MAGNETOHYDRODYNAMICS Vol. 51 (2015), No. 1, pp. 95–103

ANNULAR LINEAR INDUCTION PUMP FOR LIQUID SODIUM

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The paper provides background information on the design, development and operation of the annular induction travelling field pump for liquid sodium. A mathematical model of the device has been developed and verified. Effects of various parameters on the capacity of the pump were investigated. Simulation results were used to design and manufacture a single-section pump, which was then tested in a gallium loop. Experimental results confirmed the correctness of the mathematical model. Mathematical modelling made it possible to design and manufacture multi-section pumps with required characteristics.

1. Introduction. Electromagnetic pumps for liquid metal have numerous applications [1]. The use of such pumps has now become widely practiced in metallurgy [2], [3]. Electromagnetic pumps are also used in atomic and thermonuclear installations [4], [5]. Different models of electromagnetic pumps have long been studied both theoretically and experimentally [6], [7], [8], and such investigations are currently being continued [4], [3], [9], [10]. At present, engineers often face the need to improve and modernize the existing models and adjust a device to meet the operation conditions in a particular zone, where it will be employed. However, available information about devices of this type is sometimes insufficient, and thus they deserve further consideration.

The motivation of our investigation stems from the need to transfer liquid sodium through a closed pipeline system with the aid of electromagnetic pumps. The temperature of liquid sodium in various parts of the system is different and may reach 300 degrees Celsius. Hence, the pumps must meet the following requirements: they should generate a stationary transient flow with a low pulsation level (the r.m.s. of the pump output and pressure must not exceed 3%); they should not cause additional heat in liquid sodium; the intensity of an electric current induced by the pumps in a loop with liquid metal should be minimized; the pump channel should have an elementary configuration to prevent stagnant zones of the flow and low hydraulic resistance. The pumps should be designed such that cooling and heating devices can be readily embedded into their channels, and, finally, they should be cheap and easy to manufacture and maintain.

In order to generate a pressure drop in electromagnetic pumps, electromagnetic forces are applied, which arise due to the interaction between the electric current and the magnetic field induced in the working zone of the channel. In some pumps, an electric current is supplied to the channel from an external source. These pumps have been thoroughly studied, including our laboratory [10]. However, they have three specific features, which pose problems with their consideration in the present paper. First, the channel of such pumps has a relatively complex configuration with numerous weld joints. Next, we should have an external induction system to generate the electric current in the pump channel or realize a direct power supply to the channel via electrodes, which requires a good electrical contact with the liquid metal. Finally, an electrical current (a few thousands of amperes) passing through the liquid metal in these pumps heats the metal.

Being acceptable for metallurgical applications, these features are inapplicable in our investigation.

In other pumps, an electric current is generated in a liquid metal when exposed to its magnetic field with an alternating flux. A single-phase power source can also be used to create electromagnetic forces, but the working channels of such pumps still have a complicated configuration [11]. The high capacity of such pumps can be obtained in the presence of a rotating magnetic field, especially, in the case of a spiral channel [12], but its complex configuration is a significant challenge for manufacturers. There are also problems with sodium washing out of such channels during refilling. Another model of electromagnetic pumps has rotating permanent magnets [13], but these devices are vulnerable to high temperatures and can generate mechanical vibrations. Application of a travelling magnetic field simplifies significantly the design of the electromagnetic pumps. A channel in the pumps has, in general, a rectangular or a circular cross-section [1], [7], [9], [11]. The assembling of pumps with flat channels is simple enough, and the channel can be quickly removed and replaced in the pump, if necessary. However, the flat-channel pumps have a high hydraulic resistance, and their manufacturing requires welding or deforming the tube, which reduces safety.

As a purpose of our investigation, we chose an annular travelling field pump of traditional design [1]. The pumps of this type have been investigated in relation to their current or planned use in modern atomic and thermonuclear installations and in the context of particles' studying (see, e.g., [14], [15], [16], [17],[18]). The authors of these papers investigated the characteristics of the devices with emphasis on their application. However, our objectives are different from those of the mentioned works, and this counts in favor of our study. Moreover, it is practically impossible to obtain the design and operation characteristics described in these works. For example, the winding wire sizes determine the tooth pitches, the number of turns is selected with reference to a power source, and the dimensions of the core are taken in such a way as to prevent its saturation. All these factors affect the capacity of the pump. Hence, we can conclude that the best option is always a compromise. Our studies enable us to develop an engineering and physical basis for elaboration of new models and for modification of the existing devices.

