Electrochemical Processing of Liquids in Induction Heating Systems

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Abstract. The article discusses a new type of induction installations for heating and electrophysical treatment of liquids with ionic electrical conductivity in electromagnetic fields. Methods of their calculation and optimization are proposed due to creation of local areas with large gradients of strength of electric and magnetic fields. Mathematical dependencies describing processes of phase transformation and mass transfer of scale-forming agents in gap of magnetic apparatus and in heat exchange device are derived. Calculated and experimental dependencies on effect on anti- scale efficiency of magnetic devices are determined**.**

STATEMENT OF THE PROBLEM

The considered electrotechnological system consists of a primary winding (inductor), inside of which there is a magnetic core. On the outside the inductor is surrounded by electromagnetic screens. Screens provide conversion of electric energy into thermal energy [1]. Between screens there is a flow of treated liquid.

When different water flows pass through an electromagnetic apparatus, various processes take place in its gap. Experimental study of these processes is presented in the results of laboratory experiments. The experiments are aimed at studying the effect of magnetic treatment on the intensity of scale formation in heat exchangers [2]. The author has established the following fact. There is a fundamental difference in the operation conditions of magnetic devices in short-term laboratory experiments and in long-term industrial operation. The direction of laboratory experiments is associated with this. The magnetic apparatus is inherently a kind of magnetic filter. It holds ferromagnetic impurities in its gap. These impurities are present in various amounts in all aqueous media contacting the steel equipment of the heat exchange systems. When the magnetic field is turned on, a porous layer is formed on the gap section of the apparatus with the induction gradient opposite to the water flow direction over time. The layer has a well developed surface. It consists of ferromagnetic and mechanically retained non-ferromagnetic water impurities [3]. Laboratory experiments with real technical aqueous solutions and calculations showed the following. The period of accumulation of ferromagnetic impurities and stabilization of their amount accumulated in the gap of the laboratory magnetic apparatus (analog of the working cycle time of the magnetic filter) lasts from several hours to several days. This depends on the parameters of the magnetic apparatus, the concentration-dispersion characteristic of the medium, the flow rate in the gap. It has been found that the limit amount of ferromagnetic particles accumulated in the zone of one pole pair of the magnetic apparatus (G_{lm}) as follows dependent on the field intensity H and flow rate V_a [4, 5, 6]

$$G_{lm} = K_1 \cdot H \cdot \ln \frac{V_{lm}}{V_a} \tag{1}$$

where V_{lm} – limit flow rate in the device gap;

K_1 – constant depending on magnetic characteristics of impurity and apparatus.

Theoretical analysis of the process of accumulation of impurities in the gap allowed to determine functional dependence V_{lm} in the form of

$$V_{lm} = \frac{f \cdot \mu_0 \cdot (\mu - 1) \cdot \left(\left| \overline{H} \right| \cdot grad \overline{H} \right)_{\min} \cdot d_M^2}{-18 \cdot \delta} \qquad (2)$$

where $(|H| \cdot gradH)_{min}$ – minimum negative value of multiplication of magnetic field intensity modulus per its gradient;

δ – dynamic viscosity of solution;

d_M – average effective diameter of ferromagnetic particles trapped in the gap of the apparatus;

f – coefficient depending on particle shape;

μ_0 – magnetic permeability of vacuum;

μ – magnetic permeability of a particle.

A certain analogy has been established between devices used for anti-scale magnetic treatment of water and magnetic filters. This analogy led to the following conclusion. When modeling the operating conditions of industrial magnetic devices, it is necessary to add the third to two qualitative modes of operation of the magnetic device (the field is off and the field is on) in laboratory studies. At this mode the magnetic field is switched on, and a layer of ferromagnetic impurities is accumulated in the gap. The assertion of the existence of three characteristic modes of operation of magnetic devices formed the basis of the methodology for conducting the main experiments. The essence of the experiments is to study the effect of magnetic treatment on the technological parameters of aqueous solutions [7, 8].

