EFFECT OF A LONGITUDINAL MAGNETIC FIELD ON THE CHARACTERISTICS OF A STABILIZED CHANNEL ARC

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The results of calculations of the temperature profiles and volt–ampere characteristics of a long cylindrical argon arc in a longitudinal uniform magnetic field are presented. The calculation was made for the following parameters: pressure $p=0.1$–10.0 atm; temperatures $T=1000$–$20{,}000$°K; magnetic field induction $B=0$–10 T; diameter of cylindrical channel $d=1.0$ cm. It is shown that for strongly radiating arcs ($p \geq 1.0$ atm) the temperature profiles become more inflated with an increase in the magnetic field, while for weakly radiating arcs ($p \leq 0.1$ atm) the appearance of "loops" in the volt–ampere characteristics is typical for certain conditions ($14{,}000 \leq T \leq 20{,}000$°K, $B \geq 1.0$ T), indicating the impossibility of arcing under these conditions.

The characteristics of helium and hydrogen arcs of low pressure ($p \leq 0.05$ atm) in the presence of a longitudinal magnetic field have been calculated in earlier works [1-4] without allowance for the radiation. The marked effect of the magnetic field on the temperature profile and the volt–ampere characteristic of the arc was discovered.

The present report is devoted to the calculation of a stabilized channel arc in a longitudinal magnetic field in the presence of radiation of the gas. Some preliminary results of this study were published earlier [5].* The calculation was made for an argon arc 1 cm in diameter in the ranges of variation in the pressure $p=0.1$–10 atm, in the axial temperatures $T_0=1000$–$20{,}000$°K, and in the magnetic field induction $B=0$–10 T.

Since under these conditions an argon arc can be considered as optically transparent [6] with a certain degree of accuracy, this assumption was used in the calculation, allowing a considerable simplification of the computations.

Another assumption was also made – that local thermodynamic equilibrium (LTE) is present in the arc, as a result of which no allowance was made for separation of the temperatures of the electrons and ions or their finite recombination rate, i.e., factors which can have an effect on the arc characteristics under certain conditions (at low pressures) [7]. We note that making allowance for the nonequilibrium nature of the plasma in the presence of strong magnetic fields is presently associated with certain difficulties connected with the insufficient study of the plasma properties and the processes of energy exchange under these conditions. The adopted assumption that LTE is present should not have a marked effect on the results of a calculation of the volt–ampere characteristics at pressures of 1.0 and 10 atm, but it may affect to a certain extent the quantitative results pertaining to a pressure of 0.1 atm. Nevertheless, the use of the concept of LTE allows one to obtain important results characterizing the behavior of an arc in a longitudinal magnetic field without a very complicated computational procedure.

So let us consider the following problem. A long cylindrical arc, confined by walls, is burning in a slowly moving ($M \ll 1$) stream of argon. A uniform magnetic field with induction B is applied along the arc.

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* Unfortunately, in [5] the volt–ampere characteristic of the arc for $p=1$ atm was plotted inaccurately. This inaccuracy is corrected in the present report.