A pump with a cylindrical channel meets the above requirements. It has an easy-to-produce channel with low hydraulic resistance and without stagnant zones, which may accumulate sodium oxides and other undesirable contaminants. Ferromagnetic cores, electric coils and the frame of such a pump are simple, which provides a low-cost design and manufacturing. After examining the operation of only one section of the pump, one can select the number of sections needed to achieve the desired output of the pump.

Thus, the aim of this work is to study a travelling field pump with a cylindrical

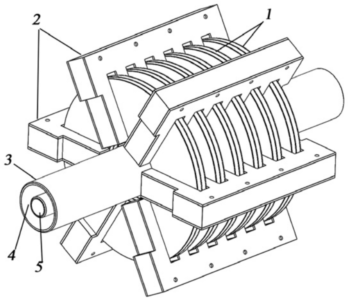

Fig. 1. Schematic of a cylindrical linear inductive pump (see comments in the text).

channel and find optimal operation characteristics. To this end, we have developed a mathematical model of the device and selected its best operation characteristics. The device of the pump must meet the requirements listed above, namely, the proper use of electricity, good cooling of windings, and the operation of ferromagnetic cores in the unsaturated state only. The next stage of our research is the design and manufacturing of the device and its testing in a loop with gallium eutectic. By comparing the theoretical and experimental results, we evaluate the efficiency of the mathematical model and predict the workability of the pump for liquid sodium.

2. Seeking an optimal configuration of the device via mathematical modelling. The main elements of the cylindrical travelling field pump are the copper ring windings *1* and the steel ferromagnetic cores *2* (Fig. 1). The windings are connected to a three-phase AC power, so their number is a multiple of *3*. The number of windings determines the number of core teeth. Simulations have been carried out for a pump with six windings. As mentioned earlier, there are guidelines for seeking the optimal geometric parameters of the windings and cores (see, e.g., [1]), but they do not take into account all the factors. A stainless steel channel 3 filled with liquid sodium *4* is placed in the axial gap of the pump. In the center of the channel, there is a complementary stainless steel channel *5* with a set of ferromagnetic plates to increase the capacity of the pump. We intend to use this channel in a different way and that is why it is empty.

The optimal parameters of the pump have been determined by applying a mathematical model for solving a three-dimensional electrodynamic problem. The model is based on the following subset of the Maxwell's equations

$$\nabla \times \mathbf{H} = \mathbf{j}, \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \cdot \mathbf{B} = 0,$$

where $\mathbf{j} = \mathbf{j}_\mathrm{s} + \sigma \mathbf{E}$ is the sum of the applied source current density vector and induced current density vector, $\mathbf{B} = \mu\mu_0 \mathbf{H}$ is the magnetic flux density vector. In this formulation, the magnetic permeability μ is a constant field. In the calculations, apart from the above volumes, the surrounding nonmagnetic space is considered as well. The problem is solved with the finite element package "ANSYS". Initially, the model has been tested during our previous experiment with an electromagnetic stirrer, which also includes a travelling magnetic field inductor [19]. The calculations have shown a good agreement with the experiment (Fig. 2*a*).

