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Effects of the regenerator on engine performance of a rhombic drive beta type stirling engine

Fatih Aksoy [a], Hamit Solmaz [b], Muhammed Arslan [a], Emre Yılmaz [c,d], Duygu İpci [b], and Alper Calam [e]

[a]Automotive Technologies, Çay Vocational High School, Afyon Kocatepe University, Afyon, Turkey; [b]Faculty of Technology, Automotive Engineering Department, Gazi University, Ankara, Turkey; [c]Automotive Department, Sakarya University of Applied Sciences, Arifiye Vocational High School, Sakarya, Turkey; [d]Sakarya University of Applied Sciences Automotive Technologies Application and Research Center, Sakarya, Turkey; [e]Vocational Technical Sciences High School, Gazi University, Ankara, Turkey

ABSTRACT
Regenerative cycles have higher thermal efficiency than other closed cycles because of their heat recovery capability. In this manner, Stirling engines have advantage because regeneration can be applied easily to the cycle. In this study, effects of the regenerator on engine performance of a beta type Stirling were examined. Stainless steel wire, having 0.15 mm diameter and 15% solidity ratio, were used as regenerator material. Experiments were carried out at 800°C hot end temperature and the charge pressures for 3, 4, 5, 6 bar. Maximum power and torque of the engine were measured as 1831.09 W at 1035 rpm, and 19.74 Nm at 837 rpm for engine without regenerator while as 1940.45 W at 1046 rpm, and 20.55 Nm at 867 rpm for engine with regenerator, respectively. It was found that the use of regenerator, the engine power and engine torque increased by 5.97% and 4% respectively.

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KEYWORDS
Stirling engine; regenerator; engine power; engine torque

Introduction

In 1816, the Stirling engine concept, an engine heated externally, was first proposed by Robert Stirling with a patent application. Stirling engines have competed for a long time with internal combustion engines (Chen, Yang, and Salazar 2015). However, due to problems such as global warming and reduced reserves of fossil fuels, studies on the Stirling engine have accelerated (Chen and Ju 2013; Chen, Wong, and Chen 2014). Stirling engines operate by compressing and expanding working fluid such as air, helium, hydrogen for different temperature levels in a regenerative closed thermodynamic cycle (Babaelahi and Sayyadi 2015; Jokar and Tavakolpour-Saleh 2015). Stirling engines have high efficiency since they work with Stirling cycle similar to Carnot cycle. At the ideal Stirling cycle, two isothermal and two isochoric processes take place between maximum and minimum temperatures. The maximum temperature limit varies depending on the material from which the engine is manufactured (Shendage, Kedare, and Bapat 2011). The efficiency of engine can be affected by the thermal properties of the working fluid and the heat transfer coefficient, temperature difference between hot and cold ends, regenerator efficiency, mechanical connections, charge pressure, and sealing ratio (Ahmadi et al. 2015). The regenerator is used to store excess heat or to give heat to the system during the operation of Stirling engine and is placed between the heater and cooler. The working fluid is transferred from heater to cooler by passing through regenerator in the first half of cycle. At this moment, regenerator takes some of the heat of heated working fluid and stores it. The working fluid is

CONTACT Hamit Solmaz hsolmaz@gazi.edu.tr Faculty of Technology, Automotive Engineering Department, Gazi University, Ankara, Turkey

transferred from cooler to heater through regenerator in the second half of cycle. In this moment, cooled working fluid takes heat which is stored in regenerator. Therefore, the regenerator behaves as a thermal storage and minimizes the heat which must be taken from heater (Almajri, Mahmoud, and Al-dadah 2017). In accordance with the "idealized" conditions (Regenerator with efficient of %100 and isothermal processes in cooler and heater), the heat transferred at constant temperatures. So, the efficient of cycle becomes the same of Carnot cycle efficient (Meijer 1960). The Stirling engines are basically divided into three classes: α-type, type-type and γ-type that depend on the flow configuration of the working fluid and the compression-expansion volumes (Barreto and Canhoto 2017). Many studies such as engine types, drive mechanisms were done on Stirling engines.

