THERMODYNAMICS OF MULTISTAGE CYCLES OF MHD APPARATUS WITH HEAT REGENERATION

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This article examines and analyzes the cycles of liquid-metal power apparatus with a single-component rotor. An examination is made of the basic factors leading to reduced effectiveness of the cycle when the cold liquid is supplied in one stage (injection system). Multistage systems are proposed, both in the injector and in the separational form with heat regeneration; these systems make it possible for the power apparatus to operate in a wide range of dryness. It is found that the effective efficiency of these cycles lies at a level of 12 - 14%. /1*

Power MHD equipment with liquid-metal rotors are characterized by great power, the possible production of a completely static device , comparatively low temperatures of the rotor in the MHD generator channel, and these characteristics have led to heightened interest in this type of equipment. However, several serious scientific and technical problems, which are primarily connected with accelerating devices, must be solved before operative liquid-metal MHD equipment can be produced.

As is known, the term accelerating device designates the transformation of the power of the thermodynamic rotor (vapor or gas) into the kinetic energy of a stream of electroconductive liquid metal. In this article, if we disregard attempts to produce a rotor which would have sufficient compressibility /2 and electroconductivity at the same time (laminar rotors, etc.), then we may investigate two aspects involved in the problem of producing an accelerating device -- the separational and injector aspects. The separation aspect, which was discussed in the article (Ref. 1, 2), assumes that an electroconductive liquid when accelerated is added to the gas or the vapor before it is expanded in the accelerating nozzle[1]. In addition, the gas (vapor) and liquid acquire a definite velocity during expansion, after which the mixture is directed to the separator. The fundamental requirements imposed on this separator are that it must separate the vapor from the liquid to as great an extent as possible, retaining the kinetic energy of the liquid. In the injector variation, which is discussed in the articles (Ref. 3, 4), for example, the liquid

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* Numbers in the margin indicate pagination in the original foreign text.

[1] A special case is represented by the utilization of a sufficiently umid vapor as the initial vapor, or even a liquid in the saturated state on the left boundary curve).

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is added to the vapor after its expansion in the nozzle. In this case, the liquid which is added is not only accelerated with the vapor, but also condenses it, leading to unnecessary separation.

In the simplest form, both the separational and the injector variations are thermodynamically imperfect. If we confine ourselves to examining single-component systems -- i.e., those in which the vapor and the liquid are one and the same substance -- then the disadvantages of the variations under consideration may be explained as follows. An analysis reveals that the optimum (characterized by the maximum efficiency) separational cycle will have the form shown in Figure 1. In other words, the initial point of the cycle must be selected very close to the left boundary curve. However, this cycle has low thermal efficiency, in view of the fact that it is characterized by a low average temperature of the heat inlet. Displacement of the initial point of the cycle to the right increases the mean temperature of the heat inlet, making it approximate T_I. However, the portion of liquid in the flow after expansion decreases, and the overall efficiency of the cycle is reduced. In addition, the displacement of the initial point to the right usually leads to such large velocities for the liquid that the losses greatly increase in the separator. /3

