DESIGN AND PRELIMINARY RESULTS OF INVESTIGATIONS OF THE EXPERIMENTAL STIRLING ENGINE SEPS-1

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Abstract. The prototype Stirling engine SEPS-1 has been designed and constructed on the grounds of information presented in publications, authors experience in mechanical engineering and results of experiments referring to some subassemblies as well as computer calculations of simulated engine internal processes. The experimental Stirling engine SEPS-1 is a single acting design of γ configuration, developing effective power of 3 kW at 25 Hz operating frequency, using helium of 3 MPa mean pressure as the working gas.

Some of preliminary results of the engine characteristics when using helium and nitrogen as working gases have been presented. They proved the well known properties of the Stirling engines. On the grounds of operating characteristics and observation, it has been considered that further experiments and engine modifications are necessary, to obtain the estimated goals of the design.

1. Introduction

Lately, many papers have been published indicating of the unique properties and operating characteristics of Stirling engines [1], [2], among other things referring to: high thermal efficiency, low level of noise and vibrations and multi-heat source ability. However, the amount of knowledge referring to design methods and construction of Stirling engines is still too conservative and so far insufficient. Like in many other fields of technology, the necessary experience may be obtained by means of the construction and experiments of prototype engines. The similar solution has been chosen in that case too, by proceeding to the construction of the experimental engine SEPS-1, characterized by the following design variables:

- power piston diameter
- displacer diameter
- regenerator matrix external diameter
- displacer and power piston stroke
- phase angle
- heater tube diameter
- cooler tube diameter
- heater tube length
- cooler tube length
- number of heater tubes

\[ D_C = 91 \text{ mm}, \quad D_E = 81 \text{ mm}, \]
\[ D_R = 91 \text{ mm}, \quad S_{EC} = 65 \text{ mm}, \]
\[ \alpha = 1.57 \text{ rad}, \quad d_H = 6 \text{ mm}, \]
\[ d_C = 2.5 \text{ mm}, \quad l_H = 280 \text{ mm}, \]
\[ l_C = 119 \text{ mm}, \quad Z_H = 27 \]

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- number of cooler tubes \( Z_C = 120 \)
- number of wire screens in regenerator \( i_k = 240 \)
- regenerator screen wire diameter \( d_w = 0.112 \text{ mm} \)
- mesh size \( \iota_w = 4700 \text{/} \)

**Fig. 1. Cross-section of the experimental engine SEPS-1**

1 - crankcase, 2 - cylinder block, 3 - cylinder cover, 4 - regenerator, 5 - cooler, 6 - combustion chamber, 7 - air pre-heater, 8 - power piston, 9 - displacer, 10 - piston rod gland, 11 - heater, 12 - crosshead, 13 - burner combustion chamber, 14 - gas supply, 15 - crankshaft, 16 - engine foundation.

All the above mentioned variables have been obtained on the grounds of computer optimization with the application of Martini code and Powell algorithm [3]. The results of design and technological activity referring to the prototype engine SEPS-1, as well as results of preliminary investigations have been presented in the following paragraphs of the paper.
2. Construction of the experimental engine

Taking into account the technical and technological abilities, the experimental Stirling engine, single-acting of γ configuration, developing effective power of 3 kW at 25 Hz operating frequency, using helium of 3 MPa mean pressure as the working gas, has been designed and constructed.

In result of experiments carried out at the special test rigs, the particular engine assemblies have been modified. This is reflected in the actual state of the engine construction, presented in fig. 1.

2.1.1. Engine frame

The two part crankcase is of prefabricated steel design, premachined by milling. The front and rear plates are screwed to the crankcase, and may be removed, if necessary. The two bores in the plates, provided with seal rings, ensure that two crankshaft ends may protrude out of the crankcase; one for driving the output power unit, the other for connecting the engine starter and CA and TDC marker. Two cross girders in which the main rolling bearings are housed give the bedplate its necessary transverse strength. Cylinder block made of cast iron Z1200 is mounted on the crankcase. The block is machined to compose in it two cylindrical spaces i.e. compression and expansion, as well as cylindrical guides (in lower part of cylinder block) for two crossheads, i.e. for power piston and displacer. The cylinder block is secured to the crank case by means of six tie bolts.

