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AIR ACCUMULATING ELECTRIC POWER STATION WITH TWO AIR-STORAGE RESERVOIRS OF DIFFERENT PRESSURE

There had been suggested the structure of air accumulating electric power station with two air-storage reservoirs of different pressure connected to each other by the compressor-gas-expansion machine. There had been determined the basic characteristics of this class of power stations and design procedure of this characteristics.

Keywords*: energy-saving, wind-power engineering, accumulating power station, air-storage reservoirs.*

1. Problem set up

With every passing year after Chernobyl nuclear power plant tragedy the forecasts regarding limited resources of natural gas are more and more accurate, and at the same time new nuclear power plants are constructed in many countries of the world. The characteristic feature of these plants is their operation on a round-the-clock basis.

According to energy supply Programme of Ukraine, elaborated till the year 2020, the construction of several nuclear power plants is scheduled. That is why, for Ukraine, as well as for many other countries, where the energy generation at nuclear power plants is planned, there arises the problem where to supply energy generated at night drops of loading.

One of the methods, already studied theoretically and applied in practice, of using "excessive", at a given moment, electric energy is its accumulation at water storage electric station (WSES) by pumping water from lower water reservoir into higher water reservoir [1]. But such approach has no prospects to be applied at large flat areas. Thus, in Ukraine, except small operating Kyiv water storage electric station, Tachlyk water storage electric station, where only the first unit functions, and Dnistrovska WSES the construction of which is not completed, the construction of new water storage electric station is not planned. But even in case, when all these three station operate in full capacity, in the periods of load drops they will be able to accumulate no more than half of the energy, generated at Zaporizhzhia nuclear power station. What is to be done with the energy generated at that period by other stations, including those nuclear stations which will be constructed in the future?

We suggest to accumulate this "excessive" electric energy in the form of compressed air, pumped into air reservoirs. Idle gas wells, iron ore and coal mines as well as cavities and quarries could be used as air reservoirs [2, 3].

As it has already been shown in our papers [2, 3], operation of air accumulating power station (AAPS) is not harmful for the environment as the operation of water storage electric stations, but ecological situation will improve.

The main drawback of AAPS characteristics, calculation of the experimental installation of is carried out in [4], and technical economic analysis - in [2], is low efficiency factor due to the fact that only minor part of electric energy used for air compression by compressors in air reservoirs is supplied back to electric energy in the process of compressed air release through gas-expansion into the environment. But it turned out that AAPS efficiency factor can be considerably increased, if used air is released from high pressure air reservoir through gas turbine not into the environment, but release it through gas-expansion unit into another, also isolated, air reservoir, but at lower pressure. The air will be pumped by compressors during load drop at NPP, using excess of energy in electric network, back to high pressure air reservoir.

The given paper considers the elaboration of the structure of AAPS with two air reservoirs as well as calculation of its characteristics.

2. Structure of AAPS with two air reservoirs

As we have already mentioned above, by analogy with hydraulic accumulating power station (HAPS) we suggest to construct AAPS with two reservoirs, one of them being high pressure air-storage reservoir (ASR1), another being low pressure air-storage reservoir (ASR2). The structure of such AAPS is shown in Fig. 1. Parameters of air are also indicated in Fig. 1 (pressure P, temperature t, volume V).

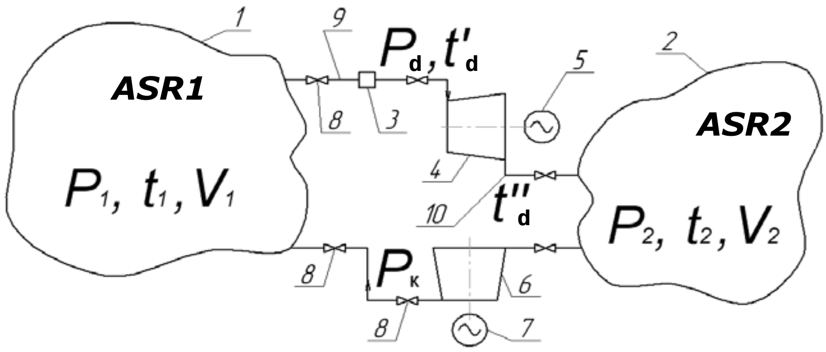

Fig. 1 Block-diagram of AAPS with two air-storage reservoirs:
1 – high pressure air-storage reservoir ASR1; 2 – low pressure air-storage reservoir ASR2;
3 – pressure regulator; 4 – gas-expansion unit; 5 – electric generator; 6 – axial-flow compressor;
7 – electric motor; 8 – stop valves.