Cheng and Yang conducted on a theoretical study to examine the effect of engine type on the shaft power. The highest shaft power was obtained from β-type Stirling engine and the lowest engine power was obtained with γ-type Stirling engine. Authors reported that the γ-type Stirling engine can operate with the lowest temperature difference between three different configurations (Cheng and Yang 2012). Çınar et al. produced a β-type single cylinder Stirling engine having a swept volume of 192 cm^3 and conducted the performance tests. For conducting the experiments, authors chosen the air as working fluid. They investigated engine performance for the hot temperatures of 800, 900, and 1000°C at charge pressures of 1, 1.5, 2, 2.5, and 3 bar. The experimental results showed that the highest engine power was 14 W at 344 rpm, 2.5 charge pressure, 1000°C hot end temperature (Çınar, Topgül, and Yücesu 2007). Sripakagorn and Srikam manufactured a β-type Stirling engine, having 100 W power and 165 cm^3 engine volume, with a medium temperature difference and performed performance tests. The experiments were carried out with parabolic corrugated collector using air at 350 and 500°C temperatures. As results of all experiments, the maximum engine power and thermal efficiency were measured as 95.4 W and 9.35% at 500°C, 7 bar pressure and 360 rpm engine speed (Sripakagorn and Srikam 2011). Çınar et al. tested a rhombic driven beta type Stirling engine with an LPG fuel heater. Experiments were carried out at 450 and 350°C for hot end temperature by using air and helium as working fluid. According to the test results, maximum torque and power of the engine were recorded as 95.77 W and 1.98 Nm for helium at 450°C hot end temperature and 2 bar charge pressure, respectively (Çınar, Aksoy, and Okur 2013). Ni et al. tested a beta type Stirling engine capable of producing 100 W power. Author were chosen the nitrogen and helium gases as working fluid. They implemented a series of experiment for engine speeds in a range of 260 to 1380 rpm and charge pressures in a range of 1.6 to 3 MPa. Maximum power and cycle efficient of the engine were obtained as 139 W and 12.2% for nitrogen and as 165 W and 16.5% for helium at 2.96 MPa charge pressure and 1120 rpm (Ni et al. 2016).

Most of the studies on Stirling regenerators are about the design of different matrix structures (Andersen, Carlsen, and Thomsen 2006; Dai et al. 2018) and their hydrodynamic and thermal analysis (Xiao et al. 2017). Experimental studies on Stirling regenerator performance are very few in the literature and numerical studies are the majority. One of the first experimental studies on regenerators was conducted by Tanaka et al in 1989. Tanaka et al. implemented an experimental study on examining the hydrodynamic and heat transfer characteristics of regenerator made with sintered metal, sponge metal, and wire netting. They carried out experiments under the oscillating flow condition to investigate heat transfer and flow characteristics of the engine. The authors presented empirical correlation equations for calculating friction factor and Nusselt number based on Reynolds number (Tanaka, Yamashita, and Chisaka 1989). In 1996, Gedeon and Wood carried out an experimentally comprehensive study of Stirling regenerator performance to publish a technical report for NASA. The authors derived Nusselt number and friction factor correlations for regenerators made with wire screen and felt (Gedeon and Wood 1996). Gheith et.al conducted on an experimental study to determined irregular temperature distributions on a regenerator due to the working conditions in the heating and cooling phases on the Stirling engine (Gheith, Aloui, and Nasrallah 2014). In another study by the authors, porosity and matrix material of the regenerator was optimized (Gheith, Aloui, and Ben Nasrallah 2015). Chen et. al. were proposed a regenerator capable of moving to improve the performance of a gamma type twin power piston Stirling engine. By using the proposed regenerator, the authors carried out experiments to understand the regenerator parameters such as regenerator matrix wire diameter, matrices arrangement, matrix material, and fill factor on the engine performance (Chen, Wong, and Chen 2014). Experimental studies examining the effect of regenerator properties on engine performance are rarely found in the literature. Numerical studies are performed by writing code with a new algorithm or by CFD analysis. Costa et al. developed numerical simulations to examine the heat transfer (Costa et al. 2014) and hydrodynamic (Costa et al. 2013) characteristics in regenerator made with woven wire matrix under the oscillating flow condition.