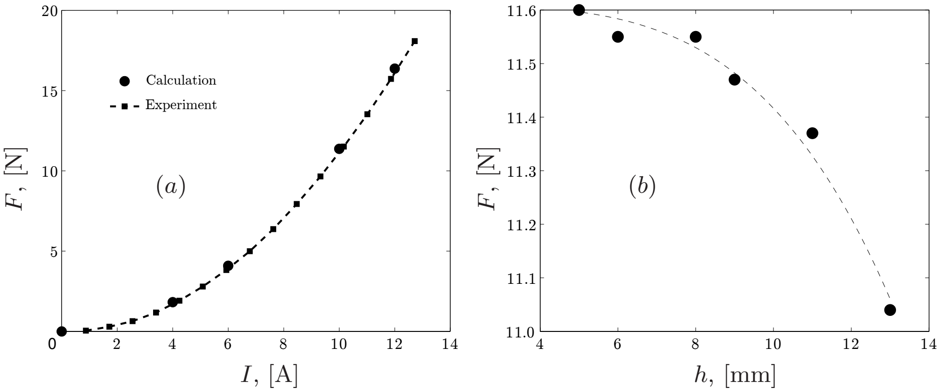

Fig. 2. Preliminary verification of calculations: (*a*) calculation of an electromagnetic force induced by a traveling magnetic field vs. the electric current in the coils [19]; (*b*) force vs. mesh step.

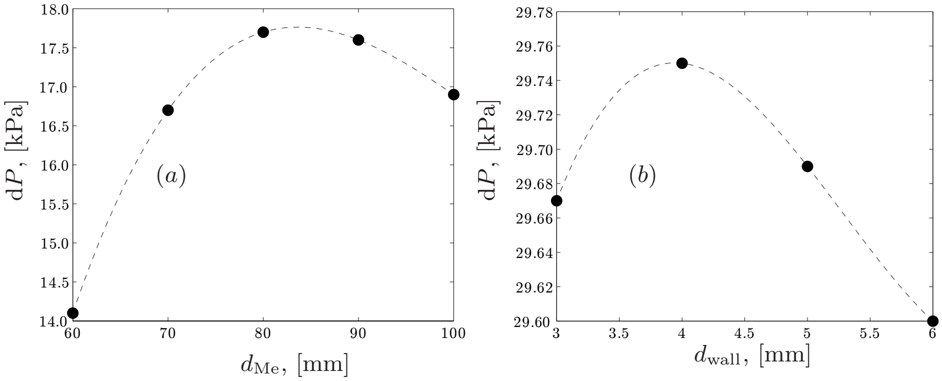

Fig. 3. Pressure vs. one of the characteristics when other characteristics are kept unchanged: (*a*) pressure vs. channel diameter; (*b*) pressure vs. channel wall thickness.

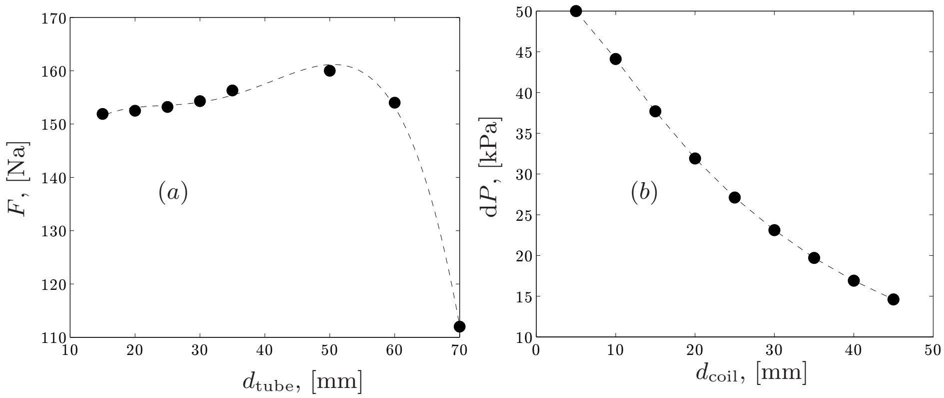

Fig. 4. Pressure vs. one of the characteristics when other characteristics are kept unchanged: (*a*) pressure vs. tube-insert diameter; (*b*) pressure vs. thickness of the electric current coils.

With decreasing the mesh width, the solution converges asymptotically (Fig. 2*b*). This evidences of the stability of calculations.

