ANNOTATION

Thesis submitted for the degree of Doctor (PhD) in the specialty «8D07102–- Heat Power Engineering»

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Development and research of porous heat exchanger for power enterprises

Relevance of the research

Parts and units of metallurgical units, especially in melting units operate at high temperature and accordingly require intensive cooling. At present, water and evaporative cooling systems are used, for this purpose; systems with porous (mesh) structure are suitable, which have found successful application in cases where it was required to increase the intensity of cooling. The need to ensure the explosion safety of melting units in metallurgy by eliminating the ingress of water into the melt and matte, which leads to the explosion of the furnace for water and evaporative cooling systems, when they are made in the form of caissons. Necessity of prevention of overheating and overburning of strongly heated surfaces of power equipment walls. The questions of development of perspective designs of heat exchangers with porous cooling structure are actual. In this case the capillary-porous cooling system, which contains a small amount of liquid, is explosion-proof and has high forcing and intensity of heat exchange, can be effective.

The aim of the study is to develop a heat exchange device on porous elements and to investigate heat exchange by vapour formation in porous structures under the combined action of capillary and mass forces.

The objectives of the research are:

1. investigation of heat and mass transfer processes at vapour formation in capillary-porous structures;
2. construction of physical and mathematical models describing the heat exchange process in capillary-porous structures;
3. development of experimental installation and its elements for research of heat and mass transfer processes by vapour formation;
4. Investigation of the mechanism of heat and mass transfer processes by vapour formation using holography and high-speed filming;
5. Calculation of heat flows and their control by means of thermohydraulic characteristics of boiling in net capillary-porous structures.

The research methods used in scientific research and assumed in this study are empirical, experimental, theoretical:

- empirical (measurement, counting, comparison);
- experimental-theoretical (experiment, analysis (analytical method), analogy, modelling);
- theoretical (generalisation).

Scientific novelty of the conducted research

1. Mathematical and physical models of the vapour formation process in capillary-porous systems have been developed:

- model of micro-layer evaporation; model of vapour bubble nucleation on the vapour generating surface in cells of porous structure;
- mathematical model of heat exchange process; model of capillary-porous coating for the limiting state of heating surface (thermoelasticity problem);

1. The mechanism of heat transfer by vapour generation using holography and high-speed filming was investigated;

1. An experimental setup for the investigation of heat transfer processes in porous structures in the caisson model was created;
2. Heat flow equations were obtained using thermohydraulic characteristics of the boiling process (D0, f, n, R) in mesh porous structures;
3. Equations for the calculation of heat transfer and hydraulic resistance of porous cooling systems based on integral characteristics (q, α, ΔT) were obtained;
4. Experimental data for vapour formation processes in the investigated porous system are summarized, and a comparative evaluation with boiling in a large volume, in heat pipes, and thin-film evaporators is given;
5. Recommendations and technical solutions of capillary-porous cooling systems have been developed and protected by the patent

Scientific and practical significance of the thesis work.

Industrial production and its environment require serious improvement of ecological conditions, labour safety, and saving of natural resources (fuel, water, air, heat). In this connection, new methods and devices are needed, which can be realised with high efficiency through the use of porous systems. The existing variety of constructive decisions of heat-exchange apparatuses does not satisfy the increasing requirements of time, besides the existing research has limited application, in connection with the limited range of change of the incoming parameters received at various methodical approaches.

Practical significance and application of the results of the work make it possible to calculate heat flows for the revealed ways of their control using thermohydraulic characteristics of boiling and vapour formation in mesh capillary-porous structures of heat exchangers widely used in power production, in particular for cooling of smelting units Possibilities of design of perspective cooling systems for metallurgical units based on evaporative cooling system. Developed based on the obtained results allows making recommendations and technical solutions for the development of capillary-porous cooling systems of highly heat-loaded vapour-generating surfaces, on the example of caissons of smelting units.

Scientific provisions put forward for defence:

- mathematical and physical models of vapour formation process in capillary-porous systems: model of micro-layer evaporation; model of vapour bubble nucleation on steam generating surface in cells of porous structure; mathematical model of heat exchange process; mechanism of vapour formation process in porous structure of heat exchanger (heat and mass transfer, hydrodynamics and strength); model of capillary-porous coating for limiting state of heating surface

- experimental setup for the study of heat exchange processes in porous structures in the caisson model;
- equations of heat flows using thermohydraulic characteristics of the boiling process (D0, f, n, R) in mesh porous structures;
- equations for calculation of heat transfer and hydraulic resistance of porous cooling system based on integral characteristics (q, ΔT);
- generalisation of experimental data for vapour formation processes in the investigated porous system and comparative evaluation with boiling in a large volume, in heat pipes and thin-film evaporators;
- developed recommendations and technical solutions of capillary-porous cooling systems, protected by patent, for high-heat-loaded steam-generating surfaces on the example of caissons of melting units.

