ABSTRACT
of the dissertation by Rustam Ravilievich Buzyakov
on the topic "Research and Development of an Energy-Efficient Electrical Heating Device as an Alternative Source of Thermal Energy" submitted for the degree of Doctor of Philosophy (PhD) in the specialty 8D07103 – "Electric Power Engineering"

The dissertation is devoted to the research and development of an energy-efficient electrical heating device based on a low-pressure steam electric heater (LPSEH) with a gravity-type electro-vacuum heat pipe, intended for local autonomous, decentralized, and hybrid electric heat supply to consumers.

The relevance of the study is determined by the need to improve the energy efficiency of end-use electricity consumption, develop controllable electrothermal loads, and reduce the dependence of local heat supply on solid fuels. With the growth of electrical loads, the ageing of energy infrastructure, the expansion of low-carbon generation, and environmental restrictions, the need for autonomous, decentralized, and hybrid heat supply systems is increasing. A promising direction is the use of electrical heating devices with internal two-phase heat transfer, which ensure the conversion of active electrical power into thermal energy directly at the point of consumption. At the same time, the operation of a low-pressure steam electric heater based on an electro-vacuum heat pipe as an energy-efficient and controllable electrical heating device has not yet been sufficiently substantiated in physical and mathematical, experimental, and electric power engineering terms. This determines the relevance of developing and studying the LPSEH as an alternative source of thermal energy for local autonomous, decentralized, and hybrid electric heat supply.

The purpose of the dissertation is to research and develop an energy-efficient electrical heating device that performs the functions of an alternative source of thermal energy for local autonomous, decentralized, and hybrid electric heat supply.

Research objectives:

– analyze the current state of electric heat supply and electrical heating devices, summarize the properties of heat pipes and two-phase thermosyphons, identify the limitations of existing solutions, and substantiate the scientific and technical gap in the study of electro-vacuum heating devices for space-heating applications;

– develop a physical, mathematical, and numerical model of the LPSEH electro-vacuum heat pipe, perform a computational analysis of temperature fields, heat fluxes, and the energy balance, and determine the conditions for stable operation of the two-phase cycle and the limiting operating modes of the device;

– develop an experimental test bench and conduct bench studies of LPSEH prototypes to obtain temperature, thermal, and energy characteristics, assess the influence of design and operating parameters, and verify the model's computational assumptions;

– substantiate the design, technological, and electrical-engineering solutions of the LPSEH, including the sectional structure, the monitoring and automatic control system, the engineering methodology for selecting parameters, and the area of rational

application of the device in local, autonomous, decentralized, and hybrid electric heat-supply schemes.

Research methods:

The research methodology is based on a set of scientific methods aimed at studying electrothermal conversion, phase heat and mass transfer, and the formation of the temperature field in the LPSEH electro-vacuum heat pipe. In particular, the following methods were applied:

– analytical and theoretical methods: an analysis was conducted of the current state of electric heat supply, electrical heating devices, the properties of heat pipes and two-phase thermosyphons, as well as the limitations of known electro-vacuum heating devices for space-heating applications;

– physical, mathematical, and numerical modeling methods: a model was developed that accounts for unsteady heat conduction in solid elements, the phase transition of the working fluid, vapor-liquid transport, condensate return, the energy balance, and external heat exchange. The numerical implementation was performed in COMSOL Multiphysics; the supply of active electrical power in the evaporation zone was specified as an equivalent heat flux;

– experimental methods: bench studies were conducted on LPSEH prototypes with monitoring of electrical power, voltage, current, temperature, residual pressure, time, and ambient parameters;

– statistical processing and verification methods: mean values, confidence intervals, regression relationships, and errors were determined, and computational and experimental results were compared.

Scientific provisions submitted for defense:

– a physical, mathematical, and numerical model of electrothermal conversion in the LPSEH electro-vacuum heat pipe, taking into account the supply of active electrical power, two-phase heat transfer, condensate return, and external heat exchange;

– experimentally established regression relationships of the local temperature rise of the working surface of an LPSEH section on the specific electrothermal load, the specific structural-mass parameter, and the volume of the working fluid, making it possible to predict the temperature regime of the section;

– design and operating principles for constructing a sectional LPSEH as a controllable electrothermal load with active-power regulation, temperature monitoring, and control of voltage, current, and power;

– an engineering methodology for selecting LPSEH parameters that links the heat load of a room, the number of sections, installed power, the temperature regime, and the operating limitations of the device.

