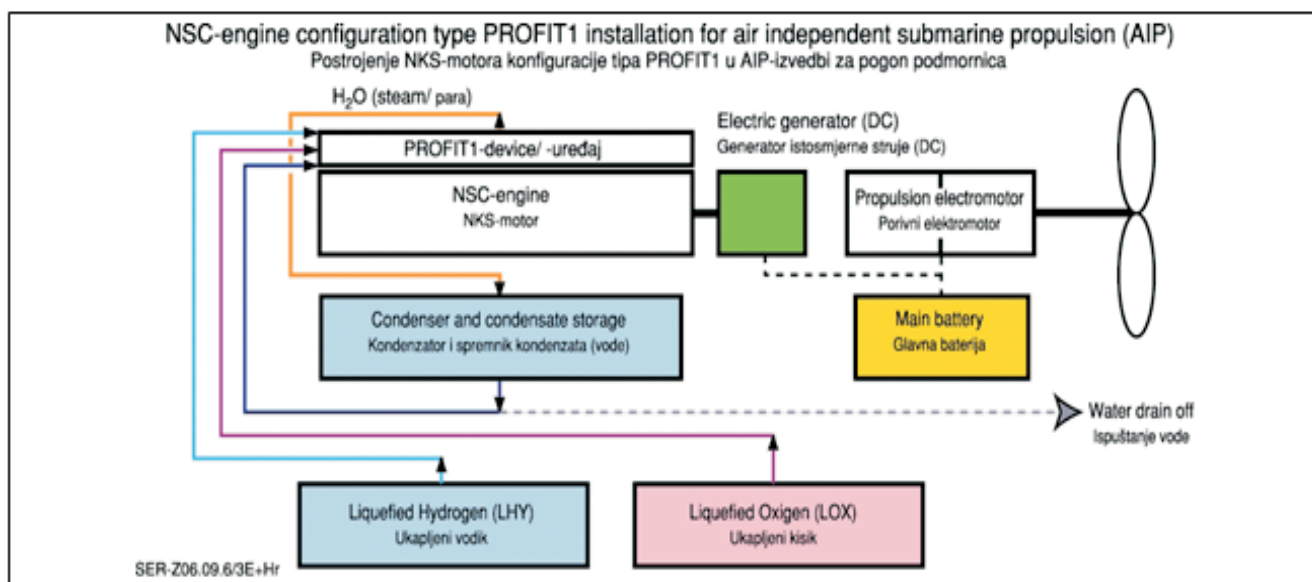


Figure 22 Schematic presentation of NSC-engine plant in configuration type PROFIT1 for air independent submarine propulsion (AIP) [26]  
Slika 22 Shematski prikaz postrojenja NKS-motora konfiguracije tipa PROFIT1 u izvedbi za pogon podmornica (AIP) [26]

### 8.1 Extrapolated power and efficiency of NSC-engines

Through the application of numerical simulations it was possible to get results (provisional) for the possible power and efficiency estimations for NSC-engines in PROFIT0, PROFIT1 and PROFIT2 configuration types.

### 8.1. Ekstrapolirane snage i korisnosti NKS-motora

Korištenjem numeričkih analiza bilo je moguće dobiti, za sada provizornu, procjenu snaga i korisnosti NKS-motora u izvedbama PROFIT0, PROFIT1 i PROFIT2.