Two horizontal plates with bores are provided in the middle part of the both cylindrical spaces for mounting the piston rod and displacer rod glands (10). The gland (see fig.2) separate the working space and buffer space (under the working gas pressure) from the crankcase (under the ambient pressure). The cylinder liners, made of stainless steel 35 HM are fitted into the cylinder block. Internal liner surface is ground and polished (Ra≤0.4μm), and surface hardened by nitration-sulphurizing. This has been preserved for better conditions of the cooperation between the piston rings and cylinder liner without lubrication.

2.1.2. Working mechanism

Taking into consideration the design needs of the engine of γ configuration, the typical, crosshead crank mechanism of own design has been used as the driving mechanism. Two single crankshafts (15) with connecting rods are of commercial origin. To obtain the necessary relation of movement of the power piston (8) against the displacer (9), stated by the constant phase angle α, the both crankshafts are interconnected by means of a gear of 1:1 ratio.

To eliminate vibrations, a special balancing unit has been designed. The unit is able to balance the centrifugal force caused by the rotation of the crankshaft as well as primary and secondary inertia forces due to reciprocating movement of crank mechanism parts. The unit provides for the possibility of balancing all forces separately, since the masses of power piston assembly and displacer assembly are quite different. The design of the balancing unit proved useful, since during the operation of the engine at whole speed range, any vibrations have been observed.
Fig. 2. Piston rod gland

The power piston made of stainless steel is provided with conical crown having a bore for nuts securing the piston with bolted end of the piston rod. The piston skirt is short and provided with one cylindrical groove for one seal ring of Glyd T type. The displacer made of stainless steel is provided with spherical crown and long skirt (L/D=1.8), with one cylindrical groove for seal ring of Glyd T type in lower part (cool). The displacer skirt is composed of two parts to ensure assembling the displacer with its rod in cooler part of the working space. The lower displacer plate is provided with 1 mm bore, to relief the displacer skirt from stresses due to the large pressure difference between compression and expansion spaces. The cylindrical piston and displacer rods are made of alloy steel 38HMJ with lower conical part and threaded for screw connection with crosshead. The cylindrical part of rod cooperates with gland rings and is accurately ground (Ra≤0.4μm) and surface hardened by nitration-sulphurizing. The crosshead of solid design is provided with a conical bracket and cylindrical two part guide shoes. Two crosshead hubs comprised with guide-shoes and steel gudgeon pin ensure swinging connection with connecting rod. In two sections the crosshead are cut out of metal to ensure free flow of air in the crankcase during the engine movement, and to eliminate air compression in the crankcase.

2.1.3. Seal rings

All rings mounted in power piston, displacer and glands operate in oil free conditions. Therefore, they are uncut rings made of plastic components, especially PTFE filled in with graphite, carbon fibre or polyamide resin. The characteristic designs of rings in diametral cross-section are given in fig. 5.
Fig. 3. Power piston and displacer

Fig. 4. Crosshead
1- conical seat for rod, 2-guide shoe, 3- hub

Fig. 5. Rings for piston, displacer and rod gland
a- Variseal M2 ring, b- Glyd Ring T, c- scraper ring Excluder 2, d- wear rings
2.1.4. Heat exchangers

The tubular heater (see fig. 6) is mounted between compression cylinder head and expansion cylinder head. It is composed of 27 tubes of 6 mm internal diameter and 280 mm length. The large amount of tubes and their dimensions resulted in the application of two linear collectors welded in the upper part of both compression and expansion heads so as to ensure gas flow to and from the collector, and minimize the resistance of the gas flow.

