Enhancing energy efficiency in reciprocating compressors through the effective recovery of secondary energy resources

*1Yuldashev Elmurod Umaraliyevich, [1]Jurayev Shaxzod Numon ugli, [1]Ergashbayev Maxkambay Dilshod ugli

[1]Almalyk State Technical Institute

ORCID: 0009-0003-7740-4177

Email: yuldashevelmurodumaraliyevich@gmail.com

Abstract: In this study, reciprocating compressors used in industrial and mining enterprises are characterized by continuous operating modes and high energy consumption. The thermal energy generated during the compression process, as well as the uncontrolled release of compressed air into the atmosphere, are identified as the primary factors that reduce the overall energy efficiency of compressor systems. This research is aimed at identifying and evaluating these energy losses occurring in reciprocating compressors and providing a scientific justification for their effective utilization as secondary energy resources. In the study, the air compression process is mathematically described based on a polytropic model, and the energy balance of the compressor system is developed and modeled in the Simulink environment. The calculations made it possible to determine the relationship between heat generation, useful work, and compressed air losses. The results demonstrate that the integrated recovery of thermal energy and unused compressed air emissions represents a significant reserve for improving the overall energy efficiency of compressor systems.

Keywords: Reciprocating compressor; energy efficiency; compression process; heat generation; compressed air losses; secondary energy resources; mathematical modeling.

INTRODUCTION.

In recent years, the efficient use of energy resources and the reduction of energy consumption in industrial and mining sectors have become key priorities in development strategies. A significant share of electrical energy consumption is associated with compressed air systems, where reciprocating compressors being the core component are characterized by high energy consumption and continuous operation. Therefore, improving the energy efficiency of reciprocating compressors is considered an important scientific and practical task in industrial energy engineering.

The air compression process in reciprocating compressors involves complex thermodynamic transformations. During compression, electrical energy is converted into mechanical work and subsequently into the internal energy of the gas, resulting in the release of a considerable amount of heat. This heat is primarily dissipated into the environment through cylinder walls, intercoolers, aftercoolers, and oil cooling systems. Under practical operating conditions, this thermal energy is not directly utilized in the compressor operation and is thus manifested as energy losses that reduce the overall system efficiency [1; pp. 85–96, 2; pp. 16–22].

In addition, within compressed air systems, a certain portion of compressed air is discharged into the atmosphere without technological utilization due to pressure regulation and protection processes. These factors significantly reduce the efficiency of electrical energy usage in compressor stations [3; pp. 146–253, 4; pp. 13–17].

Existing scientific studies are predominantly focused on improving the structural design of reciprocating compressors or optimizing their electric drives. However, the integrated analysis of thermal energy generated during compression and the unused portion of compressed air, as well as their recovery as secondary energy resources, has not been sufficiently investigated in a systematic manner. In particular, there is a need for comprehensive approaches that directly link the recovery of these energy losses to improvements in the overall energy efficiency of compressor systems.

The recovery of thermal energy generated during air compression and the reduction of unjustified compressed air discharge into the atmosphere represent promising directions for enhancing energy efficiency in reciprocating compressors. Determining the energy potential of secondary energy resources and directing them toward practical applications can significantly improve the overall performance of compressor units.

This study is devoted to a comprehensive analysis of the causes of thermal energy generation and compressed air losses in reciprocating compressors, as well as to the development of technical solutions aimed at reducing and recovering these losses. The proposed approaches enable a reduction in energy consumption and promote the rational use of energy resources in industrial and mining compressor stations.

RESEARCH METHODOLOGY

This study is aimed at identifying and evaluating the thermal energy generated during the air compression process in reciprocating compressors, as well as the unused losses of compressed air, and at substantiating the possibilities for their beneficial recovery. The research methodology is based on a combination of theoretical thermodynamic analysis, mathematical modelling, and the development of technical solutions for the effective utilisation of recoverable energy.

In reciprocating compressors, the air compression process under actual operating conditions is considered a polytropic process accompanied by heat transfer and mechanical losses. During compression, electrical energy is converted into mechanical work and then into the internal energy of the compressed air, which results in heat release. This thermal energy is mainly transferred to the external environment through the cylinder walls, intercoolers, aftercoolers, and the oil cooling system.

The overall energy balance of the compressor was considered to consist of the following main components: useful compression work, heat losses, and losses associated with the discharge of compressed air into the atmosphere. Therefore, thermal energy and compressed air losses were evaluated as secondary recoverable energy resources, and their beneficial utilisation was regarded as an important factor in improving the overall energy efficiency of the compressor system.

To characterise the energy state of the compressor system, the compression process was modelled on the basis of the polytropic equation:

$$pV^n = const$$

The specific work required for single-stage compression is expressed as follows:

$$L = \frac{n}{n-1} \cdot RT_1[(\frac{p_2}{p_1})^{\frac{n-1}{n}} - 1]$$

Here:

R gas constant;

T_1 inlet temperature;

p_2, p_1— inlet and outlet pressures, respectively.

