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Original Research Article

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STUDYING CHARACTERISTICS OF THE HEAT PIPE OF A LOW-PRESSURE STEAM ELECTRIC HEATER WITH DIFFERENT TYPES OF HEATERS

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Abstract. *The article deals with developing and analyzing a heat pipe of a low-pressure steam electric heater intended for autonomous heating systems. The object of the study is two types of heating elements: a tubular electric heater with a nichrome spiral and an induction heater. Experimental analysis methods have been used to evaluate the heating characteristics, the temperature distribution and the energy efficiency. It has been established that the induction heater provides a higher heating rate and uniform temperature distribution, while the tubular heater is characterized by stable operation and economy. The obtained results allow proposing the ways to optimize the design of the electric heater to increase its efficiency and reliability. The findings confirm the practical potential of using the devices under study in various types of heating systems.*

Keywords: steam electric heater, heat pipe, energy efficiency, nichrome coil, induction heater, autonomous heating, low pressure.

1. Introduction

Low-pressure steam electric heaters (LPSEH) are one of the promising technologies for autonomous heat supply. Their use is relevant in the context of the need to reduce energy consumption, to transit to environmentally friendly heat sources and to increase reliability of engineering systems in remote or energy-independent facilities. These devices combine high energy efficiency, environmental friendliness and ease of use, and their operation is based on the principle of a heat pipe, a device in which at reduced pressure a phase transition of the coolant occurs: evaporation and subsequent condensation. This process ensures intense heat transfer with minimal energy costs.

Present day developments in the field of heat pipes cover a wide range of issues: selecting design solutions, selecting coolants and the intensifying heat transfer. A generalized review of these areas is presented in work [1], where design varieties and new technical approaches are considered. High thermal conductivity, resistance to temperature fluctuations and operational reliability allow considering heat pipes as the basis for energy-efficient systems, which is emphasized by the authors of studies [2] and [3], who have proposed a design with a simplified evaporator that maintains stable performance with variable power supply. The key advantage of heat pipes, according to work [4], is the capillary liquid circulation without the use of pumps, which makes such systems energy-independent and durable. The authors of work [5] confirm the efficiency of heat pipes when used with low-potential heat sources, demonstrating a fast thermal response and high energy output compared to traditional water heating systems. Work [6] emphasizes low thermal resistance and versatility of heat pipes when working in vacuum and with low-temperature flows.

Similar approaches are actively used in solar energy. Work [7] considers solar water heaters in which heat pipes can significantly increase thermal efficiency and reliability due to phase transitions and operation at reduced pressure. In the context of increasing requirements for energy efficiency and sustainability of energy supply, the LPSEH is becoming a logical alternative to traditional systems. Due to the possibility of autonomous operation without pumping equipment and an extensive pipeline network, they are especially in demand in regions with a harsh climate. The approach to sustainable heat supply is in particular implemented in study [8], where a dual heat source system has been developed that include heat pumps and energy storage devices, providing reliable heating at low operating costs.

This study continues and develops the scientific aspects outlined in works [9–12], where the design parameters of the LPSEH, the vacuum conditions, the weight and geometry of heat pipes, as well as the integration of new types of electric heaters have been analyzed. Based on the accumulated experimental material, the need for a comparative analysis of two types of heating elements: a tubular electric heater with a nichrome spiral and an induction heater used in the LPSEH has been identified. The tubular electric heater is characterized by a simple design, reliability and affordable cost, which makes it suitable for mass application. However, the limited uniformity of heat distribution reduces the overall efficiency of the system. In contrast, the induction heater uses eddy currents for fast and uniform heating which increases the performance of the device. However, its high cost and design complexity limit widespread implementation.

The purpose of this work is to carry out a comparative analysis of the thermal characteristics of the specified types of heaters, to evaluate their impact on the LPSEH efficiency, and to identify the most rational engineering solutions for increasing reliability and energy efficiency of autonomous heating systems.

2. Experiment description

The aim of this study is a comparative analysis of the efficiency of two types of heating elements used in the design of LPSEH vacuum electric heaters. The experiment assessed the effect of the heater type on the rate of thermal response, the temperature distribution along the tube, the energy efficiency of the system and its operational stability at different vacuum pressure levels.

