# HYDRODYNAMIC CHARACTERISTICS OF THE LIQUID-METAL BLANKET OF FUSION REACTORS

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A theoretical method of determining the hydraulic resistance of liquid-metal blankets of fusion reactors is presented along with numerical results.

One of the most important elements of fusion reactors of the "tokomak" type is the blanket — a device designed to convert the kinetic energy of thermonuclear neutrons to heat, produce tritium to participate in the synthesis reaction and (if it contains uranium-bearing compounds) to make nuclear fuel $_{94}P^{239}$. The blanket is located behind the first wall of the reactor chamber and consists of individual sections — modules. Water, gas, or liquid metals have been suggested for use as the coolants in the blanket.

Questions related to the flow of liquid-metal coolants in the blanket under the influence of strong magnetic fields have been studied relatively little. In connection with this, it is interesting to compare the hydraulic resistances of the main types of liquid-metal blankets when the heat removed from them is the same. In the analysis below, the wide range of designs of uranium blankets are divided into three types.

The first type is a blanket in which the coolant flows in the transverse direction over corridor bundles of fuel elements which constitute the uranium zone. Here, the inlet and outlet header sections are located in front of and behind the uranium zone. This type of blanket was examined in [1, 2].

The second type is a blanket in which the coolant again flows over bundles of fuel elements, but the header sections are located on the sides of the uranium zone [3].

The third type is a blanket in which coolant flows along fuel-element bundles located in circular or rectangular channels [4]. The headers are located above or below the uranium zone. We will henceforth assume that all three types of blankets have the same geometric dimensions: length, thickness, and height of the uranium zone. We also assume that the volume contents of uranium are the same in each type of blanket, which means that their thermal capacities are roughly the same.

It is known [5] that, in the absence of a magnetic field, flow in the inter-row space of dense corridor (in-line) bundles is streamlike in character. The plane jet issuing from the narrow gap of the preceding row expands and impacts against the front surface of the new row, while the outer boundary of the jet intersects this surface at an angle on the order of 30-40°. This produces an extensive region of circulating flow, and most of the hydraulic resistance is the result of form drag. Frictional drag amounts to only a small percentage of the total drag.

A completely different pattern is seen in the flow of an electrically conducting fluid in the inter-row space in the presence of strong transverse magnetic fields. To analyze the character of flow in this case, use should be made of the results of the theory of MHD jets [6, 7]. In this case, the plane jet from the source into a half-space with a transverse magnetic field rapidly expands under the influence of electromagnetic forces and its velocity on the axis $x_{st}$ vanishes a certain distance from the source. For example, $x_{st} < 10^{-3}$ m for the first type of blanket with $v_{av} = 0.04$ m/sec in the narrowest section of a bundle in a lithium flow and with $B_t = 5$ T for the toroidal component of the induction of the magnetic field.

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Determination of the boundary in the presence of a transverse magnetic field shows that even at $B_t$ = 0.5 T the boundary of the jet nearly coincides with the boundary of the inter-row space, i.e. the surface of the fuel element. Thus, a sufficiently strong transverse magnetic field eliminates the circulatory flow region in the inter-row space, motion in this space becomes quasi-potential in character, and form drag vanishes.

Ignoring friction on the surface and allowing for the electrical conductivity of the fuel element shells, we obtain the pressure gradient on an elementary section Δh [8]:

$$\Delta p = \sigma_t B_t^2 v \Delta h \alpha/(\alpha + 1). \tag{1}$$

Here, v and α are functions of the longitudinal coordinate and change from section to section in the inter-row space.

The mean values $v_{av}$ and $\alpha_{av}$ are determined by the relations:

$$v_{av} = 2W/\rho c_p \Delta T dl (1 + \gamma), \tag{2}$$

$$\alpha_{av} = 2\sigma_{sh} \delta_{sh} (1 - \gamma)/\sigma_t (1 + \gamma) a, \tag{3}$$

the value of a being taking equal to the radius of a fuel element.

Then, without allowance for the hydraulic resistance of the headers, the pressure drop for the first type of blanket can be determined from the formula

$$\Delta p = \sigma_t B_t^2 v_{av} h \alpha_{av}/(\alpha_{av} + 1). \tag{4}$$

As will be shown below, allowance for the effect of the poloidal component of the magnetic field $B_p$ = 0.5 T has a significant effect on the redistribution of flow rate along the headers and makes it necessary to choke or shape the rate. With allowance for these factors, the pressure drop on the uranium zone will be considerably greater than the value found from Eq. (4).

It should be noted that the smooth character of flow about the bundles and the absence of circulatory flow significantly improve heat-transfer conditions. The angular dependence of the local heat-transfer coefficient smoothes out [5] and the trough in the region corresponding to the previously-existing recirculation zone disappears.