In this study, the effect of using of regenerator on engine performance of a rhombic drive beta type Stirling engine was investigated using helium as working fluid. Regenerator volume was 120 cm^3 and stainless steel wire, having 0.15 mm diameter and 15% solidity ratio, was used as regenerator material. The engine performance was investigated by testing at different charge pressures for both with and without regenerator.

Materials and methods

The rhombic driven beta type Stirling engine consists of the subsection, in which the drive mechanism is located, and the upper section, in which heating-cooling-regenerator sections are located. The engine structure is seen in Figure 1. The subsection of the engine consists of the engine block and covers, crankshafts, and bearings, helical gears, connecting rods, interconnecting elements, and flywheel. The top side of the engine includes a cooler and a power-cylinder, bottom part of the power-cylinder, an inner cylinder of the displacement, the top cylinder of the displacement, bottom cylinder of the displacement, the power-piston, and the displacer. To allow the working fluid to pass through the regenerator volume, a snap ring is placed bottom part of the displacer. The transfer of working fluid between the hot and cold volume was carried out through the regenerator volume located between the bottom cylinder of displacement and the top part of the power-cylinder. With parts made of aluminum material placed in this section, the volume of the regenerator was changed.

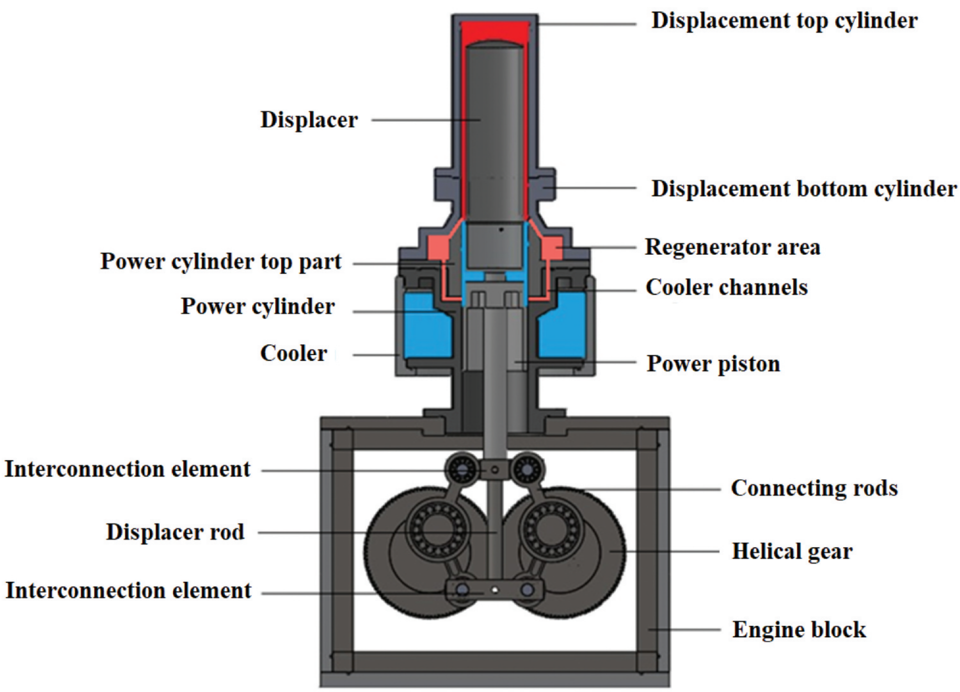

Figure 1. Schematic view of Stirling engine with regenerator.