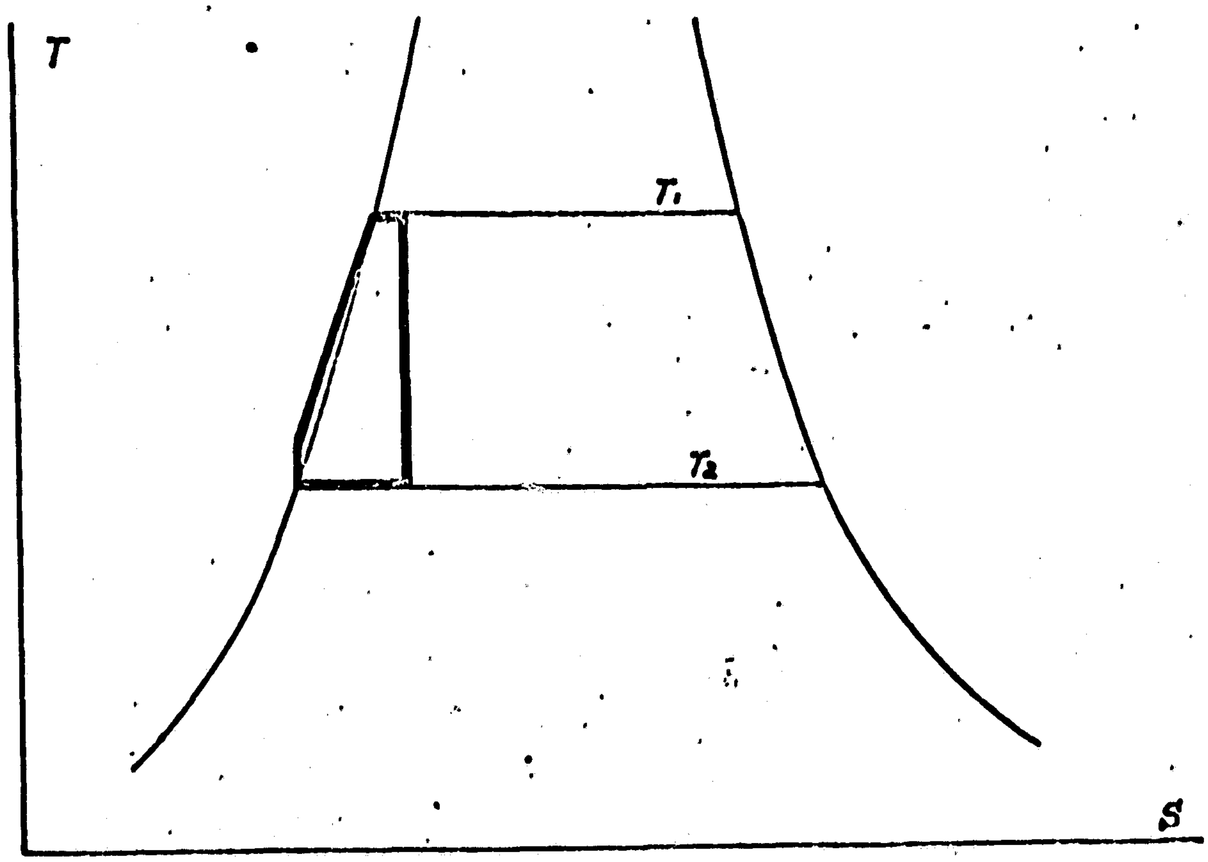

Figure 1

In the case of the injector variation, the initial simplest thermodynamic cycle can be fairly efficient, or its efficiency may coincide with the

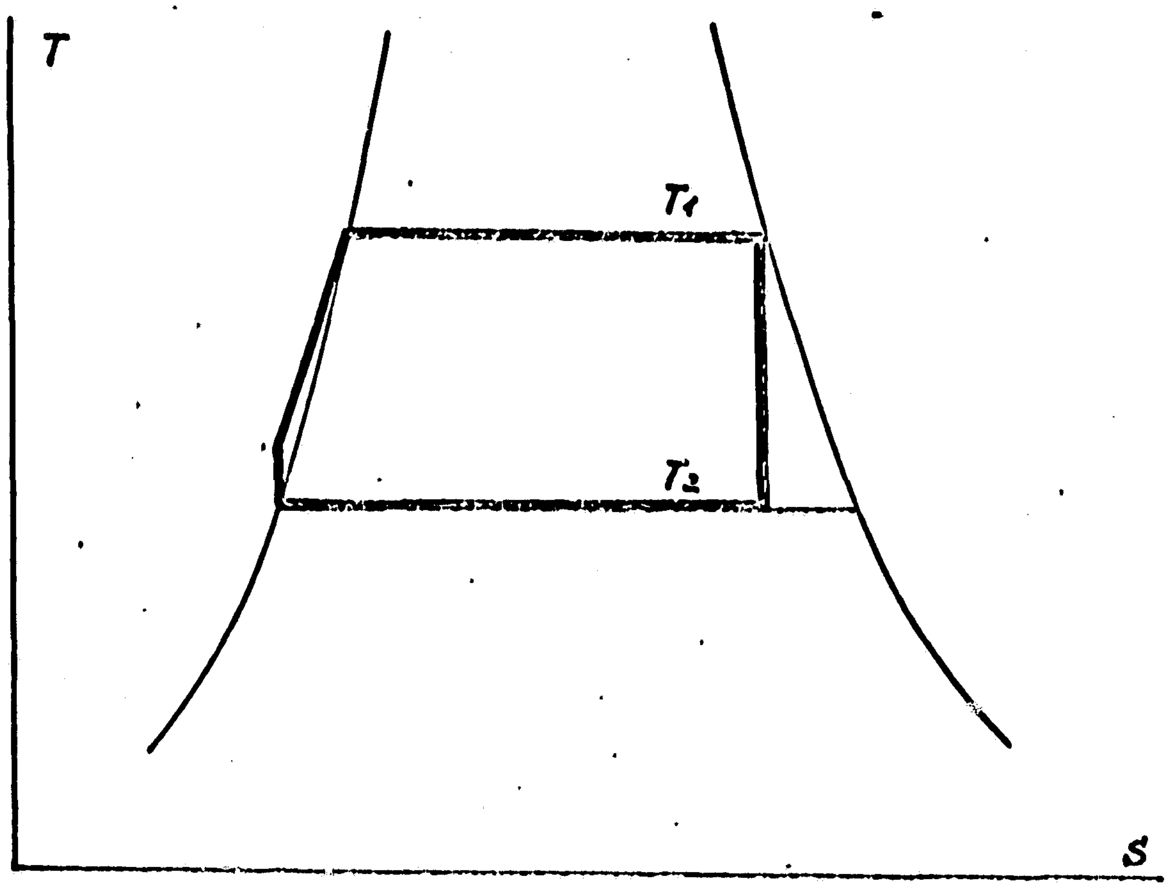

Figure 2

efficiency of the Rankine cycle at the temperatures selected[1] (Figure 2). However, such a cycle is characterized by very low internal efficiency due to great impact losses in the injector. It is impossible to reduce these losses by injecting a liquid having the same velocity as the vapor into the mixing chamber, because the vapor velocity at a high thermal efficiency of the cycle (i.e., in the case when the initial cycle point lies close to the right boundary curve) is extremely high. Optimization of the injector cycles shows that in this case the cycle beginning close to the left boundary curve will have the maximum efficiency, i.e., the cycle which is similar to that shown in Figure 1.