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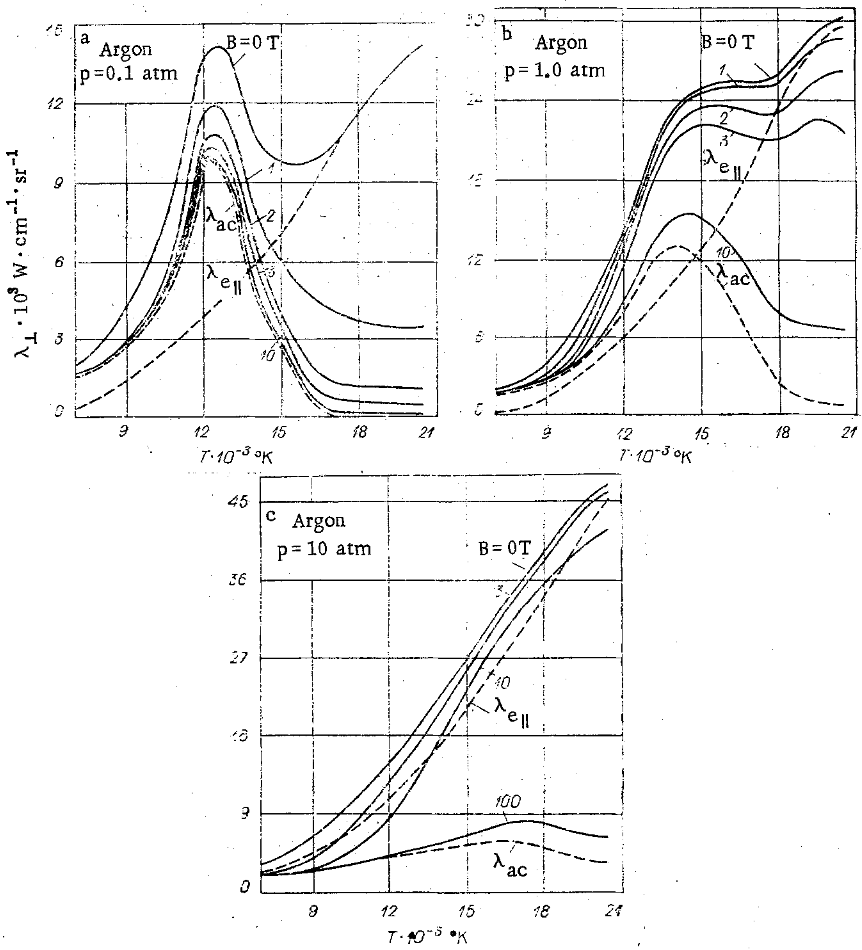

Fig. 1

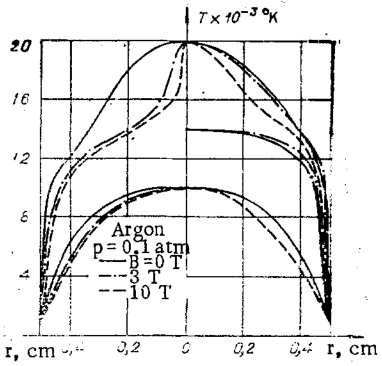

Fig. 2

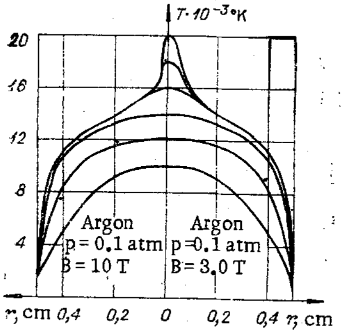

Fig. 3

Moreover, it is assumed that the temperature gradient along the arc is considerably smaller than the radial gradient, while convection can be neglected. Thermal diffusion and thermomagnetic effects were not taken into account.

With allowance for these assumptions the state problem is reduced to the solution of the energy equation for a cylindrical arc

$$\frac{1}{r}\frac{d}{dr}\left(\lambda_{\perp} r\frac{dT}{\partial r}\right)+\sigma_{\parallel} E^{2}-u=0 \tag{1}$$