Next, we study how a change in single parameter affects the capacity of the pump provided that other parameters remain unchanged. The calculations allow us to obtain the values of the channel diameter (Fig. 3*a*), wall thickness (Fig. 3*b*) and of the diameter of the central tube-insert (Fig. 4*a*), at which the highest capacity of the pump can be achieved. A change in channel wall thickness has no sufficient effect on the pump capacity. When choosing the gap between the tubes (through which liquid sodium flows), we take into account the fact that a reduction of the gap under the increasing pressure increases also the hydraulic resistance. Moreover, the thinner the gap, the more difficult is to clean the pipe from residual sodium. A change in number of ferromagnetic cores (even if the total weight of ferromagnets changes) has only a slight effect on the capacity of the pump. A decrease in tooth pitch and in cross-sectional area of the coils at a fixed number of ampere-turns increases essentially the pump capacity (Fig. 4*b*), which confirms the well-known fact. The density current in the coils increases, hence worsening their cooling and resulting in overheating. Thus, the results of the thermal analysis of the problem must be taken into account when selecting the tooth pitch.

To determine the saturation degree of ferromagnetic cores, we calculate the dependence of the magnetic field $\mathbf{B}$ on the current in the windings $\mathbf{j}_{\mathrm{s}}$. In this

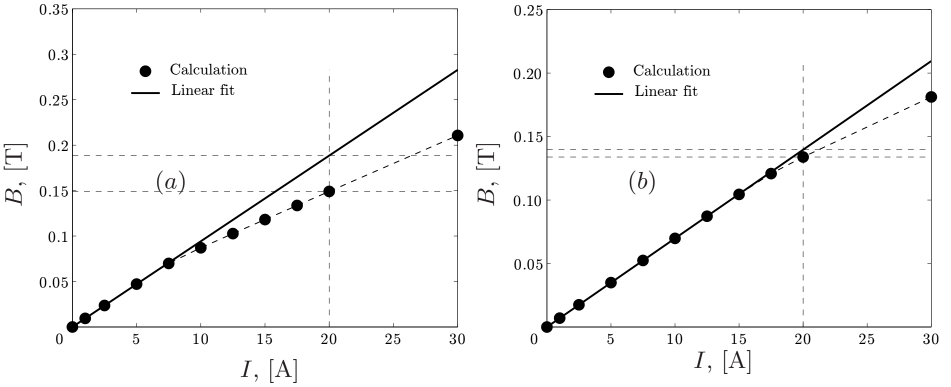

Fig. 5. Magnetic induction vs. current in coils when selecting parameters of cores with high (*a*) and low (*b*) saturation.

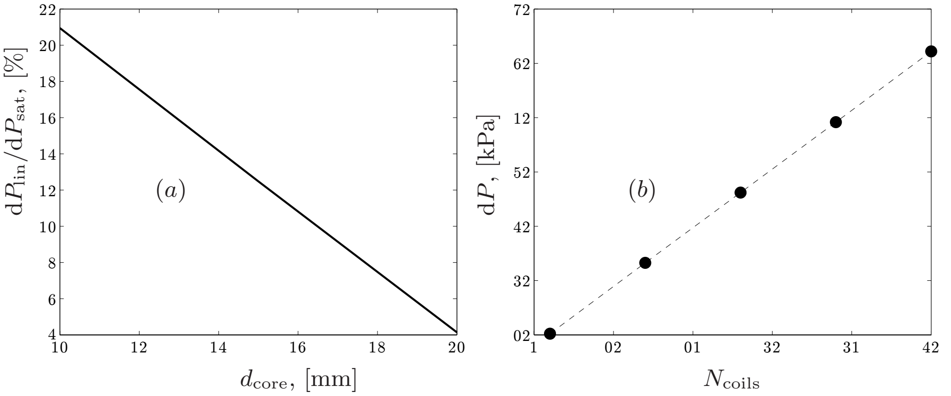

Fig. 6. (*a*) The saturation degree vs. the core thickness; (*b*) pressure vs. the number of coils (other characteristics are kept unchanged).