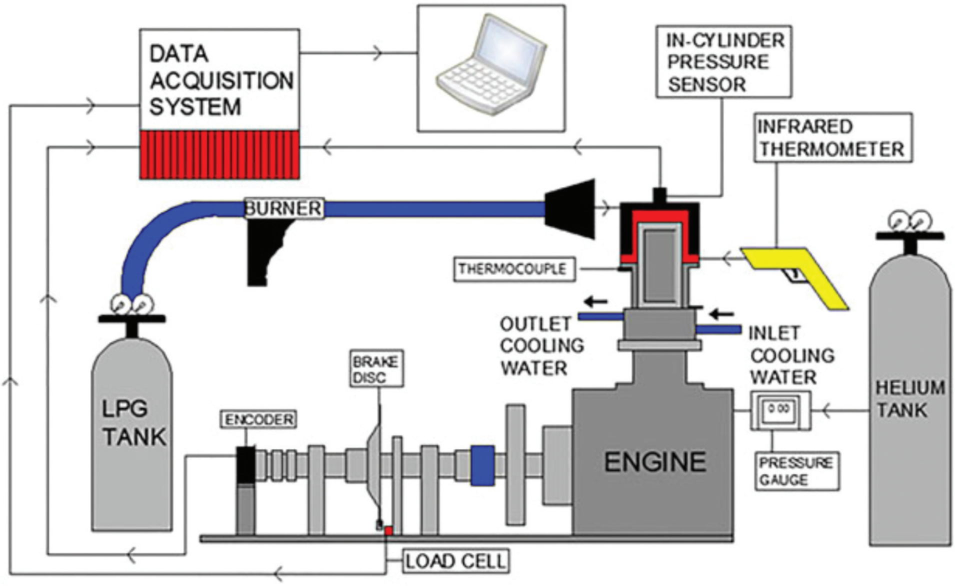

Figure 2. Test setup.

Table 1. Accuracy and uncertainty of the measurements.

Parameter	Accuracy	Uncertainty
Temperature	±1.5°C	-
Speed	±1 rpm	-
Engine Power	–	0.3–0.7%
Engine Torque	±0.05 kg (load cell)	±0.017 Nm

After the assembly of the engine parts and the mechanical problems were eliminated, engine performance tests were carried out using LPG fuel heater, prony type dynamometer, encoder, infrared thermometer, pressure gauge, load cell, and data recording program. Engine performance tests were carried out in Alternative Engines Laboratory at Automotive Engineering Department, Technology Faculty in Gazi University. The test setup is shown in Figure 2. The accuracies and uncertainties of the measurements are given in Table 1.

The hot end of the Stirling engine was heated with an LPG-fired heater; the cold end was cooled by the city water. The hot end temperature is determined by infrared thermometer and the charge pressure is determined by digital manometer. The engine torque was determined with a prony type dynamometer and load cell consisting of a hydraulic braking device. The measurement values of engine torque and speed from the load cell and encoder are transferred to the computer via the data recording program. The regenerator, which is used to improve engine performance, and regenerator's place on the engine are shown in Figure 3. The regenerator was produced by stainless steel wire and had 0.15 mm diameter and 15% solidity ratio.

Results and discussions

At the first experimental study, working performance of the engine was analyzed depending on the engine speed at different charge pressures for engine both with and without regenerator. Figures 4 and 5 are indicated the variations of engine torque depending on the engine speed for engine with regenerator and engine without regenerator, respectively. In the experiments with regenerator and

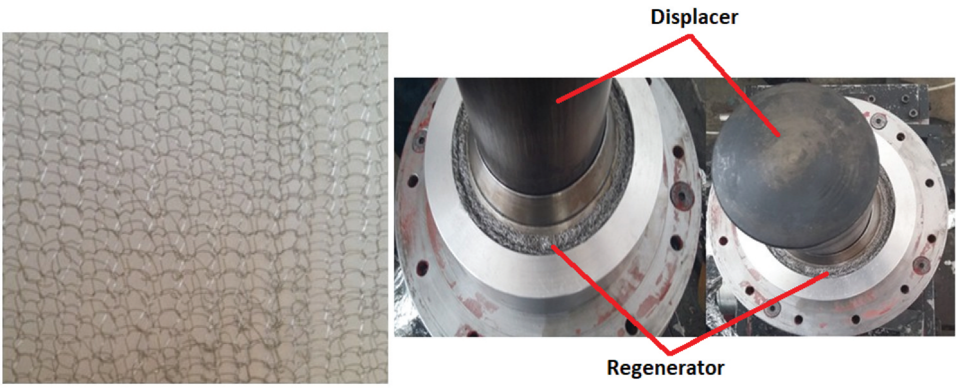

Figure 3. Regenerator and regenerator's place on the engine.

