A THERMAL-HYDRAULIC SYSTEM FOR THE CONVERSION AND THE STORAGE OF ENERGY

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Abstract - The paper proposes the concept design of a thermal-hydraulic system that converts the thermal energy (from the geothermal water, from the cooling water of power equipment, from exhaust gasses, and so.) in hydrostatic energy, that is stored in a hydraulic accumulator. The hydraulic energy can be converted into electrical energy when needed.

Keywords - thermal-hydraulic generator, hybrid system, Stirling cycle, heat transfer, synchronous electric generator.

I. INTRODUCTION

THE energy stored in the geothermal water is a non-polluting one. By recovering the thermal energy from the cooling water or from the exhaust gasses of the power systems the consumption of fossil fuels and the CO_2 emissions in the environment are reduced

The thermal-hydraulic system for the conversion and the storage of energy is a hybrid one in which two energy conversions are taking place. The thermal energy is transformed into hydrostatic one and is stored in an accumulator. According to the needs (in conditions of a variable consumption), the energy stored in the accumulator can be converted into electric current.

II. THE OPERATION SCHEME

The system for the conversion and the storage of the energy consists of two subsystems (Fig. 1): the subsystem for the conversion of thermal energy to hydraulic energy and it's storage in the accumulator and the subsystem for the conversion of the hydrostatic energy into electrical energy.

The subsystem for the conversion of the thermal energy in the hydrostatic energy and its storage in the accumulator consists of: the thermal-hydraulic generator (position 6 in Fig. 1), the hydro-pneumatic piston accumulator (position 5 in Fig. 1) and the oil tank (position 1 in fig. 1). The thermal processes in the thermal-hydraulic generator take place based on a Stirling cycle, with a coaxial arrangement of the cylinders.

The generator has an automatic operation: in the moment in which the hydraulic pressure inside the accumulator reaches the maximum admissible value (the capacity of the accumulator is the maximum admissible), the generator stops it's operation and starts only when the hydraulic pressure in the accumulator drops to the minimum admissible value (the capacity of the accumulator is the minimum admissible) [1].

The subsystem for the conversion of the hydrostatic energy into hydraulic energy consists of: the variable hydraulic motor (position 2 in Fig. 1), the synchronous electric generator (position 3 in fig. 1) and the electric transformer (position 4 in Fig. 1). The hydraulic fluid flow for the supply of the hydraulic motor can be varied automatically so that the rotational speed of the electric generator's shaft remains constant (at the synchronous rotational speed), whichever the variations in the electrical power demanded by the consumer.

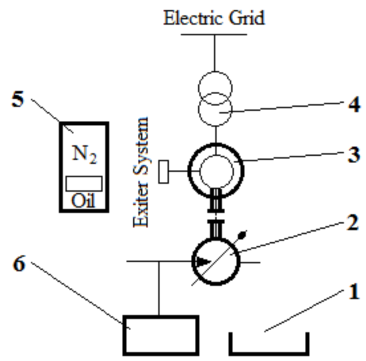

Fig. 1. The scheme of the thermal-hydraulic system

In conclusion, the system for the conversion and the storage of the energy is one with an automatic operation, which produces electrical energy in variable consumption conditions.

III. THE THERMAL-HYDRAULIC GENERATOR

The generator consists of three coaxial arranged cylinders (Fig. 2): the motor cylinder *Cm* and two hydraulic cylinders *Ch1* and *Ch2*, disposed at both ends of the motor cylinder. Inside the cylinders, the pistons *Ps1* and *Ps2* have a rectilinear alternative movement. The pistons drive is hydraulic and the movement's coordination is realized by the one sense valves S1 and *S2*, and by the unlock one sense valves *Sd1*, *Sd2* and *Sd3*.

The control of the unlock one sense valves *Sd1*, *Sd2*, and *Sd3* is realized by the position distributors *D1*, *D2*, and *D3*. Due to the pistons movement inside the motor cylinder *Cm*, two variable hydraulic chambers are formed: the compression chamber *C* and the transfer chamber *E*. The thermal processes take place inside the variable volume chambers.

The heat exchangers are disposed at the ends of variable volume chambers. The heater *H* is disposed at the end of the expansion chamber *D* and the cooler *K* is disposed at the end of the compression chamber *C*. In order to increase the thermal efficiency, between the two heat exchangers is disposed the regenerator *R*. The regenerator is a heat accumulator. It accumulates heat from the thermal agent (nitrogen) when it flows to the cooler (the cool zone) and releases heat to the thermal agent when it flows to the heater (the warm zone).

