N69-13240

International Atomic Energy Agency
SYMPOSIUM ON THE PRODUCTION OF ELECTRICAL ENERGY BY MEANS OF MHD-GENERATORS
Warsaw, 24-30 July 1968

SM-107/153

THE EFFECTIVE ELECTRICAL CONDUCTIVITY OF A TWO-PHASE LIQUID-METAL FLOW *

by

N.D. Gavrilova, L.D. Dodonov, and I.T. Aladyev
G.M. Krzhizhanovsky Institute of Power Engineering, Moscow, USSR

At the present time scientific engineering problems associated with the creation of high-temperature power plants using alkaline metals with MHD generation of electric power are being intensely studied. If these plants turn out to be profitable at the upper temperature of the cycle $T < 1500°K$, then their industrial realization will become feasible in the next few years. The possibilities of creating [producing] a plant with a single-phase (liquid) and a two-phase (vapor-liquid) flow in the MHD generator are being examined. For the latter case, the study of the characteristics [performance curves] of the MHD generator in the presence of a vapor flow and the determination of the optimum vapor content in the duct is important. Since the generated power is proportional to $W^2\sigma$, the assumption of a certain vapor content can turn out to be advantageous, since in this case along with the decrease of the conductivity of the flow ($\sigma_{liq} = (10^6-10^7)\sigma_{vap}$) at a given flow rate. The velocity of the working medium is increased in the duct, and consequently, the effective values are $W_{2\varphi}$ and $\sigma_{2\varphi}$, corresponding to a maximum of production $W^2_{2\varphi}\sigma_{2\varphi}$. Moreover, in this case an increase in the efficiency of the separator (injector-condenser) is possible and consequently of the entire plant as a whole.

The range of change in the gas contents to which belong the optimum values of $W^2_{2\varphi}\sigma_{2\varphi}$ is defined experimentally. Data are limited on these characteristics of the two-phase flow [ref. #1-6]. They differ according to working media and temperatures, shape of the ducts, the effect of the magnetic field, as well as the values and character of the change in conductivity. In this paper the results are presented of the investigation of the changes in the e.m.f. induced by vaporized potassium flow ($T \approx 1050°K$ in the MHD duct, along with the electrical conductivity of this flow, a comparison and analysis of existing data.

If the liquid wets the surface of the duct, then the two-phase flow can have one of the following five basic structures: bubble, emulsion, cork (charge), annular (bar), diffuse-annular (disperse-film). In the first four structures the entire liquid phase of the flow is in contact with the wall of the duct and there are not discrete formations of liquid in the vapor. These can be called "vapor-in-liquid" structures. In the diffuse-annular structure, part of the liquid flows along the wall, and another part of it is sprayed in the vapor in the form of discrete formations (drops). When $\sigma_{liq} > \sigma_{vap}$, the drops are in practice electrically

Page - 6 [Cat 03] No. - CR-97872
Code - 1

* TRANSLATED FOR JET PROPULSION LAB, NAS 7-100, 1968.

isolated [insulated] from the liquid in the film and do not participate in the generation of energy in the MHD duct.

Structures of the two-phase flow in the ducts are basically defined by the volume flow rate of the vapor content β and the velocity of the mix W_{mix} [ref. #7,8]. Due to the relative velocity of the motions of the phases which are a function of the structure of the flow and the regime parameters, the actual (true) volume vapor content in the flow φ differs from the flow rate β. Consequently, the effective velocity of generation and the effective conductivity of the two-phase flow that are a fucntion of the true parameters of the flow are also functions of the structure of the flow. When $\sigma_{liq} > \sigma_{vap}$, the effective conductivity for the different structures of the flow are expressed by the following relationships:

A. For the bubble and emulsion structures of the two-phase flow, by the Maxwell relationship

$$\frac{\sigma_{liq}}{\sigma_{2\varphi}} = \frac{2 + \varphi}{2(1-\varphi)} \tag{1}$$

B. For the purely annular structure

$$\frac{\sigma_{liq}}{\sigma_{2\varphi}} = \frac{1}{1 - \varphi} \tag{2}$$

C. For the diffuse-annular structure

$$\frac{\sigma_{liq}}{\sigma_{2\varphi}} = \frac{1}{1 - \varphi^*} \tag{3}$$

For this structure (2) is a limit function, since due to the carrying off of the moisture into the vapor nucleus the moisture content of the flow, averaged along the duct cross section 1-φ, is greater than the moisture content of the film 1-φ*. In the presence of a substantial conductivity of vapor $\sigma_{2\varphi}$ increases and $\sigma_{liq}/\sigma_{2\varphi}$ decreases.