Compressor-gas-expansion station is installed between high-pressure air-storage reservoir ASR1 and low-pressure air-storage reservoir ASR2. It comprises compressors 6 with electric drives 7, pressure regulator 3, gas-expansion units (gas turbines) 4 with electric generators 5, stop valves 8 on lines of high 9 and low pressure correspondingly.

During operation of AAPS in energy generation mode, the air from air-storage reservoir ASR1 through pressure regulator 3 under the pressure P_d is supplied to gas-expansion units. Air parameters drop in gas-expansion units to values P_2 and t''_d as a result of expansion and performance of mechanical work of shaft rotation. Air, used in gas-expansion units is supplied to air-storage reservoir ASR2. In the period of "load drop" the air from ASR2 is pumped by compressors into ASR1.

3. Computation of AAPS characteristics

According to the data, obtained in [1] load peak of energy consumption is observed twice a day, in morning hours and in evening hours. That is why the period between starts of AAPS can be within the range of 5 to 7 hours. It is quite natural, that within the period between the starts the air in air-storage reservoirs will be cooled. Cooling intensity depends on temperature difference between the air and walls of air-storage reservoir. We will proceed from the assumption that the decrease of air temperature in ASR1 is 50-60 $°C$, and in ASR2 – 10-20 $°C$.

Let us consider the peculiarities of AAPS operation. Efficiency of AAPS operation will be evaluated applying energy utilization factor η_e which is the ratio of the energy supplied to electric network by gas-expansion-generator units (GEGU), to the energy, consumed by compressors drivers for filling ASR1 with air, i.e.

$$\eta_e = E_d / E_k = N_d \cdot \tau_d /(N_k \cdot \tau_k), \quad (1)$$

where E_d and E_k – supplied and consumed electric energy, correspondingly; N_d and N_k – power of GEGU and compressors; τ_d and τ_k – operation time of GEGU and compressors.

In the formula (1) values of powers N_d and N_k are equal:

$$N_d = G_d \cdot C_p (t'_d - t''_d)\eta_{em}, \; N_k = G_k \cdot C_p (t_k - t_2)/\eta_{em}, \tag{2}$$

where G_d and G_k – air mass flow rate in gas-expansion units and compressors, correspondingly; C_p – mass isobar heat capacity of the air; t'_d and t''_d – air temperature an at the intake of gas-expansion unit and at its outlet; t_2 and t_k – air temperature before the compressor and at its outlet; η_{em} – electromechanical efficiency factor.

Absolute temperatures of the air after the compressor and gas-expansion unit are determined by the known formulas [5]:

$$T_k = T_2 \left[1 + \left(\lambda^m - 1\right)/\eta_k\right], \tag{3}$$

$$T''_d = T'_d \left[1 - \left(1 - \beta^{-m}\right)/\eta_d\right]. \tag{4}$$

These formulas contain the following designations: $\lambda = P_k / P_2$; $\beta = P_d / P_2$; η_k and η_d – efficiency factor of the compressor and gas-expansion unit, correspondingly; P_2 and P_k – air pressure before and after the compressor; $m = (k-1)/k$; $k = 1{,}4$ – adiabatic exponent for air; P_d – air pressure before gas-expansion unit.

Air mass in ASR1 after its filling and partial usage [5]:

$$M_1 = P_1 \cdot V_1 / (R \cdot T_1); \; M_2 = P_d \cdot V_1 / (R \cdot T'_d), \tag{5}$$

where P_1 and V_1 – air pressure in ASR1 and volume of ASR1, correspondingly; R – air gas constant.

Mass flow rate of air in compressors and gas-expansion unit, $kg \cdot s^{-1}$:

$$G_k = (M_1 - M_2)/(3600 \cdot \tau_k) = \Delta M / (3600 \cdot \tau_k);$$
$$G_d = (M_1 - M_2)/(3600 \cdot \tau_d) = \Delta M / (3600 \cdot \tau_d). \tag{6}$$

Serviceability of AAPS can be estimated by means of the coefficient, which characterizes energy generation in GEGU by each ton of used air, $kW \cdot h \cdot t^{-1}$, i.e.

$$e = E_d / \left(\Delta M \cdot 10^{-3}\right). \tag{7}$$

We have researched the operation of AAPS for modes, when air pressure in ASR1 doesn't exceed 5 MPa. For compression and pumping of the air from ASR2 into ASR1 we chose the compressor for gas-turbine unit ГТ-750-6 with reference pressure increase $\lambda = 4{,}6$ and mass flow rate $G_к = 52{,}7\ kg \cdot s^{-1}$ [6]. It was assumed, that in the period between starts, air temperature decrease in ASR1 was $60\,°C$, whereas in ASR2 – $20\,°C$. Pressure losses in air conduits were 0,1 MPa, and temperature decrease in these air conduits $10\,°C$. Efficiency factors of the devices were the following: of the compressor – 0,84; of gas-expansion units – 0,8; electromechanical factor – 0,96. Duration of compressors operation – 5 hours, duration of gas-expansion units operation – 2 hours. Calculations were performed under condition that ASR1 volume was $10^5\ m^3$. Value of pressure P_2 in ASR2 on which both ASR1 pressure value and air mass flow rate from ASR1 depend, varied in calculations.

