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POWER AND HEAT COGENERATION USING VARIABLE DISPLACEMENT STIRLING ENGINE

BY
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Abstract. The construction of the Stirling engine with on load variable displacement and its employment in heat and power microcogeneration units is analyzed. Engine performance and power adjustment capability are analyzed.

Keywords: variable displacement Stirling engine, cogeneration, heat, power.

1. Introduction

The urge of efficiently using natural gas inside population households led to the idea of employing heat and power cogeneration units of small size. As a competitive, alternative system to classic central heating, individual cogeneration enjoys great perspectives and concerted efforts are mainly directed toward improving its versatility and control by users. Natural gas in population households is commonly used inside individual households in order to produce the necessary of heat and hot water. Employing the same heat yielded inside the burning chamber a cogeneration installation also produces domestic power.

Classic thermal engines (comprising either pistons or blades) inside which natural gas is burnt are not fit to drive the electric generators comprised by household cogeneration installations, and that is because of the noise implied by their functioning as well as the inconveniences encountered at technical level when small dimensions are involved. Stirling engines are characterized by gaseous working agent, closed thermodynamic cycle and external combustion. Their main and great advantage is their quiet and vibrationless functioning that thus recommends them for employment in domestic heat and power cogeneration.

The paper proposes the employment inside cogeneration installations of a variable displacement Stirling engine (VDSE) allowing the on load mechanical adjustment of the power produced [1].

2. Power and Heat Microcogeneration Installations Using VDSE

According to the schematic diagram on fig. 1, the VDSE 1 receives heat from a natural gas burning chamber 2. Once removed, the exhaust gases heat the agent inside the heat exchanger 3 (the agent being water delivered by the circulating pump 6). The heated agent feeds the heat consumers and the domestic hot-water heat exchanger 4. The VDSE drives the alternator 12, the power produced being converted to direct current by the charger 11 connected to the battery 2. The inverter 10 provides the consumers with alternative current even when the VDSE is rests.

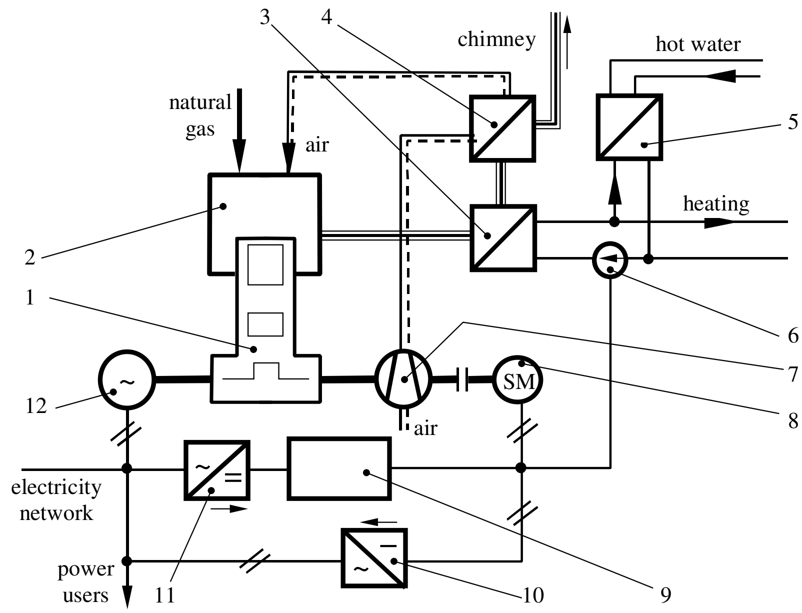

Fig. 1.- Schematic diagram of a power and heat microcogeneration installation using VDSE: 1 - VDSE; 2 - burning chamber; 3 - heat exchanger; 4 - air preheater; 5 - heat exchanger for domestic hot-water; 6 - water circulating pump; 7 - air fan; 8 - starting motor; 9 - storage battery; 10 - inverter; 11 - charger; 12 - alternator.

On the principle schematic diagram on fig. 1 the cooler of the VDSE (see fig. 2 and explanations) was not introduced in the heating circuit, so the cooler exchanges heat with the environment. The VDSE cooler can be used as water preheater and directly (or indirectly, through another heat exchanger) introduced in the hot-water production circuit or inside domestic heating.

3. Variable Displacement Stirling Engine

In the VDSE engine schematic diagram (fig. 2) there are the following components: the cylinder 16, the power piston 17, the displacer 21 and three heat exchangers, 19 - the low temperature one, 23 - the high temperature one and the regenerator 20.