Scientific novelty of the dissertation:

– for the first time, for a low-pressure steam electric heater based on a gravity-type electro-vacuum heat pipe, a physical, mathematical, and numerical model of electrothermal conversion has been developed with the integration of an electric heater into the evaporator zone; using this model, relationships have been established for integral heat fluxes, time to reach the operating mode, and the temperature field of the heat-emitting surface on dynamic modes of electric heat input;

– the conditions for stable operation of the two-phase cycle have been determined for specified values of electrical power, the volume of the working fluid, and the geometry of the evaporation zone;

– new relationships have been established for the temperature and energy characteristics of the LPSEH electro-vacuum heat pipe on electrical power, the amount of working fluid, initial residual pressure, and geometric parameters, including when comparing tubular and induction methods of electric heat input;

– calculated and experimental indicators of an operable two-phase LPSEH regime have been determined, including the energy balance of heat input and heat removal, the permissible temperature level of the evaporation zone, stable return of the liquid phase, the correspondence of pressure and temperature to the saturation condition of the working fluid, and the reproducibility of start-up temperature-time curves;

– design and operating principles for coordinating two-phase heat and mass transfer in the electro-vacuum heat pipe of a sectional LPSEH with algorithms for automatic control of the electrical load have been scientifically substantiated, ensuring the use of the device as a controllable electrical load in autonomous and hybrid electric heat-supply schemes.

Practical significance of the results obtained:

– a model, experimental relationships, and an engineering methodology for selecting the parameters of a local electrical heating device based on an electro-vacuum heat pipe have been developed;

– constructively-mode solutions of the LPSEH as a sectional electrical heating device with a monitoring, automatic control, and electrical protection system have been developed;

– parameters for selecting power and the number of sections, the amount of working fluid, evacuation, heat transfer, and temperature control have been determined, taking into account the heat load of the room and the available electrical power;

– the scope of rational application of the LPSEH has been substantiated for autonomous and detached buildings without access to heat-supply networks, facilities undergoing reconstruction, rooms with zonally uneven heat loads, hybrid schemes in industrial and public buildings, as well as local supplementary heating of work areas;

– recommendations have been proposed for using the LPSEH as a controllable local electrical source of heat that supplements centralized and hydronic heating when sufficient electrical power, appropriate tariff conditions, and the technical possibility of connection are available.

Degree of reliability of the research results:

The validity and reliability of the scientific provisions, results, and conclusions are ensured through the use of well-established principles of electrical engineering, heat transfer, heat and mass transfer, phase-transition theory, and thermodynamics; the correct formulation of the physical and mathematical model; energy-balance control; and comparison of computational data with experimental results.

Experimental reliability is confirmed by the use of a laboratory test bench; control of temperature, electrical power, voltage, current, residual pressure, mass, and geometric parameters; and a series of tests under various LPSEH operating modes.

The results were evaluated taking into account measurement errors, statistical data processing, and determination of confidence intervals.

The results of the dissertation research have been implemented in the educational process of NJSC "Abylkas Saginov Karaganda Technical University" in the study of the discipline "Electromechanics and Electrical Equipment" of the educational program 6B07107 "Electric Power Engineering". Practical approbation of the results was carried out at Global Light LLP, and the results were also presented at Silumin of Qazaqstan LLP ("Silumin of Kazakhstan"). The practical significance of the results is confirmed by obtaining Utility Model Patent of the Republic of Kazakhstan No. 10146 and Copyright Certificate No. 63992.

The author's personal contribution consists in setting the purpose and objectives of the study, formulating the working hypothesis, developing the physical and mathematical model of the LPSEH electro-vacuum heat pipe and its numerical implementation in COMSOL Multiphysics, designing and assembling the experimental test bench, conducting bench tests, statistically processing the results and verifying the computational model, substantiating the design, technological, and electrical-engineering solutions of the sectional LPSEH, developing the monitoring and automatic control system, the engineering methodology for selecting parameters, and the techno-economic assessment, as well as generalizing the results obtained, formulating the conclusions of the dissertation research, and developing practical recommendations.