case, the mathematical model is based on the following subset of the Maxwell's equations

$$\nabla \times \mathbf{H} = \mathbf{j}_{\mathrm{s}}, \quad \nabla \cdot \mathbf{B} = 0,$$

where $\mathbf{j}_{\mathrm{s}}$ is the applied source current density vector, $\mathbf{B} = \mu_H \mu_0 \mathbf{H}$ is the magnetic flux density vector. In this formulation, the magnetic permeability μ_H is derived from the B versus H curve. If the geometric parameters are not optimal, then a significant deviation of this curve from the initial straight segment is seen (Fig. 5*a*). If the deviation of the curve at the electrical current value used in this study is inessential, we can suggest that the cores are almost unsaturated, and the parameters thus found are correct (Fig. 5*b*). An increase in thickness of the cores reduces the degree of saturation (Fig. 6*a*), and thus one can always select correct parameters by way of increasing the weight of the pump. To sum up, with increasing the number of coils, the pump capacity increases linearly (Fig. 6*b*). This figure shows the curve for the final configuration of the pump.

Finding the geometric parameters also depends significantly on the applied power source. In our study, we use a three-phase 50 Hz AC voltage source with 380 V at a maximum load. Adjustment (reduction) of the pump capacity is realized with the aid of pulse width modulation. Therefore, we need to select the resistance of the windings (in fact, windings of several pumps) and the method of their connection in such a way as to be sure that the voltage does not exceed a maximum

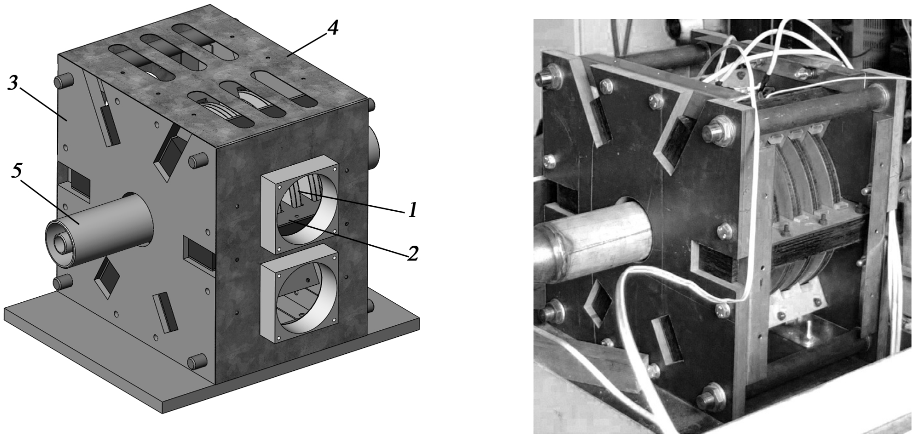

Fig. 7. (*a*) Schematic of a single-section pump (see comments in the text); (*b*) photo of the pump without a casing in the gallium experiments.

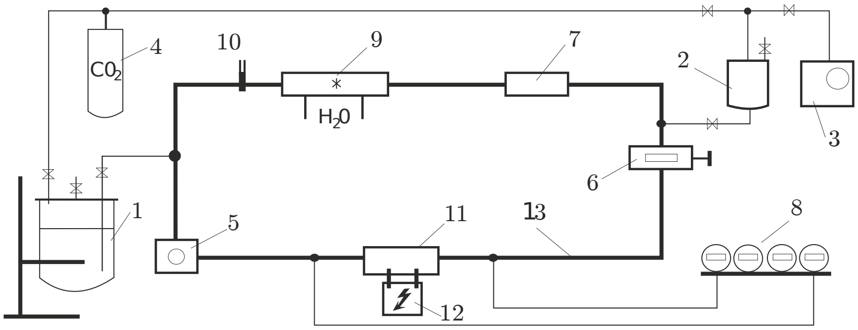

Fig. 8. Schematic of a hydraulic loop for testing pumps with liquid gallium eutectic (see comments in the text).

value at a limited current density. It is also necessary to take into account the reactance, which exceeds many times the ohmic resistance and is determined by the electrodynamic problem solution. This has led to the need to find optimal parameters by solving the problem of multi-criteria optimization.

So finding the best design parameters is a complicated optimization process, which includes determination of high electromagnetic force, best cooling, proper use of electricity and creation of a model easy to assemble and operate.