Two heat pipes of identical design that differ only in the heating element used, have been assembled for the tests: the first one used a tubular electric heater with a nichrome spiral, and the second one used an induction heater. Both units operated at the same power of 120 W, which ensured the correctness of the comparative analysis of the operating characteristics. The design of the tubes included two sections of a copper pipe with the diameter of 22 mm and the length of 210 mm, hermetically sealed at the ends. The mass of each tube with the coolant filled was 230 g.

Distilled water with the volume of 15 ml has been used as the coolant. It has been selected due to its high purity and stability of thermophysical properties, eliminating the effect of impurities on the thermal process. Such a choice of liquid, as well as the assessment of its composition effect on the efficiency of heat transfer, have been considered in detail in a number of works, including the study by Barrak et al. [13], where the characteristics of single- and multi-component coolants, including binary mixtures, have been analyzed.

To provide the conditions for an effective phase transition, vacuum pressure in the range of 5–10 kPa (0.05–0.1 atm) has been maintained inside the tubes. Decreasing pressure leads to decreasing the boiling point of water, accelerates the onset of evaporation, and contributes to increasing the intensity of heat transfer. Such dependences between the vacuum level, the coolant flow modes, and the device orientation have been studied in detail in [14], where the optimal operating conditions for pulsating heat pipes have been determined.

The vacuum environment has been provided and stabilized using a DUO 6/M SERIES vane pump (Pfeiffer Vacuum) that is capable of achieving residual pressure of up to 10^{-3} mbar. This ensures reliable maintenance of the specified pressure range throughout the entire experimental cycle, which is critical for the results reproducibility.

The temperature parameters were recorded using digital thermometers Fluke 51 (USA) with a measurement error of ±0.05% + 0.3 °C and HT-9815 (China) with an accuracy of ±0.1%. The wide operating temperature range of the instruments (from –200 °C to +1372 °C) ensured reliable temperature registration under the experimental conditions. In the present study, temperature measurements were performed in the range from 20 °C to 250 °C, corresponding to the operating modes of the low-pressure steam electric heater.

To ensure the multi-point monitoring of thermal distribution along the length of the tube, contact thermocouples connected to the data collection system have been additionally used. This made it possible to record expected temperature non-uniformities, especially in the upper and lower parts of the tube. Both heat pipes have been connected to a single power source with nominal voltage of 220 V. The current power and total energy consumption have been measured using two digital multimeters (UNI-T and UT61B), as well as a JUANJUAN qt01 wattmeter with the error of ±2%.

These measurements allow calculating the efficiency coefficient (EC) that is used as the main criterion for comparative evaluation of the device efficiency. The parameter measurement diagram is shown in Figure 1. The diagram indicates the main components of the heater and displays the heat transfer processes: solid arrows indicate the upward movement of steam, and dotted arrows indicate the reverse flow of condensate downward.