with the boundary conditions

$$r=0: T=T_0 \text{ and } dT/dr=0;$$
$$r=r_0: T=T_w.$$

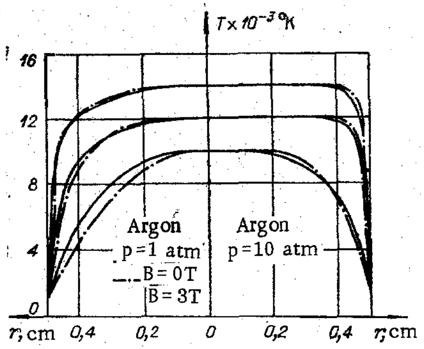

Fig. 4

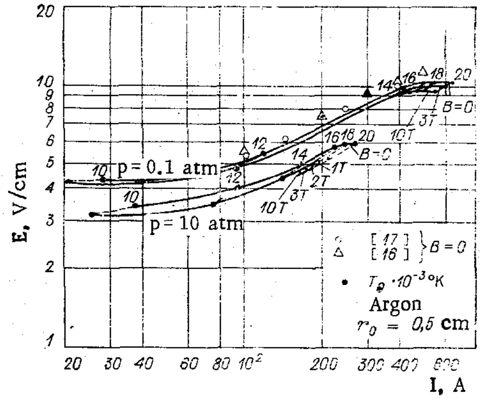

Fig. 5

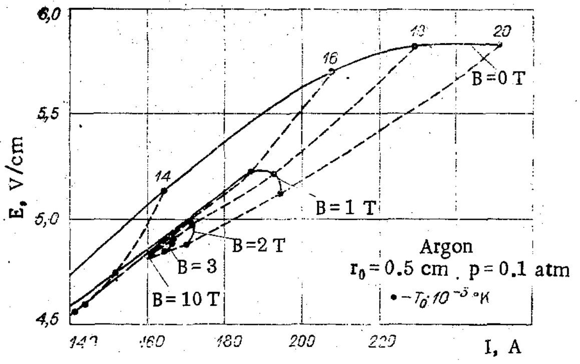

Fig. 6

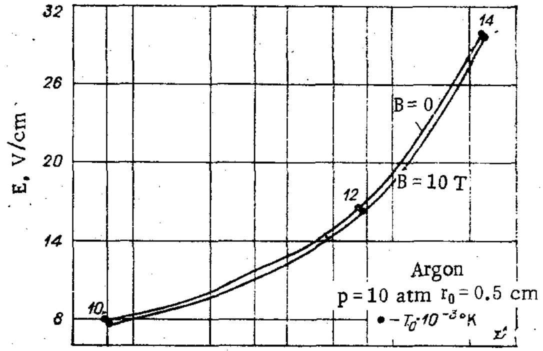

Fig. 7

Here T is the gas temperature; E is the electric field strength; u is the power of the volumetric radiation of the gas; $\sigma_{||}$ is the electrical conductivity of the plasma in the direction of the magnetic field; $\lambda_\perp$ is the thermal conductivity of the gas in the direction perpendicular to the magnetic field vector.

On the basis of physical concepts concerning the effect of a magnetic field on the electrical and thermal conductivity of a plasma one can come to the conclusion that $\lambda_{||}$ and $\sigma_{||}$ should coincide with the corresponding values of λ and σ in the absence of a magnetic field. The value $\lambda_\perp=\lambda_{e\perp}+\lambda_{ac}$, where $\lambda_{e\perp}$ is the thermal conductivity of the electron gas across the magnetic field and λ_{ac} is the thermal conductivity of the atomic gas and the chemical thermal conductivity due to the transfer of ionization energy. Under the given conditions the contribution of the ion component to the thermal conductivity of the plasma is extremely small [8].

The electron thermal conductivity $\lambda_{e\perp}$ was calculated from the equation [9]

$$\lambda_{e\perp}=\frac{\lambda_{e\parallel}}{1+(\alpha\beta_e)^2},$$

where the coefficient α characterizes the form of interaction of the particles in the plasma and is a function of the exponent m in the expression for the collision frequency of the particles as a function of their velocity and β_e is the Hall parameter for the electrons, which varies within wide limits from $\beta_e=0$ to $\beta_e \ll 1$. We note that the Hall parameter is extremely small for the ions. According to [9],

$$\alpha=\frac{2{,}5}{2.5+m+m^2}.$$

For low temperatures ($T \leq 8000$°K) in argon the electron thermal conductivity is determined mainly by the electron–atom interactions, which can be described with the help of a model of solid spheres ($m=0.5$), while for high temperatures ($T>10{,}000$°K) the Coulomb interactions ($m=-1.5$) have the dominant effect on the value of λ_e. In both cases $\alpha=0.77$. Only in the small temperature interval of $8000<T<10{,}000$°K, when the contributions of the Coulomb and electron–atom collisions are comparable, can the value of α vary in the range of 0.77–1.1.