3. Study of the device operation conditions. Upon finding the optimal parameters, we have designed and manufactured a single-section pump with six windings (Fig. 7). It consists of six copper windings *1* with 132 turns of 7 mm ×1 mm "PSDK" wire (Kamkabel, Russia), ferromagnetic cores *2* composed of plates made of 0.5 mm thick transformer steel. The thickness of the coils with insulation is 16 mm and their electrical conductivity is $\sigma = 58.8{\cdot}10^6$ Sm/m. The sizes of the core finger are 20 mm ×20 mm ×100 mm. The maximum value of the magnetic permeability μ of the transformer steel is 15000. The magnetic permeability μ depends on the magnetic field strength. The pump frame *3* is a parallelepiped and its bottom and walls are made of 20 mm thick temperature-resistant glass-fibre plastic. Air fans of the cooling system, the intensity of which is controlled by a thermosystem, are mounted on the upper casing *4*. A stainless steel pipeline *5* with an external diameter of about 76 mm with a tube-insert of an external diameter of 32 mm placed axially is embedded inside the pump, the electrical conductivity of the tubes is $\sigma = 1.2 \cdot 10^6$ Sm/m. The pump is fed from a three-phase voltage source of 50 Hz (380 V) and adjusted via a pulse width modulator "MBT3F160T3" (Thermodat, Russia). The saturation of the pump ferromagnetic cores must be negligible (Fig. 5*b*).

The pump performance was investigated in a hydraulic loop with an internal diameter of 20 mm. The loop was filled with a gallium eutectic Ga87.5% + Sn10.5% +Zn2% having the following properties: the electric conductivity $\sigma = 3.56 \cdot 10^6$ Sm/m, the density $\rho = 6256\,\mathrm{kg/m^3}$, and the kinematic viscosity $\nu = 3.1 \cdot 10^{-7}\,\mathrm{m^2/s}$. The loop (Fig. 8) consists of a metal storage system *1*, an expansion tank *2*, a vacuum system used for filling *3*, a gas system *4*, and a cleaning system *5*. A valve *6* controls the flow rate, an electromagnetic flowmeter *7* measures the flow rate, and a pressure gauge set *8* adjusts the pressure. The loop includes a water cooling system *9* and thermocouples *10*. A pump *11* with a power source *12* is connected to the loop pipe line *13* via flanges. All readings of the circuit are transferred to a computer by the data acquisition boards "NI9225, NI9227, NI9239" and processed by the LabView software.

The experiments have shown that the pump is able to create a stationary flow rate. The level of the flow and pressure pulsations, in this case, does not exceed the permissible 3%. Fig. 9*a* shows that the dependences of the pressure on the current in the windings obtained in the calculations and experiments are in good agreement. This gives confidence that the pump is able to operate in other configurations and metals and, therefore, this relationship (Fig. 6*b*) is thought to be close to reality. The calculated (218 V) and experimental (214.5 V) voltage values at the current 20 A in the windings turned out to be close as well. This fact testifies that the reactance of the coils has been accessed correctly.

The pressure–flow rate curve of the pump seems to be flat (Fig. 9*b*), which is typical of this type of pumps and evidences of the low hydraulic resistance of the channel. Our experience gives evidence of a tendency to maintain this type of characteristics even at the high flow rate [11], which makes it possible to predict the operation of the pump with more productive configurations. It is known that hydrodynamic instabilities may appear in the cylindrical and annular linear induction pumps. We studied it for the flat linear inducion pump in [11]. In the present work, we only checked the level of pulsations. The pressure pulsations

