Energy characteristics of induction water heater

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Abstract. Many agricultural facilities do not have the ability to connect to gas supply networks; at such facilities electric water heaters are used as sources of thermal energy for heating and hot water systems. The issue of the use of induction heating as one of the most effective at such facilities is relevant. The aim of this work is to study energy characteristics of an induction water heater, such as efficiency and power factor. In order to determine the estimated efficiency and power factor the energy balance method was used. The experimental values of the efficiency and power factor are determined by the calorimetric method and with the help of an electric energy quality analyzer. The obtained value of the efficiency and power factor of the induction water heater corresponds to the calculated value with an accuracy of ±1%.

1. Introduction

The process of heating the liquid is an integral part of most technological processes, both production facilities and agricultural. The most convenient and economical type of fuel at the moment is natural gas but the level of gasification in Russia as of 2018 is 68.5% and over the past year the increase was about 0.5%.

It can be argued that a large number of facilities do not have the ability to connect to gas supply networks; at such facilities electric water heaters are most widely used in heating and hot water supply systems.

In agricultural production, the most common electric heaters are elemental and electrode water heaters; they have gained their distribution due to the simplicity of design [1]. Acceptable electrode boilers have variable power depending on the temperature of the heated water and on the chemical composition [2]. Elemental boilers are prone to scale that also reduces the life of the heaters. In this situation induction heating is the most promising at such facilities. Currently there is a tendency to replace elemental and electrode water heaters with induction water heaters [3-5].

Induction heating is based on the Faraday-Maxwell law of electromagnetic induction and the Joule-Lenz law. In metallic bodies placed in alternating magnetic field a vortex electric field is excited. Under the influence of electromagnetic induction, eddy currents (Foucault currents) flow in the bodies, which also generate heat according to the Joule-Lenz law [6]. The main advantages of the induction water heater, in comparison with other methods of electric heating lies in the high efficiency of the conversion of electromagnetic field energy into thermal energy as well as in the absence of scale formation and in a stable efficiency [7,8].

Geetha V [7] and Quevedo L [8] conducted research on the use of induction heating as a source of thermal energy in heating and hot water systems. Serrano J [9] raised the issue of measuring the efficiency of household induction cookers operating at frequencies from 40 to 70 kHz. Acero J [10] reviewed the design and simulation of household induction heaters. An induction fluid heater providing...
a methodology for selecting the frequency of the inductor's supply current and the choice of heater power was considered in [11]. This entailed the experience of operating induction fluid heaters in heat supply and hot water systems [12].

Based on the studied works it becomes necessary to conduct experimental studies to determine the energy characteristics of the induction water heater. Experimental studies are aimed at determining the energy characteristics of the induction water heater and determining the effectiveness of the induction water heater used as a source of thermal energy in heating systems and hot water supply for household consumers.

2. Methodology
The geometric dimensions of the induction water heater, electrical parameters of the structural materials of the heater and inductor were taken into account while conducting the experiment.

2.1. Energy balance
Determining the effectiveness of the induction heater comes down to determining the efficiency. The efficiency is determined on the basis of energy balance. The energy balance of the induction water heater system is shown in figure 1.

Figure 1. Energy balance of the induction water heater: $P_T$ is the active power supplied to the induction water heater; $P_{ind}$ is the active power dissipated in the inductor; $P_2$ is the active power transmitted to the heat transfer tube; $P_p$ is the heat power dissipated into the environment due to heat conduction and convection; $P_w$ is the heat power transmitted to water.

According to the energy balance the active power supplied to the induction water heater system is calculated by the formula:

$$P_\Sigma = P_{ind} + P_2,$$  \hspace{1cm} (1)

where, $P_{ind}$ is the active power dissipated in the inductor; $P_2$ is the active power transmitted to the heat transfer tube.

Not all the power transferred to the heat exchanger tube is effectively transferred to water, part of the heat is dissipated into the environment, this can be expressed as:

$$P_2 = P_w + P_p,$$  \hspace{1cm} (2)

where, $P_w$ is the heat power transmitted to water; $P_p$ is the heat power dissipated into the environment due to heat conduction and convection.

Then the electrical efficiency is defined as:
The thermal efficiency is determined by the formula

$$\eta_t = \frac{P_t}{P_2}.$$  \hfill (3)

The overall efficiency of the induction water heater system can be defined as the product of the electrical and thermal efficiency. This can be expressed as follows:

$$\eta_{\Sigma} = \eta_e \cdot \eta_t.$$  \hfill (5)

Substituting expressions (3) and (4) in the formula (5) we obtain the following expression for determining the overall efficiency:

$$\eta_{\Sigma} = \frac{P_2}{P_2} \cdot \frac{P_t}{P_2} = \frac{P_w}{P_2}.$$  \hfill (6)

The amount of thermal power in watts transmitted to water can be determined by the formula [4]:

$$P_w = m \cdot C_p \cdot (t_2 - t_1) \cdot \frac{1}{3.6 \cdot \tau},$$  \hfill (7)

where, \(m\) is the mass of heated water, kg; \(C_p\) - average heat capacity of water, J/(kg · K); \(t_1\) - initial water temperature, °C; \(t_2\) - final water temperature, °C; \(\tau\) is the time of heating water from temperature \(t_1\) to \(t_2\), hours.