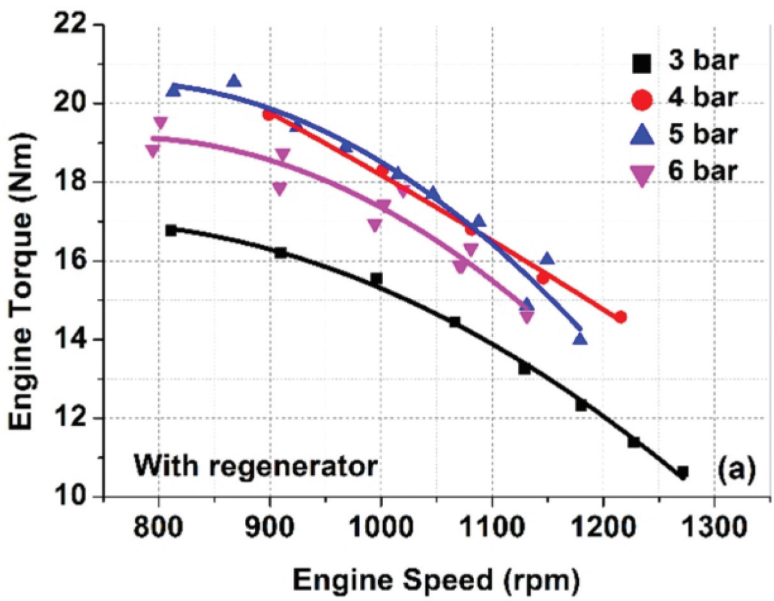

Figure 4. The engine torque values measured versus engine speeds for engine with regenerator.

without regenerator, maximum engine moments were obtained at 5 bar charge pressure and were 20.55 Nm at 867 rpm and 19.74 Nm at 837 rpm for the engine with regenerator and without regenerator, respectively. For both Figures 4 and 5, the engine torque values are measured as high at low engine speeds, the engine torque decreases with increasing engine speed for per charge pressures. Engine speed affects the heating-cooling time negative. At low engine speeds, when the heating-cooling time is enough to transfer heat, this time decreases with increasing engine speed. Therefore, higher engine torque is obtained at low engine speeds.

Figures 6 and 7 are about the engine power values measured versus the engine speed for engine with regenerator and engine without regenerator, respectively. In the experiments with regenerator and without regenerator, maximum engine powers were obtained at 5 bar charge pressure and were 1940 W at 1046 rpm and 1831 W at 1035 rpm for engine with regenerator and without regenerator, respectively. It should be noted that this study is a production of a continuing study since 2015. Previous results about the project was presented before (Aksoy et al. 2017; Karabulut et al. 2016; Solmaz et al. 2020). By considering

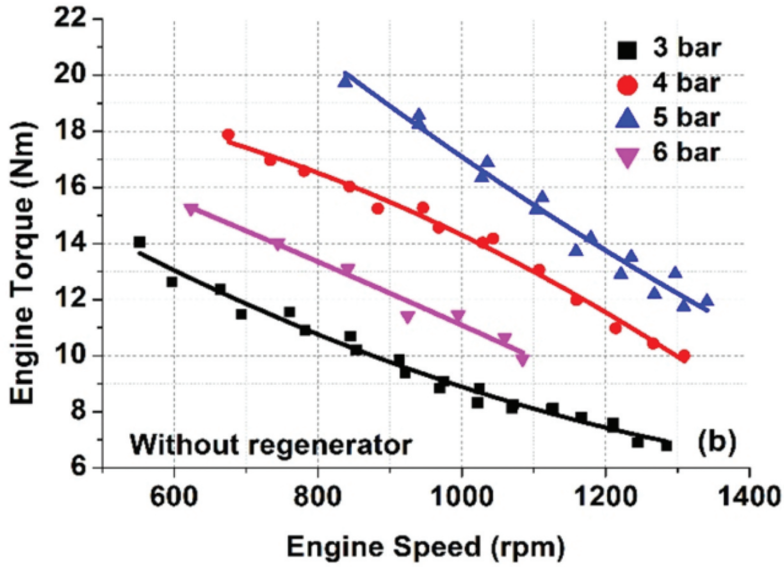

Figure 5. The engine torque values measured versus engine speeds for engine without regenerator.