For fixed reference value of pressure increase in the compressor λ air temperature after compressor and specific operation of the compressor remain constant. With the increase of pressure decrease reference in gas-expansion unit β the specific operation of the unit increases to some extent. But at the same time, the required pressure before gas-expansion unit $(P_d = P_2 \cdot \beta)$, as well as the volume of remaining air M_2 in ASR1 increase. The latter provides reduction of air flow rate from ASR1, that, in its turn, reduces energy generation in GEGU. That is why first of all it is necessary to determine the influence of β on main factors of AAPS operation. Table 1 presents the results of calculations of AAPS operation factors for $\lambda = 4{,}6$; $P_2 = 1\ MPa$; $T_2 = 278\ K$.

Table 1

Influence of pressure reduction reference in gas-expansion unit on AAPS operation factors

Factors	**Value of β**				
	2,6	2,8	3	3,2	3,4
Air temperature, K: - after compressor; - before gas-expansion unit; - after gas-expansion unit.	 459 379 306	 459 371 301	 459 379 297	 459 379 293	 459 379 289,5
Air mass flow rate, $kg \cdot s^{-1}$: - in compressor; - in gas-expansion unit.	61,2 153	51 127,46	40,77 101,94	30,5 76,24	20,34 50,87
Power, MW: - of compressor; - of gas-expansion unit.	 11,6 10,72	 9,66 9,34	 7,73 8,025	 5,76 6,31	 3,85 4,36
Energy consumed, $MW \cdot h$	58	48,33	38,65	28,8	19,29
Generated energy, $MW \cdot h$	21,44	19,08	16,05	12,62	8,72
Energy utilization factor	0,37	0,395	0,415	0,438	0,452

Table 1 shows, that with the decrease of β, the air flow rate in compressor and gas-expansion units increases, this leads to the increase of their power and amount of generated energy, but, at the same time, to the reduction of energy utilization factor at AAPS. It is seen from Fig. 2, where changes of η_e and N_d values are shown.

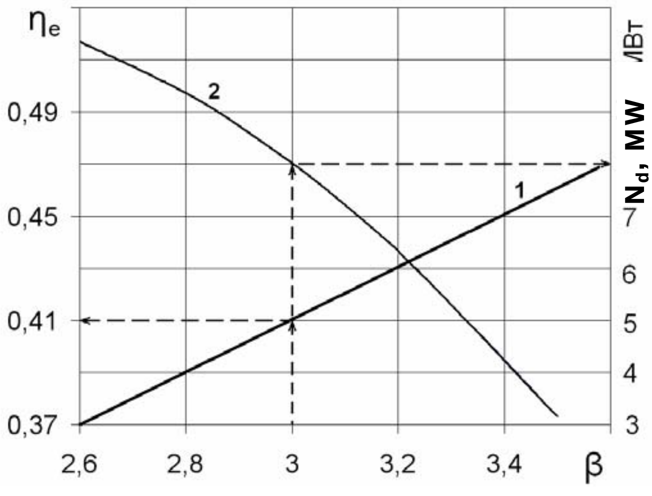

Fig. 2. Geometrical interpretation of the character of energy utilization factor change at AAPS and GEGU power: 1 – $\eta_e = f(\beta)$; 2 – $N_d = f_1(\beta)$.

The results obtained enable to select optimal value of β for the given AAPS. The number of installed GEGU must be taken into consideration during such a selection. It is obvious, that their smaller number results in reduction of capital investments in the equipment needed for AAPS. Specification of GEGU, manufactured by power plant industry, by the rated power, is the following: 1,5; 2,5; 4; 6 and 12 MW [7]. Thus, the most expedient reference value of pressure reduction in gas-expansion unit for the set volume V_1 is $\beta = 3{,}2$, for which $N_d = 6{,}31$; $\eta_e = 0{,}438$.

Now we evaluate the influence of P_2 in ASR2 on operating factors of AAPS for rated and calculated values of parameters: $\lambda = 4{,}6$; $\beta = 3{,}2$; $T_k = 459\ K$; $T'_d = 379\ K$; $T''_d = 293\ K$; $T_2 = 278\ K$. The results of variant calculations, performed by means of above-mentioned calculation technique are given in Table 2.