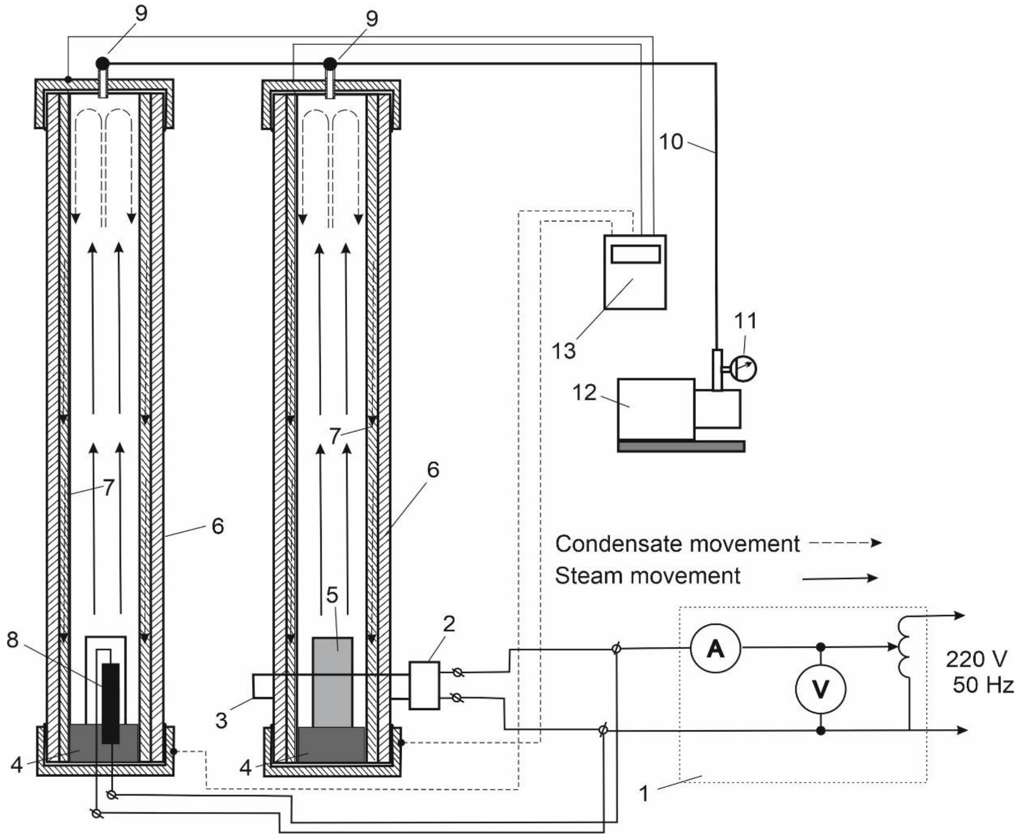

Fig.1. Diagram of measuring the heat electric vacuum tube parameters:
1 – measuring unit with autotransformer; 2 – mini ZVS Low Voltage Induction Heating Power Supply Module; 3 – inductor coil; 4 – coolant; 5 – steel core; 6 – housing of the heat pipe of the LPSEH electric vacuum heater; 7 – drainage porous channel of the regenerator; 8 – tubular electric heater; 9 – check valve for pumping air from the inner cavity of the tube; 10 – air pumping system pipeline; 11 – vacuum gauge; 12 – vacuum pump, 13 – counter.

The experiment has been carried out in the sequence that ensured stable and reproducible conditions. After evacuating the internal volume to pressure of 5–10 kPa, distilled water has been poured into the tube. The valve has been sealed, ensuring pressure stability. From the moment the voltage has been applied, the heating element has been heated either through a nichrome spiral or by inducing eddy currents in a metal core. As a result, the process of evaporation of the coolant has begun, the steam has risen to the upper part of the tube, where it has been condensed, giving off heat to the walls, and then has returned to the lower part as condensate through a drainage channel made of a metal wire structure. Thus, a closed cycle has been formed inside the tube, ensuring continuous and effective heat transfer due to the circulation of steam and liquid in different phase states. The initial operating temperature of the heater casing was reached in less than one minute after switching on, indicating a rapid onset of the heating process. Further temperature increase to higher operating levels occurred during continued heating, as reflected by the experimental temperature–time dependences. A comparative analysis of the thermodynamic characteristics of tubes with different types of heaters has made it possible to identify key differences in the energy output, the uniformity of the temperature field and the overall efficiency of the design.

3. Results and discussion

Experimental studies have shown significant differences in the heat transfer characteristics and energy performance of the two types of heating elements used in the LPSEH design. Based on the data obtained, the temperature dependences on the heater operating time have been plotted (Figure 2). The graph has been plotted and experimental data have been approximated using the Microsoft Excel analysis and visualization tools.

For a quantitative description of the experimental temperature dependences, semi-empirical approximating functions were used, reflecting the temperature rise as a function of heating time. The approximation was performed using third-order polynomial regressions obtained by the least-squares method:

$$T_1(t) = -0.3333t^3 - 4.7619t^2 + 94t - 66.143,$$

$$T_2(t) = -0.5t^3 + 3.2024t^2 + 34.06t - 11.857,$$

where $t$is the heating time, T_1 is the temperature of the induction heater, and T_2 is the temperature of the tubular electric heater. The argument $t$corresponds to the time coordinate (s) shown on the horizontal axis in Figure 2.

The coefficients of determination were R^2=0.9975 for the induction heater and R^2=0.9999 for the tubular heater, indicating a high degree of agreement between the approximating functions and the experimental data.