The useful power of the compressor is determined based on the mass flow rate:

$$N_u = m \cdot L$$

Here: m mass flow rate of the compressed air.

The thermal energy generated during the compression process is evaluated based on the energy balance as follows:

$$Q_{heat} = N_{el} - N_u$$

The energy lost due to the unused losses of compressed air is expressed as follows:

$$Q_{loss} = m_{loss} \cdot c_p \cdot (T_2 - T_1)$$

Here:

m_{loss} mass flow rate of lost (unused) compressed air;

c_p specific heat capacity of air;

T_2, T_1 inlet and outlet temperatures, respectively.

The total recoverable energy potential is expressed as follows:

$$Q_{rec} = Q_{heat} + Q_{loss}$$

Using this mathematical model, a quantitative assessment of thermal energy and compressed air losses under varying compressor operating conditions was determined, and the possibility of improving energy efficiency through their effective utilization was substantiated.

In the scheme, the specific compression work and useful power are determined using input parameters (pressure, temperature, mass flow rate, and polytropic index), after which the heat generation is calculated by comparing these values with the electric drive power. The discharge of compressed air into the atmosphere without utilization is considered as a separate source of recoverable energy, and its thermal equivalent is determined. As a result, an overall recoverable energy indicator, combining heat generation and compressed air losses, is obtained.

RESULTS AND DISCUSSION

Based on the developed mathematical model and Simulink computational scheme, the energy performance of the reciprocating compressor system was calculated for various operating modes. The nominal operating condition was taken as the baseline, and a comparative analysis was carried out with respect to variations in the pressure ratio, mass flow rate, and polytropic index.

The results showed that with an increase in the compression ratio, the specific compression work L increases by 15–22%. At the same time, the growth of useful power N_u amounts to 12–18%, and it increases more slowly compared to the power consumed by the electric drive. This behavior is explained by the increase in the amount of heat released during the compression process.

The heat release Q_{heat} determined based on the energy balance, was found to account for 28–35% of the total electrical power consumed by the compressor. This result confirms that thermal energy represents a major source of energy losses in the compressor system. The highest share of heat release was observed under operating conditions with a high pressure ratio and large mass flow rates.

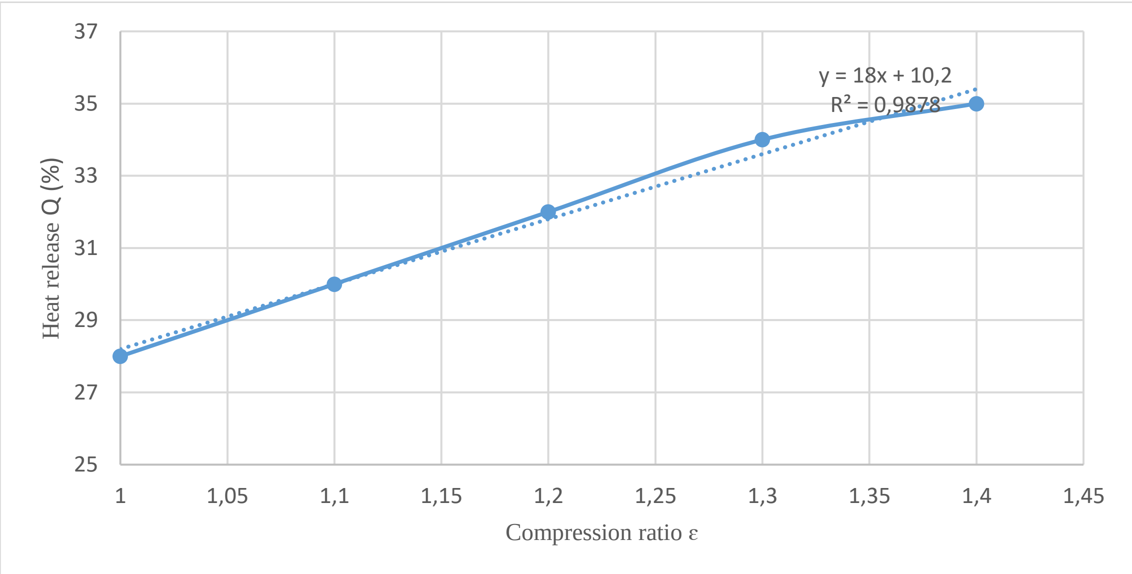

Figure 1. Graph of heat generation as a function of the compression ratio.

Energy losses associated with the wasteful consumption of compressed air, Q_{loss} were found to account for 6–10 % of the total energy consumption. The calculation and experimental results showed that each 1 % increase in compressed air losses leads to an average decrease of 0.6–0.8 % in the overall energy efficiency of the compressor system.