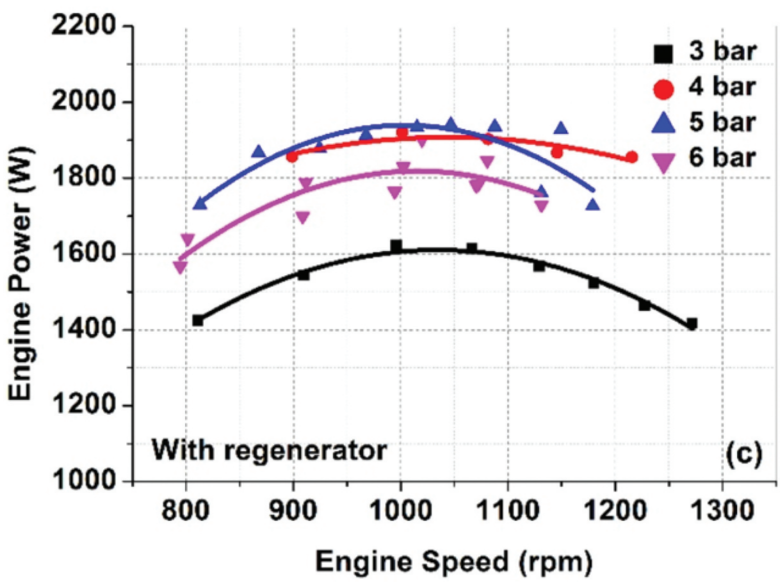

Figure 6. The engine power values measured versus engine speeds for engine with regenerator.

the power level achieved in this study, it can be said that the engine performance was considerably better than the previous versions of the test engine. The maximum power of the previous version of the engine was 1.2 kW without regenerator (Aksoy et al. 2017). In addition, the maximum engine power of 1940 W obtained at such a low charge pressure of 5 bar is highest engine performance achieved at that charge pressure for a single cylinder beta type rhombic drive Stirling engine up to date. When examining Figures 6 and 7, it is shown that the engine power improves to a certain value depending on the increasing engine speed and then decreases for per charge pressures. Engine power values were affected from engine speed and engine torque. Decreasing heat exchange time and increasing friction losses due to the increasing of

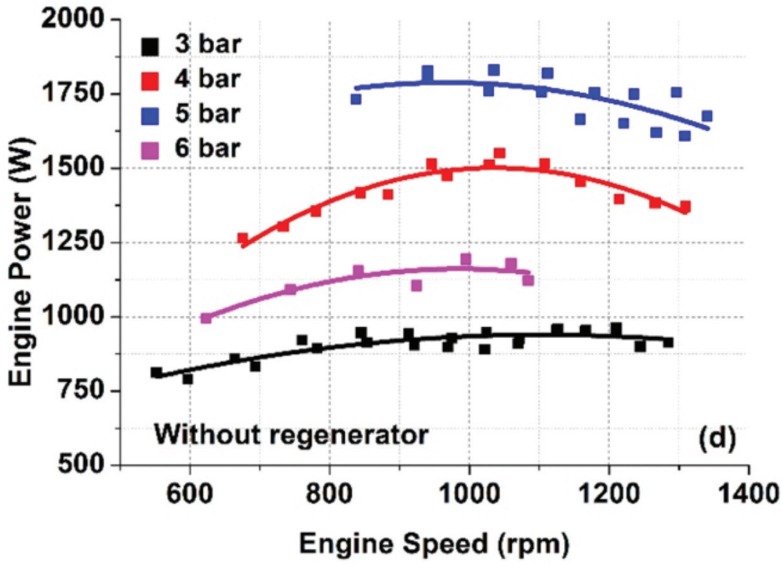

Figure 7. The engine power values measured versus engine speeds for engine without regenerator.

engine speed cause decreasing of the engine power. At the optimum charge pressure 5 bar, the engine power increases slightly due to regenerator, while the engine power increases considerably at other charge pressures. As a result, the regenerator significantly affects the performance of the engine.