Empirically, the following was established. When a magnetic field (H = 220 kA/m) was applied to the water flow, the nature of deposition $CaCO_3$ at the control heat exchange section was not changed compared to the first mode. However, if magnetite particles were introduced into the magnetic apparatus gap before the start of the test and accumulated there up to the value G_{lm}, this changed the nature of the scale formation in the control area of heat exchange. This was due to intense phase transformations in the gap. The deposits in the control area of heat exchange in the third mode were loose. They washed up at a 60… 80 % increasing the flow rate to 0,8…1,0 m/s. In the first and second modes of operation of the magnetic apparatus, the scale deposits on the control area have a dense structure. Therefore, when the flow rate increased to 0,8…1,0 m/s, only 10…20 % of their landed amount was washed out.

The experiments carried out to study the processes that occur in the gap of magnetic devices during magnetic treatment of supersaturated technical water solutions allowed to put forward and physically justify one of the possible mechanisms of this phenomenon. It comes down to the following:

- magnetic device delays ferromagnetic water impurities in its gap. After a period of time T_{lm}, an equilibrium porous layer with a developed surface is formed in the gap of the magnetic device;
- this impurity will be released from the solution on ferromagnetic particles in the gap of the magnetic apparatus if the aqueous medium entering the magnetic apparatus is unstable, supersaturated by salt or gas impurity. In water treatment practice, such impurities may be calcium carbonate, magnesium hydroxide, calcium sulfate, carbon dioxide, nitrogen, oxygen;
- separation of the supersaturation impurity from the solution on the surface of the filtering layer retained by the magnetic field leads to accumulation of this impurity in the gap of the apparatus in a different phase state (solid, gaseous). Crystals or gas bubbles arise and grow. When they reach a certain size, they are washed away by the flow of water and leave the magnetic apparatus. At the same time dynamic equilibrium is established in processes of separation and carry-over from the magnetic apparatus of water supersaturation impurity in new phase state (solid, gaseous);
- due to the above-mentioned processes in the water stream leaving the magnetic apparatus, the degree of supersaturation of the dissolved impurity will decrease and the concentration of this impurity in the new state (solid, gaseous) will increase. In addition, the magnetic treatment will change the characteristics of

ferromagnetic impurities (degree of dispersion, surface properties). This is due to magnetic coagulation and crystallization on particles of water-dissolved salts.

The experiments carried out and the conclusions drawn on their basis make it possible to consider anti-scale magnetic treatment in the form of a complex of known simultaneous technological processes, namely:

- purification of water from ferromagnetic impurities on magnetic filters;
- contact stabilisation of an aqueous solution supersaturated by scale-forming agents;
- introduction of anti- scale granular additive.

Changes in the water content of dissolved gases (oxygen, carbon dioxide) should influence the course of corrosion processes in the equipment located behind the magnetic apparatus. It can be argued that due to these processes, magnetic treatment can affect the technological parameters of technical aqueous solutions. This will occur by heterogeneous catalysis increasing the rate of phase transformations in metastable systems.

The calculated specific electrical resistance of water is about 2000 *Ohm·cm* (at a temperature of 20°C). The heating cylinders are located at a minimum distance from each other and from the case of the device (about 5 *mm*), This makes the device compact. All heated water passes between the cylinders. This provides a uniform temperature field across the cross section of the water heater. Consequently, more favorable operating conditions of the heating cylinders are created as scale formation and corrosion are reduced [8, 9, 10, 11]. A great convenience in operation is the presence of a power indicator directly connected to the power supply system.

In order to ensure long-term failure-free operation of induction heaters, correct (rational) organization of water mode and tightness of heat carrier circulation circuit are important. When the operating circuit of the water heater is closed (when heat carrier leaks and feed with raw water are insignificant), the initial period is clearly separated during operation. It is characterized by impermanence in time of water parameters.

The pH value of water increases during the initial period. This results from partial thermal desorption of dissolved carbon dioxide and corrosion processes in the system. These processes are particularly intensive under the influence of a variable electromagnetic field.