When heat release and compressed air losses are considered jointly, the total recoverable energy Q_{rec} was determined to be 34–45 % of the electrical energy consumed by the compressor. It was demonstrated that the effective utilization of this energy can increase the overall energy efficiency of the system by 10–16 %.

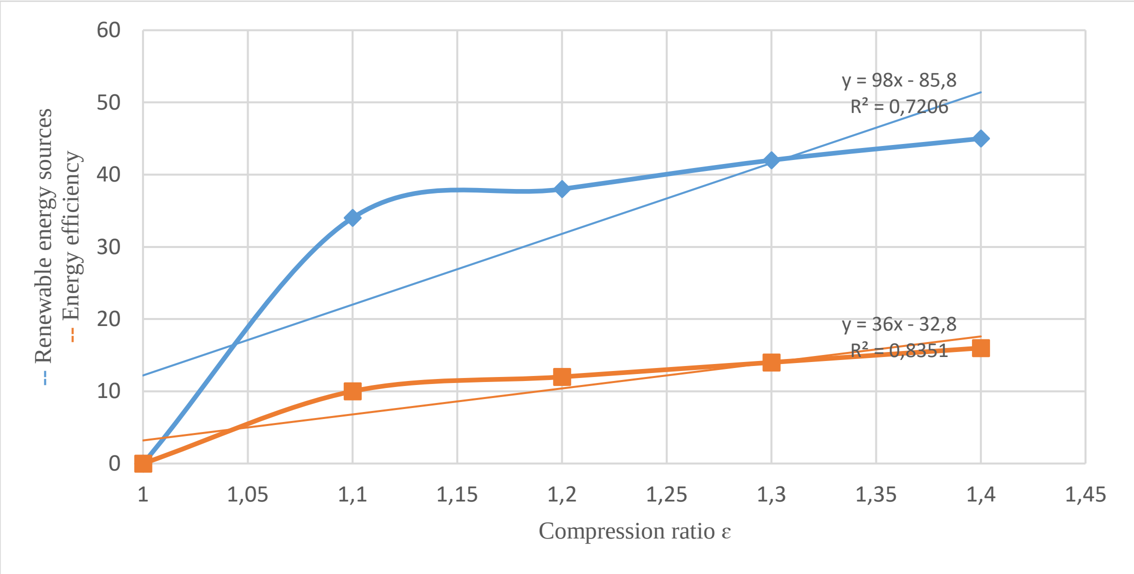

Figure 2. Effect of compression ratio on energy efficiency and recoverable energy

- The obtained results confirm that the developed mathematical model and Simulink computational scheme adequately describe the main energy components arising during the compression process with sufficient accuracy and can be practically applied for the evaluation of secondary energy resources.

The obtained results demonstrate that improving the energy efficiency of reciprocating compressors is primarily associated with heat release and compressed air losses. According to the findings, heat release accounts for 28–35 % of the total electrical energy consumption. This value is quantitatively consistent with the literature, where thermal losses in reciprocating compressors are typically reported within the range of 25–40 %.

Energy losses associated with the unnecessary discharge of compressed air into the atmosphere were found to range between 6–10 %. Previous studies have reported these losses within 5–12 %, mainly attributed to safety valves, pressure regulation processes, and operational interruptions. In contrast to existing studies, the present work considers the energetic equivalent of compressed air losses as a separate component, thereby improving the accuracy of the overall energy balance.

The total recoverable energy potential reaching 34–45 % significantly exceeds the 20–30 % estimates reported in many previous studies, which were based solely on heat recovery. This difference is explained by accounting not only for thermal energy but also for the unused portion of compressed air as an energy resource.

The analysis indicates that effective utilization of recoverable energy can increase the overall energy efficiency of the system by 10–16 %. This improvement exceeds the typical 5–10 % gains achieved through structural enhancements or electric drive optimization, highlighting the practical advantage of the proposed approach.

The results confirm that the integrated consideration of heat and compressed air losses in reciprocating compressors has significant scientific and practical importance for improving energy efficiency. The proposed technical solutions complement existing research and establish a new scientific basis for the utilization of secondary energy resources in compressor systems.

CONCLUSION

This study analyzed the problem of improving energy efficiency in reciprocating compressor systems by comprehensively considering heat release and the unused losses of compressed air. The developed mathematical model and Simulink computational scheme demonstrated sufficient accuracy in describing the main energy components arising during the compression process.

According to the calculation and experimental results, the thermal energy generated during compression accounts for 28–35% of the total electrical energy consumption and represents the largest source of energy losses in the compressor system. Energy losses associated with the wasteful discharge of compressed air into the atmosphere were found to range between 6–10% of the total energy consumption, with an increasing trend observed under unstable operating conditions.

It was determined that the total recoverable energy, considering both heat release and compressed air losses, amounts to 34–45% of the electrical energy consumed by the compressor. The results demonstrate that the effective utilization of this energy can increase the overall energy efficiency of the compressor system by 10–16%.

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