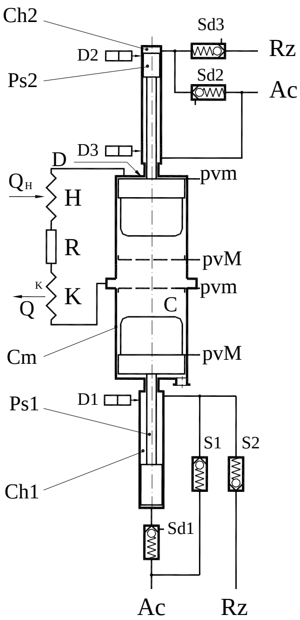

Fig. 2. The scheme of the thermal-hydraulic generator

The theoretical cycle consists of the following thermal processes (Fig. 3a) [2]: the isothermal compression (1-2), the isochoric heating (2-3); the isothermal expansion (3-4) and the constant pressure cooling (4-1). During the compression the cooler maintains the thermal agent's temperature almost constant (compared with an isothermal process). In a similar mode, during the expansion the heater maintains the thermal agent temperature almost constant. In conclusion, the Stirling cycle [3] consists of two isothermal processes and of two isochoric ones.

The operation of the generator is as follows (Fig. 2): the piston *Ps2* is blocked at the point of minimum volume (pvm) and the piston Ps1 moves from the point of maximum volume (pvM) to *pvm*. During this time, the compression process takes place (1-2) and it ends when the piston *Ps1* reaches *pvm*. Then follow the isochoric heating process (2-3). The piston *Ps2* moves from *pvm* to *pvM* and the piston *Ps1* remains blocked in *pvm*. The heating process takes place until the thermal agent from chamber *C* is transferred, through the heater *H*, in chamber *D*. During the transfer, the gas volume is constant. After the heating follows the expansion process (3-4), during which the gas volume is constant. Then follows the expansion process (3-4). The piston *Ps2*, together with the piston *Ps1*, moves from *pmv*. The last process of the cycle is the cooling one (4-1). The piston *Ps2* moves from *pvM* to pmv and the piston *Ps1* stays blocked in *pvM*. The thermal agent inside the expansion chamber *D* is transferred, through the cooler *K*, to the compression chamber *C*.

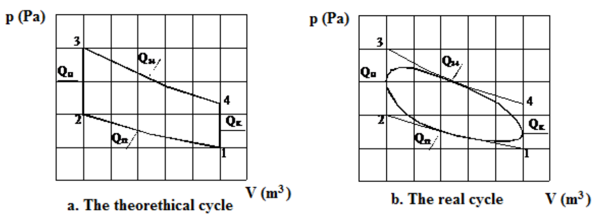

Fig. 3. The Stirling cycle

The thermal processes of the real cycle include the losses (Fig. 3b). The losses are of thermal-gas-dynamic nature and due to: the fact that the heat exchange takes place only if there's a temperature difference between the heat exchanger's wall and the gas, the heat losses through the heater and motor cylinder walls, the mechanical loss between the parts in relative movement and the aerodynamic losses at the gas flow through the heat exchangers.

The Stirling cycle is characterized by the complete thermal regeneration, the mechanical work exchanged during the isochoric heating-cooling processes of the thermal agent is null. In the conditions of a conductive-convective heat transfer in the heat exchangers, the optimum ratio of the extreme temperatures of the thermal cycle is given by the relation [3]:

$$\left(\frac{T_3}{T_1}\right)_{optim} = \sqrt{\frac{T}{T_0}} \tag{1}$$

where: T_3 (K) - is the maximum temperature of the thermal agent;

T_1 (K) - is the minimum temperature of the thermal agent;

T (K) - is the warm source temperature;

T_0 (K) - is the cold source temperature;

The calculus model of the generator is based on the following assumptions (Fig. 4). The generator consists of five chambers:
1) the expansion chamber D;
2) the heating chamber H;
3) the regenerative chamber R;
4) the cooling chamber C,

These chambers are serial linked, but separated them by control surfaces. The thermal fluid is considered to be a perfect gas (nitrogen). The following parameters are neglected: the kinetically energy of the thermal agent, the gas dynamic losses, the sealing losses. Also, the instantaneous pressure in all the chambers is considered to be constant. The temperatures of the agent inside the heat exchangers are considered to be constant and equal to those of the neighboring heat exchangers: $T_D = T_H$ și $T_C = T_H$. The evolution of the thermal fluid in the expansion chamber and in the compression one is considered to be isothermal (the Schmidt model). Each one of the spaces interacts between them through a mass transfer, and with the environment it interacts through a mechanical work and a heat exchange [1], [4], [5].