Alkaline reaction of water and its heating to 95°C promotes thermal decomposition of bicarbonates of calcium and magnesium with settling out of calcium carbonate $CaCO_3$ and magnesium hydroxide $Mg(OH)_2$. This explains the decrease in water stiffness during the initial operation of the water heater (Fig. 1, *a*). However, after some time the stiffness stabilizes (in the tests carried out – at the level of 0,2 *mg.EQ/kg*). For the experimental installation, this period is approximately 200…300 hours. The initial water stiffness is approximately 2,5 *mg.EQ/kg* and 5,0 *mg.EQ/kg* (Fig. 1, *a*).

In a closed system, not only the stiffness water is stabilized at the end of the initial period. The specific electric resistance of water is also stabilized, and therefore the ability to salt deposition. At the same time change ρ is in inverse proportion to change of water stiffness.

The value of specific electrical resistance $\rho_{20.lm.}$, which will be established in a system after removal from water of scale-forming agents approximately can be determined by a formula

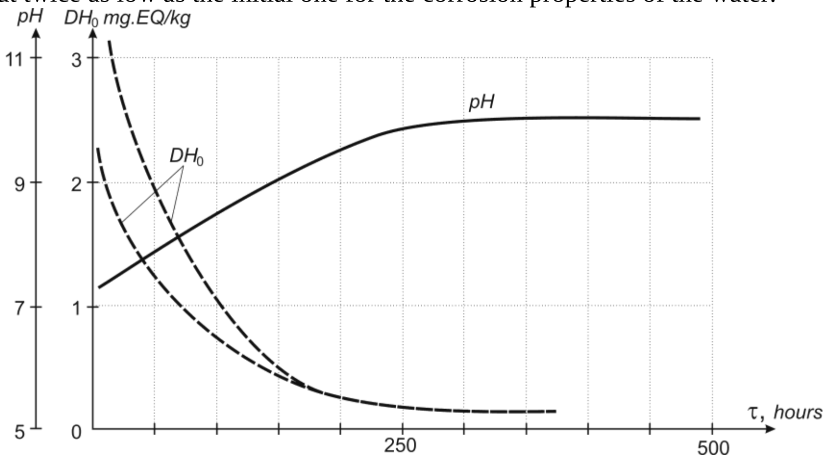
$$\rho_{20.lm} = \frac{k}{\frac{1}{\rho_{20}} - \frac{\Delta DH_0}{C_{EQ}}} \tag{3}$$

where $\Delta DH_0 = DH_{in} - DH_{est}$ – change of stiffness during initial period of water heater operation, *mg.EQ/kg*;
C_{EQ} – constant coefficient, $C_{EQ} = 11{,}2 \cdot 10^3$ *Ohm·cm·mg.EQ/kg*;
ρ_{20} – the specific electrical resistance of initial water measured at a temperature of 20°C, *Ohm·cm*;
k – correction factor, $k = 0{,}85$.

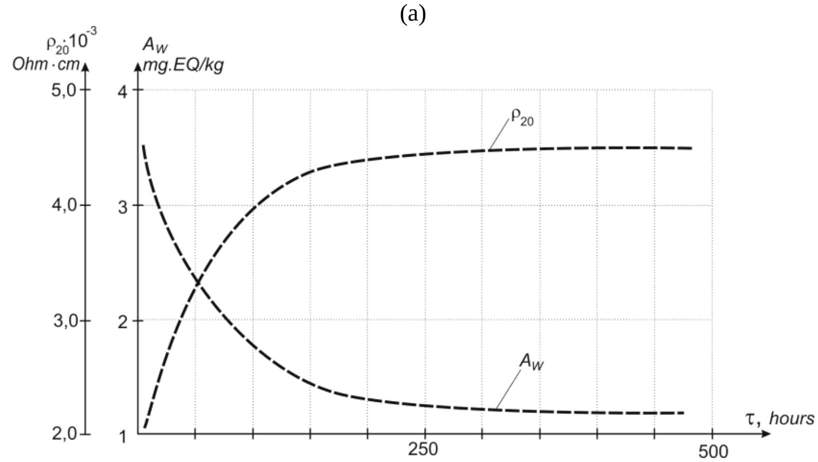
Values of ρ_{20} and DH_{in} are determined by analysis of the raw water sample. Value of DH_{est} adopted on the basis of previous work experience. In the performed tests received $DH_{est} = 0{,}2$ *mg.EQ/kg*.