Table 2

Influence of air pressure in ASR2 on factors of AAPS operation

Factors	Value of P_2 pressure, MPa				
	0,6	0,7	0,8	1	1,1
Air pressure after the compressor, MPa	2,76	3,22	3,68	4,6	5,06
Air pressure before gas-expansion unit, MPa	1,92	2,24	2,56	3,2	3,52
Air mass flow rate ($M_2 \cdot 10^{-5}\ kg$)	3,745	4,38	5,02	5,5	6,13
Compressor power, MW	3,92	4,58	5,25	5,75	6,42
Gas-expansion power, MW	4,29	5,02	5,75	6,31	7,028
Energy consumed, $MW \cdot h$	19,6	22,93	26,28	28,8	32,09
Energy generated, $MW \cdot h$	8,58	10,04	11,51	12,62	14,05
Energy utilization factor	0,438	0,438	0,438	0,438	0,438
Specific generation of energy by ton of the air, $kW \cdot h \cdot t^{-1}$	22,9	22,9	22,9	22,9	22,9
Ratio of ASR2 volume to ASR1 volume	0,527	0,527	0,527	0,462	0,468

The data, presented in Table 2 show that for the fixed values of λ and β of air temperature after the compressor, before and after the gas-expansion unit remain constant, as a result the value of specific operation in such units also remains constant. Variation of the power of compressor and gas-expansion unit is due to changes of air mass flow rate during AAPS operation. In case of AAPS operation with selected reference value of pressure reduction in gas-expansion unit ($\beta = 3{,}2$) its efficiency and performance do not practically depend on air pressure in ASR2. It should be noted that AAPS operation if $\beta = 3{,}2$ is characterized by sufficient energy generation with minimum GEGU and with less value of required volume of low pressure air reservoir.

In our calculations the efficiency factor of compressor η_k is approximate to real value. However the efficiency factor of gas expansion unit may differ to some extent from the selected value. In this connection Fig. 3 shows values of correction factor K_d, values N_d, E_d and η_e must be multiplied by this factor if η_d is no equal 0,8.

It should be noted that for construction of AAPS, the multistage axial – flow compressors of other types of gas – turbine installation, in which reference value of pressure increase at each stage λ_1 is, as a rule, 1,245-1,25 can be used. For instance, usage of seven – stage compressor with $\lambda_1 = 1{,}245$ provides general reference value of pressure increase $\lambda = 4{,}63$. We should note, that to obtain relatively small energy generation increase at AAPS, it is necessary to increase the capacity of air reservoirs ASR1 and ASR2.

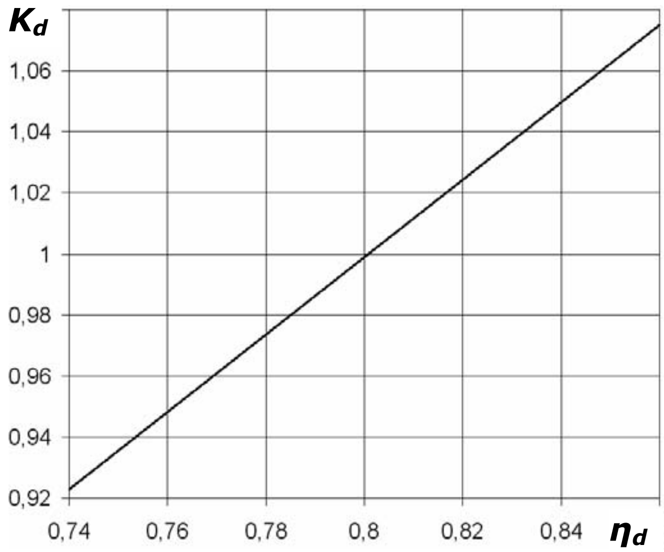

Fig. 3. Graph of correction factor K_d value dependence on η_d.

In spite of the fact that calculations were performed proceeding from using the parameters of operating equipment, the results obtained cannot be considered as final, since air temperatures in air reservoirs in real conditions could differ from the selected ones. But these results are basic for further forecasting of operation indices of AAPS of various power with different parameters of the air used in the circuit.

4. Conclusions

1. New structure of AAPS with two air reservoirs of various pressure ASR1and ASR2, connected with each other by compressor-gas-expansion unit is suggested.
2. Basic characteristics of AAPS with two air reservoirs of different pressure are obtained.
3. On condition, that pressure in high pressure air reservoir ASR1 does not exceed 5 MPa, the most expedient reference value of pressure reduction in gas – expansion unit is determined, the value is 3,2 and provides AAPS operation with similar efficiency with all values of air pressure in low pressure air reservoir ASR2.
4. It is shown that in order to increase energy generation at AAPS it is necessary either to increase the capacity of air reservoirs or to increase pressure in high pressure air reservoir.
5. Prerequisites for realization of technical – economic calculations needed for design of AAPS of the suggested type have been obtained.

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