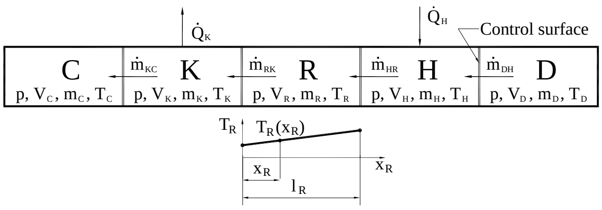

Fig. 4. The scheme of the calculus model

The instantaneous volume of the expansion chamber *D* and the one of the compression chamber *C* are determined depending on the piston position *x*: $V_D = V_D(x)$, and $V_C = V_C(x)$. For the calculus of these volumes, the theory of the kinetically energy theorem must be applied.

It is considered that the temperature t inside regenerator has a linear variation:

$$T_R(x_R) = T_K + (T_H - T_K)\cdot\frac{x_R}{l_R} \quad (K) \tag{2}$$

where: x_R (m) – is the position of a point on the trajectory of the gas flow in the generator;
l_R – is the regenerator's length;
T_K (K) – is the temperature in the cooler;
T_H (K) – is the temperature in the heater;

The mean temperature of the gas inside the regenerator is:

$$T_R = \frac{T_H - T_K}{\ln\left(\frac{T_H}{T_K}\right)} = \text{const.} \quad (K) \tag{3}$$

The gas mass inside the regenerator results from the equation:

$$m_R = \int p\cdot dV_R = \frac{p\cdot V_R}{R\cdot T_R} \quad (kg) \tag{4}$$

where: ρ (kg/m^3) - is the density of the thermal agent
V_R (m^3) – is the regulator volume;
p (Pa) – is the pressure of the thermal agent;
R (J/kg K) – is the gas universal constant;

For the calculus of the thermodynamics parameters of the engine cycle one can apply the equation of the mass balance, the state equation of the perfect gas and the energetic balance equation.

The mass balance equation is:

$$m = m_D + m_H + m_R + m_K + m_C \quad (kg) \tag{5}$$

where: m_D, m_H, m_R, m_K, m_C (kg) - are the thermal agent masses;

The mass balance equation for a generator chamber is:

$$dm = m_i - m_e \ (kg) \tag{6}$$

where: m_i is the mass of thermal agent that enters the chamber and; m_e is the mass that exits from the chambers. The differential equation of the energetic balance in a chamber (neglecting the kinetic energy) is:

$$c_v\cdot d(m\cdot T) = \delta Q + c_p\cdot(m_i\cdot T_i - m_e\cdot T_e) - p\cdot dV \tag{7}$$

where: c_v, c_p (J/kg K) - is the specific heat of the thermal agent at constant volume, and at constant pressure respectively;
T_i, T_e (K) – is the temperature of the thermal agent at the entrance to the chamber and at the exit respectively;
p (Pa) – is the pressure of the thermal agent ;

Through the control surfaces a mass and a heat transfer take place. The heat flow exchanged through the control surfaces depends on the mass flow $\dot{m}$ and on the gas temperature. For example, the heat flows transmitted through the control surface between chambers *D* and *H* is:

$$\dot{Q}_{DH} = c_p\cdot\dot{m}_{DH}\cdot T_{DH} \ (J/s) \tag{8}$$

if $\dot{m}_{DH} > 0$ (the flow sense of the thermal agent is from *D* to *H*) and $T_{DH} = T_D$;
or

$$\dot{Q}_{DH} = -c_p\cdot\dot{m}_{DH}\cdot T_{DH} \quad (J/s) \tag{9}$$

if $\dot{m}_{DH} < 0$ (the flow sense of the thermal agent is from *H* to *D*) and $T_{DH} = T_D$. The time is denoted by τ.