In the case when the direction of motion of the coolant in corridor bundles and the direction of the magnetic field are colinear, the magnetic field should not be expected to have a significant effect on drag. It is known from the theory of MHD jets [7] that the magnetic field acts in this case through the mechanism of turbulence suppression. This should shift the point of intersection of the boundary of the jet with the fuel-element surface upstream to some extent. Such a shift will not appreciably affect the character of flow in the inter-row space.

The results of experiments on bundles in a transverse flow in a strong longitudinal magnetic field confirm this hypothesis. Depending on the width of the channel, drag at the narrowest point changes only 5-10% due to the magnetic field. However, it should be considered that along with the toroidal component of the magnetic field, there is also the poloidal component $B_p$ = 0.5 T perpendicular to it. However, as was shown earlier, a complete transition to smooth flow over the bundles takes place with such a value for the magnetic field component transverse to the flow direction. The pressure drop in the channels of the uranium zone will henceforth be determined from Eq. (4) with the substitution of $B_t$ for the first variant of blanket and, accordingly, the substitution of $B_p$ and d in place of h for the second variant.

In performing calculations for the second type of blanket, it is necessary to consider the action of the toroidal component in the lateral header sections and to take into account the poloidal component of the magnetic field in the uranium zone.

The pressure drop can be determined by using the solution of the MHD equations in the header sections in a unidimensional approximation [9]. The complex $B_e^2$ enters into this approximation:

$$B_e^2 = \frac{c_1 B_t^2 h^2 (\alpha_{av} + 1)(1 + \gamma)}{2\sigma_t B_p^2 \alpha_{wa} \gamma d (a + \delta)}. \tag{5}$$

Here, $c_1$ and $\alpha_1$ are determined as

$$c_1 = \sigma_t \alpha_1/(\alpha_1 + 1); \quad \alpha_1 = \sigma_{wa} \delta_{wa}/\sigma_t S.$$

The expression for $B_e^2$ corresponds to the ratio of the electromagnetic forces in the header to the same forces in the channels of the uranium zone.

The pressure drop in the channels of the uranium zone is determined with allowance for the effect of the poloidal component of the magnetic field from the formula

$$\Delta p = \pm c\partial G/\partial x, \tag{6}$$

where G is the mass rate in the inlet (−) and outlet (+) headers, while

$$c = \frac{4\sigma t B_p^2 \alpha_{av} \gamma d (a + \delta)}{(\alpha_{av} + 1)(1 + \gamma)\rho F}. \tag{7}$$

Considering the nonuniformity of the energy release through the thickness of the uranium zone − which is exponential − it becomes necessary to shape the discharge in order to realize uniform heat removal. This can be done by installing a choking grid at the inlet of the uranium zone. The pressure drop in this case is determined by the relation

$$\Delta p = \frac{cG_0}{h}\left[B_e^2\left(-p - \frac{1}{\exp\left(-\frac{1}{p}\right) - 1}\right) - \frac{1}{p\left(\exp\left(-\frac{1}{p}\right) - 1\right)}\right]. \tag{8}$$

Without allowance for choking, the value of Δp is determined from the approximate formula:

$$\Delta p = cG_0 B_e/h. \tag{9}$$

Shaping of the flow rate instead of choking is possible in principle, but it involves a significant broadening of the channels of the uranium zone on the sections of greatest energy release and a corresponding deterioration in the neutron-physical characteristics of the blanket. If we compare Eqs. (8) and (9), we see that $\Delta p \sim B_t^2$ in the first case but $\Delta p \sim B_t B_p$ in the second case. It is clear from this that the contribution of choking to the drag of the blanket is quite large.

When we examine a blanket of the first type, we see that the poloidal component of the magnetic field will be directed perpendicular to the flow in the header sections and that the toroidal component will be directed perpendicular to the flow in the channels of the uranium zone. The pressure gradient is found from the formula

$$\Delta p = cG_0 B_e^2/2d, \tag{10}$$

where $B_e^2$ and c are calculated from (5) and (7); here, d and h are transposed, as are $B_t$ and $B_p$.