For the flows with a "vapor-in-liquid" structure, the effective velocity of generation is equal to the mean true velocity of the liquid phase and is defined by the relationship:

$$\overline{W}_{2\varphi} = \overline{W}' = \frac{\overline{W}_0(1-x)}{1 - \varphi} \tag{4}$$

For the diffuse-annular structure and when $\sigma_{liq} > \sigma_{vap}$, the effective velocity of generation is defined by the relationship:

$$\overline{W}_{2\varphi} = \frac{\overline{W}_0(1-x^*)}{1 - \varphi} \tag{5}$$

and is less than the cross-sectional mean true velocity of the liquid. Here W_0 is the velocity of circulation, $(1-x^*)$ is the mass moisture content of the flow along the film.

Let us examine the results of the experimental research of conductivity of two-phase flows.

In the paper [ref. #1] a change in $\sigma_{liq}/\sigma_{2\varphi}$ of the mix[ture] of the eutectic Na-K with nitrogen at low temperatures, $W_\rho = 900 - 2000$ kg/m²sec and $\varphi < 0.6$ ($x < 0.02$) at which structures of the "vapor-in-liquid" flow are known to exist was investigated by the conduction-flowmeter method (B = 6000-8000 gauss) in a flat duct of 50 X 6.7 mm having a length of L = 115 mm. In the tests the φ-values were measured as to the absorption of gamma rays at the input and output of the MHD duct. The experimental data are approximated by the relationship:

$$\frac{\sigma_{liq}}{\sigma_{2\varphi*}} = \exp 3.8\varphi \qquad (6)$$

Figure 1 shows a comparison of this relationship with function (1), valid inthe investigated range of φ and confirmed by the authors of [ref.#1] and the data with the air-water flow [ref. #2]. The cause of the divergence of the data for Na-K—N_2 [ref. #1] and the data for the air-water flow [ref. #2], as indicated by the authors themselves in [ref.#3], is the interaction of the flow with the magnetic field. However, the actual cause is not the presence itself of a supplementary force effect on the flow, but the fact that under its influence, the slippage of the phases increases and consequently the volume vapor content of the flow changes, and possibly even its structure. In the processing and approximation of the results of [ref. #1], the φ-values were used that were in fact measured outside the magnetic field (at the input and output of the duct), while obviously pondermotive forces in the flux affected the changed e.m.f. The very effect of the pondermotive forces on water water due to its small conductivity is negligible.

Maxwell's formula is the general [overall] relationship forthe effective value of any characteristics of permeability (λ, σ, ε) of a two-phase medium consisting of a matrix and occlusions dispersed [diffused] in it with a total relative volume φ having a value of permeability different from the permeability of the matrix. Relationship (1) is written in values of electrical conductivity for the condition $\sigma_{liq} \gg \sigma_{vap}$.

The paper [ref. #4] presents data on the relative electrical capacity of the two-phase vapor-water flow at atmospheric pressure as a function of the true volume vapor content. These data which relate to the bubble structure of the flow are transformed into values of relative electrical conductivity and are shown in figure 1 for comparison. They agree well with relationship (1).

The investigation of the characteristics of the two-phase flow of the eutectic Na-K with argon purging have been conducted in the work [ref.#5]. Measurements were made for the "gas-in-liquid" structures at the following regime parameters of flow: P = 1.5 atm abs, T = 320-420°K, $W\rho$ = 330-600 kg/m^{2}sec, $\varphi < 0.65$, ρ'/ρ'' = 450-650. The flow was sampled by the conduction-flowmeter method, the electrical-resistance method, and the gamma-attenuation method. The results of the measurements by the electrical-resistance and the conduction-flowmeter methods processed as a function of the φ-values measured by the gamma-attenuation method are presented in the form $\sigma_{liq}/\sigma_2 = f(1-\varphi)$ and are shown in figure 1 for comparison. As is seen from the graph, the data of [ref. #5] satisfy Maxwell's formula. The coincidence of the results of measure-

PRECEDING PAGE MISSING

where $F_1(R_{ex}/R_{in})$, $F_2(R_{ex}/R_{in})$ are functions of R_{ex}/R_{in}. Here additional information is necessary concerning the structure of the flow and its true volume vapor contents. Due to the absence of such information, the analysis was made as a function of the cross-sectional mean true volume vapor contents of the flow at the input into the duct.

In an investigation that we performed earlier on the hydrodynamics of a two-phase vapor-potassium flow [ref. #9], it was established that the regularity of the change in the hydrodynamic characteristics of the vapor-potassium flow are the same as for the vapor-water flow and Armand's formulas is recommended for the calculation of the true volume vapor contents [ref. #3]. In processing the data, we used φ-values calculated after [ref. #8]whose functions were obtained in the absence of pondermotive forces, and consequently, the φ-values characterize the state of the flow at the input into the MHD duct.

The results of the data processing are shown in figure 1. From the graph it is evident that in the region $(1 - \varphi) > 0.1$, i.e., for a "vapor-in-liquid" structure, there is sufficiently [fairly] good coincidence of our data with [ref. #2, 4, 5] and function (1). This confirms the fact that in our tests, due to the small length of the duct in the magnetic field (L = 36 mm), the effect of the magnetic field on the structure of the flow was small.