Since in the indicated temperature interval, as will be shown below, the value of $\lambda_\perp$ does not change very much under the effect of a magnetic field, in the subsequent calculations we took $\alpha = 0.77$ for the entire temperature range T = 1000-20,000°K. The calculation of $\lambda_{e\|}$ was made using the third approximation of the Chapman–Enskog method for T > 10,000°K and by the approximate methods of [10] for T < 10,000°K. The values of λ_e were calculated and the values of λ_{ac} were determined as the difference between the data of [8] on $\lambda_\|$ and the calculated values of λ_e. The results of the calculation of $\lambda_\perp$, $\lambda_{e\perp}$, and λ_{ac} of argon as functions of the temperature for pressures of 0.1, 1.0, and 10.0 atm and different values of the magnetic field induction (B = 0-10 T) are shown in Fig. 1(a-c). It is seen that the effect of the magnetic field on $\lambda_\perp$ and $\lambda_{e\perp}$ is especially important at p = 0.1 atm.

Equation (1) was solved numerically on an electronic computer with allowance for the values of $\lambda_\perp$ obtained. The values of $\lambda_{||}$, $\sigma_{||}$, and u were taken from [8, 11-14]. The results of the calculations are presented in Figs. 2-4, where some characteristic temperature profiles are shown, and in Figs. 5-7, where the volt–ampere characteristics of the arcs are shown.

Let us examine the results obtained in more detail. It is seen from the calculations that with fixed values of p, r_0, and T_0 the electric field strength and the arc current decrease monotonically with an increase in the magnetic field strength. In this case the decrease in E is slight while that of the current strength I is considerable. For example, with p = 0.1 atm and T_0 = 20,000°K the values E = 5.83, 5.12, 4.88, 4.84, and 4.81 V/cm and I = 251, 194, 170, 164, and 160 A correspond to B = 0, 1, 2, 3, and 10 T, while in the case of p = 1 atm and T_0 = 20,000°K the values E = 10.4, 10.1, and 9.7 V/cm and I = 633, 614, and 521 A correspond to B = 0, 3, and 10 T.

It should be noted that the calculated volt–ampere characteristic for B = 0 T and p = 1 atm agrees satisfactorily with the experimental one of [15]. In this case rather good agreement is observed for E in the entire range of variation of T_0 examined while a certain understating is observed for the current in the range of T_0 = 10,000-12,000°K. For T_0 = 12,000-14,000°K the agreement of the calculated and experimental values of the current strength, as seen from Fig. 5, is quite satisfactory. A comparison between the calculated results obtained and the data of preliminary experiments at pressures of 0.1 and 10 atm [16] shows that because separation of the electron temperature is neglected the calculated values of I at p = 0.1 atm can be understated compared with the experimental values in a wider interval of T_0. Some understating of the calculated values of E is evidently observed at p = 10 atm.

Let us examine the temperature profiles presented in Figs. 2 and 4. In order to interpret the results obtained more clearly, let us analyze Eq. (1). After integration we obtain

$$T = T_0 - \int_0^r \frac{dr}{\lambda_\perp r} \int_0^r (\sigma_\| E^2 - u)\, r\, dr. \tag{2}$$

From this it is seen that two values affect the form of the radial temperature profile in a stabilized discharge in the presence of volumetric radiation: $(\sigma_\| E^2 - u)$ and $\lambda_\perp$. The role of the first of these is discussed in detail in [17]. For the case of strongly radiating, optically transparent arcs in the case when u becomes commensurate with $\sigma_\| E^2$ the temperature profile is made more inflated than follows from (2).

