

# Evaluation of possibility of using self-ventilation to cool forced electromagnetic shock engines

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**Abstract.** The use of shock machines with linear electromagnetic engines, for example, for immersing metal rod elements in the ground, seems quite effective due to the relatively low power consumption, the direct conversion of electrical energy into mechanical work and comparatively high specific indicators. At the same time, increased values of the impact power of machines with linear electromagnetic engines are provided under the condition of forced consumption of energy from accumulators or capacitive storage devices. Because of the relatively low voltage, these sources give significant currents (120 ... 200 A) to the winding of linear electromagnetic engines during the operating cycle. In this case, the value of the ratio between losses and useful energy of the machine is significant, which limits the possibilities of creating frequency-impact machines with a long operating regime on the basis of pulsed linear electromagnetic engines with natural cooling. Thus, the intensification of the cooling process of linear electromagnetic engines of shock machines is important. In this paper, we estimate the possibility of using self-ventilation for cooling the forced linear electromagnetic engines of shock machines; the dependence of the taken-away power of losses of linear electromagnetic engines on geometrical characteristics of axial ventilating channels is defined.

## 1. Introduction

The use of shock machines (SM) with linear electromagnetic engines (LEME), for example, for immersing metal rod elements in the ground [1, 2], seems quite effective due to the relatively low power consumption, the direct conversion of electrical energy into mechanical work and comparatively high specific indicators. At the same time, increased values of the impact power of machines with LEME are provided under the condition of forced consumption of energy from accumulators or capacitive storage devices [3, 4]. Because of the relatively low voltage, these sources give significant currents (120 ... 200 A) to the winding of LEME during the operating cycle. In this case, the value of the ratio between losses and useful energy of the machine is significant, which limits the possibilities of creating frequency-impact machines with a long operating regime on the basis of pulsed LEME with natural cooling [5, 6]. Thus, the intensification of the cooling process of LEME of shock machines is important.

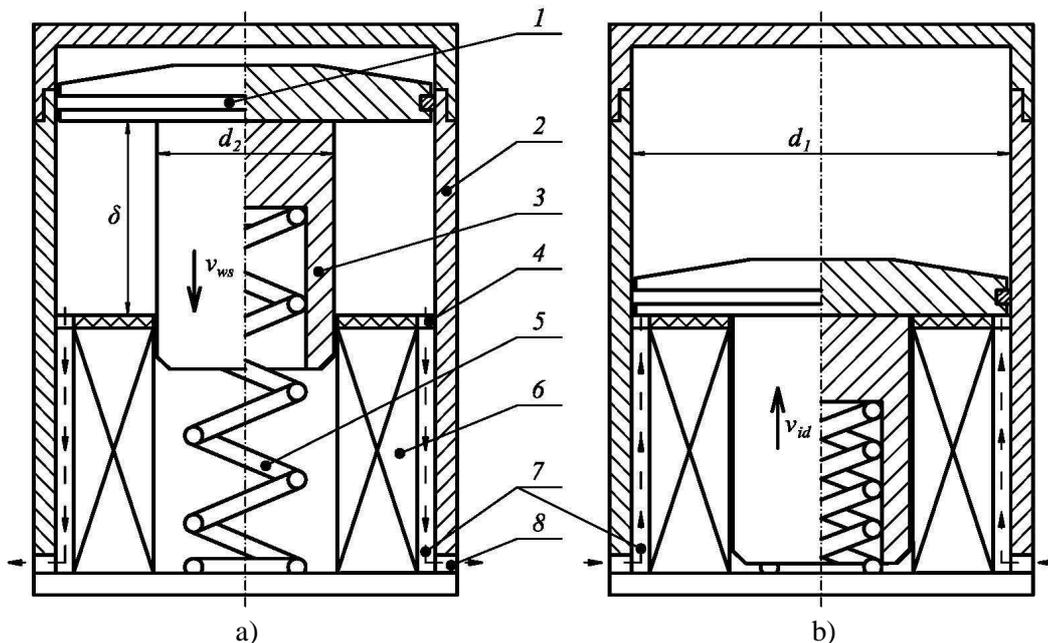
## 2. The object and method of research

In this paper, we estimate the possibility of using self-ventilation for cooling the forced linear electromagnetic engines of shock machines; the dependence of the taken-away power of losses of LEME on geometrical characteristics of axial ventilating channels is defined.



Figure 1 shows a constructive LEME circuit with self-ventilation, the feature of which is the direct cooling by surrounding air of current-carrying parts of the engine (windings) through ventilation ducts [1, 7, 8].

When the winding 6 is connected to the power supply, the armature 3, under the action of electromagnetic force, makes a working stroke at a speed of  $v_{ws}$  (Fig. 1, a). The air streams 7, moving along the axial channels 4, which are induced by the combined armature 3 with the compression ring 1, cool the winding 6 and exit through the ventilation holes 8. At idle at a speed of  $v_{id}$  (Fig. 1, b), the armature 3, under the action of the return spring 5, moves to the upper part cylindrical stator 2. Thus ambient air is sucked through the holes 8 and, passing through the ventilation channels, cools the winding 6, and at the next working stroke it is removed outwards [1, 7, 8].