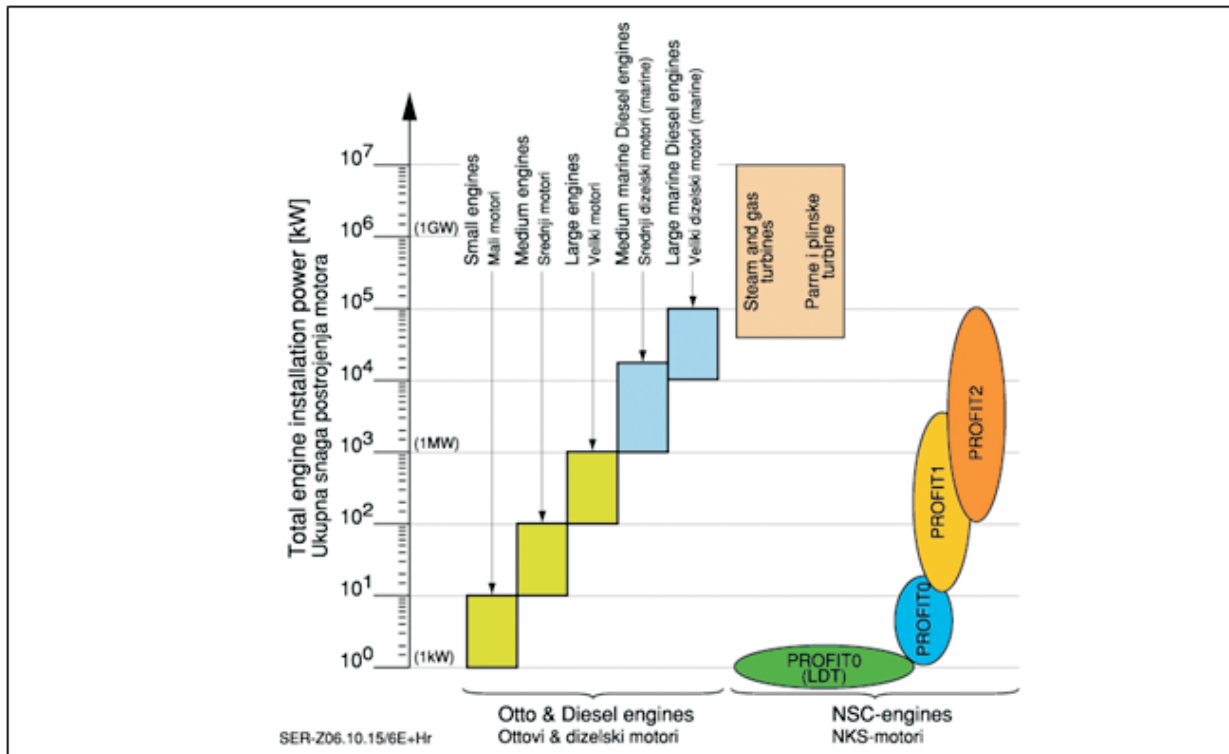


Figure 23 Estimation of the NSC-engine plant power and comparison with other thermal engines [26]  
 Slika 23 Procjena snaga postrojenja NKS-motora i usporedba s drugim toplinskim strojevima [26]

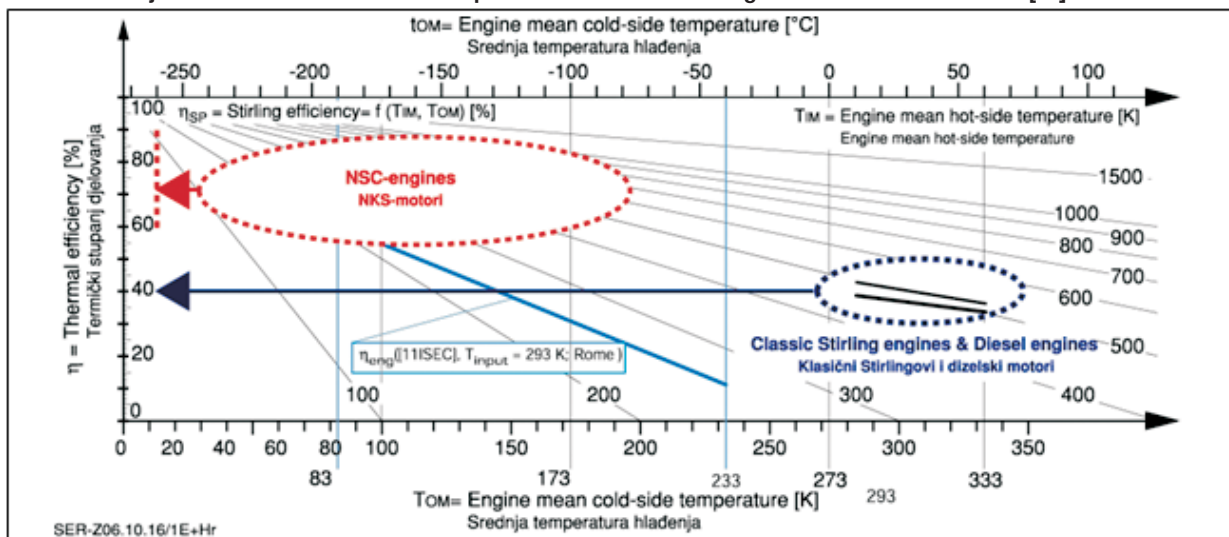
The Figure 23 presents the results of power estimation, where engine powers are the following ones:

