DOI: 10.65322/j.srd.05192026.22

DEVELOPMENT OF ABSORPTION COOLING UNITS UTILIZING LOW-GRADE WASTE HEAT RESOURCES OF INDUSTRIAL ENTERPRISES AND SUBSTANTIATION OF THEIR OPTIMAL OPERATING MODES

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Abstract. *This article examines the use of low-grade waste heat resources generated at industrial enterprises as a secondary energy source in absorption cooling processes. Because the direct conversion of low-temperature waste heat into electricity may be inefficient under certain conditions, transforming it into cooling energy is one of the important approaches. The main objective of the study is to determine the relationship between the operating temperatures of the waste heat source, generator, absorber, condenser, and evaporator and the concentration of the working solution, and to substantiate the optimal operating mode of the unit. Thermodynamic balance, heat transfer, exergy analysis, and multi-factor optimization approaches are proposed for the study. The principal performance indicators adopted are the coefficient of performance (COP), exergy efficiency, the degree of waste heat utilization, and the heat consumption per unit of cooling energy. As a result, a scientific and methodological basis is formed for selecting an absorption cooling system suited to the actual waste heat parameters of an industrial enterprise and for controlling its operating mode.*

Annotatsiya. *Ushbu maqolada sanoat korxonalarida hosil bo‘ladigan past potensialli ikkilamchi issiqlik resurslaridan absorbsion sovitish jarayonlarida ikkilamchi energiya manbai sifatida foydalanish masalasi ko‘rib chiqilgan. Past haroratli ikkilamchi issiqlikni to‘g‘ridan-to‘g‘ri elektr energiyasiga aylantirish muayyan sharoitlarda samarasiz bo‘lishi mumkinligi sababli, uni sovitish energiyasiga transformatsiya qilish muhim yo‘nalishlardan biri hisoblanadi. Tadqiqotning asosiy maqsadi — ikkilamchi issiqlik manbai, generator, absorber, kondensator va bug‘latgichning ishchi haroratlari hamda ishchi eritma konsentratsiyasi o‘rtasidagi bog‘liqlikni aniqlash va qurilmaning optimal ish rejimini asoslashdan iborat. Tadqiqot uchun termodinamik muvozanat, issiqlik almashinuvi, eksergetik tahlil va ko‘p omilli optimallashtirish usullari taklif etilgan. Asosiy samaradorlik ko‘rsatkichlari sifatida sovitish koeffitsiyenti (COP), eksergetik FIK, ikkilamchi issiqlikdan foydalanish darajasi hamda birlik sovitish energiyasiga to‘g‘ri keladigan issiqlik sarfi qabul qilingan. Natijada sanoat korxonasining haqiqiy ikkilamchi issiqlik parametrlariga mos absorbsion sovitish tizimini tanlash va uning ish rejimini boshqarish uchun ilmiy-uslubiy asos shakllantirilgan.*

Аннотация. *В данной статье рассматривается использование низкопотенциальных сбросных тепловых ресурсов промышленных предприятий в качестве вторичного источника энергии в процессах абсорбционного охлаждения. Поскольку прямое преобразование низкотемпературного сбросного тепла в электрическую энергию в определенных условиях может быть неэффективным, его трансформация в энергию холода является одним из актуальных подходов. Основная цель исследования заключается в определении взаимосвязи между рабочими температурами источника вторичного тепла, генератора, абсорбера, конденсатора и испарителя, а также концентрацией рабочего раствора, и обосновании оптимального режима работы установки. Для исследования предложены методы термодинамического баланса, теплообмена, эксергетического анализа и многофакторной оптимизации. В качестве основных показателей эффективности приняты холодильный коэффициент (COP), эксергетический КПД, степень утилизации сбросного тепла и удельный расход теплоты на единицу производимого холода. В результате формируется научно-методическая база*

DOI: 10.65322/j.srd.05192026.22

для выбора абсорбционной холодильной системы, соответствующей реальным параметрам вторичных тепловых ресурсов промышленного предприятия, и управления режимами ее работы.