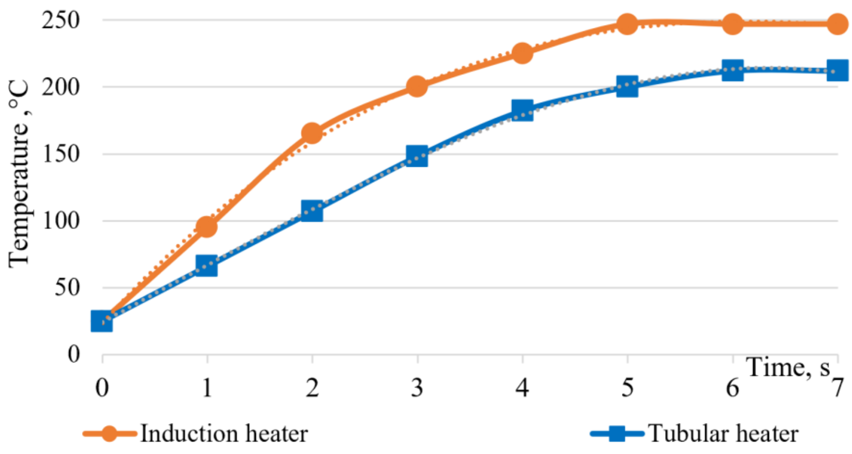

Fig.2. Temperature dependence on the operation time of heaters

The experimental curves were processed using regression analysis. The experimental data were approximated by third-order polynomial regression functions obtained using the least-squares method, which are shown in Figure 2. The high values of the determination coefficients indicate good agreement between the experimental data and the approximating functions. The high reproducibility of the experimental data and the consistency of the obtained temperature trends indicate the reliability of the results and the adequacy of the applied approximation approach.

The maximum temperature reached by the tube with a tubular electric heater has been 212 °C, while for the induction heater this figure has been 247 °C. In addition, the induction heater demonstrated a higher thermal response rate: the average time to reach the temperature of 200 °C has been 3 minutes versus 5 minutes for the tubular heater. This advantage can be explained by a higher heat flux density, characteristic of induction heating, as well as better uniformity of heat distribution along the length of the tube. The analysis of thermal profiles has shown that the induction heater provides a stable temperature field along the entire length of the heat pipe. In particular, a smaller temperature gradient is observed in the upper part of the tube compared to the tubular heater, where local fluctuations and reduced thermal stability have been observed. This indicates a more uniform heat transfer and less local overheating in the case of using the induction method.

The energy efficiency assessment revealed that the efficiency of the induction heater exceeds that of the tubular electric heater by an average of 15%. For a clear comparison of the operational and design features of the investigated heating elements, their main characteristics, summarized on the basis of experimental data and qualitative analysis of the test results, are presented in Table 1.

Table 1. Comparative characteristics of the investigated heating elements.

Characteristic	**Tubular electric heater**	**Induction heater**
Time to reach operating regime	Longer	Shorter
Maximum achieved temperature	Lower than induction	Higher than tubular
Temperature response	Less uniform	More uniform
Energy efficiency	Lower	Higher
Structural complexity	Low	Increased
Cost	Lower	Higher
Technological availability	High	Limited

The data presented in Table 1 clearly demonstrate that induction heating offers advantages in terms of heating rate, temperature uniformity and energy efficiency. These advantages are primarily explained by reduced heat losses due to more targeted energy transfer and the absence of mechanical contact between the heating element and the heated surface. The obtained results are consistent with previously published studies on induction heating systems [15], where high energy efficiency (up to 97.34%) and favorable power factor values (up to 0.81) have been reported for induction-based heaters, confirming the effectiveness of this heating method in high-energy-output applications.

Additional confirmation of the energy and thermal advantages of induction heating is given in [16], where more uniform temperature distribution and increasing of up to 25 °C have also been established compared to resistive elements with equal input power. Thus, experimental and literature data indicate the technological superiority of the induction heating method in the context of energy efficiency and thermal stability.