Taking these factors into consideration, reports have been presented in the literature stating that the efficiency of the injector cycle may be increased by employing the multistage injector, in each stage of which the /4

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[1] We must keep the fact in mind that, when metals are employed as the working substances, the lowest cycle temperature is significantly greater than the temperature of the surrounding medium. In this discussion, we shall not deal with the losses connected with this, assuming that the lowest cycle temperature is given.

velocities are small. This makes it possible to greatly reduce, or even completely eliminate, the impact losses (Ref. 5, 6, 7). However, calculations have shown [see, for example, (Ref. 8)] that the efficiency is increased to a very insignificant extent by using a multistage injector. This result, which at first glance appears strange, may be explained quite simply. The fact of the matter is that in an examination of a single-stage injector, the temperature T_2 for which may be assumed to be given, it is usually assumed that a liquid with the temperature of the surrounding medium T_0 must be used as the condensing liquid which is to be added. The fact that two streams with essentially different temperatures T_2 and T_0 are mixed has no influence on the cycle efficiency, because this mixing takes place beyond the limits of the cycle itself. In addition, since the basic losses in the simplest injector are impact losses, it is advantageous that the temperature T_0 be below T_2 as much as possible. Thus, the amount of liquid to be added is reduced, and consequently the impact losses are decreased.

It was tacitly assumed in (Ref. 8) that in the case of a multistage cycle a liquid with the temperature T_0 may be added in each stage, and that -- just as in a single-stage cycle -- the mixing of streams with different temperatures is insignificant. However, in actuality this is not the case. In the intermediate stage of a multistage injector, a cold liquid with the temperature T_0 and a vapor with the temperature $T_1 > T_2$ are mixed within the cycle temperature interval. Unavoidable additional losses are connected with this irreversible mixing. These losses lead to the fact that, in spite of a decrease in the impact losses, the efficiency of the multi-stage cycle is practically the same as in the case of a single-stage cycle.

A natural conclusion follows from this analysis -- a multi-stage /5
injector cycle is more efficient only when not only impact losses are eliminated, but also losses due to irreversible mixing of the streams with different temperatures. In other words, if a liquid is added to the intermediate stages of the injector with a temperature equalling the vapor temperature in these stages. It is found that in this case vapor condensation will not occur in the intermediate stages. Condensation must thus occur at the last stage with the vapor temperature T_2, to which a liquid with the temperature T_0 may be added based on the considerations discussed previously.

The liquid with the temperature necessary for being added to the intermediate states would have to be heated at the heat source. However, in this case the average temperature of the heat inlet would be reduced, and the cycle would be in essence equivalent to the cycle shown in Figure 1. In order to have a high thermal efficiency of the cycle, it is possible[1] to employ regeneration to heat the liquid. In the cases which we are

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[1] We are not discussing the possible unbalancedstates, when a cold liquid occurs in a vapor, is accelerated with it, but does not enter into heat exchange with it during a certain brief period of time.

investigating, regeneration encounters certain difficulties due to the fact that possible losses in kinetic energy must be taken into account when it is employed.

Our assumptions regarding the improvement of thermodynamic multi-stage cycles with regeneration may be primarily reduced to the following three variations:

(1) A separational multi-stage device with regenerative heaters;

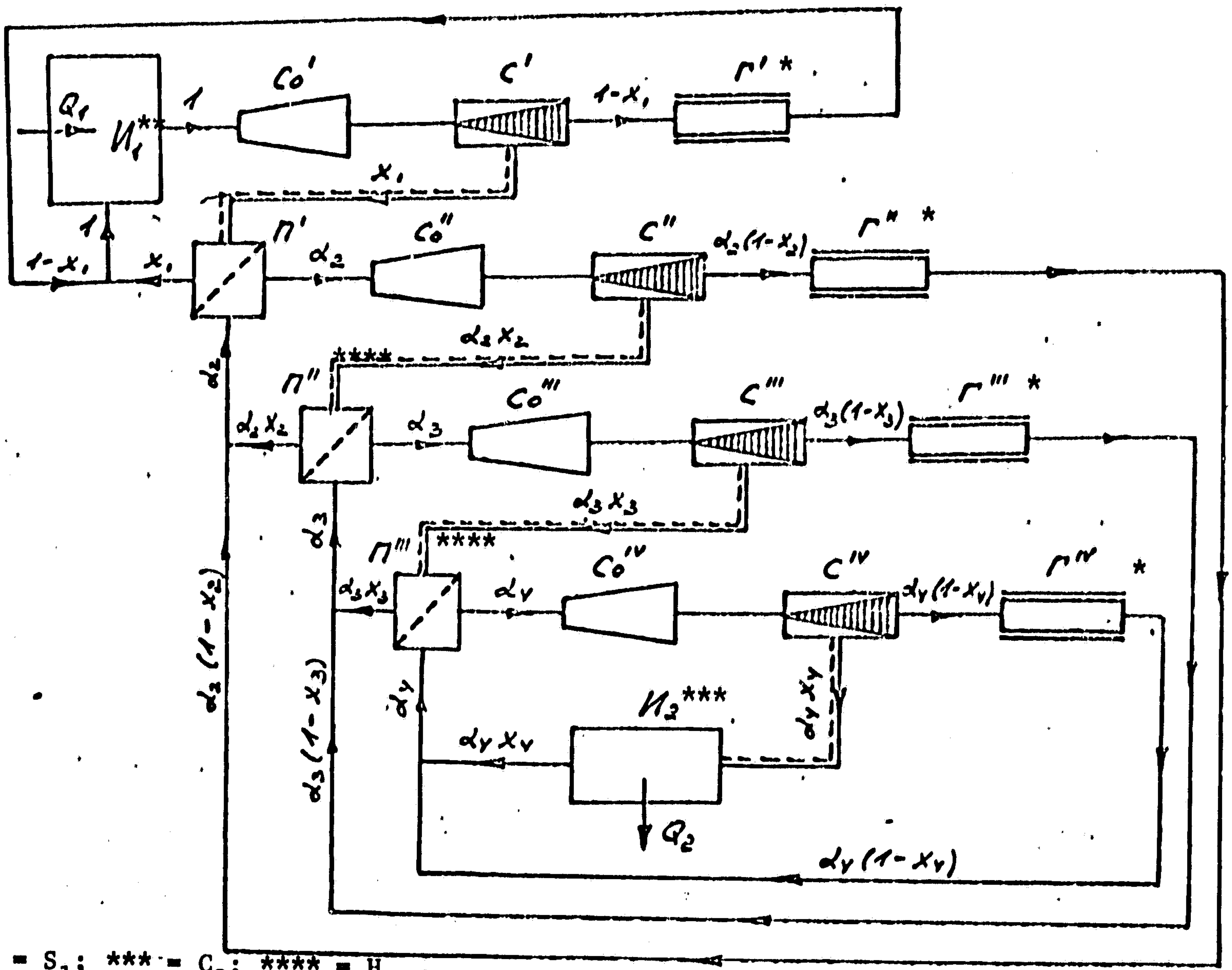
(2) Injector multi-stage device with condensation of the vapor phase with optimum velocities of vapor and liquid;