The third type of blanket is the most complex for obtaining design equations. If we examine the uranium zone as consisting of densely-packed bundles of fuel elements, then drag in a cell with allowance for the finite electrical conductivity of the fuel-element shells can be determined by direct integration of the velocity of the core of the flow over the entire cross section of the cell. Here, no allowance is made for the redistribution of velocity in the boundary layer, which introduces a correction on the order of $\mathrm{Ha}^{-1}$. Using a Eulerian substitution of the third kind, we can obtain an expression for the drag of dense bundles in analytical form. Omitting the cumbersome intermediate calculations, similarly to [10] we obtain the following expressions to calculate drag for a pipe with conducting walls:

at Ha α > 1

$$\lambda = \frac{\mathrm{Ha}^2 \alpha}{\mathrm{Re}} \frac{(4-\pi)}{4}\left[\frac{\pi}{4} - \frac{(\mathrm{Ha}\,\alpha + 1)(\mathrm{Ha}\,\alpha + 1 - \alpha)}{2\mathrm{Ha}^2\alpha^2(\mathrm{Ha}^2\alpha^2 - 1)^{0.5}} \times \right.$$
$$\times\left(\ln\left|\frac{1 + \mathrm{Ha}\,\alpha - (\mathrm{Ha}^2\alpha^2 - 1)^{0.5}}{1 + \mathrm{Ha}\,\alpha + (\mathrm{Ha}^2\alpha^2 - 1)^{0.5}}\right| - \ln\left|\frac{\mathrm{Ha}\,\alpha - (\mathrm{Ha}^2\alpha^2 - 1)^{0.5}}{\mathrm{Ha}\,\alpha + (\mathrm{Ha}^2\alpha^2 - 1)^{0.5}}\right|\right) + \tag{11}$$
$$+ \frac{1}{2\mathrm{Ha}^2\alpha^2}\left(\mathrm{Ha}^3\alpha^3\left(1 - \frac{\pi}{4}\right) - \left(2 - \frac{\pi}{4}\right)\mathrm{Ha}^2\alpha^2 + \right.$$
$$\left.\left. + \left(1 - \frac{\pi}{2}\right)\mathrm{Ha}\,\alpha^2 + (\pi - 1)\mathrm{Ha}\alpha + \frac{\pi}{2}(1 - \alpha)\right)\right]^{-1},$$

at Ha α < 1

$$\lambda = \frac{Ha^2 \alpha (4-\pi)}{4Re} \left[ \frac{\pi}{4} - \frac{(Ha\alpha + 1)(Ha\alpha + 1 - \alpha)}{Ha^2 \alpha^2} \times \right.$$
$$\times \left( \operatorname{arctg} \frac{1 + Ha\alpha}{(1 - Ha^2\alpha^2)^{0.5}} - \operatorname{arctg} \frac{Ha\alpha}{(1 - Ha^2\alpha^2)^{0.5}} \right) + \tag{12}$$
$$\left. + \frac{1}{2Ha^2\alpha^2} \left( Ha^3 \alpha^3 \left(1 - \frac{\pi}{4}\right) - \left(2 - \frac{\pi}{4}\right) Ha^2\alpha^2 + \left(1 - \frac{\pi}{4}\right) Ha\,\alpha^2 + (\pi - 1) Ha\,\alpha + \frac{\pi}{2}(1-1) \right) \right]^{-1}.$$

For the case of complete electrical insulation of the surface of the fuel elements, drag can be calculated from the formula

$$\lambda = \frac{2Ha}{0.446\,Re} [1 + O(Ha^{-0.5})]. \tag{13}$$

However, the nonuniformity of the energy release in the uranium zone makes it necessary to shape the flow rate here by arranging for variable spacing between rows of fuel elements. A problem here is that the cell model then ceases to be exact, even if turbulent momentum transfer between adjacent channels is ignored.

If we examine rows of fuel elements with small gaps on the order of $2\text{-}3\cdot10^{-3}$ m between one another, then the character of the streams circulating in adjacent cells should remain unchanged. It is hard to imagine that the introduction of additional resistance in the form of a thin layer of coolant with an electrical conductivity comparable to that of a fuel-element shell would lead to such radical changes in stream topology as a change in direction and opening of the stream contours. Evidently, Eq. (4) can also be used in this case for the cell: it should provide a degree of accuracy on the order of several dozen percent. If the gap between the rows of fuel elements is enlarged further to improve cooling conditions — which, indeed, would lead to a significant deterioration in the neutron-physical characteristics of the blanket for coolants such as a bismuth—lead eutectic — then we create a narrow gap and cause the toroidal component of the magnetic field to be directed along the long side of this gap [4].

Hydraulic resistance is determined from the following formula in the only known empirical relation obtained on a sodium loop for a slit-type channel with conducting walls and a magnetic field oriented along the long side [12]

$$\lambda = 0.063\,N^{0.8} \tag{14}$$

with $2.4 \le N \le 812$; $a = 21.5\cdot10^{-3}$ m; $\delta_{wa} = 2\cdot10^{-3}$ m. This relation provides good agreement with (4) at N = 93.6, corresponding to the parameters of the blanket.