On the other hand, an increase in the magnetic field, i.e., a decrease in $\lambda_\perp$, leads to the opposite effect: the temperature profile should be less inflated. In this case one should expect the greatest effect of the magnetic field to be displayed only for axial arc temperatures T_0 = 16,000-18,000°K, which corresponds to a very strong decrease in $\lambda_\perp$ (see Fig. 1). At lower axial temperatures the decrease in $\lambda_\perp$ is not so great, so that the effect of the magnetic field on the temperature profile of the arc is displayed to a lesser extent. The temperature distributions presented in Fig. 2 for T_0 = 20,000 and 10,000°K at p = 0.1 atm illustrate the effect of the dependence $\lambda_\perp = f(B, T)$ on the temperature profile, since the role of radiation is insignificant in this case. Whereas for T_0 = 10,000°K a very small change in the temperature distribution is observed upon an increase in B from 0 to 10 T, for T_0 = 20,000°K the temperature profile is deformed very considerably with an increase in B. The formation of a temperature peak in the center of the arc with an increase in the magnetic field strength in the interval of 18,000-20,000°K is characteristic. In this case a "loop" appears in the volt–ampere characteristic of the arc (see Fig. 6), indicating that when the arc is supplied from ordinary current sources its burning becomes impossible under the given conditions.

It is convenient to clarify the behavior of the volt–ampere characteristics on the example of a nonradiating arc (with p ≤ 0.1 atm, let us say). From Eq. (1) we find that

$$E^2 \sim \frac{1}{\sigma_\|} \frac{1}{r} \frac{d}{dr} \left(\lambda_\perp r \left| \frac{dT}{dr} \right| \right). \tag{3}$$

In addition,

$$I = 2\pi E \int_0^{r_0} \sigma r dr. \quad (4)$$

Since $\sigma_\|$ (T) increases monotonically for $T \geq 8000$°K ($\sigma \sim T^{3/2}$) while the dependence $\lambda_\perp(T)$ has a complicated nature it is convenient to divide the temperature interval T_0 into three parts to evaluate the effect of $\lambda_\perp$ on E.

In the interval of $T_0 = 10^4 - 12.5 \cdot 10^3$°K the value of $\lambda_\perp$ increases strongly with T_0, as a consequence of which E and I increase, as seen from (3) and (4). In the region of $12{,}500 < T_0 \leq 17000$°K at a fixed B the thermal conductivity $\lambda_\perp$ decreases faster than $\sigma_\|$ increases with an increase in T_0, as a consequence of which E decreases while I continues to increase. Finally, in the third region of $17000 \leq T_0 \leq 20{,}000$°K the value of $\lambda_\perp$ varies little with an increase in T_0 when B is fixed, while the temperature profile becomes sharply irregular. Therefore, under certain conditions, when $B \geq 2$ T and $p = 0.1$ atm, for example, E and I can decrease with an increase in T_0.

At high pressures ($p \geq 1.0$ atm) the formation of the temperature profile of an arc burning in a longitudinal magnetic field can be affected in equal measure by both the reduction in $\lambda_\perp$ and the increase in the radiation, i.e., the decrease in the value ($\sigma_\| E^2 - u$), which is illustrated in Fig. 4. Thus, in the case of $p = 1$ atm the temperature profile becomes less inflated with an increase in B at $T_0 = 12{,}000$°K and 10,000°K while at $T_0 = 14{,}000$°K it becomes more inflated. In the case of $p = 10$ atm, as indicated above, the temperature profile is made more inflated in the core of the arc while in the boundary regions the temperature gradients are decreased in all cases because of the reduction in the amount of energy transferred by thermal conduction.

An estimate of the effect of the separation of the electron temperature from the temperature of the heavy particles, made by the method presented in [17], shows that, for example, for $p = 1$ atm and $T_{e0} = 14{,}000$°K at $B = 0$ and 10 T the values of E differ little from the corresponding values found under the conditions of the absence of a temperature separation, while the currents are somewhat increased (by about 10-12% in this case). The nature of the temperature profiles and the volt–ampere characteristics is not altered essentially in this case.

In conclusion, we note that the problem of the magnetogasdynamic instability of an arc burning in a longitudinal magnetic field is not considered in this report since this question requires an independent detailed study.

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