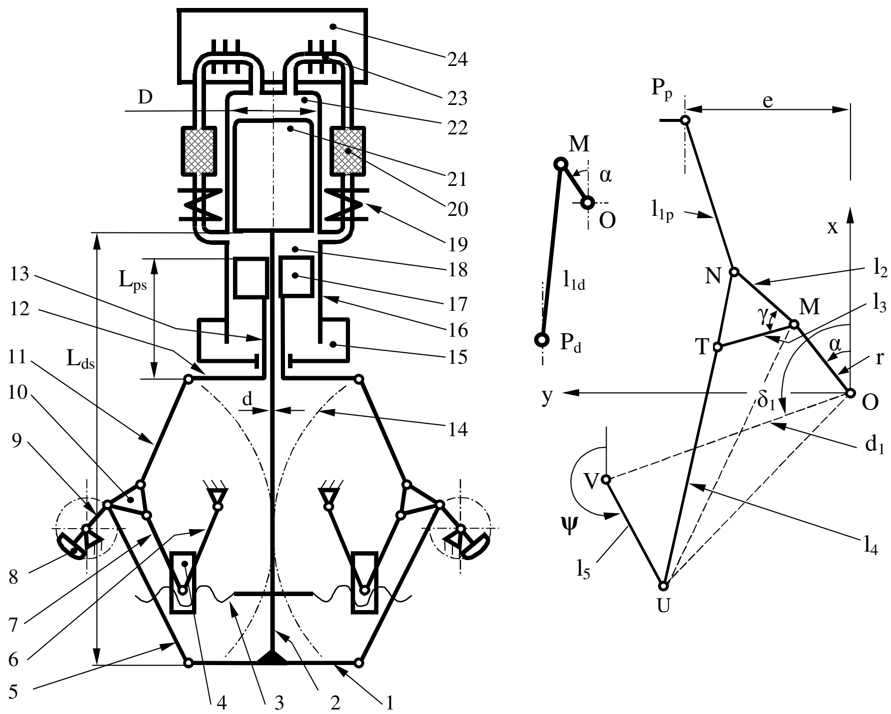

Fig. 2.- VSSE schematic diagram:
1 - lower yoke; 2 - stem; 3 - adjustment screw; 4 - nut; 5 - lower rod; 6 - leaning bar; 7 - adjustment bar; 8 - counterbalance; 9 - crankshaft; 10 - triangular plate; 11 - upper rod; 12 - upper yoke; 13 - cylindrical stem; 14 - gear wheel; 15 - buffer; 16 - cylinder; 17 - power piston; 18 - compression space; 19 - cooler; 20 - regenerator; 21 - displacer; 22 - expansion space; 23 - heater; 24 - burning chamber.

The low temperature heat exchanger is cooled with water (or air, the case of small Stirling engines) and the heater is placed in the burning chamber 24.

The expansion space 22 is found between the cylinder head and the displacer and the compression space 18 between the two pistons. The motive drive has two crankshafts 9 which spin in opposite directions. The crankshaft movements are synchronized by the gear wheels 14. The displacer 21 is equipped with a stem 2 which pierces through the power piston 17 in the middle. The stem 2 finishes at the lower yoke 1, at the ends of which the lower rods 5 are socketed. The power piston 17 is equipped with a cylindrical stem 13 which finishes at the upper yoke 12, at which's ends the upper rods 11 are socketed. Between the upper rods 11 and the crankshafts 9 have been introduced the sides MN of the triangular plates 10. The ends T of the triangular plates are socketed with the adjustment bars 7. The adjustment bars themselves are socketed in the leaning bars 6 which can oscillate in the fixed sockets V. The sockets U between the 6 and 7 bars are able to move along circle arcs thanks to the adjustment screw 3 which has two distinct regions of opposite threading. The screw 3 is spun from outside through the nuts 4 which stand for the U sockets. The spinning effect is that the ends T of the triangular plates 10 shift and thus the lengths of the "equivalent rods" MP are modified resulting in the displacement variation of the VDSE analyzed here.

4. Variable Displacement Stirling Engines Performances

The performance of a Stirling engine and therefore of a VDSE also, can be analytically calculated with isothermal or adiabatic physico-mathematical models. The isothermal model [2], [4] assumes that inside all engine chamber isothermal processes only take place and the instantaneous pressure is common to all chambers of the machine. Pressure variation law is obtained from the equations of state applied for each chamber and from the agent total mass conservation equation, as:

$$p(\alpha,\psi) = \frac{m_T \; R}{\dfrac{V_e(\alpha)+V_h}{T_h} + \dfrac{V_{reg}}{T_{reg}} + \dfrac{V_c(\alpha,\psi)+V_k}{T_k}} . \tag{1}$$

The adiabatic model assumes that the processes inside the compression and expansion chambers are adiabatic. It is also assumed that processes inside the heat exchangers are isothermal. Using the equation of state, the energy conservation equations written for each chamber and the agent total mass conservation equation, a differential equation system is obtained [3]:

$$dm_c = \frac{1}{R T_{c-k}}\left(\frac{V_c}{k}dp + p\,dV_c\right), \quad dm_e = \frac{1}{R T_{h-e}}\left(\frac{V_e}{k}dp + p\,dV_e\right), \text{(2), (3)}$$

$$dp = \frac{-k\,p\left(\dfrac{dV_c}{T_{c-k}} + \dfrac{dV_e}{T_{h-e}}\right)}{\dfrac{V_c}{T_{c-k}} + \dfrac{V_e}{T_{h-e}} + k\left(\dfrac{V_k}{T_k} + \dfrac{V_{reg}}{T_{reg}} + \dfrac{V_h}{T_h}\right)}, \tag{4}$$

$$dT_c = T_c\left(\frac{dp}{p} + \frac{dV_c}{V_c} - \frac{dm_c}{m_c}\right), \qquad dT_e = T_e\left(\frac{dp}{p} + \frac{dV_e}{V_e} - \frac{dm_e}{m_e}\right). \quad \text{(5), (6)}$$

By integration the engine pressure variation law is obtained in the shape of numerical values sets for the variate positions of the crankshaft and for variate instances of the adjustment angle ψ.