Keywords: *low-grade waste heat, absorption cooling, industrial power engineering, LiBr–H_2O, NH_3–H_2O, generator, absorber, evaporator, condenser, COP, exergy, energy efficiency, optimization.*

Kalit so‘zlar: *past potensialli ikkilamchi issiqlik, absorbsion sovitish, sanoat energetikasi, LiBr–H_2O, NH_3–H_2O, generator, absorber, bug‘latgich, kondensator, COP, eksergiya, energiya samaradorligi, optimallashtirish.*

Ключевые слова: *низкопотенциальное сбросное тепло, абсорбционное охлаждение, промышленная энергетика, LiBr–H_2O, NH_3–H_2O, генератор, абсорбер, испаритель, конденсатор, COP, эксергия, энергоэффективность, оптимизация.*

Introduction. At various stages of technological processes in industrial enterprises, secondary energy resources are generated in the form of hot gases, steam, hot water, and other heat carriers. A portion of these streams is reused in subsequent stages of the technological process, while the remainder is discharged into the environment. Waste heat recovery is one of the important ways of reducing energy consumption, increasing the efficiency of fuel resource utilization, and reducing heat emissions. Absorption cooling systems are of particular interest for the utilization of low-grade heat sources. In such systems, a generator–absorber pair, which acts as a thermal compressor, is used in place of a mechanical compressor. The most widely used working pairs are LiBr–H_2O and NH_3–H_2O. In the LiBr–H_2O system, water acts as the refrigerant and lithium bromide as the absorbent; in the NH_3–H_2O system, ammonia is used as the refrigerant. The literature extensively documents the possibility of using waste heat and renewable heat sources in absorption systems [1–3].

At the same time, when the temperature of a low-grade source is insufficient, an operating limit of the simple single-stage cycle arises. Studies from 2023 proposed combining an absorption heat transformer with an absorption refrigeration cycle in order to couple heat sources below 100 °C with low-temperature cooling. The authors showed that the thermal matching between the heat source and the cycle strongly affects system efficiency [4].

A 2024 study modeled triple-effect absorption systems oriented toward the use of low-grade heat at temperatures down to 60 °C [5].

Accordingly, the main issue in the present study is not to present absorption cooling itself as a new phenomenon, but to match the variable low-grade waste heat available at an industrial enterprise with a specific cooling load, to determine the optimal operating mode, and to assess energy and exergy efficiency jointly.

Problem statement and literature review. Although absorption cooling technology has been developing for a long time, the question of optimal operation under real conditions, in which the temperature and flow rate of industrial waste heat vary, remains topical. The studies identify the principal advantage of absorption cooling as the possibility of converting low-grade heat directly into a cooling effect [2, 3].

The LiBr–H_2O system is generally suitable for air conditioning and for cooling above 0 °C. Owing to the freezing temperature of water, such a system is limited for sub-zero cooling. The NH_3–H_2O system, by contrast, allows operation at lower evaporation temperatures [3]. The choice of working pair therefore depends on the waste heat temperature and the required cooling temperature. Studies devoted to the use of low-grade waste heat have proposed various cycles, cascade systems, heat transformers, and exergy-based optimization approaches. For example, the joint operation of NH_3/H_2O and LiBr/H_2O cycles in a cascade absorption cooling system has been studied, and the effects of generator temperature, pressures, and solution concentration on COP

DOI: 10.65322/j.srd.05192026.22

were analyzed [6]. These results show that, under industrial conditions, it is necessary to optimize not a single parameter but several interrelated parameters. In this article, the following scientific problem is posed as the research direction: to determine the optimal relationship between the heat source parameters and the thermodynamic parameters of the cycle in an absorption cooling system that uses a low-grade waste heat source with variable temperature.

Aim and objectives of the study. The aim of the study is to develop a thermal-energy model of an absorption cooling unit that utilizes the low-grade waste heat resources of industrial enterprises, to determine the effect of the main parameters on cooling efficiency, and to substantiate the optimal operating mode.

To achieve this aim, the following objectives are set:

1) to develop a classification of industrial waste heat sources by temperature, flow rate, and thermal power;

2) to formulate the energy and mass balances of the absorption cooling cycle;

3) to determine the effect of generator, absorber, condenser, and evaporator temperatures on COP;

4) to assess the effect of working solution concentration on cycle stability and efficiency;

5) to determine exergy efficiency alongside energy efficiency;

6) to develop an algorithm for selecting the optimal operating mode under variable waste heat conditions;

7) to compare computational and experimental results.