Power \(P_2\) can be measured using the electric energy quality analyzer.

2.2. Experimental research stand

In order to measure the energy characteristics and determine the efficiency of the induction water heater a stand was made, the diagram is shown in figure 2. The stand consists of the following elements: induction water heater 2 kW, circulation pump TAIFU GR S25 / 4, heat-insulated water tank, microprocessor controller “Oven” TPM1 with a temperature sensor, the accuracy class of the device is 0.25, the electric energy quality analyzer AKE-824 with current loops HTFLEX 33 with a maximum permissible error of ± 1% and a group of security.

The experiments were carried out in a room at a temperature of 23 °C, a relative humidity of 64%, atmospheric air pressure in the room 747 mm Hg, the volume of heated water 12.8 liters.

A common electric network with a voltage of 230 V and a frequency of 50 Hz was used as a power source for the induction water heater.

![Figure 2. Experimental stand: 1 – induction water heater; 2 – circulation pump TAIFU GR S25/4; 3 – insulated water tank; 4 – microprocessor controller "Oven" with a temperature sensor; 5 – electric energy quality analyzer AKE-824; 6 – security group; 7 – airspace.](image)
The design of the induction heater used in this study is presented in figure 3.

![Diagram of Induction Heater](image)

**Figure 3.** Induction heater: 1 – inlet pipe; 2 – outlet pipe; 3 – inductor; 4 – bottom cover; 5 – top cover; 6 – heat and electrical insulation material; 7 – channel system.

The induction heater consists of steel pipes assembled coaxially and forming a system of channels 7, steel pipes are welded to the lower 4 and upper 5 lids and create a single structure. An inductor 3 is placed between two steel pipes forming a heat exchange surface. To protect the inductor coil from shorting to the body of the induction heater as well as to protect the inductor from overheating the inductor is wrapped in heat and electrical insulation material 6. For connection to the heat supply system inlet 1 and outlet 2 pipes are provided.

The proposed design of the induction heater allows to reduce the power loss due to dissipation in the inductor and into the environment, due to the fact that the inductor is placed in heated water, as a result of which the generated heat in the inductor and on the external surfaces of the metal tubes are completely transferred to the water.

3. Results

According to the method proposed in [13], the energy characteristics of the induction heater were calculated. We determine the magnetic field strength on the surface of the heat exchange tubes by the equation (8):

\[
H_z = \sqrt{\frac{p_2 \cdot 10^6}{\sqrt{\rho_2 \cdot \mu_r \cdot f \cdot F_2}}},
\]

where, \(p_2\) – the specific surface power in heat transfer tubes, kW / m²; \(\rho_2\) – electrical resistivity of steel, Ohm·m; \(\mu_r\) – the calculated value of the relative magnetic permeability at the corresponding temperature; \(f\) – the frequency of the supply current, Hz; \(F_2\) – correction function for heat transfer tubes showing how many times the value of active power for conductive bodies of finite dimensions differs from active power for a semi-infinite body.
The magnetic field strength on the surface of the inductor is calculated by the formula (9):

$$H_t = \frac{H_z}{k_{co}}$$

(9)

where, $k_{co}$ is the coupling coefficient. The active power dissipation in the inductor is determined by the equation (10):

$$P_{ind} = \pi \cdot 10^{-6} \cdot H_z \cdot h_1 \cdot d_1 \cdot \sqrt{\rho_1 \cdot f \cdot F_l} \cdot \frac{1}{k_{ff}}$$

(10)

where, $h_1$ and $d_1$ are the height and diameter of the inductor respectively, m; $\rho_1$ - electrical resistivity of the material of the inductor winding, Ohm · m; $F_l$ is the correction function for the inductor showing how many times the value of the active power for conducting bodies of finite dimensions differs from the active power for a semi-infinite body; $k_{ff}$ – fill factor of the inductor.

According to the calculation results the active power dissipation in the inductor is 0.048 kW.

We determine the active power of the induction water heater as the sum of the active power dissipation in the inductor $P_{ind}$ and the active power transmitted to the heat transfer tubes $P_2$ according to the formula (1).

Value of the active power transmitted to the heat exchange tubes of 2.0 kW, the total power of the induction water heater is 2.048 kW.

Reactive power in the inductor is calculated as:

$$Q_t = |P| \cdot \frac{G_t}{F_t}$$

(11)

where, $G_t$ is the correction function for the inductor showing how many times the value of reactive power for conducting bodies of finite sizes differs from reactive power for a semi-infinite body.