Fig. 6. Tubular heater

At present design, the heater has been thoroughly welded from stainless steel components, using the TIG method. The mesh wire regenerator (see fig. 7) is composed of cylindrical housing made of stainless steel, two specially shaped lids of sufficient thickness, to ensure as large as possible cross-section of gas flow area and stiffness, as well as home appropriate number of wire screens made of stainless steel. The cooler (see fig. 8) is of tubular design made of stainless steel thoroughly (i.e. tubes, casing and plates). The internal partition is used for changing the flow direction of water and increasing the heat transfer coefficient. The tube ends are soldered in two lids with copper in vacuum furnace. We have experienced very good tightness of the all soldered connections.

2.1.5 Combustion chamber

The combustion chamber of rectangular cross-section comprises the space between cylinder heads with heater tubes (see fig. 9), so as to ensure exhaust gas flow providing effective heat
Fig. 7. Mesh wire regenerator

Fig. 8. Tubular cooler

transfer from exhaust gas to working gas through heater tube walls. There is a gas burner unit with primary tubular combustion chamber in front of the combustion chamber (see fig. 10).
The ignition of gas-air mixture is provided by the spark or glow plug. The exhaust gas leaving the combustion chamber flows through the air preheater, supplied with air by appropriate blower, and finally enters the atmosphere. The secondary air, heated up in tubular preheater, contacts the combustion chamber along its three walls. Then, heated up to the relatively high temperature enters the holes in second part of the gas burner. The holes are situated in that manner, as to increase the length of gas flow in burning region without large increase of the burner length. Owing to this design the high gas temperature within the combustion chamber is obtained.
The second amount of air of low temperature, flows as primary air to the gas burner close to gas flow section. Two flap valves are situated in air ducts, for changing the ratio of primary and secondary air as well as fuel-air ratio (described by excess air number $\lambda$), according to the amount of gas fuel-providing the required engine effective power. The gas (propane) is supplied from a gas reservoir under regulated pressure to the gas burner.

3. The experimental investigations of the engine

3.1. Test rig

The operation of Stirling engine looks for continuous flow of working fluids which thermodynamic parameters should be in required limits. Therefore, the test rig of the engine has been provided with appropriate instrumentation and pick-ups, on the grounds of their indications the necessary engine characteristics may be accomplished. The diagram of the test rig has been presented in fig. 11.

For measuring pressure, temperature, number of revolutions, engine moment and flow rates, appropriate instrumentation of adequate accuracy has been used for the purpose. The selected results of measurements given in fig. 12 and 13 indicate the main characteristics of the experimental engine versus the engine speed. At constant mean pressure of the working gas, the maximum effective power is obtained for different engine speeds. For nominal pressure of 3 MPa this takes place for 700 rpm. In general the characteristics of moment and effective power are pretty flat (see fig. 12).

![Graph showing engine performance](image)

**Fig. 12. Effect of helium mean pressure on engine moment and effective power**

The engine reached 5.6% overall efficiency (see fig. 13) which is well below the calculated values. It is believed that the engine efficiency may be increased by changing some variables. However, larger improvement of engine characteristics would be obtained by design changes and variation of design variables, resulted from more sophisticated methods of optimisation [6] as well further development of seals and design of the working mechanism. The pressurised crankcase is considered, as more effective.
Fig. 11 Diagram of the test rig
Fig. 13. Effect of type and pressure of the working gas on engine total efficiency

On the grounds of theoretical analysis [2] it has been appreciated that helium is the most useful working gas. The results of experiments given in fig. 13 proved these considerations. When using nitrogen as the working gas, both the effective power and efficiency have been decreased considerably.

4. Summary and conclusions

On the grounds of preliminary tests of the experimental Stirling engine SEPS-1 it may be stated that the design under considerations have proved the advantages of these type of engines, i.e. relatively flat characteristics of moment; noiseless operation as well as multi-fuel operation. However, the experimental engine has to be modified, so as to improve operation of seals and heat exchangers and decrease mechanical losses of moving parts. It has been considered that dimensions of heat exchangers have to be selected according to more sophisticated methods of optimization, using the third order code and genetic algorithms.

References