Object and methodology of the study. The object of the study is an absorption cooling unit driven by a low-grade heat stream discharged from an industrial enterprise. The subject of the study is the laws governing heat and mass transfer, the thermodynamic state of the working substance, and the variation of cooling efficiency. The general scheme of the system is expressed as follows:

WASTE HEAT → GENERATOR → CONDENSER → EVAPORATOR → ABSORBER → GENERATOR.

Heat is supplied to the generator from hot water or waste gas. The generator separates part of the refrigerant from the solution. The refrigerant condenses to a liquid in the condenser, is then reduced in pressure, and produces useful cooling by evaporation in the evaporator. The resulting vapor is absorbed by the working solution in the absorber, and the solution is returned to the generator. The energy balance is generally written as:

$$Q_g + Q_e + W_p = Q_c + Q_a \quad (1)$$

where Q_g is the heat supplied to the generator,

Q_e is the cooling capacity in the evaporator,

W_p is the pump work,

Q_c is the heat rejected in the condenser,

Q_a is the heat rejected in the absorber.

The coefficient of performance is:

$$COP = Q_e / (Q_e + W_p) \quad (2)$$

Assuming that the pump work is small:

$$COP = Q_e / Q_g \quad (3)$$

The heat obtained from the waste heat stream is:

DOI: 10.65322/j.srd.05192026.22

$$Q_w = \dot{m}_w c_p (T_{in} - T_{out}) \quad (4)$$

where $\dot{m}_w$ is the flow rate of the heat carrier stream,
c_p is the specific heat capacity,
T_{in} and T_{out} are the inlet and outlet temperatures of the stream.
For a heat exchanger:

$$Q = K A \Delta T_{lm} \quad (5)$$

where K is the overall heat transfer coefficient,
A is the heat transfer surface area,
ΔT_{lm} is the logarithmic mean temperature difference.

Because the temperature of industrial waste heat varies, the study takes into account not only the nominal mode but also partial-load modes [6].

Thermodynamic and exergy assessment. It is not sufficient to evaluate an absorption cooling unit by COP alone, because different forms of energy differ in their degree of usefulness. For this reason, exergy analysis is also applied. The exergy of low-grade heat depends on its temperature and decreases as that temperature approaches the ambient temperature. In simplified form, the exergy of a heat stream is expressed as:

$$Ex_{,Q} = Q (1 - T_0 / T) \quad (6)$$

where T_0 is the absolute ambient temperature,
T is the absolute temperature of the heat source.
Exergy efficiency can be defined as:

$$\eta_{ex} = Ex_{,useful} / Ex_{,input} \quad (7)$$

Such an analysis helps to identify in which component the main irreversibility and loss of energy quality occur. Studies that applied advanced exergy and exergoeconomic analysis to absorption cascade systems likewise show the importance of isolating the irreversibilities by component [7]. On this basis, the exergy loss in each of the generator, absorber, condenser, evaporator, and heat exchangers is determined separately.

Determination of the optimal operating process. In determining the optimal process, the principal controllable factors selected are the generator temperature T_g, condenser temperature T_c, evaporator temperature T_e, absorber temperature T_a, working solution concentration x, and heat carrier flow rate ṁ. The objective function can be formulated as follows:

$$F = w_1 COP + w_2 \eta_{ex} - w_3 q_w \quad (8)$$

where w_1, w_2, w_3 are weighting coefficients appropriate to the research conditions,
q_w is the heat consumption per unit of cooling capacity.
Constraints: $T_{g,min} \le T_g \le T_{g,max}$;

$$T_{e,min} \le T_e \le T_{e,max};$$
$$T_{c,min} \le T_c \le T_{c,max};$$
$$x_{min} \le x \le x_{max}.$$

The optimal point should correspond to a high COP and acceptable values of exergy losses. In practical research, in addition to varying each factor separately, it is advisable to use a multi-factor experimental design. On the basis of the data obtained, a regression model can be constructed in the form:

DOI: 10.65322/j.srd.05192026.22

$$COP = b_0 + \Sigma b_i x_i + \Sigma b_{ii} x_i^2 + \Sigma b_{ij} x_i x_j \quad (9)$$

Through this model, the interaction of the parameters and the optimal operating region are determined.