Personal contribution of the co-researcher consists in substantiation of the relevance of the work, patent search, experimental review, analysis and generalisation of literature data; creation of an experimental unit and experimental studies of heat exchange processes in porous structures in the caisson model; analysis and generalisation of the obtained results on the development of a new high-force capillary-porous cooling system, construction of models and obtaining calculation dependencies based on integral characteristics (q, ΔT); development of a metrological model of heat transfer in porous structures.

Approbation of the results of the thesis. The main results of the work were presented and discussed at scientific and practical international and foreign conferences and seminars:

1. International conference "Proceedings of the 5th International Conference on Thermal Equipment, Renewable Energy and Rural Development TE-RE-RD" (Bulgaria, 2016);
2. International Conference "Međunarodna konferencija Elektrane - 2016" (Belgrade - Serbia, 2016);
3. International Scientific and Practical Conference "Modern trends in the development of science and production" (Kemerovo - Russia, 2017);
4. Foreign conference "The55th Annual Science Conference of Ruse University Smart Specialisation-Innovative strategy for regional economic transformation" (Ruse - Bulgaria, 2016);
5. Foreign conference with international participation "18th Symposium on Thermal Science and Engineering of Serbia, Energy - Efficiency - Ecology" (Sokobanja - Serbia, 2017);
6. International Conference "First International Scientific Conference "Alternative Energy Sources, Materials and Technologies (AESMT'18)" (Plovdiv - Bulgaria, 2018, 2017) (Plovdiv - Bulgaria, 2018);

7. International Conference "The 7th International Conference on Thermal Equipment, Renewable Energy and Rural Development TE-RE-RD 2018" (Drobeta Turnu Severin - Romania, 2018);

8. Overseas conference with international participation "The 3rd SDEWES conference on sustainable development of energy, water and environment system" (Novi Sad - Serbia, 2018);

9. Overseas conference with international participation "EENVIRO 2018 - Sustainable Solutions for Energy and Environment" (Cluj Napoca - Romania, 2018);

10. International Conference "XXIII International Conference Energy, Ecology, Comfort, Self - Confidence" (Sozopol - Bulgaria, 2018);

11. X International Scientific and Technical Conference of AUES, dedicated to the memory of the First Rector G.J. Daukeev (Almaty - Kazakhstan, 2018);

12. International Conference "The 8th International Conference on Thermal Equipment, Renewable Energy and Rural Development TE-RE-RD 2018" (Targoviste - Romania, 2018); 12. (Targoviste - Romania, 2019);

13. Overseas Conference with International Participation "The XXIInd National Conference on Thermodynamics with International Participation NACOT 2019" (Galati -Romania 2019)

14. Overseas Conference with International Participation "The 4th International Conference on Communications, Information, Electronic and Energy Systems (CIEES), (Plovdiv- Bulgaria, 2023).

The results of scientific research on the subject of the thesis have been published in 52 scientific articles and materials of scientific conferences: 2 articles in the journal on the basis of Web of Science (Thomson Reuters); 10 articles in the journals on the basis of Scopus; 21 articles in the journals recommended by the Committee for Control in the Sphere of Education and Science,; 19 publications in the materials of international and foreign scientific-practical conferences; 7 research reports (ONIR) and 1 patent for invention of the RK.

Scope and structure of the work. Dissertation work consists of introduction, 7 sections, conclusion, list of used literature and appendices. The main text of the dissertation work is set out on 138 pages an, including, appendices, 6 tables, 65 figures and the list of used literature of 177 names.

The introduction presents the relevance of the research work, specifies the problem under study. The main idea, scientific novelty, reliability of the work, as well as approbation of the results and publications are shown.

The use of porous materials in heat-exchange devices is one of the promising and effective ways of intensification of heat and mass transfer processes. A wide range of structural, thermophysical, hydraulic, chemical, optical and other properties of porous materials, simplicity of manufacturing of structural elements from them, high intensity of heat exchange, all this makes it possible to use porous heat exchange elements in various extreme conditions.

The questions of development of perspective designs of heat exchangers with porous cooling structure are actual. In this case capillary-porous cooling system, which contains a small amount of liquid, is explosion-proof and has a high forcing and intensity of heat exchange, can be effective.

Thus, the relevance of this problem is obvious, work is needed to investigate, design and implement more economical devices to intensify the processes. The aim of the study was to develop a heat exchange device on porous elements and to investigate heat exchange by vapour formation in porous structures under the joint action of capillary and mass forces.

In Chapter I the results of patent search and experimental review are given, a number of existing models are described in detail.