- a) Design PROFIT<sub>0</sub> (low delta temperature, LDT) → up to approx. 1 kW
- b) Design PROFIT<sub>1</sub> → up to approx. 15 kW
- c) Design PROFIT<sub>1</sub> → up to approx. 5 MW
- d) Design PROFIT<sub>2</sub> → up to approx. 100 MW

Na slici 23 dani su rezultati numeričke procjene snaga NKS-motora:

- a) U izvedbi PROFIT<sub>0</sub> (niskotemperaturni, LDT) → do oko 1 kW
- b) U izvedbi PROFIT<sub>1</sub> → do oko 15 kW
- c) U izvedbi PROFIT<sub>1</sub> → do oko 5 MW
- d) U izvedbi PROFIT<sub>2</sub> → do oko 100 MW

Figure 24 Estimation of the NSC-Engine efficiency and comparison with classical Stirling and Diesel engines [26]  
 Slika 24 Procjena korisnosti NKS-motora i usporedba s klasičnim Stirlingovim i dizelskim motorima [26]



From these extrapolated values it is possible to see, that the NSC-engine, when compared with other thermal engines data, can cover a very broad range of all actually needed engines

Figure 24 presents the results for numerical estimation of NSC-engine efficiency, where it is evident that these engines with cryogenic heat removal can achieve process efficiency of up to approx. 80% in the case of PROFIT<sub>2</sub> design.

## 9 Conclusions

Based on the performed experiments and measured NSC-engine (here named as PROFIT<sub>0</sub>) operation parameters, and on the results of numerical simulations of PROFIT<sub>1</sub> and PROFIT<sub>2</sub> named engines, the following can be concluded:

1. By lowering the temperature of the heat removal, with the idealised NSC-engine process, essentially higher thermal efficiency is achieved at the same conditions in comparison with the classic Stirling engine process. This efficiency is for really possible operation of the NSC-engine higher than the efficiency of the idealised Diesel processes (Sabathé) or of other internal combustion engines.

2. Possible compression ratio increase, increase in process operation pressure, increase in process maximum temperature, direct heat introduction from the heater or heat removal to or from the working fluid in the engine cylinder space, application of a hybrid displacer and improved heat regenerating device are all contributing to the improvement of the thermal efficiency of the NSC-engine. The simplification of the engine kinematics (introduction of classic cranking mechanism) enables the introduction of further improvements and lowers the price of the NSC-engine.

3. Energy supply for the NSC-engines is possible from various available energy sources using not only heat, but also freeze (as for example in liquefied gases at LNG terminals and onboard ships for liquefied gas transport), at heat discharges (for example from thermal power plants, conventional or nuclear, from geothermal sources), from catalytic or other combustors, or from alternative energy sources (for example low- or high-concentrated solar light).

This is why the NSC-engines can be applied as basic or utilised drive engines for electric energy production or mechanical drive for ship or vehicle propulsion. Their operation is accompanied by very low or no emission of harmful gases, depending on the engine design and heat power source.

As NSC-engines can work without atmospheric air, when they do not need combustion as heat source, they are convenient for space applications with solar heating and heat removal by heat radiation into space with actually three-fold efficiency when compared with solar cells. They are also convenient for possible application in submarines.

4. The achieved results of R&D activities, presented in this paper, give a reliable basis for further development and application of NSC-engines aiming at rational use of energy resources and prevention of environment pollution for better future life on the Earth.