Technical concept of the proposed unit. In the practical part of the study, it is proposed to develop an experimental test rig of a small-capacity absorption cooling unit suited to the waste heat source of an industrial enterprise. The main components of the rig comprise a generator, condenser, evaporator, absorber, solution pump, solution heat exchanger, and measuring instruments. Waste heat may be transferred to the generator directly or through an intermediate heat carrier. With direct coupling, the composition of the waste stream and the risk of corrosion are taken into account. Using an intermediate loop increases the operational safety of the unit, but introduces additional thermal resistance and pumping energy.

The following parameters must be recorded continuously on the test rig: generator inlet and outlet temperatures, absorber temperature, condenser temperature, evaporator temperature, pressures, heat carrier flow rate, solution concentration, and cooling load [9]. Using the measurement results:

$$Q = \dot{m}\, c_p\, \Delta T \quad (10)$$

$$COP = Q_e / Q_g \quad (11)$$

and the exergy indicators are calculated. Such a rig subsequently serves as a means of verifying the mathematical model before testing at a real industrial enterprise.

Expected scientific and practical results. Upon completion of the study, the following results are expected to be achieved:

1. The limits of using low-grade waste heat in an absorption cooling system will be determined.
2. The law governing the effect of waste heat temperature and flow rate on cooling capacity will be established.
3. The effect of generator, absorber, condenser, and evaporator temperatures on COP will be quantitatively assessed.
4. The acceptable operating region for the working solution concentration will be determined.
5. Efficiency indicators will be developed on the basis of the unit's energy and exergy balances.
6. An optimal control algorithm for variable waste heat conditions will be proposed.
7. A calculation methodology for the design parameters of the experimental unit will be developed.

Scientific novelty should be formulated with specific numerical indicators only after the experimental results have been obtained. At this stage, writing results such as "COP increased by a certain percentage" without experiments is scientifically incorrect. For this reason, the expected results are presented in this article in methodological form.

Discussion. The literature review shows that the scientific foundations for using low-grade waste heat in absorption cooling have been established. For example, a 2018 study proposed a cascade system that utilizes low-grade waste heat and examined the effect of generator temperature and other parameters on COP [6]. Subsequent studies have focused on the use of heat sources at around 80 °C and on improving the temperature match between the source and the system [8].

These results substantiate the chain selected in this study: "waste heat parameters – cycle parameters – cooling capacity – COP – exergy." However, the waste heat temperature, flow rate,

DOI: 10.65322/j.srd.05192026.22

and load profile of a specific enterprise may differ. Therefore, rather than directly transferring the results of a ready-made foreign unit to local conditions, re-optimization based on the enterprise's real data is necessary.

From a practical standpoint, in enterprises with a cooling demand, using waste heat for cooling provides a twofold benefit: on the one hand, the amount of heat discharged into the environment decreases; on the other, the electrical energy required to meet the cooling load is reduced. In assessing economic efficiency, the capital cost of the unit, maintenance, the stability of the heat source, and the duration of the cooling demand must also be taken into account [7].

Conclusion. The use of low-grade waste heat resources of industrial enterprises in absorption cooling systems is one of the promising directions for the reuse of secondary energy resources. The study substantiated the direction of developing a methodology for transferring waste heat to the generator, formulating the energy balance of the cooling cycle, determining COP and exergy efficiency, and selecting the optimal operating mode.

The main scientific direction of the study is not limited to creating the unit itself, but is aimed at matching the parameters of the waste heat source with the cooling demand. In this context, the generator temperature, the absorber and condenser conditions, the evaporator temperature, the working solution concentration, and the heat carrier flow rate are considered the main optimization factors.

In the future, verifying the mathematical model on an experimental test rig, testing it against the waste heat profile of a real industrial enterprise, integrating exergy and economic analysis, and developing an automatic control algorithm will enhance the practical value of the study.

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