ANNOTATION
of the dissertation for the degree of Doctor of Philosophy (PhD) according to the educational program 8D07104 – «Heat power engineering»

Aripova Nazgul Mikhailovna

INCREASING THE ENERGY EFFICIENCY OF THE FILLING BUCKETS BY RATIONALIZING THE COOLING MODES OF THE LINING

The relevance of the problem. According to the report of the Minister of Energy of the Republic of Kazakhstan A.Satkaliev during a Government meeting, it was noted that in 2023 the consumption of electric energy in the Republic of Kazakhstan amounted to 115 billion kWh, while production volumes amounted to 112,8 billion kWh. At the same time, according to the projected balance of electric energy in the unified energy system of the Republic of Kazakhstan, in the period from 2024 to 2030, there is an increase in energy consumption from 120,6 to 155,9 billion kWh.

Despite the implementation of the energy saving policy, the industrial sector remains one of the main consumers of energy resources. In the structure of the energy complex of the Republic of Kazakhstan, the total final energy consumption of the industrial sector accounts for 30,3 % of energy resources (second in terms of consumption after the housing sector).

The most energy-intensive kinds of industry is the manufacturing and extractive industries, which account for more than 90 % of the energy consumption of the industrial sector. At the same time, the largest share of energy consumption in industry falls on the ferrous metallurgy sector 30,1 % [1].

Some of the reasons for the significant energy saving potential of industrial enterprises of the Republic of Kazakhstan are the obsolescence of the technological process and physical wear of equipment. Physical wear reaches 45-60 %, which leads to incomplete use of production capacity and high specific energy consumption by production lines [2].

In order to raise the level of energy saving and increase energy efficiency in industry, it is necessary to create conditions for the modernization of thermal technology processes and high-temperature equipment, as well as the introduction of energy-saving measures in industries [2].

The energy efficiency of most metallurgical units is largely determined by the work of the linings. The duration of the unit's working campaign, energy consumption under non-stationary thermal conditions and other indicators depend on the condition of the linings.

The problem of increasing the energy efficiency of high-temperature units should be solved by rationalizing the modes of their thermal operation, the design of individual elements and units as a whole.

Such high-temperature units of ferroalloy production as casting ladles work with high-temperature working environments because the temperature of the

molten metal drained from the furnace is 1600-1650 °C.

The increase in the energy efficiency of ferroalloy casting ladles during their cooling is determined by the following factors:

- the use of secondary energy resources for smooth reduction of the temperature of the lining of the casting ladle during its cooling;

- reducing the cooling time of the lining of the casting ladle before carrying out repair work, increasing their turnover (the number of drains of molten metal into the casting ladle per day);

- maintenance of cooling modes with increased speeds, at which the resulting thermal stresses do not exceed the stress limit of the lining materials used. This allows reducing the downtime of casting ladles during repair, as well as increasing their working time by extending the service life of refractory materials and reducing their specific consumption per ton of the technological product.

In this regard, the tasks and proposals for improving the energy efficiency of the casting ladles by rationalizing the cooling modes of the linings are relevant.

The object of the research: the linings of casting ladles of ferroalloy production.

The subjects of the research are the patterns of occurrence of thermal stresses in the linings of casting ladles of ferroalloy production during their cooling.

The connection of the dissertation topic with general scientific (state) programs: the dissertation was carried out within the framework of a research work funded by the State Institution "Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan" on the topic: IRN AP19675777 «Development of a system for evaluating the residual life of heat-technological equipment to improve the reliability of its operation» (2023-2025).

The aim of the work: to increase the energy efficiency of the casting ladles by rationalizing the cooling modes of the linings.

To achieve this aim, the following tasks were set and solved:

1. To analyze the current state of production and operation of refractory materials used in high-temperature units.

2. To perform an analysis of the thermal operation of the linings of casting ladles in non-stationary operating modes.

3. To develop a mathematical model of the thermally stressed state of the linings during the cooling of casting ladles.

4. To carry out experimental studies in order to determine the temperature dependence of the thermophysical parameters and thermomechanical properties of the refractory materials used.

5. To develop rational cooling schedules for the linings of casting ladles, taking into account the temperature dependence of the thermophysical parameters and thermomechanical properties of the refractory materials used.