Inside relations (1) … (6) the notations were used as following R = gas constant; k = isentropic exponent; m = agent mass; V = volume; T = temperature. The following subscripts were used: c, e = compression and expansion chambers; reg = regenerator, h = heater; k = cooler; T = total.

For both models the work is obtained as a sum of the works exchanged in the expansion and the compression chambers:

$$L = L_e + L_c = \int_0^{2\pi} p(\alpha)\, dV_e + \int_0^{2\pi} p(\alpha)\, dV_c \,. \qquad (7)$$

The indicated power of the engine is

$$P = \frac{n}{60} L \,. \qquad (8)$$

Thermal efficiency of the Stirling engine, also known as indicated efficiency, is defined as

$$\eta_t = \frac{L}{L_d} \,. \qquad (9)$$

The brake horsepower and the brake thermal efficiency are obtained using the indicated efficiency and the mechanical efficiency. The indicated efficiency takes into account the mechanical losses occurring along the frictional flow of the working agent inside the machine as well as the losses due to the non-isothermal functioning of the heat exchangers.

For an engine described by the following values: r = 0,0385 m; e = 1,6 r; l_{1d} = 3 r; l_{1p} = 2,5 r; $l_2 = l_3 = l_5$ = 2 r; l_4 = 3 r; d_1 = 2,5 r; γ = 50°; δ_1 = 100°; D = 0,073 m; d = 0,02 m; L_{ps} = 5 r; L_{ds} = 12,5 r; $V_h = V_k$ = 0,05 V_{emax}; V_{reg} = 1,2 V_{emax}; m = 0,002 kg H_2; T_h = 750 K; T_k = 300 K and n = 1500 rpm, for adjustment angle ψ between 160° ... 205°, the performances presented in fig. 3 were obtained . The subscript max stands for the maximum value.

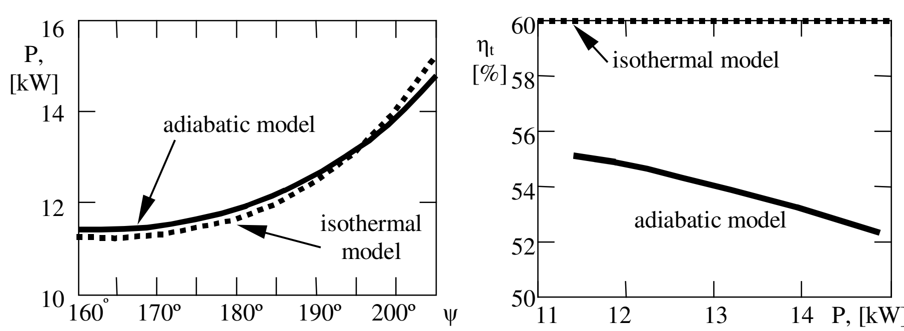

Fig. 3.- VDSE performances.

Calculated with both methods, i.e. isothermal and adiabatic, the work yielded during a single cycle provided values close one to the other. Greater differences appeared in which concerns the thermal efficiencies. Calculated with the isothermal model, the thermal efficiency was found equal to the Carnot cycle efficiency (working between the same extreme temperatures). The thermal efficiency calculated for the adiabatic model was obtained as less than the

Carnot efficiency and varying with the adjustment angle ψ (the load in effect). The adiabatic thermal efficiency of VDSE decreases with the load, approximately with 5% of its maximum value.

The VDSE can regulate the load within the ratio

$$\frac{P_{max}}{P_{min}} = \frac{14862}{11390} = 1{,}3\,. \qquad (10)$$

By optimizing the dimensions of the VDSE motive drive, a raise of the maximum/minimum power ratio up to 1,5 was estimated.

5. Conclusions

By employing VDSE in the context of ever growing endeavors for improving domestic cogeneration a new way of regulating the electric power provided to individual users was auspiciously proposed as a better way to fit their needs and thus adding to system versatility.

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MICROCOGENERAREA ENERGIEI ELECTRICE ŞI TERMICE
CU MOTOARE STIRLING CU CILINDREE VARIABILĂ
(Rezumat)

Se prezintă construcţia motorului Stirling cu cilindree variabilă sub sarcină şi utilizarea lui în instalaţii de microcogenerare a energiei termice şi electrice. Se apreciază performanţele motorului şi capacitatea de reglare a puterii electrice.