The questions of heat transfer intensification by means of porous elements; different approaches to the mechanism of vapour formation process; effective cooling methods of heating surfaces of highly moulded plants; evaporative cooling of metallurgical furnaces are considered. To achieve the research goal the following tasks were set:

1. investigation of heat and mass transfer processes at vapour formation in capillary-porous structures;
2. construction of physical and mathematical models describing the heat transfer process in capillary-porous structures;
3. development of experimental installation and its elements for research of heat and mass transfer processes by vapour formation;
4. investigation of the mechanism of heat and mass transfer processes by vapour formation by means of holography and high-speed filming;
5. calculation of heat flows and their control by means of thermohydraulic characteristics of boiling in net capillary porous structures.

Chapter II is devoted to the analytical study of physical and mathematical models of the vapour formation process (heat and mass transfer, hydrodynamics and strength) in capillary-porous structures. Such models are given and considered: a model of the heat transfer process in micro-layer evaporation; mathematical and physical models of the vapour formation process; a model of vapour bubble nucleation; a mathematical model of the vapour formation process for the conditions of the limiting state of the heat transfer surface; a mechanism of the vapour formation process in a porous heat exchanger structure. The models chosen for the work are mathematically sound.

Chapter III describes the experimental setup and their elements for the study of heat and mass transfer in capillary porous structures, The study of vapour formation processes in porous structures operating with excess liquid is carried out. A device for cooling the elements of high-force refractory installations, made on the model of caissons of melting units, the idea of which is patented, is described. The methodology of experiments, description and characteristics of measuring devices, basic equations for determining the main parameters, as well as estimation of measurement errors are presented.

Chapter IV describes a porous heat exchanger, which refers to industrial high-force fire engineering units. The proposed capillary-porous caisson cooling system increases the reliability of the units operation, intensifies heat transfer in the porous system, and ensures explosion safety of the operation of high-force fire engineering plants. The heat transfer mechanism was studied with the involvement of holographic interference and high-speed film photography. Comparison of the investigated system with heat pipes and thin-film evaporators is given. The use of coarse-mesh meshes simplifies the coolant requirements.

Chapter V analyses the influence of mode and design factors in capillary porous structures on heat transfer, hydrodynamics and durability. The analysis of holographic interferograms and kinograms of boiling processes in porous structures makes it possible to estimate and calculate the thermal and hydrodynamic state of heat and mass transfer processes by the degree of deformation of the shape and density of interference fringes for different values of q. The analysis of holographic interferograms and kinograms makes it possible to estimate and calculate the thermal and hydrodynamic state of heat and mass transfer processes. It becomes possible to judge about micro-processes and some local processes, such as temperature micro-relief, fluctuation phenomenon, droplet ejection. The more intensive the process is, the more pronounced are the patterns. Based on the analysis of heat flux density at boiling of a single vapour bubble in the cells of a porous structure, the dependence of individual heat flux density in the vicinity of the base of the vapour bubble on the time growing in the cells of the porous structure is obtained.

Chapter VI presents a generalisation of experimental data allowing us to obtain calculated semiempirical dependences of the described thermohydraulic characteristics of the vapour formation process in mesh porous structures, such as the detachable (destructible) diameters of vapour bubbles, the density of generation centres, the frequency of detachment and the rate of their growth. These values are established as a function of the thermophysical properties of the fluid (pressure) and wall, temperature head and coolant excess. On the basis of internal boiling characteristics, physical models can be constructed and simple engineering formulae can be derived to calculate the dissipated heat fluxes depending on the type of porous structure and geometry of the vapour generating surface.

Chapter VII reviews the applications of capillary-porous heat exchangers, listing devices on porous structures designed to improve the reliability and efficiency of stationary heat exchangers in an environmentally friendly manner. The application of capillary porous systems in metallurgical applications is described in detail. Capillary-porous heat exchangers for cooling of melting units are illustrated. The results of investigation of influence of various factors on heat and mass transfer processes in different capillary-porous systems of heat-exchange equipment are given

The developed and investigated capillary-porous heat exchangers of box-type in the form of caissons for the purpose of providing explosion-safe operation of smelting units are shown. Porous systems are not narrow-targeted and can be used in metallurgical production for oil cooling (heating of fuel oil) in order to protect from water basin pollution, for steam coolers and drums of boilers, heat utilisation of flue gases of furnaces and their purification, for irrigation elements of cooling towers. The cooling capillary-porous system, keeping advantages of evaporative cooling, has a number of new positive factors to which should be referred: tens times further reduction of coolant volume, explosion safety of units, reduction of capital investments and operational costs, self-regulation of heat transfer, increase of forcing and intensification of heat removal, reduction of sharply variable cyclic destructive stresses, economic and ecological effects.

The conclusion reflects the main results and conclusions of the thesis work on the set research tasks in the search for solutions to the issues of cooling intensification with the use of capillary-porous systems.

The appendices include criteria calculation for heat exchange in a capillary-porous cooling system; calculation of measurement error and experimental planning; research and calculation of a highly forced capillary-porous heat exchanger.