A comparison of the main operating characteristics of the two types of heaters allows highlighting a number of key differences. Firstly, induction heating provides a higher speed of reaching the target temperature, which makes it preferable for systems with limited warm-up time. Secondly, the temperature field along the tube during induction heating is more uniform, which increases the efficiency of heat transfer and reduces the risk of local overheating. Thirdly, the achieved energy efficiency of the induction element exceeds the resistive analogue by 10-15%, which makes it attractive for use in energy-saving installations.

Another important advantage is the reduced thermal gradient on the tube surface during induction heating, which reduces the risk of overheating and improves the operational safety of the device. However, it should be noted that induction heaters are characterized by greater design complexity, as well as a significantly higher cost, which limits their use in serial and low-cost heating systems.

Thus, the results of the experiment confirm the high efficiency of induction heating in the context of heat transfer, the uniformity of temperature distribution and the overall energy efficiency. These findings are consistent with the theoretical provisions and applied recommendations set out in [17], which summarizes the design principles of induction systems, including frequency parameters, coil configuration and thermal response of materials. Despite this, tubular heaters remain relevant due to their simple design, availability and reliability in operation. In conditions of a limited budget, as well as when mass production of devices is required, resistive elements remain an economically viable solution.

A promising area for further research is optimization of the induction heater design to reduce the cost, simplify the manufacturing technology and increase the technological reliability. The development of hybrid systems with a controlled type of heating can also be of interest for expanding the scope of LPSEH application in energy-efficient engineering systems.

4. Conclusion

The present study was devoted to a comparative analysis of the thermal behavior of a low-temperature steam electric heater employing tubular electric and induction heating elements under identical experimental conditions. The obtained experimental results demonstrated that the type of heating element has a significant influence on the temperature characteristics of the heat pipe and on the formation of the overall thermal regime.

The induction heater exhibited a higher heating rate, a higher maximum operating temperature, and a more uniform temperature distribution along the length of the heat pipe. In particular, the time required to reach the operating regime was shorter, and the temperature gradients along the tube were lower than those observed for the tubular electric heater. Moreover, the energy efficiency of the induction heater exceeded that of the tubular heater by an average of approximately 15%, which confirms its potential for application in energy-efficient autonomous heat supply systems. A comparison of the obtained experimental data with previously published studies [15–17] confirms the key advantages of induction heating under conditions requiring high heating rates, thermal stability, and uniformity of heat transfer.

At the same time, the tubular electric heater demonstrated stable and reproducible operation, adequate thermal performance, and structural simplicity. Its lower cost and high technological availability make this type of heater a practical and economically justified solution for mass production and for applications in which economic and technological constraints play a decisive role. Therefore, the selection of a heating element should be based not only on thermal and energy performance, but also on structural, technological, and economic considerations. Despite the clear operational advantages of induction heating systems, their increased structural complexity and higher cost currently limit their widespread industrial implementation.

The scientific novelty of this work lies in the experimental comparison of heating elements of different physical nature under vacuum heat pipe conditions, which made it possible to identify their key advantages and limitations. The practical significance of the obtained results is associated with the possibility of a well-founded selection of heating elements for specific operating conditions, as well as with the development of recommendations aimed at improving the energy efficiency of low-temperature steam electric heaters.

Further research should focus on optimizing induction heater designs in order to reduce cost, enhance manufacturability, and improve operational reliability. Particular interest is also associated with the development of hybrid heating systems and intelligent control strategies capable of adapting thermal characteristics to changing external conditions and energy efficiency requirements in modern autonomous heat supply systems.

Conflict of interest statement
The authors declare that they have no conflicts of interest in connection with this study, whether financial, personal, authorial or otherwise, that could influence the study and its results presented in this article.

CRediT author statement
Buzyakov R.R.: Conceptualization, Investigation, Formal analysis, Writing – original draft; **Mekhtiyev A.D.:** Methodology, Resources, Writing – review & editing; **Neshina Ye.G.:** Literature review, Theoretical analysis; **Alkina A.D.:** Visualization, Formal analysis; **Bilichenko A.P.:** Data curation, Investigation, Validation. The final version of the manuscript was read and approved by all authors.