(3) Injector-separational multi-stage device with humid metal vapor.

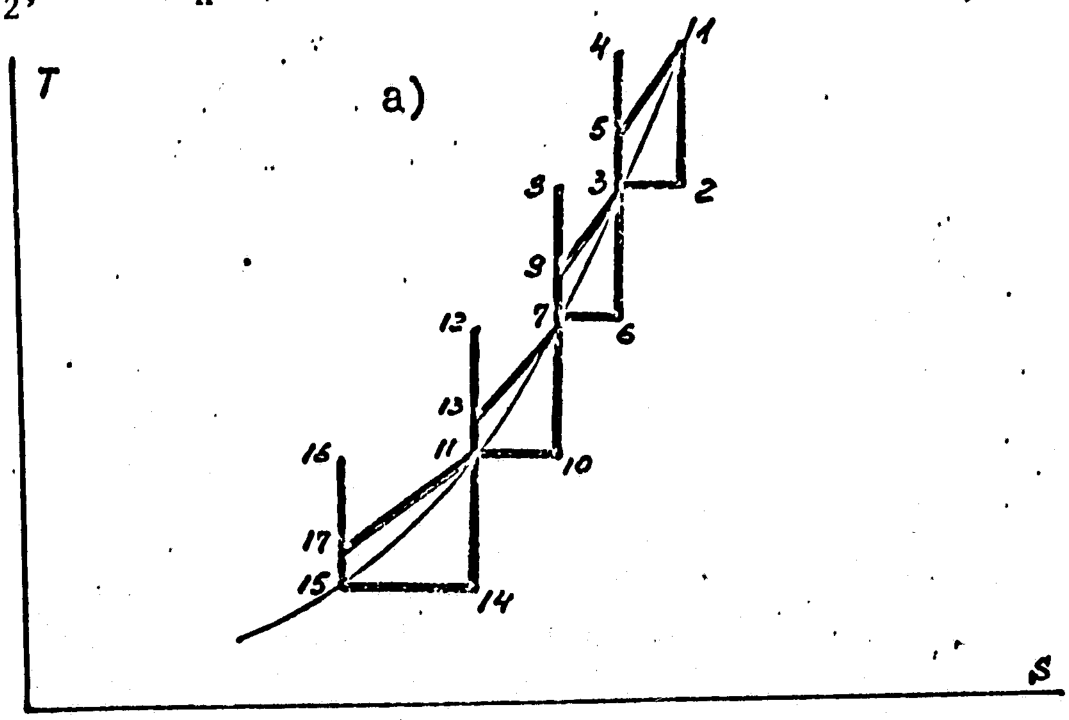
Figure 3 presents a diagram of a separational four-stage device with heat regeneration. At the output of the heat source there is 1 kg of liquid metal in the saturated state. At the nozzle of the first stage Co^1 this liquid expands up to a pressure corresponding to the initial pressure in the second stage. The humid vapor which is formed with a specific (specified by the optimization conditions of the entire system) velocity enters the separator of the first stage C^1, where X_1 kg of dry saturated vapor is separated and directed to the regenerative heater H^1, and $(1 - X_1)$ kg of liquid enters the generator of the first stage G_1, where it loses its kinetic energy. It is most advantageous to not employ all the kinetic energy of the liquid in the generator, but to recover part of it in the diffusor at a pressure slightly above the initial pressure at the input to the nozzle Co^1. In this case, pumps are not necessary to close the cycle.

The vapor extracted in the heater H^1 is condensed, producing the heat of the liquid entering into the second stage. The amount of this liquid α_2 is selected from the equation of thermal equilibrium, so that the liquid is heated /7 up to the saturation state at its pressure. The vapor condensate χ_1, together with the liquid $(1 - \chi_1)$, is returned to the heat source S_1. In order to make the diagram readily understandable, Figure 3 shows the heater H^1 on one plane. In actuality, It is advantageous to make this a mixing heater, since the vapor pressure after the first stage equals the liquid pressure before the second stage.

The subsequent stages operate similarly to the first stage. In the last stage, expansion in the nozzle occurs up to the final pressure (temperature) of the cycle, selected from structural or technical-economic considerations. The vapor which can be separated from this stage is condensed in the cooler C_2, giving off heat Q_2 to the surrounding medium. In principle, the vapor of the last stage can be removed not by separation, but by condensing it in the injector.