The mass flow equations are:

$$\dot{m}_{DH} = -\frac{1}{R\cdot T_D}\cdot\frac{d(p\cdot V_D)}{d\tau} \tag{10}$$

$$\dot{m}_{HR} = \dot{m}_{DH} - \frac{V_H}{R \cdot T_H} \cdot \frac{dp}{d\tau} \qquad (11)$$

$$\dot{m}_{RK} = \dot{m}_{HR} - \frac{V_R}{R \cdot T_R} \cdot \frac{dp}{d\tau} \qquad (12)$$

$$\dot{m}_{KC} = \dot{m}_{RK} - \frac{V_K}{R \cdot T_K} \cdot \frac{dp}{d\tau} \qquad (13)$$

The heat flow exchanged with the environment (from the warm source to the cold source) by the thermal agent inside the heater *H* or inside the cooler *K*, is:

$$\dot{Q}_H = (c_p - c_v) \cdot (\dot{m}_{HR} - \dot{m}_{DH}) \cdot T_H \qquad (14)$$

$$\dot{Q}_K = (c_p - c_v) \cdot (\dot{m}_{KC} - \dot{m}_{RK}) \cdot T_K \qquad (15)$$

The relation for the calculus of the instantaneous pressure inside the generator's chambers is obtained from the state equation of the ideal gas:

$$p(x) = \frac{m \cdot R}{\frac{V_D(x)}{T_D(x)} + \frac{V_H}{T_H} + \frac{V_R}{T_R} + \frac{V_K}{T_K} + \frac{V_C(x)}{T_C(x)}} \qquad (16)$$

where: m (kg) - is the mass of the thermal agent inside the generator;

The function $p(x)$ given by (16) represents the indicated diagram of the thermal cycle. The indicated mechanical work developed in a thermal cycle is:

$$L_i = \oint p(x) \cdot \left(\frac{dV_D(x)}{dx} + \frac{dV_C(x)}{dx} \right) \cdot dx \qquad (17)$$

In conclusion, the model is used for the pre-dimensioning and allows a fast evaluation of the generator's performances. In order to realize a better evaluation, the parameters are corrected with the parameters that take into account the losses.

IV. HYDROPNEUMATIC PISTON ACCUMULATOR

The main parts of the hydro-pneumatic accumulator are the cylinder and the piston. The piston is a part that separates the gas (nitrogen) from the hydraulic liquid and during the operation it has rectilinear alternative movement. The constructive structure of the accumulator, without the bottles, is presented in Fig. 5.

The gas evolution during the process of loading and unloading of the accumulator can be considered as isothermal. In these conditions, the pre-loading pressure p_0 is equal to the minimum operating pressure p_1. The gas volume V_1 at the pressure p_1 is equal to the accumulator's capacity V_0, and it results: $p_1 = p_0$, $V_0 = V_1$.

The maximum volume of liquid that can be stored in the hydraulic accumulator is:

$$\Delta V = V_0 \cdot \left(1 - \frac{p_1}{p_2} \right) \quad [m^3] \qquad (18)$$

where: V_0 (m^3) - is the accumulator volume,
p_1 (Pa) - is the minimum operating pressure;
p_2 (Pa) - is the maximum operating pressure;

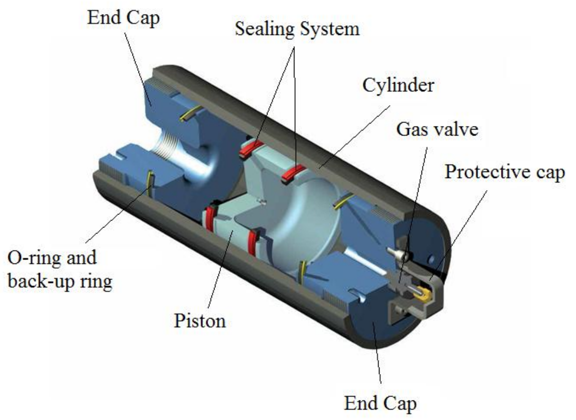

Fig. 5. The constructive structure of the hydro-pneumatic piston accumulator [5]

V. CONCLUSION

The new type of the conversion of the renewable thermal energy in electrical energy realizes the energy conversions in an efficient way in variable consumption conditions. The system has an automatic operation and can be operated independently from an electrical network (it can supply isolated consumers, but with energy resources).

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