6. To develop a methodology for assessing the residual life of the linings of casting ladles.

7. To develop a method for cooling the linings of casting ladles and a device for its implementation.

8. To calculate the economic efficiency of the proposed technical measures.

The research methods. To solve the tasks set in the dissertation, the following work was carried out:

- measurement of the temperature fields of the linings of casting ladles during their cooling;
- analysis of the thermal operation of the linings of casting ladles in non-stationary operating modes;
- mathematical modeling of the thermally stressed state of the linings during the cooling of casting ladles;
- experimental study of thermophysical parameters and thermomechanical properties of refractory materials used in laboratory conditions**.**

The scientific novelty:

1. A mathematical model of the thermally stressed state of the linings during the cooling of casting ladles has been developed.
2. A method has been developed for determining ultimate tensile strength of bent refractory materials at elevated temperatures, which is protected by the patent of the Republic of Kazakhstan.
3. The temperature dependence of the tensile strength of chamotte refractory of the SHKU-32 brand is obtained.
4. A method for determining the thermophysical properties of refractory materials has been developed, which is protected by a patent of the Republic of Kazakhstan.
5. Rational cooling schedules for the linings of ferroalloy ladles have been developed, taking into account the dependence of thermophysical parameters and thermomechanical properties on temperature.
6. A methodology has been developed for determining the residual life of the linings of casting ladles, which is protected by a patent of the Republic of Kazakhstan.
7. A method for cooling the lining of the casting ladle and a device for its implementation have been developed, which are protected by patents of the Republic of Kazakhstan.

The practical value:

1. The obtained dependences of ultimate strength of the compressive and tensile stresses of SHKU-32 chamotte refractories on temperature can be used by design organizations and design departments of enterprises in calculations related to the thermomechanical properties of refractories.
2. The developed mathematical model of the thermally stressed state of the linings during the cooling of casting ladles can be used by producing departments of enterprises, as well as by design organizations for calculating the thermally stressed state of the linings.
3. The developed device for cooling the linings of casting ladles will increase the accuracy of compliance with the cooling schedule of the linings of high-temperature units of industrial enterprises.
4. The developed methodology for determining the residual life of the linings of casting ladles can be used when performing multivariate predictive

calculations in the design and operation of high-temperature units, as well as for educational purposes.

Approbation of the results of the research. The main results of the dissertation work have been tested at international scientific practical and technical conferences:

- international scientific practical conference "XV Toraighyrov Readings" dedicated to the 130th anniversary of S. Toraighyrov (Pavlodar, 2023);
- XXXVII international scientific practical conference: "Modern scientific research: current issues, achievements and innovations" (2024, Penza, Russian Federation).

Publications. According to the results of the dissertations, 14 publications were published, including four in journals recommended by CQAFSHE, five patents of the Republic of Kazakhstan (Appendix A); three articles were published in journals included in the SCOPUS and Web of Science databases: Energies (2023), Energies (2024), Refractories and Industrial Ceramics (2023); two articles in the collections of international conferences.

The reliability of the results. The reliability of the results obtained is confirmed by the use of modern research methods and techniques, sufficient convergence of the experiments with the calculated data (a discrepancy of less than 3 %), adequacy of the mathematical model.

The points for the dissertation protection:

- the results of thermal engineering studies of the cooling process of the linings of casting ladles;
- the calculation method for determining thermal stresses in the lining of the casting ladle during its cooling;
- the mathematical model of the thermally stressed state of the linings during the cooling of casting ladles;
- the dependence of ultimate strength of compressive and tensile stresses of chamotte refractories on temperature;
- the rational cooling schedules for the linings of ferroalloy ladles, taking into account the dependence of thermophysical parameters and thermomechanical properties on temperature;
- the method for determining the residual life of linings of high-temperature units.

Implementation of the results. The obtained results of computational and experimental studies using the model of the thermally stressed state of the linings of casting ladles are implemented in the educational process of NJSC "Toraigyrov University" (section of the lecture on the discipline "Reliability of high-temperature units" for undergraduates of the educational program 7M07106 – Heat Power Engineering) (Application B). Moreover, some regional enterprises have also implemented the obtained research results. For example, Aksu Ferroalloy Plant of the branch of JSC TNK “Kazchrome” has implemented a method for determining the residual life of casting ladles; PF LLP “KSPSteel” has implemented a methodology for calculating the cooling modes of the linings of casting ladles to assess the permissible residual life (Application B).

The author's personal contribution consists in: setting research objectives, analyzing and generalizing literary data, measuring the temperature fields of the linings of casting ladles during the cooling process on existing industrial equipment, developing new technical solutions and conducting experimental studies to determine the thermomechanical and thermophysical properties of refractory materials of the linings of casting ladles, developing a mathematical model for determining thermal stresses in the linings of casting ladles during their cooling, calculation of thermal stresses when using existing lining cooling modes and development of rational schedules for cooling modes of casting ladles.

The scope and structure of the dissertation. The dissertation work consists of a section «Definitions, designations and abbreviations», an introduction, five sections, a conclusion, a list of references and appendices. The dissertation is presented on 139 pages of a computer set, including 42 figures and 8 tables, 33 formulas, and 168 titles of bibliographic sources.

The introduction presents the relevance, goals and objectives of the research, scientific novelty, the points submitted for the dissertation protection, the reliability of the work, the personal contribution of the author, as well as the approbation of the results and publications.