*= G^1; ** = S_1; *** = C_2; **** = H



(B)

Figure 3

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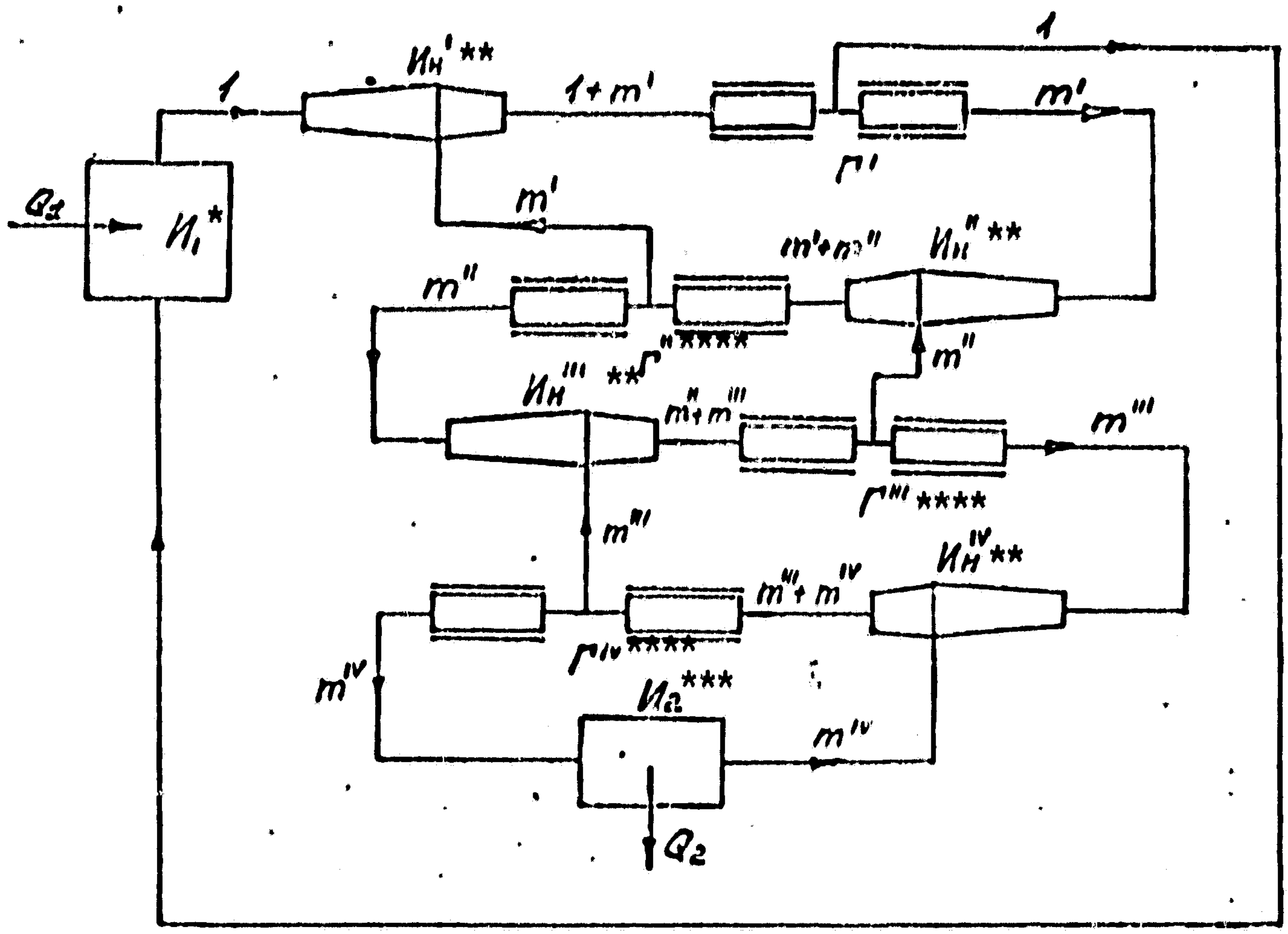
The operation of the multistage separator MHD device becomes clearer from and analysis of the T - S diagram shown in Figure 3b.

The liquid metal on the left boundary curve (point 1) at the pressure P_{01} is expanded in the nozzle up to the state 2. After the separator, the parameters of the total liquid retardation are determined by point 4, without allowance for losses in the separator. If pumps are not included in the MHD device, the temperature drop in the MHD generator equals the segment 4-5.

After the separator, at the static pressure P_1 (this pressure is the pressure of total retardation P_{02} for the second stage), the vapor heats the liquid in the amount of α_2, in the state 9 after the generator of the second stage. After the heater, the liquid reaches the saturation state (point 3) /8
and is directed toward the nozzle of the second stage. The work produced in the generator of the second stage, is shown by the segment 8-9. Thus, all of the subsequent stages, beginning with the second, receive heat in the regenerative heaters from the vapor separated in the previous stage. Consequently, the advantage of this system is as follows. In the first place, the heat from the external source is supplied in the amount of Q_1 only in the first stage, i.e., at a high, mean integral temperature. Simultaneously the heat is supplied to the cold source from only the last stage at the same temperature as in the single-stage cycle. This leads to an increase in the cycle efficiency. In the second place, in the proposed MHD device the heat source distributes the liquid, and not the vapor, which is quite important in several cases.