According to the calculation results the reactive power in the inductor is 0.076 kvar.

Reactive power in heat transfer tubes is determined by the formula (12):

$$Q_2 = 0.6 \cdot |P_2| \cdot \frac{G_2}{F_2}$$

(12)

where $G_2$ is the correction function for heat transfer tubes showing how many times the value of reactive power for conductive bodies of finite sizes differs from reactive power for a semi-infinite body.

The reactive power of the heat exchange tubes is 0.95 kvar.

Reactive power in the space between the inductor and heat transfer tubes is determined as:

$$Q_3 = \pi \cdot 10^{-9} \cdot H_z^2 \cdot f \cdot h_1 \cdot (d_1^2 - d_2^2)$$

(13)

where $d_2$ is the outer diameter of the heat exchange tube, m.

The reactive power in the space between the inductor and the heat exchange tubes is determined for the outer and inner tubes and according to the calculation results a total of 0.026 kvar is obtained.

Reactive power in the space of the internal heat transfer tube is determined by the equation (14):

$$Q_4 = \frac{1}{2} \cdot \mu_0 \cdot H_z^2 \cdot f \cdot V$$

(14)

where $\mu_0$ is the magnetic constant, Gn/m; $V$ is the volume of the space of the internal heat transfer tube, m$^3$.

The calculated value of reactive power in the space of the internal heat transfer tube was 0.391 kvar. The total reactive power of the induction heater $Q_\Sigma$ is 1.433 kvar. The total power of the induction heater is determined by the formula (15):

$$S = \sqrt{P_\Sigma^2 + Q_\Sigma^2}$$

(15)

and equal to 2.505 kVA.

The power factor of the induction heater can be determined by the formula (16):

$$P_F = \frac{P_\Sigma}{S}$$

(16)
Then the calculated power factor $P_f$ of the induction heater is 0.817.

Assuming that all the active power from the heat exchange tubes $P_2$ is transferred through the heat exchange to the heated water without loss formula (2) can be written as follows:

$$P_2 \approx P_w.$$  

Then the total estimated efficiency of the induction water heater is:

$$\eta_2 = \frac{P_w}{2.048} \cdot 100\% = 97.66\%.$$  

In order to confirm the calculations, an experimental study of the induction heater device was carried out. The dynamics of heating and the change in the active power of the inductor during the heating process are presented in figure 4. According to the testimony of the ‘’Oven’’ microprocessor controller TPM1, at the beginning of the heating process the water temperature in the system was 24.2 °C, at the end of the heating process, the temperature was 62.7 °C, and the heating time was 19 min. The volume of heated water is 12.8 liters poured into the system at room temperature 24 °C.

![Figure 4. Dynamics of heating and changes in active and apparent power in the process of heating of induction water heater.](image)

It is necessary to determine the mass of water in the system through the volume and density of water. At a temperature of 24 °C, the density of water is 997.3 kg/m³, then the mass of water will be:

$$m = V \cdot \rho_w = 12.8 \cdot 10^{-3} \cdot 997.3 = 12.77 \text{ kg}.$$  

It is necessary to determine the average heat capacity of water in the temperature range from 24.2°C to 62.7 °C by the equation (19):

$$C_p = \frac{C_{p1} \cdot t_1 + C_{p2} \cdot t_2}{t_1 + t_2},$$  

where, $C_{p1}$, $C_{p2}$ are the heat capacity of water at $t_1$ and $t_2$, respectively, kJ/kg·K.

The heat capacity of water is 4.1797 and 4.1855 kJ/kg·K at 24.2 and 62.7°C, respectively.

The average heat capacity of water according to formula (19) was 4.18 kJ/kg·K. According to formula (7), the thermal power given to water during heating was 1804.38 watts. The amount of electric energy $W$ spent on the process of heating water is determined by the data of the electric energy quality
analyzer AKE-824, which is 587.02 W·h. Then the average active power consumed from the network during heating can be determined by the formula (20):

\[ P_\tau = \frac{W}{\tau}. \]

The average active power was 1,854 W. The experimental efficiency of the induction water heater determined by formula (6) was 97.34%. According to an AKE-824 quality analyzer of electric energy the power factor \( P_F \), is 0.81 without the use of devices correcting the power factor.

4. Conclusion

In this work we studied the energy characteristics of the induction water heater. In order to determine the estimated efficiency and power factor the energy balance method was used. The experimental values of the efficiency and power factor are determined by the calorimetric method and with the help of the electric energy quality analyzer. The induction water heater is designed to operate at industrial frequency of 50 Hz.

The obtained value of the efficiency and power factor of the induction water heater corresponds to the calculated value with an accuracy of ± 1%. The decrease in the active power of the inductor during heating can be explained by increasing of the specific electrical resistance of the inductor winding with temperature change. Thus, the study of the values of the efficiency and power factor of the induction water heater indicates the high efficiency of this type of water heaters.

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