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References

1 Jose J., Hotta T. K. (2023) A comprehensive review of heat pipe: Its types, incorporation techniques, methods of analysis and applications. *Thermal Science and Engineering Progress, 42*, 101860. https://doi.org/10.1016/j.tsep.2023.101860

2 Jouhara H., Khordehgah N., Almahmoud S., Delpech B., Chauhan A., Tassou S.A. (2018) Waste heat recovery technologies and applications. *Thermal Science and Engineering Progress, 6*, 268–289. https://doi.org/10.1016/j.tsep.2018.04.017

3 Buffone C. (2014) Testing of a low-cost loop heat pipe design. *Journal of Electronics Cooling and Thermal Control*, *4*(1), 33–38. https://doi.org/10.4236/jectc.2014.41004

4 Faghri A. (2014) Heat pipes: Review, opportunities and challenges. *Frontiers in Heat Pipes, 5*(1). https://doi.org/10.5098/fhp.5.1

5 Kerrigan K., Jouhara H., O'Donnell G. E., Robinson A.J. (2011) Heat pipe-based radiator for low grade geothermal energy conversion in domestic space heating. *Simulation Modelling Practice and Theory, 19*(4), 1154–1163. https://doi.org/10.1016/j.simpat.2010.05.020

6 Vasiliev L. L. (2005) Heat pipes in modern heat exchangers. *Applied Thermal Engineering, 25*(1), 1–19. https://doi.org/10.1016/j.applthermaleng.2003.12.004

7 Rahimi-Ahar Z., Khiadani M., Rahimi Ahar L., Shafieian A. (2023) Performance evaluation of single stand and hybrid solar water heaters: A comprehensive review. *Clean Technologies and Environmental Policy*, *25*, 2157–2184. https://doi.org/10.1007/s10098-023-02556-6

8 Wang Y., Quan Z., Jing H., Wang L., Zhao Y. (2021) Performance and operation strategy optimization of a new dual-source building energy supply system with heat pumps and energy storage. *Energy Conversion and Management*, *239*, 114204. https://doi.org/10.1016/j.enconman.2021.114204

9 Mekhtiyev A., Breido I., Buzyakov R., Neshina Y., Alkina A. (2021) Development of low-pressure electric steam heater. *Eastern-European Journal of Enterprise Technologies*, *4*(8(112)), 34–44. https://doi.org/10.15587/1729-4061.2021.237873

10 Mekhtiyev A., Buzyakov R., Shapenova Z. (2022) Low-pressure steam electric heater. *Bulletin of Toraighyrov University*, *3*(4(89)), 123–134. https://doi.org/10.48081/SYOY6805

11 Mekhtiyev A., Buzyakov R., Kim P., Alkina A. (2021) Research of parameters of an induction electric vacuum heater of a low-pressure steam electric heater. *Proceedings of the University*, *3*(4(84)), 262–267. https://doi.org/10.52209/1609-1825_2021_3_262

12 Mekhtiyev A., Buzyakov R. (2023) A low-pressure steam electric heater as the basis of a new generation autonomous heating system. *The Bulletin of KazATC*, *5*(128), 474–481. https://doi.org/10.52167/1609-1817-2023-128-5-474-481

13 Barrak A.S., Saleh A.A. M., Naji Z.H. (2019) An experimental study of using water, methanol, and binary fluids in oscillating heat pipe heat exchanger. *Engineering Science and Technology, an International Journal.* https://doi.org/10.1016/j.jestch.2019.05.010

14 Saha N., Das P.K., Sharma P.K. (2014) Influence of process variables on the hydrodynamics and performance of a single loop pulsating heat pipe. *International Journal of Heat and Mass Transfer*, *74*, 238–250. https://doi.org/10.1016/j.ijheatmasstransfer.2014.02.067

15 Korepanov A., Lekomtsev P., Niyazov A. (2020) Energy characteristics of induction water heater. *IOP Conference Series: Earth and Environmental Science*, *433*, 012035. https://doi.org/10.1088/1755-1315/433/1/012035

16 Szychta E., Szychta L. (2020) Comparative analysis of effectiveness of resistance and induction turnout heating. *Energies*, *13*(20), 5262. https://doi.org/10.3390/en13205262

17 Rudnev V., Loveless D., Cook R. (2017) *Handbook of induction heating* (2nd ed.). CRC Press. https://doi.org/10.1201/9781315117485

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