However, the conditions of this experiment were far from adequate in terms of approximating the service conditions for a blanket of the third type, so that the question of exact determination of the drag of such systems remains unanswered.

Let us use the above relations to calculate the pressure drops for different types of blankets for an experimental 500-MW fusion reactor [13] cooled by liquid metals. Pure lithium is used as the coolant in the first and second types of blankets, while a bismuth—lead eutectic is used in the third type. According to the results of neurtron-physical calculations, with a volume content of uranium of 50% the thermal capacity of the blanket W = 70 MW.

We take the following values for the parameters: $\ell = 5$ m; d = 4 m; h = 0.2 m; $\gamma = 0.23$ (for the first and second types); $\gamma = 0.3$ (for the third type); $\sigma_{sh} = 1.2\cdot10^6$ 1/(Ω·m); $\delta_{sh} = 5\cdot10^{-4}$ m; $\sigma_t = 2.2\cdot10^6$ 1/(Ω·m) (for Li); $\delta_t = 0.75\cdot10^6$ 1/(Ω·m) (for Bi—Pb); $a = 5\cdot10^{-3}$ m; ΔT = 200 K; $\delta_{wa} = 0.01$ m; $\delta = 1.5\cdot10^{-3}$ m; p = 0.33; $G_0 = 83$ kg/sec; S = 0.03 m (for the first type); S = 0.05 m (for the second type).

Using Eqs. (5), (7), and (8) and allowing for choking of flow rate along the headers, we obtain the following: for type I, $B_e^2 = 7.67\cdot10^2$; c = 37 sec$^{-1}$; $\Delta p = 0.29\cdot10^6$ Pa; for type II, $B_e^2 = 2.58\cdot10^3$; c = 5.66 sec$^{-1}$; $\Delta p = 4.04\cdot10^6$ Pa. Without allowance for choking, in accordance with (9), $\Delta p = 2.16\cdot10^4$ and $1.75\cdot10^5$ Pa, respectively.

Neutron-physical calculations for a blanket of type III yielded $v_{av} = 0.98$ m/sec; α = 0.16; Ha = 541; Ha α = 86.6. In accordance with (11), $\Delta p = 9.2\cdot10^6$ Pa. With complete electrical insulation of the surface of the fuel elements, $\Delta p = 0.38\cdot10^6$ Pa according to (13).

For rows of fuel elements with small gaps (geometric shape of a slit), if we use (4) with a = 0.05 m, we find that $\Delta p = 29.4 \cdot 10^6$ Pa.

The values of pressure gradient obtained above show that the application of electrically-insulating coatings on the channel walls and the shell of the fuel elements is necessary to ensure the proper functioning of blankets which employ a longitudinal flow scheme. Such measures are not necessary for blankets of the first and second types.

## NOTATION

$\Delta p$, pressure gradient; $\rho$, density; v, velocity; $v_{av}$, mean velocity in the cross section of the channel; $\nu$, kinematic viscosity; $\Delta h$, length of an elementary section; $\ell$, d, and h, height, length, and thickness of the blanket; $\gamma$, porosity of the blanket; a, radius of fuel element; W, thermal capacity of blanket module; $\delta$, half-width of the narrow section in corridor bundles; $\delta_{sh}$, thickness of shell of fuel element; $\delta_{wa}$, thickness of wall of header; S, width of header section; x, distance from the inlet of the header section; G, mass rate in the header; F, cross-sectional area of header section; $G_0$, mass rate at the inlet of the header section; $\lambda$, drag; $c_p$, heat capacity of coolant at constant pressure; $\Delta T$, temperature drop of coolant in the blanket; $B_t$ and $B_p$, toroidal and poloidal components of the induction of the magnetic field; $x_{st}$, length of path of electromagnetic stagnation of stream; $\sigma_{wa}$, $\sigma_{sh}$, and $\sigma_t$, electrical conductivity of wall, fuel-element shell, and coolant; $\alpha = \sigma_{wa}\delta_{wa}/\sigma_t S$, relative conductivity of the material of the walls and fluid, analogous to $\alpha = \sigma_{sh}\delta_{sh}/\sigma_t$ for the fuel-element shell and coolant; $\alpha_{av}$, mean value of relative conductivity along the channel; P, dimensionless index of change in energy release through the thickness of the blanket; $B_e^2$, complex characterizing the ratio of electromagnetic forces in the header and in the channels of the blanket; c, $c_1$, dimensional constants characterizing the parameters of the header section; Re, Reynolds number; $Ha = Ba(\sigma/\rho\nu)^{0.5}$, Hartman number; $N = \sigma B^2 a/\rho v$, Stewart number; $O(Ha^{-0.5})$, small quantity on the order of $Ha^{-0.5}$.

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