**Figure 1.** LEME self-ventilation circuitry: a) working stroke; b) idling

To evaluate the thermal and hydraulic processes occurring in the linear electromagnetic engine of the shock machine (Figure 1), we use the technique presented in [9]. The power loss  $\Delta P$  in the LEME winding and the retracted  $P_{ret}$  by self-ventilation are determined by the expression [1, 9]:

$$\Delta P = I^2 R \quad (1)$$

$$P_{ret} = Q \cdot c \cdot \rho \cdot \theta_{max} \quad (2)$$

where  $i$  - the current in the LEME winding;  $R$  - resistance of the motor winding;  $Q$ ,  $c$ ,  $\rho$  - consumption, specific heat and density of cooling air;  $\theta_{max}$  - permissible excess of the temperature of the cooling gas for a given class of heat resistance of the insulation of the machine.

From [9], the value of  $Q$  is determined from the expression:

$$Q = \sqrt{\frac{\Delta p_m}{z_m}} \quad (3)$$

where  $\Delta p_m$  - loss of pressure in the engine cooling system;  $z_m$  - total hydraulic resistance LEME.

The necessary pressure  $p_n$ , created by the combined armature with the compression ring on the working stroke, is defined as the ratio of the axial force of the armature  $F_{arm}$  to the area of the upper surface of the winding blown by the air flow (Figure 1):

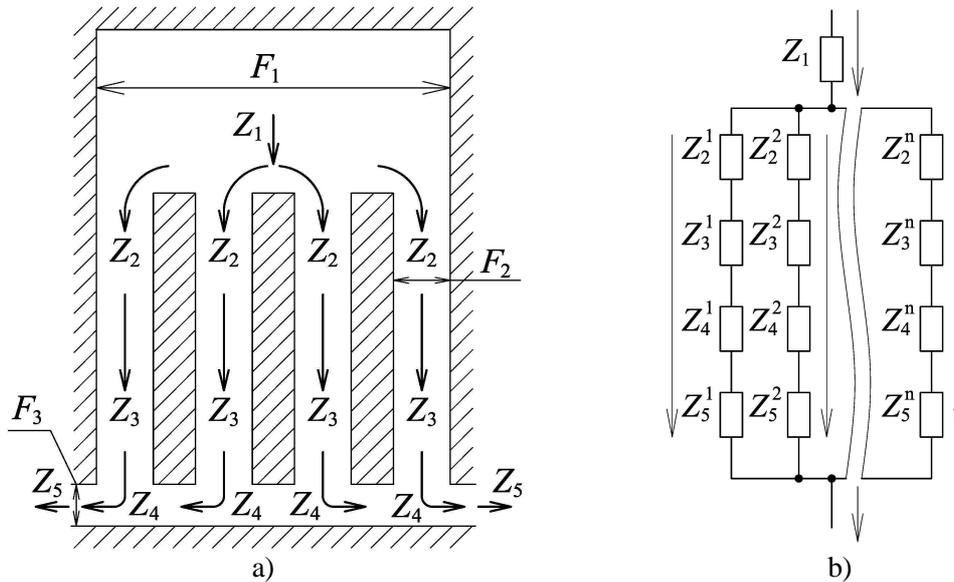
$$p_n = \frac{4F_{arm}}{\pi(d_1^2 - d_2^2)} \quad (4)$$

where  $d_1$  - internal diameter of the stator in the superfluous space, m;  $d_2$  - armature diameter, m.

Assuming that the pressure loss  $\Delta p_m$  is equal to the created pressure  $p_n$ , expression (2) taking into account (3) and (4) takes the form:

$$P_{ret} = c\rho\theta_{max} \sqrt{\frac{4F_{arm}}{z_m \pi(d_1^2 - d_2^2)}} \tag{5}$$

The method of determining the total hydraulic resistance of the vent channel  $z_m$  [8] is as follows: when the cooler moves inside  $n$  number of axial channels, it overcomes in each of them the local resistance  $z_2$  at the entrance, the path resistance  $z_3$  during the movement along the channel, the local resistance  $z_4$  at the outlet from it and the local resistance  $z_5$  when moving from the electric motor to the environment (Fig. 2). The movement of the cooler from the point of exit from the channel to the point of exit from the engine is insignificant, so the magnitude of the track resistance on this gap can be neglected.



**Figure 2.** Diagrams of ventilation channels LEME: a – a simplified image of the ventilation duct; b – equivalent hydraulic circuit.