Approbation of the work. The main scientific and practical results of the dissertation were presented and discussed at the IV International Scientific Conference "Priority Areas of Innovation Activity in Industry" (Kazan, April 29–30, 2020) and the International Scientific and Practical Online Conference "Integration of Science, Education and Production as the Basis for Implementing the Plan of the Nation" (Saginov Readings No. 12, Karaganda, June 18–19, 2020). The research results were also discussed at meetings of the Department of Automation of Production Processes and the Scientific and Technical Council of NJSC "Abylkas Saginov Karaganda Technical University".

Publications and protection documents. The main scientific results of the dissertation are reflected in 10 scientific and methodological works, including 2 articles in international peer-reviewed scientific journals indexed in Scopus, 4 articles in publications recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan, 2 publications in proceedings of international scientific and practical conferences, and 2 protection documents for intellectual property objects.

Articles in international peer-reviewed scientific journals indexed in Web of Science Core Collection and Scopus:

1. "Development of low-pressure electric steam heater" // Eastern-European Journal of Enterprise Technologies. – 2021. – Vol. 4/8 (112). – P. 34–44. DOI: 10.15587/1729-4061.2021.237873. Percentile – 39 Scopus. Co-authors: Mekhtiyev A.D., Breido I.V., Neshina Ye.G., Alkina A.D.

2. "Studying characteristics of the heat pipe of a low-pressure steam electric heater with different types of heaters" // Eurasian Physical Technical Journal. – 2025.

– Vol. 22. – No. 4 (54). – P. 46–52. DOI: 10.31489/2025N4/46-52. Percentile – 25 Scopus. Co-authors: Mekhtiyev A.D., Neshina Ye.G., Alkina A.D., Bilichenko A.P.

Articles published in publications recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan:

3. "Efficiency of the Building Heating System with the Use of Low-pressure Steam Electric Heaters" // University Proceedings. – 2025. – No. 4 (101). – P. 435–441. DOI: 10.52209/1609-1825_2025_4_435. Co-authors: Mekhtiyev A.D., Yurchenko A.V., Alpysbayeva N.A., Bilichenko A.P.

4. "A low-pressure steam electric heater as the basis of a new generation autonomous heating system" // The Bulletin of KazATC. – 2023. – No. 5 (128). – P. 474–481. DOI: 10.52167/1609-1817-2023-128-5-474-481. Co-author: Mekhtiyev A.D.

5. "Low-Pressure Steam Electric Heater" // Toraighyrov University Bulletin. Energy Series. – Pavlodar, 2022. – No. 3. – P. 123–134. DOI: 10.48081/SYOY6805. Co-authors: Mekhtiyev A.D., Shapenova Z.R.

6. "Study of the Parameters of an Induction Electro-Vacuum Heater of a Low-Pressure Steam Electric Heater" // University Proceedings. – 2021. – No. 3 (84). – P. 262–267. DOI: 10.52209/1609-1825_2021_3_262. Co-authors: Mekhtiyev A.D., Kim P.M., Alkina A.D.

Publications in proceedings of international scientific and practical conferences:

7. "Prospects for the Application of Electrotechnological Systems for Heat Supply to Industrial Enterprises" // Priority Areas of Innovation Activity in Industry: collection of scientific articles of the IV International Scientific Conference, April 29–30, 2020. – Kazan: Konvert LLC, 2020. – Part 1. – P. 42–47. Co-author: Breido I.V.

8. "Application of Infrared Electric Heaters for Heat Supply to Production Premises" // Proceedings of the International Scientific and Practical Online Conference "Integration of Science, Education and Production as the Basis for Implementing the Plan of the Nation" (Saginov Readings No. 12), June 18–19, 2020. – Karaganda: KSTU Publishing House, 2020. – Part 1. – P. 711–713. Co-author: Breido I.V.

Patents, certificates, and intellectual property objects:

9. "Heating Radiator with an Induction Heater" – utility model patent of the Republic of Kazakhstan No. 10146; January 31, 2025, bulletin No. 5. Co-authors: Mekhtiyev A.D., Alkina A.D., Mekhtiyev R.A., Neshina Ye.G., Yugai V.V.

10. "Computer 3D Model of an Energy-Efficient Steam Electro-Vacuum Heater (SEVH) for Domestic and Industrial Heating" – certificate of entry of information in the State Register of Rights to Copyright-Protected Objects No. 63992 dated November 7, 2025. Co-authors: Alkina A.D., Mekhtiyev A.D.