The boundary between the "vapor-in-liquid" structures and the diffuse-annular structure of the flow in [ref. #2] is defined as $\varphi > 0.9$. Our estimates of this boundary with respect to the critical velocity of the vapor [ref. #9] agree with the recommendation of [ref. #2]. For the disperion-film structure of the flow ($(1-\varphi) < 0.1$), the development [processing] and representation of the data as a function of the cross-sectional mean flow of the true volume vapor contents bear a conditional character since, under the conditions of only liquid conducivitity of the flow, only the film of the liquid takes part in generation, and the mean moisture contents of the flow along the film are less than the cross-sectional mean of the duct. However, such processing enables us to compare the results with the limit function (2). From figure 1 it is evident that in this processing, our results for $(1-\varphi) < 0.1$ lies further to the right than the limit function (2) and consequently the conductivity of the diffuse-annular vapor-potassium flow at temperatures of approximately 1050°K is lower than the conductivity of the flow which can be provided by the liquid phase of the two-phase flow under the condition that it is entirely in contact with the electrodes. The above presented indirect proof of that which our data, obtained without the effect of the magnetic field (the effect of the pondermotive forces are negligibly small) makes it possible to suggest that the deviation from the limit function is caused by the carrying off of the liquid into the nucleus of the flow.

For purposes of comparison figure 1 shows the results of the work [ref.#6] developed [processed] according to the true volume vapor content at the input into the duct, calculated after [ref. #8] (dark dots) and after $\varphi = \beta$ (light open dots). From figure 1 it is evident that following the data of [ref. #6] as well as following other data, the value $\sigma_{liq}/\sigma_{2\varphi}$

are greater than the limit values $\sigma_{liq}/\sigma_{2\varphi} = 1/(1-\varphi)$ which are provided only by the conductivity of the liquid in the flow.

A comparison of the data of [ref. #6] and ours processed by identical methods—according to the true volume vapor content at the input into the duct—shows that they are located farther to the right of our data and although there is a continuation of relationship (6) which according to the magnetic effect is obtained at the close values B^2L, that also the data of [ref. #6], as discussed above, are plotted with respect to the φ-values at the input into the duct. This makes it possible to judge the effect of the magnetic field as to φ, and consequently, to the electrical conductivity of the flow.

The pondermotive forces in the two-phase flow, acting basically on the liquid metal, increase the slippage of the phases and, as a result of this, the carrying away of the liquid from the boundary-layer film to the vapor nucleus of the flow should [must also] increase in the flow of the diffuse-annular structure, and the conductivity of the flow should decrease. This is well illustrated in figure 1 by a comparison of our data and the data of [ref. #6] which differ only by the effect of the magnetic field. Experimental research is necessary in a broad range of change in the magnetic effect of B^2L and flow rate parameters of the flow.

References

1. M. Petrik and K.Yu. Lee, "Characteristics of Liquid-Metal MHD Generators. Magnetohydrodynamic Formations of Energy." *Proceedings of an International Symposium, Paris, 1964*, VINITI Publishing House, Moscow, 1966, p. 543.

2. M.Petrik and K.Yu Lee, "MHD Generators in Tow-Phase Liquid Metal Streams," *Proceedings of an International Symposium*, Salzburg, Austria, 1966.

3. in English

4. in English

5. in English

6. P.L. Kirillov, V.I. Subbotin, and I.P. Stakhanov, "Measurements of Electric Conductivity of Liquid Vapor Mixtures of Potassium," see, *Proceedings of an International Symposium*, Salzburg, 1966.

7. B.K. Koslov, *Regimes and Forms of Motion of an Air-Water Mixture in a Vertical Tube*, Collection on "Hydrodynamics and Heat Exchange while Boiling in a High-Pressure Vessel," Academy of Sciences of the USSR, 1955.

8. A.A. Armand, "Resistance During the Motion of a Two-Phase System in a Horizontal Tube," *Izvestiya VTI*, No.1, 1946.

9. I.T. Alad'yev, N.D. Gavrilov, and L.D. Dodonov, "Hydrodynamics of the Two-Phase Flow of Potassium in a Tube," Collection on *Investigations of Heat Exchange, Hydrodynamics, and Thermophysical Properties of Matter*, Nauka Publishing House, Moscow, 1968.

Figures

1. Comparison of the calculated formulas and experimental data for the effective electrical conductivity of two-phase flow. 1. According to Maxwell's formula (1); 2. According to the ratio in Ref 2; 3. According to the ratio in Ref.6 -- an approximation of the data in Ref 1; 4. Given in Ref.2; 5. Given in Ref.4; 6. Given in Ref 5; 7, and 8. Given in Ref 6, corresponding to the treatment for ϕat the duct inlet and for $\phi=\beta$; 9. Given by the authors.

2. Relative change in the e.m.f. generated in a duct in the course of a two-phase potassium vapor flow in a magnetic field depending on $x$and W_{mix}.

   1. $W\rho = 225$ *kg/m² sec,* *2.* $W\rho = 415$ *kg/m² sec*