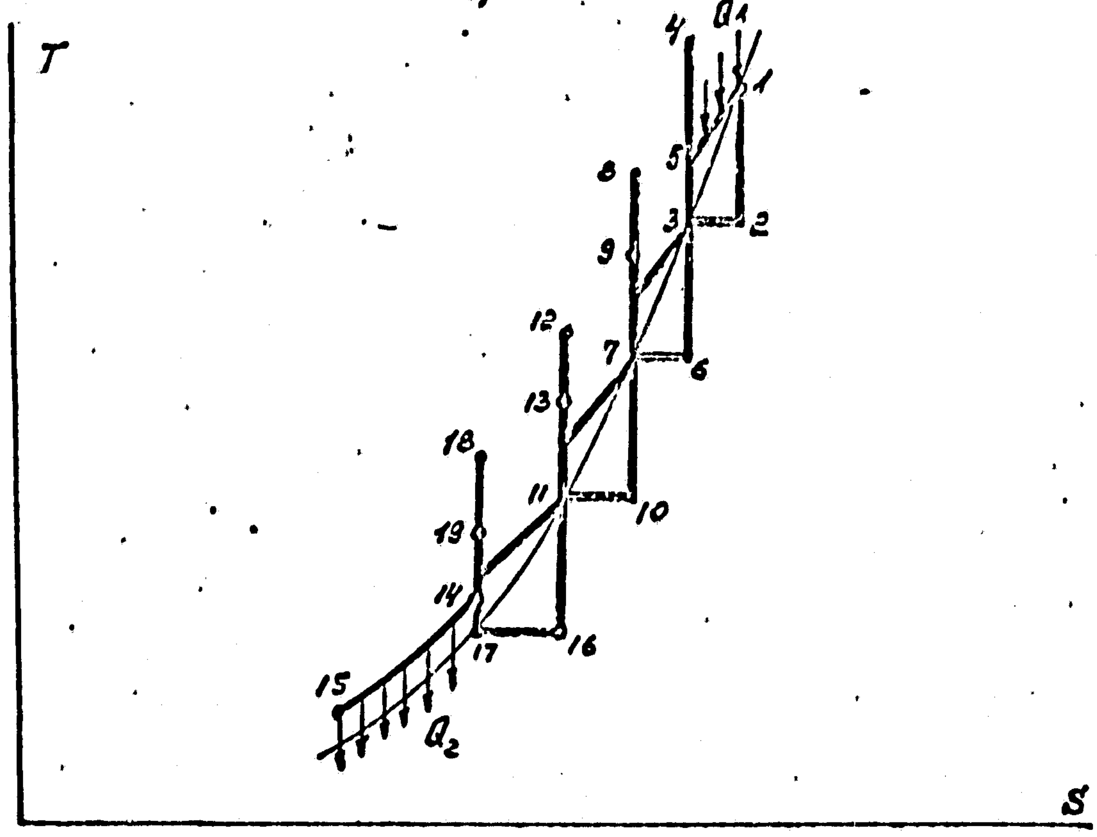
By way of an example, a calculation of the multi-stage regenerative system for Hg, Cs and K was made. It was assumed that the upper temperature equalled $T_1 = 1200°K$. A temperature corresponding to the pressure of $P_2 \approx 0.05$ technical atm. was used as the lower temperature of the cycle T_2. The number of stages n was varied from two to eight. The temperature drop in one stage was determined as $\frac{T_1 - T_2}{n}$. The thermodynamic coefficient of the cycle efficiency equalled the following, without allowance for losses in the two-phase nozzles, separators, and MHD generators: for potassium $\sim$ 19%, caesium $\sim$ 23%, and mercury $\sim$ 34%. A determination was made of the effective efficiency coefficient for potassium η_{eff} for $\eta_{nozzle} = 0.9$, $\eta_{separator} = 0.85$, and $\eta_{MHD\ generator} = 0.7$. For a four-stage device, $\eta_{eff} = 12\%$. /9

The diagram of the injector four-stage device is shown in Figure 4a, and its cycle is shown in the T - S-diagram in Figure 4b. Just as in the separator diagram, it is understood that 1 kg of liquid metal in the saturated state (1) leaves the heat source S_1. The metal expands in the nozzle of the injector of the first stage In^1, and thus its static parameters are characterized by point 2. Liquid in the amount of m^1, removed from the generator of the



* = S_1; ** = In; *** = C_2; **** = G

a)



(B)