The first chapter analyzes the current state of production and operation of refractory materials. The use of refractory materials in casting ladles is considered, as well as the design and operation of modern linings of casting ladles. The influence of operational factors on the service life of the linings of casting ladles is estimated. From the operating conditions of casting ladles, the influence of significant temperature differences on the service life of the linings can be distinguished. The temperature difference in the thickness of the linings causes its destruction due to the occurrence of thermal stresses, the value of which exceeds the tensile strength of the materials used, established by the technological regulations.

The analysis of the thermal operation of casting ladles showed that the conditions of their operation are largely determined by the duration of the linings' working campaign.

Based on the analysis, the main ways to increase the energy efficiency and service life of the linings of casting ladles have been identified.

The second chapter: the thermal operation of the linings of casting ladles is investigated, and the characteristics of the object of study is given. With the help of modern measuring instruments, thermal imaging and visual examinations of the linings of casting ladles were carried out. An analysis of the repairs of the linings of casting ladles was carried out, which showed that the wear of the slag belt occurs mainly as a result of the chemical action of aggressive slag. The effect of molten metal when it is drained into the ladle and spilled from the ladle has a limited local effect. The main cause of the lining wear is thermal stresses arising from a significant temperature gradient across the thickness of the lining during non-stationary thermal processes, including when cooling the lining of the casting ladle at high speeds.

The cooling modes of the lining of casting ladles have been studied. The results of the study showed that the cooling modes of the linings of casting ladles at the considered enterprise have not been developed, and their cooling is carried out without controlling the rate of temperature decrease under natural convection in the conditions of the workshop atmosphere.

The third chapter: the analysis of the thermally stressed state of the linings during the cooling of casting ladles was carried out and a mathematical model of the thermally stressed state of the linings during the cooling of casting ladles was developed.

An analysis of the cooling process of the lining of a ferroalloy casting ladle shows that the cooling process of the lining is very uneven in conditions of natural convection, without control over temperature decrease. The temperature of the inner surface of the lining decreases by 300 °C in 30 minutes from the moment of cooling, which exceeds the values of the cooling rate given in the technical literature. At the final stage of cooling, the temperature decreases by 300 °C within 10 hours and 10 minutes. Thus, the cooling rates of the inner surface of the lining at different stages differ by more than 20 times.

A mathematical model of the thermally stressed state of the lining during its cooling has been developed, which includes two components: a mathematical model of temperature fields and a mathematical model for calculating thermal stresses in the linings of casting ladles.

The found values of thermal stresses are necessary for the analysis of existing cooling rates and the development of rational cooling modes for the linings of casting ladles by comparing the resulting thermal stresses with the tensile strength of the refractories used.

In the fourth chapter, the thermomechanical properties of refractory materials are experimentally investigated. The stress characteristics of chamotte refractories is revealed.

Experimental studies have shown that the compressive stress of chamotte refractories of the SHKU-32 brand for refractories after 1-2 melts is higher than their nominal value at 20 °C over the entire temperature range from 20 °C to 800 °C. For refractories after three melts, the compressive stress is higher than the nominal value of refractories after 1-2 melts in the ranges from 100 to 380 ^{o}C and from 480 to 680 ^{o}C by 22% and 40%, respectively.

The value of the tensile stress for refractories after 1-2 melts turned out to be 25% higher than the reference value in the range from 440 ^{o}C to 800 ^{o}C. In the area from 450 ^{o}C to 550 ^{o}C, the tensile stress for refractories after three melts is only 2% higher than the reference value of refractories after 1-2 melts.

It has been experimentally proved that the operating conditions of refractory lining ladles significantly affect the values of the thermal conductivity coefficient. The conducted studies have shown that the values of the thermal conductivity coefficient of refractories after three melts increase to 12% of the initial value.

In the fifth chapter, the analysis of thermal stresses arising during the cooling of the linings of casting ladles is carried out. It was found that for refractories after three melts, the graphs of the dependence of the compressive

strength on time have a similar shape to the graphs of the dependence of the ultimate tensile strength on time for refractories after 1-2 melts.

Based on the developed program for calculating the thermally stressed state of the lining of the castng ladle, a rational mode and cooling schedule for its lining are proposed. As a result of using the developed schedule, in which thermal stresses do not exceed the tensile strength of the refractory materials used, the cooling time is reduced from 19 hours 30 minutes to 10 hours 10 minutes, as well as an increase in the service life of the refractory lining, according to literature data, up to 5%.

An assessment of the residual life of the linings of casting ladles has been carried out and recommendations for controlled cooling of the linings of casting ladles have been developed. An assessment of the economic efficiency of the proposed technical measures has been carried out.

The conclusion reflects the main results of the research and provides conclusions on the dissertation work.