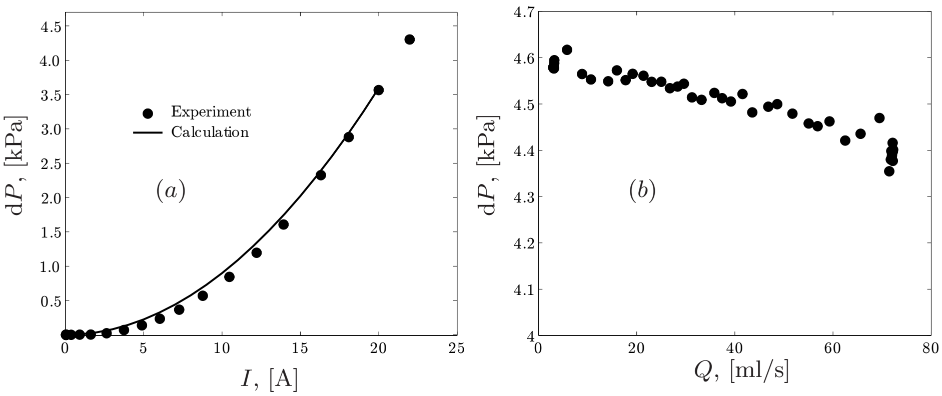

Fig. 9. (*a*) Pressure drop vs. electric current in windings (experiment and calculations for gallium); (*b*) pressure drop vs. flow rate (experiment with gallium).

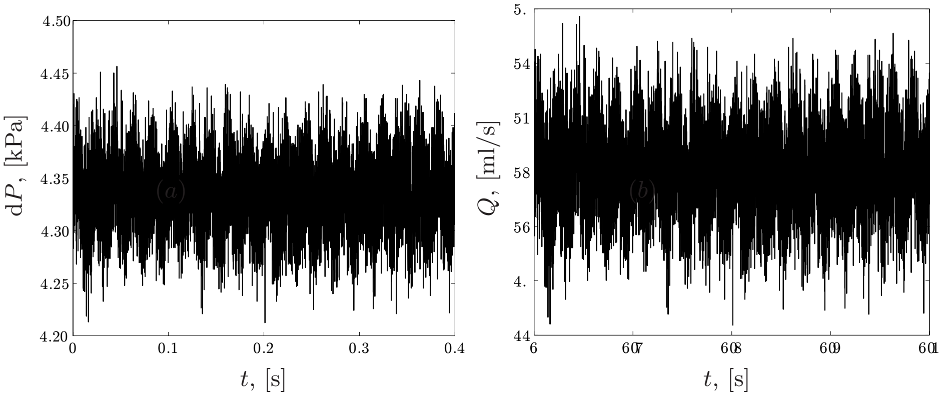

Fig. 10. Examples of pressure drop (a) and flow rate (b) evolutions (experiment with gallium).

(Fig. 10a) and the flow rate variations (Fig. 10b) were assumed to be small. With the pressure average value $\langle P \rangle = 4.33\,\mathrm{kPa}$, the r.m.s. was $P_{\mathrm{rms}} = 0.034\,\mathrm{kPa}$ (less than 1%). With the flow rate average value $\langle Q \rangle = 72.05\,\mathrm{ml/s}$, the r.m.s. was Q_{rms}=1.58 ml/s (less than 2%). Thus, the r.m.s. did not exceed 3% and the pulsation level remained low. After the study, we have manufactured two other pumps consisting of three (18 windings) and four (24 windings) sections, and all these have demonstrated the required characteristics when working with liquid sodium.

4. Conclusions. So far we have demonstrated that the annular travelling field pump satisfies all the requirements for its parameters, capacity and design. The pump is easy to design, manufacture and assemble. The calculations have shown that the development of a pump with required characteristics is simple enough, but in each case it is necessary to solve the optimization problem and find a compromise solution. The gallium experiments allowed us to obtain the desired characteristics and verify the efficiency of the mathematical model proposed in this study. The flow rate and pressure pulsations turned out to be small. In this paper, no attempt has been made to reduce them, because this operation requires additional experiments. The operation of the pump demonstrates that the use of pulse width modulation is a convenient way to control the pump flow rate and it has no impact on the pump workability. It should also be noted that the design of the pump was chosen in such a way as to exclude overheating of the windings and provide the optimal operation of the cooling system. Thereofe, we can conclude that the objective of our study has been attained. A similar mathematical model of the device with a traveling magnetic field has been developed and verified. Three pumps, having the desirable performance characteristics, have been manufactured using the predictions of the mathematical model.

Acknowledgments. This research was supported by the Grant of the Russian Foundation for Basic Research No. 14-08-96014.

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Received 17.02.2015