Figure 4

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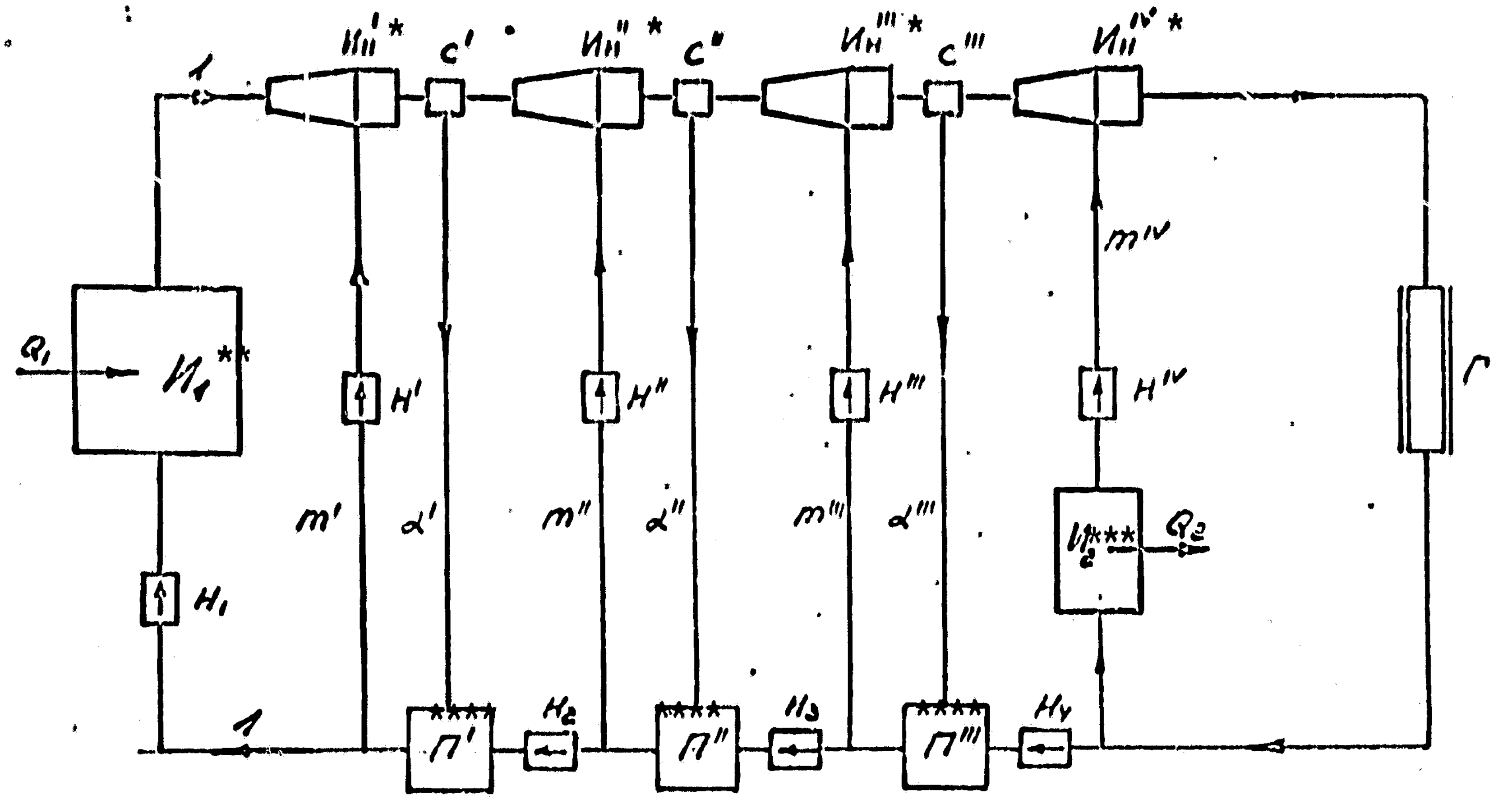
second stage G", is added to the mixing chamber of the injector. This liquid has retardation parameters characterized by point 9, and static parameters characterized by point 7. Point 9 is selected so that the liquid, entering the mixing chamber, has the optimum velocity. After the injector of the first stage, $(1 + m^1)$ kg of liquid metal, having the retardation parameters characterized by point 4, enters the generator of the first stage G^1. After the retardation parameters in the generator are reduced to point 5, one kg of liquid is removed and regurned to the heat source S_1 The remaining m^1 kg continue to operate in the generator G^1 until the retardation parameters and the static parameters corresponding to point 3 are reached, which is the initial state for the second stage at the input to the injector In". The subsequent stages operate in a similar manner. In the last stage, the stream m^{IV}, leaving the generator G^{IV} with the retardation parameters and static parameters corresponding to point 14 is cooled in the cooler C_2 to the point 15, giving off the heat Q_2 to the surrounding medium. With the temperature corresponding to point 15, this stream enters the mixing chamber of the injector of the last stage, with the previous optimum velocity.

As compared with the preceding system, one advantage of this system is the fact that the use of an injector with optimum stream velocities makes it possible to increase the efficiency coefficient of the device due to the absence of impact losses. In addition, in the injector system, the kinetic energy of the liquid removed from each subsequent stage is utilized in an efficient manner. /10

A specific calculation was performed for K, Cs and Kg for the same operational temperatures and pressures as in the separator system. Thus, for a four-stage device with potassium, the effective efficiency of the cycle amounted to 14% (thus $\eta_{MHD\ generator} = 0.7$; $\eta_{nozzle} = 0.9$; and $\eta_{diff.} = 0.85$).