As a result of chemical analysis of deposits on the elements of electrode group (scale powder) content of compounds *Ca* and *Mg* is found in them. It is relatively small (from 0,3 to 2,5 % in terms of *CaO* and *MgO*); Iron oxides make up a large proportion (from 88 to 95 % in terms of Fe_2O_3). Thus, in induction water heaters with a closed circulation circuit, the formation of scale from natural water impurities has less impact on the reliability of operation than corrosion of the system, primarily pipes of heating systems.

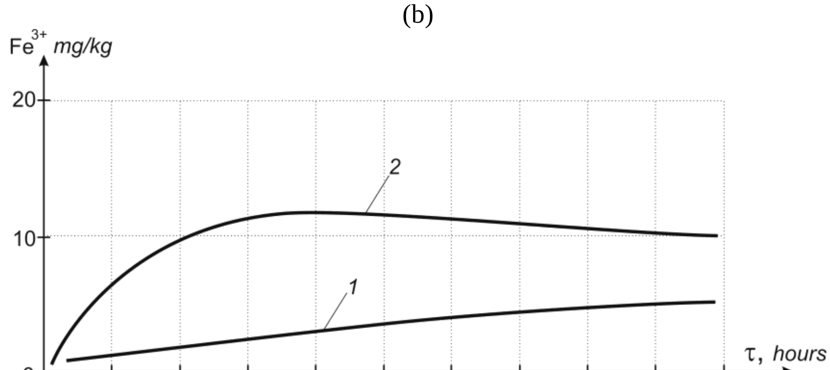
The corrosive effects of alternating current are currently insufficiently studied. Our researches have shown that one of the decisive factors of metal corrosion under the influence of alternating current is the composition of the electrolyte. Long-term tests of the induction-type electric heater showed that the iron content in water after long-term operation is about twice as low as the initial one for the corrosion properties of the water.



(a)



(b)



(c)

FIGURE 1. Dependences of water quality indicators on the time of induction heater operation: (a) – indicator of hydrogen ion concentration pH and the water stiffness DH_0; (b) – specific electrical resistance ρ_{20} and alkalinity of water A_W; (c) – iron concentration when Na_2CO_3 (1), *NaCl* and Na_2SO_3 (2) are added to water

The volume of particles formed is three times less than in the initial period. Thus, on the basis of the carried out researches, the induction electric heater has been created, which meets the modern requirements of consumers. It will significantly increase the efficiency of using water heaters.

MAIN FINDINGS AND RESULTS

- Carried out laboratory experiments, industrial tests and theoretical researches of operation of magnetic devices in the circuit of thermal power equipment make it possible to consider anti- scale magnetic treatment of water as a complex of simultaneously occurring technological processes, including:
    - purification of water from corrosion products on magnetic filters (magnetic filtration);
    - contact stabilization of the aqueous solution supersaturated by the scale formation;
    - introduction of granular anti-scale additive.
- The calculated and experimental dependences on influence on the anti-scale efficiency of magnetic devices of different parameters are determined. These are the intensity and gradient of the magnetic field intensity, the flow rate of water in the gap of the magnetic apparatus and in the heat exchanger, the number of pairs of magnetic poles and their mutual location, the degree of supersaturation by the scale -forming agent and the concentration of ferromagnetic impurities in the aqueous solution and other liquids.
- The mechanism of influence of electromagnetic devices on gas phase dissolved in technical water systems is revealed. The acceleration of kinetics of gas impurities extraction from supersaturated aqueous solution under the influence of magnetic treatment is noted. This can affect the course of corrosion processes in heat exchange circuits.
- It has been experimentally proved that the intensity of the magnetic field does not affect the intensity of the release of gas impurities from the water on the unit surface of the ferromagnetic impurities retained in the gap. Value of the magnetic field intensity affects the amount of gas impurities released from water in the magnetic apparatus gap through change of surface size of the retained ferromagnetic impuritiesthe.

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