Conclusions

In this study, helium charged, beta type Stirling engine was designed and tested, effect of regenerator material on the engine performance was investigated. Experiments were conducted at hot end temperature 800°C and 3, 4, 5, and 6 bar charge pressures with regenerator, and without regenerator. For the test engine, the best performance values were determined for hot end temperature 800°C and 5 bar charge pressure. The highest engine power and torque were measured as 1831.09 W at 1035 rpm and 19.74 Nm at 837 rpm for engine without regenerator while as 1940.45 W at 1046 rpm and 20.55 Nm at 867 rpm for engine with regenerator, respectively. It was seen that the increasing in charge pressure up to 5 bar increased engine performance, but decreased the engine performance at higher charge pressures due to insufficient heat transfer and lower top temperature. The 120 cm^3 regenerator increases the performance of the engine by providing using of some of waste heat. With using of regenerator, an increase in maximum engine torque and power by 4% and 5.97% were observed, respectively, compared to engine without regenerator. By using of regenerator, heat transfer surface area and dead volume increase but the increasing in dead volume leads to decreasing of engine performance. So regenerator properties must be optimized to obtain optimum engine performance.

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Notes on contributors

Fatih AKSOY was born in 1980, Eskişehir, Turkey. He received the MSc and PhD degrees in Mechanical Education from the Gazi University in 2005 and 2011, respectively. He is working as a Professor at Automotive Engineering Department, Faculty of Technology, Afyon Kocatepe University. He has interested in internal combustion engines, alternative fuels and Stirling engine. He has published about 40 papers articles in SCI-indexed journals.

Hamit Solmaz received his PhD at Gazi University, Turkey, in 2014. He performed studies as a visiting post-doc scholar about low temperature combustion engines between 2015-2016 at Mechanical Engineering&Engineering Mechanics department, Michigan Technological University. He is working as an Associated Professor at Automotive Engineering Department, Faculty of Technology, Gazi University since 2016. He has over 100 publications and more than half of them have been published in SCI indexed respected journals. He is the editor of International Journal of Automotive Science and Technology that is published by Turkish Society of Automotive Engineers and founder editor of Engineering Perspective journal. His research interests include internal combustion engines, low temperature combustion modes suc as HCCI, RCCI, PCCI etc., alternative fuels and combustion, Stirling engines, engine vibration.

Muhammed Arslan graduated with an undergraduate degree at Automotive Engineering at 2014 and a master's degree at Mechanical Engineering at 2016 from Afyon Kocatepe University at Turkey. He worked as a scholarship holder at TUBITAK project with number 113M192 between 2014-2016. He has being still a student in PhD programme at Automotive Engineering since 2016. At the same time, he works as a lecturer at Afyon Kocatepe University, Çay Vocational School, Department of Motor Vehicles and Transportation Technologies. His master's thesis is on Stirling engines; his doctoral thesis is on biogas power plants.

Emre Yilmaz received his PhD at Gazi University, Turkey, in 2018. He is working as an Associated Professor at Automotive Technology Department, Arifiye Vocational School, Sakarya University of Applied Sciences since 2020. He is the section editor of International Journal of Automotive Science and Technology that is published by Turkish Society of Automotive Engineers. His research interests include internal combustion engines, low temperature combustion modes such as HCCI, RCCI etc., alternative fuels and combustion, Stirling engines.

Duygu İPCİ is an Assistant Professor in the Automotive Engineering Department at the Gazi University from the beginning of the year of 2021. She worked as a Research Assistant at the same department between 2013 and 2020. She completed her Ph.D. at Gazi University about the fluid flow and heat transfer in narrow radiator channels. Her research interests include internal combustion engines, Stirling engines, automotive aerodynamics, numerical analysis, and CFD.

Alper Calam is an Assoc. Prof. at Gazi University, Ankara, Turkey. He received his MSc and PhD in 2011 and 2018 respectively at Gazi University. He has published many papers at various international journals. His research areas include SI and CI engines, low temperature combustion modes (PPCI, HCCI, RCCI etc.), emission reduction, biofuels and fuel additives.

ORCID

Fatih Aksoy http://orcid.org/0000-0003-0877-9373
Hamit Solmaz http://orcid.org/0000-0003-0689-6824
Muhammed Arslan http://orcid.org/0000-0001-8387-7008
Duygu İpci http://orcid.org/0000-0002-8862-7662

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