Iz tih ekstrapoliranih navoda se usporedbom s podacima za druge toplinske strojeve može vidjeti, da se za NKS-motore već u ovoj prvoj fazi razvoja vide mogućnosti pokrića svih potreba današnjih potrošača mehaničkog rada, kao i nove niše primjena tih motora.

Na slici 24 dani su rezultati numeričke procjene korisnosti NKS-motora, iz kojih se može vidjeti da će ti motori pri najpovoljnijim uvjetima rada (u izvedbi tipa PROFIT<sub>2</sub>, s kriogeničkim hlađenjem) moći postizati termičke korisnosti do vrijednosti od oko 80 posto (pritom se ne uzima u obzir i dodatna mogućnost korištenja otpadne topline postrojenja motora).

## 9. Zaključci

Na temelju provedenih pokusa i mjerenja parametara klasičnih Stirlingovih i NKS-motora PROBA3D (po NKS-konceptu u ovdje pokazanoj izvedbi tipa PROFIT<sub>0</sub>), te na osnovi rezultata numeričkih analiza procesa NKS-motora tipa PROFIT<sub>1</sub> i PROFIT<sub>2</sub> može se zaključiti:

1. Snižanjem temperature odvođenja topline postižu se (pod istim uvjetima) s idealiziranim NKS-procesom bitno veća termička korisnost i proizvedeni rad u usporedbi s idealiziranim klasičnim Stirlingovim procesom. Ta korisnost i proizvedeni rad su za realno moguće uvjete rada kod NKS-procesa bitno veći od korisnosti i rada idealiziranoga suvremenog dizelskog procesa (Sabathé/ Seiliger).

2. Na povećanje termičke korisnosti i količine rada NKS-procesa (i kao posljedica) i mjerene korisnosti i rada s po tom procesu izvedenim NKS-motorom, također povoljno utječu: mogućnost povećanja stupnja kompresije, mogućnost povišenja radnih tlakova tijekom procesa, mogućnost povišenja maksimalne temperature tijekom procesa, izravni način dovođenja odnosno odvođenja topline procesu motora, korištenje hibridnog istiskivača i korištenje poboljšanog regeneratora (igličastog regeneratora).

Pojednostavljenje kinematike motora, uvođenjem klasičnog motornog mehanizma, olakšava provedbu ostalih mjera i pojeftinjuje izvedbu NKS-motora.

3. Pogon NKS-motora moguće je ostvariti primjenom danas raspoloživih (i novih alternativnih) goriva, korištenjem izvora hladnoće sadržane u ukapljenim plinovima (npr. u LNG-terminalima i brodovima za prijevoz LNG-tereta), korištenjem otpadne topline velikih energetske sustava (npr. konvencionalnih ili nuklearnih elektrana, geotermičkih izvora topline), korištenjem katalitičkog ili izravnog izgaranja nekoga gorivog radnog medija (ovisno o tipu motora), ali i pomoću korištenja sunčeve energije (nisko ili visoko temperaturni kolektori).

Stoga se NKS-motori mogu primijeniti kao osnovni ili kao utilizacijski motori za proizvodnju električne struje ili mehaničkog rada za pogon brodova, automobila itd., tim prije što njihov rad ne prati uvijek emisija štetnih plinova (što ovisi i od tipa izvedbe motora odnosno od korištenog radnog medija ili goriva).

Kako NKS-motori mogu raditi i bez prisutnosti atmosferskog zraka, moguća je njihova vrlo pogodna primjena na svemirskim letjelicama ili svemirskim postajama (solarno grijanje/ kriogeničko hlađenje zračenjem topline u svemir) uz aktualno približno trostruko višu korisnost u usporedbi sa solarnim ćelijama, ali i osobito pogodna primjena na podmornicama (katalitičko grijanje vodikom/ hlađenje s kondenzatom).

4. Postignuti rezultati znanstvenih i razvojnih istraživanja pokazani ovim radom pružaju realnu osnovu za dalji razvoj i korištenje NKS-motora s ciljem racionalnoga korištenja energetske izvora i očuvanja ekoloških uvjeta za bolji život na Zemlji.

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