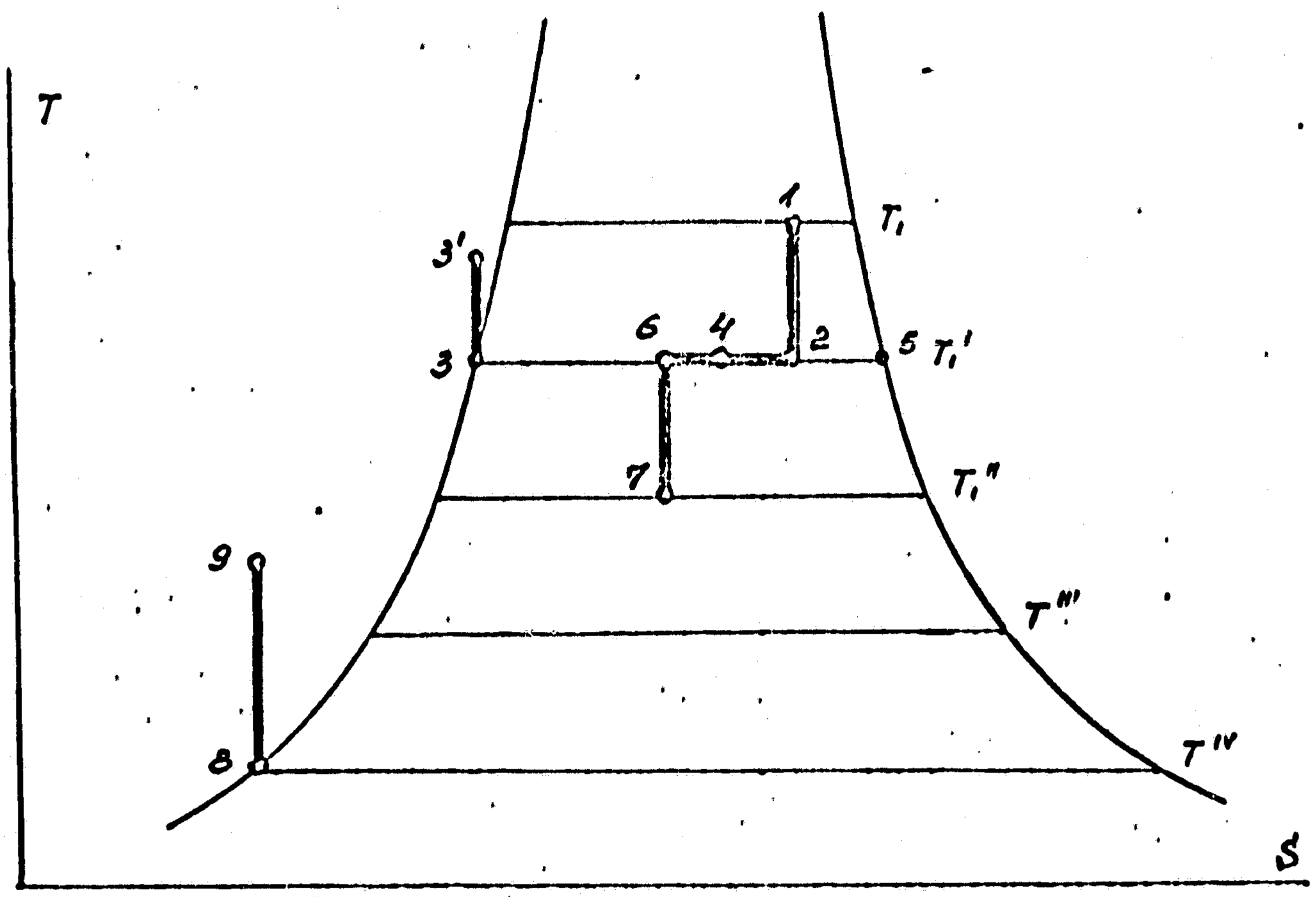
The multi-stage injector system examined in Figures 4a and 4b is not a regenerative system in the true sense of this word. Its advantage consists of the fact that not a cold liquid, but a liquid proceeding from the subsequent stage, is supplied to the mixing chamber of the injectors of all stages, with the exception of the last. Thus, the kinetic energy of the liquid streams introduced into the mixing chamber is employed advantageously. However, in this system there is total condensation in each injector, and each stage, beginning with the second, must operate from the left boundary curve.

Figures 5a and 5b show the diagram and cycle of a multi-stage injector device, built according to a different principle. Regeneration is employed here in explicit form, the injectors of the intermediate stages are only mixers, and the condensing stage is only the last stage. In this case, vapor with /11 any initial degree of dryness may be employed in the cycle, including a dry saturated vapor. In accordance with Figures 5a and 5b, 1 kg of humid vapor (point 1) leaves the heat source S_1. This vapor expands in the injector



* = In; ** = S_1; *** = C_2; **** = H

a)



(B)

Figure 5

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nozzle of the first stage In^1 up to the state with static parameters at point 2. m^1 kg of liquid with the same temperature T_1^1 is supplied to the injector mixing chamber. The static parameters of this liquid correspond to point 3, and its retardation parameters correspond to 3^1. The pressure at point 3^1, produced by the pump H^1, is selected in such a way that the liquid enters the mixing chamber at the optimum velocity. The amount of liquid m^1 must also be optimized. Due to the fact that the liquid m^1 is mixed, the stream of vapor is moistened somewhat and slowed down, accelerating the liquid which is added. The static parameters of the stream at the output of the injector In^1 corresponds to point 4. α^1 kg of dry-saturated vapor with static parameters at point 5 are removed from this stream of vapor. This vapor is employed in the mixing heater H^1 to heat the liquid to the temperature T_1^1. The amount of vapor α is found from the equation of thermal equilibrium. The kinetic energy of the vapor removed is not employed in this system. A very rough separator (C', C", C'" in Figure 5a) is employed to remove the vapor, because the problem is not to completely separate the vapor from the liquid, but only to remove a certain amount of vapor. After the vapor is removed, the stream acquires static parameters at point 6, with which it enters the injector of the second stage. The subsequent stages operate in a similar manner. Pumps H_1; H_2; H_3; H_4 are employed to obtain the correct pressure in the mixing heaters. /12
A liquid is injected into the injector of the last stage; this liquid is cooled to the lowest possible temperature since the heat Q_2 in the cooler C_2 is delivered to the surrounding medium. Thus, the last stage of the injector is the condensing stage. After this stage, the stream with the static parameters at point 8 and the retardation parameters at point 9 enters the generator. In the system under consideration, both impact losses as well as losses related to irreversible heat exchange in the intermediate stages can be greatly reduced. Naturally, a certain irreversibility remains in the mixing heaters. At the present time, this system is being optimized in order to clarify the effective efficiency values which can be achieved.

We may thus present the following conclusion.

1. A thermodynamic analysis of a multistage cycle with mixing of a cold liquid in the intermediate stage has shown that the cycle efficiency in this case is practically equal to the efficiency of a one-stage cycle.

2. Multi-stage regenerative cycles are proposed (with injector and separator), whose efficiency is very high (12 - 14%), due to an increase in the temperature level of the heat inlet , and also due to a decrease in losses during mixing caused by a difference in the vapor and liquid temperatures.

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