The resistances overcome by the cooler in the axial channel are connected in series, therefore, in accordance with the known formulas [9], the total resistance  $z_{ch}$  will be equal to:

$$z_{ch} = z_2 + z_3 + z_4 + z_5 = \frac{\rho}{4F_2^2} \left(1 - \frac{F_2}{F_1}\right) + \frac{\xi_{ch} \rho l_{ch}}{2F_2^2 d_{ch}} + \frac{\rho}{2F_2^2} \left(1 - \frac{F_2}{F_3}\right)^2 + \frac{\zeta_{fr} \rho}{2F_3^2};$$

$$z_{ch} = \frac{\rho}{2} \left[ \frac{1}{2F_2^2} \left(1 - \frac{F_2}{F_1}\right) + \frac{\xi_{ch} l_{ch}}{F_2^2 d_{ch}} + \frac{1}{F_2^2} \left(1 - \frac{F_2}{F_3}\right)^2 + \frac{\zeta_{fr}}{F_3^2} \right] \tag{6}$$

where  $F_1, F_2, F_3$  – the area of passage sections of ventilation ducts (Fig. 2, a);  $l_{ch}$  and  $d_{ch}$  – the length and hydraulic diameter of the axial channel;  $\xi_{ch}$  – coefficient of friction path loss in the channel;  $\zeta_{fr}$  – coefficient of local friction losses at the output of the engine [9].

The method of determining the hydraulic or equivalent diameter of the axial channel is as follows  $d_{ch}$  [10]:

$$d_{ch} = \frac{4F}{P} \tag{7}$$

where  $F$  – channel cross-sectional area,  $m^2$ ;  $P$  – perimeter length of channel cross-section,  $m$ .

Since the cooling channels have a rectangular section profile (7), we transform:

$$d_{ch} = \frac{2a_d b_d}{a_d + b_d} \quad (8)$$

where  $a_d$  – groove depth, m;  $b_d$  – groove width along the arc, m.

The areas of passage cross-sections of ventilation ducts are defined by expressions:

$$F_1 = \frac{\pi}{4}(d_1^2 - d_2^2) \quad (9)$$

$$F_2 = a_d b_d \quad (10)$$

$$F_3 = \frac{\pi d_3^2}{4} \quad (11)$$

where  $d_3$  – outlet diameters on the side surface of the LEME housing.

If we assume with the slightest part of the error that the cooler overcomes in each of the axial channels the same resistance, then the total hydraulic resistance of the vent duct LEME  $z_m$  can be found by the formula:

$$z_m = z_1 + \frac{z_{ch}}{n^2} \quad (12)$$

where  $z_1$  – road resistance when moving the cooler inside the stator in the superfluous space.

$$z_1 = \frac{\xi_{st} \rho \delta}{2F_1^2 d_{sp}} \quad (13)$$

where  $\xi_{st}$  – coefficient of frictional losses in the stator;  $\delta$  – size of the working course of an armature, m;  $d_{sp}$  – hydraulic diameter of the internal surface between the armature and the stator in the superfluous space, m.

The internal superspinning surface between the armature and the stator is in the form of a ring, therefore, in accordance with (7), the hydraulic diameter  $d_{sp}$  can be determined as follows:

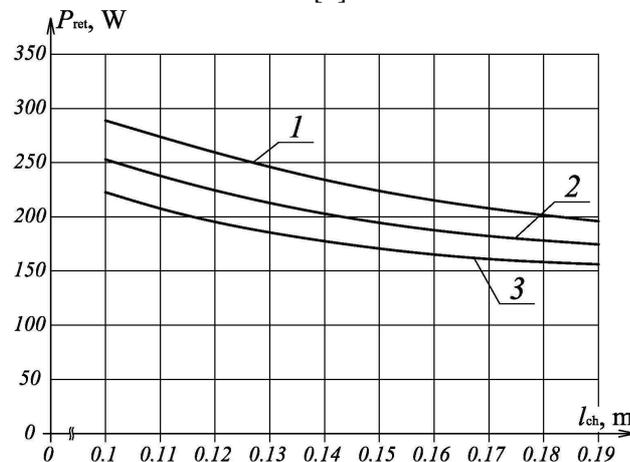
$$d_{sp} = d_1 - d_2. \quad (14)$$

The total hydraulic resistance of the ventilation duct LEME  $z_m$  is found by the expression:

$$z_m = \frac{\rho}{2} \cdot \left\{ \frac{\xi_{st} \delta}{F_1^2 d_{sp}} + \frac{1}{n^2} \left[ \frac{1}{2F_2^2} \left( 1 - \frac{F_2}{F_1} \right) + \frac{\xi_{ch} l_{ch}}{F_2^2 d_{ch}} + \frac{1}{F_2^2} \left( 1 - \frac{F_2}{F_3} \right)^2 + \frac{\zeta_{fr}}{F_3^2} \right] \right\} \quad (15)$$

### 3. Conclusion

Figure 3 shows the dependence of the retracted power  $P_{ret}$  on the length  $l_{ch}$  with a change in its hydraulic diameter  $d_{ch}$  for the LEME shock machine [1].



**Figure 3.** Dependence of the withdrawn power on the geometric parameters of the ventilation duct: 1 –  $d_{ch}=0.0029$  m; 2 –  $d_{ch}=0.0039$  m; 3 –  $d_{ch}=0.0049$  m.

The maximum value of the output power of  $P_{\text{ret}}$  LEME is achieved by decreasing the channel length  $l_{\text{ch}}$  and increasing its hydraulic diameter  $d_{\text{ch}}$ . However, for large values of  $d_{\text{ch}}$ , the cross-section of the magnetic circuit decreases, which contributes to a deep saturation of the stator and a decrease in the output energy indices of the LEME shock machine.

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