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Fig. 1

Figure 1: Fig. 1

**Abstract****Full Text**

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**PHYSICS**

Foreign Member of the USSR Academy of Sciences M. STEENBECK, Academician of the Academy of Sciences of the Latvian SSR I. M. KIRKO, A. GAILITIS, A. P. KLAVINYA, F. KRAUSE, I. Ya. LAUMANIS, O. A. LIELAUSIS

## EXPERIMENTAL DETECTION OF AN ELECTROMOTIVE FORCE ALONG AN EXTERNAL MAGNETIC FIELD, INDUCED BY THE FLOW OF A LIQUID METAL ( $\alpha$ -EFFECT)

M. Steenbeck and F. Krause <sup>(1,2)</sup> predicted the existence of the so-called  $\alpha$ -effect—the presence, along the magnetic field, of an electromotive force induced in a moving conducting medium with a velocity field that has no mirror symmetry.

**Fig. 1.**  $\alpha$ —Distribution of the mean velocity vectors of liquid metal in individual channels of the installation along the liquid vector line.

*b:* 1—common inlet of liquid sodium; 2,3—inlets of the two halves of the flow; 4—flow running in the plane of the drawing; 5—flow running perpendicular to the plane of the drawing; 6,7—outlets of the flows; 8—common outlet of the flows; 9—copper walls hydraulically separating the flows; 10—solenoid creating the longitudinal magnetic field; 11,12—electrodes for measuring the e.m.f. of the  $\alpha$ -effect; 13—installation walls made of stainless steel.

This effect is, by its nature, proportional to the square of the velocity and to the magnitude of the magnetic field. It increases with increasing magnetic Reynolds number.

In the experiment performed, a flow of liquid sodium was produced with a velocity distribution of helical symmetry (Fig. 1a). Liquid

Fig. 2. Photograph of the installation box, removed from the loop with liquid sodium.

The corner was cut out after the end of the experiment

Fig. 4. Ratio of the measured voltage to that calculated by formula (1)

Figure 2: Fig. 4. Ratio of the measured voltage to that calculated by formula (1)

Fig. 3. *a*—quadratic dependence of the  $\alpha$ -effect on the velocity at magnetic-field values of 0.083 tesla (1), 0.129 tesla (2), 0.171 tesla (3), 0.208 tesla (4), 0.257 tesla (5), 0.298 tesla (6), 0.320 tesla (7);  $T = 200^\circ$ . *b*—dependence of the  $\alpha$ -effect on the magnetic-field strength at velocities of 1.15 m/sec (1), 3.45 m/sec (2), 5.75 m/sec (3), 8.05 m/sec (4)

**Fig. 4.** Ratio of the measured voltage to that calculated by formula (1)

sodium flows through an installation consisting of a stainless-steel box measuring  $152 \times 152 \times 515 \text{ mm}^3$ , in which a system of copper walls (according to the scheme of Fig. 1b) forms two interlacing mutually perpendicular flows. Thus, along the magnetic field  $\mathbf{B}$  there is formed a velocity field of liquid sodium in the form of a stepwise rotation of the vector  $\mathbf{v}$ , in which mirror symmetry is absent. Along the box there are 28 channels transverse to the axis, each 15 mm wide and with copper wall thickness 4 mm. Each flow of liquid sodium underwent 13 turns through  $180^\circ$  and 2 through  $90^\circ$ . The construction of the box is visible from Fig. 2. The magnetic field along the axis of the box was produced by a solenoid and was varied from 0 to 0.3 tesla. The box was connected to a closed sodium circuit with two electromagnetic pumps. The flow velocity was varied from 0 to 11 m/sec. The sodium temperature in each experiment was kept stable and varied from 150 to  $300^\circ$ . Between the bases of electrodes 11 and 12 (Fig. 1b) the electrical resistance was  $6 \cdot 10^{-6} \Omega$ . This value indicates perfect electrical contact between the sodium and the copper walls 9 separating the flow.

If the transverse dimensions of the installation were sufficiently large in comparison with the channel width, then the e.m.f. between the electrodes due to the  $\alpha$ -effect would be

$$U_\infty = \frac{1}{2} n \sigma \mu_0 B v^2 l^2, \quad (1)$$

where  $l$  is the channel width;  $\sigma$  is the conductivity of liquid sodium;  $\mu_0$  is the magnetic permeability of vacuum;  $n$  is the number of channels ( $n = 28$ ). In accordance with (1), the *experimentum crucis* for the existence of the  $\alpha$ -effect is the observed independence of the sign of the voltage  $U$  between electrodes 11 and 12 from the direction of the velocity and the change of this sign upon reversal of the direction of  $\mathbf{B}$ . Fig. 4a shows that  $U$  is proportional to  $v^2$  for various values of the magnetic field. From Fig. 4b it is seen that  $U$  is proportional to the magnitude of the magnetic field for small values of it, with a subsequent decrease of the effect.

The flow in the installation is turbulent ( $\text{Re} = (2 \div 5) \cdot 10^5$ ), and therefore the

direct influence of viscosity may be neglected. Thus,

The determining quantities are the induction, velocity, conductivity, and linear size of the apparatus. The influence of these factors is expressed by the dimensionless criteria—the Stuart number  $N = B^2 l \sigma / \rho v$  and the magnetic Reynolds number  $Re_m = \mu_0 \sigma v l$ . Figure 3 shows the dependence of the ratio of the measured voltage  $U$  to the quantity  $U_\infty$  from formula (1) on  $N$ , from which its unambiguous dependence on the Stuart number is evident. Since no influence of  $Re_m$  on this nondimensional criterion was found, one may speak of the phenomenon of self-similarity within the given range of  $Re_m$  values.

The decrease of the voltage by approximately a factor of 5 in comparison with formula (1) at small values of  $N$  (large velocities) can be explained by edge effects. The decrease of the effect with increasing Stuart number (small velocities, large fields) should be explained by a redistribution of the flow over the cross section of each channel.

This experiment proves the existence of the  $\alpha$ -effect and is the fundamental basis for the theory of self-excitation of an electromagnetic field due to the presence, in Ohm's law, of a term proportional to  $\mathbf{B}$ :

$$\mathbf{j} = \sigma(\mathbf{E} + \alpha\mathbf{B}). \quad (2)$$

The dependence of the emf on the Stuart number is one of the nonlinear factors determining the magnitude of the field under self-excitation.

The next step in this investigation will be self-excitation of a magnetic field in an annular system of similar apparatuses as a model of the magnetic field of planets and stars. The possibility of creating such a model in the laboratory is demonstrated by the results of this experiment: if electrodes 11 and 12, in a field of order 0.1 tesla, were short-circuited, then along the vector  $\mathbf{B}$  there would flow a current of order  $60 \cdot 10^{-3} \text{ V} / 6 \cdot 10^{-6} \Omega = 10^4 \text{ A}$ —a current quite sufficient to excite a field of the same order, i.e., for self-reproduction of the  $\alpha$ -effect.

Institute of Magnetohydrodynamics  
Jena, GDR

Institute of Physics  
Academy of Sciences of the Latvian SSR

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3. M. Steenbeck, F. Krause, *Magnetohydrodynamics*, No. 3 (1967).

*Note: Figure translations are in progress. See original paper for figures.*

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