the HCU accelerates again and reaches the TDC. During the no-load movement of the BDC, the HCU gains sufficient speed to overcome the load peak and accelerates for two revolutions, with a significantly longer start-up time than in the first two cases (0.25 s).

Experiments to determine the most probable position of the piston after 100 stops of the HCU under load, i.e. before the subsequent start-up, allowed to establish the following.

The most probable position of the piston after stopping under load of single-cylinder FGP-2,2 is in the range of 180...225°, where the counteracting torque is practically equal to zero. Through the observation window in the housing it can be seen how the shaft of the HCU under load was retarded for a fraction of a second, and then under the action of pressure forces acting on the piston, moved to the opposite side and after oscillations the shaft (piston) stopped before the BDC.

Determining the most probable position of the piston after stopping the two-cylinder KFGV-14 engine proved to be quite difficult. Tests showed that after power failure the shaft had time to make about 14 revolutions by inertia, and then abruptly stopped practically in any position. However, multiple repetition of the experiments allowed us to establish a range of angles 100...130°, at which the HCU stops more often. For subsequent startup, this condition proved to be the most difficult, since the electric motor had to develop a torque sufficient to accelerate the inertial masses and overcome the resistance of the two cylinders in the series.

Conclusions. The conducted experiments allowed us to determine the parameters, explain the physical essence of the processes occurring in the transient modes (start, stop) of the HCU, and reasonably select the initial conditions for calculation.

REFERENCES

[1] Redkozub B.D., Dorosh V.S. Study of starting mode of the hermetic piston compressor/ B.D. Redkozub // Cooling technology. – 1971. – № 3. –. P. 24–27.

УДК 621.57

ENHASING THE FUEL EFFICIENCY OF GAS TURBINES IN SUBTROPICAL CLIMATIC CONDITIONS OF CHINA THROUGH INLET AIR COOLING

BAO Guozhi
Assistant Professor of School of Energy
and Power, Jiangsu University of Science and Technology, Zhenjiang, Jiangsu, P. R. China
gzbao2005@163.com
YANG Zongming
Ph.D, Professor of School of Energy and Power,
Jiangsu University of Science and Technology, Zhenjiang, Jiangsu, P. R. China
zongmingy@just.edu.cn
RADCHENKO Andrii
Candidate of Technical Sciences, Assistant Professor of the Turbine Department,
Admiral Makarov National University of Shipbuilding,
Mykolaiv, Ukraine

Annotation. Enhancement of gas turbine (GT) efficiency by inlet air cooling, known as TIAC, in chillers using the heat of exhaust gas is one of the most attractive tendency in energetics. A sustainable operation of GT at stabilized low intake air temperature is impossible without determining rational design cooling capacity of the chiller and TIAC system as a whole to match current duties without overestimation. The most widespread absorption lithium-bromide chillers (ACh) of a simple cycle is unable to reduce the GT intake air temperature below 15 °C because the temperature of its chilled water is approximately 7 °C. Deeper cooling air would be possible by applying a boiling refrigerant as a coolant in ejector chiller (ECh) as the cheapest and simplest in design. However, the coefficients of performance (COP) of ECh are considerable lower than those of ACh: about 0.3 against 0.7 of ACh. Therefore, the ECh is applied for subsequent cooling air less than 15 °C, whereas the efficient ACh – is for ambient air precooling to 15°C. The application of absorption-ejector chiller (AECh) enables deeper inlet air cooling and greater effect accordingly. However, the peculiarities of subtropical climate, characterized by high temperature and humidity and thermal loads as result, require extended analyses to reveal the character of thermal load and modify the methodology of TIAC system designing, respectively. The advanced designing methodology that enables to reveal and thereby to forecast the peculiarities of TIAC system thermal loading has been developed to match those peculiarities and gain maximum effect without oversizing as result.

Key words: heat conversion, thermal load, design cooling capacity.

Introduction. Gas turbine intake air cooling (TIAC) is kept as a sustainable and prosperous trend in enhancing GT operation efficiency. Most of TIAC system design methods proceeds from the approaches to determine a design thermal load covering current peaked loads that inevitably leads to overestimation.

Issuing from the above, developing the method to determine more precise value of design thermal load avoiding overestimation is desirable. Moreover, such a method should be able to reveal the peculiarities of the TIAC system current thermal loading in response to actual needs.

To enhance the efficiency of the TIAC system in actual climatic conditions a two-stage inlet air cooling can be used. The application of such two-stage GT exhaust heat conversion in combined absorption-ejector chiller (AECh) for two-stage TIAC by hybrid coolants (chilled water from ACh and refrigerant from ECh).

It was shown that in the temperate climatic conditions the two-stage TIAC with AECh provides nearly 1.5 times enlarged annual fuel reduction compared to cooling in ACh [1,2]. But the efficiency of two-stage TIAC in subtropical climate is questioning.

The subtropical climate is characterized by high temperature and humidity of ambi-ent air simultaneously leading to converging dry bulb and wet bulb ambient air tempera-tures. This peculiarity causes increased thermal load on the GT intake air exhaust heat recovery cooling system, that requires extended analyses of the operation efficiency of TIAC system to reveal the character of thermal load and modify the methodology of TIAC system designing to forecast its efficient on-site operation with maximum effect without oversizing.

The **aim** of the research is to increase the efficiency of GT intake air cooling when operating in subtropical climate through adopting the TIAC system designing to peculiarities of ac-tual thermal loading to provide fuel efficient decarbonized turbine performance without oversizing.

Main Section.

The following hypotheses to prove novel approaches to develop innovative TIAC system designing and operation to match the actual subtropical climatic conditions are assumed.

The peculiarity of subtropical climatic conditions is characterized by high temperature and humidity of ambient air simultaneously, that results in converging actual dry bulb and wet bulb ambient air temperatures and raising thermal loads on TIAC systems as a consequence. This peculiarity makes it possible to generate the following hypotheses as the phenomenological base of TIAC system designing methodology.

1. Approaching the values of TIAC system cooling capacity, which provide the maximum rate of the summarized annual effect increment due to TIAC, to the values, providing practically maximum annual effect, for instance as reduction in fuel consumption, takes place due to converging dry bulb and wet bulb ambient air temperatures leading to raising actual thermal loading in subtropical climatic conditions.

2. Converging the values of cooling capacities, which provide the maximum rate of the summarized effect increment due to TIAC and maximum annual effect, enables to design the TIAC

systems proceeding from the maximum rate of annual effect increment at minimum installed cooling capacity and system sizes accordingly.

In temperate climate deeper intake air cooling has been approved as a prosperous trend to improve turbine efficiency [8,57].

The task of the present research is to approve the efficiency of deep TIAC in subtropical climatic conditions of central China as an example.

The methodology developed for TIAC system designing is aimed to define a rational value of the overall cooling capacity and its subsequent distribution according to actual thermal loading that enables to achieve the annual fuel saving closed to its maximum value but without overestimation.

The basic methodology of TIAC system designing was developed in [57]. It is focused on defining the optimal design cooling capacity that enables to provide the maximum rate of the summarized effect increment due to TIAC as the first step and the value of rational design cooling capacity enabling to achieve close to maximum value of annual effect.

In contrast to comfort (space) air conditioning [71,72] with annual refrigeration energy production in response to its consumption as criterion [73,74], in engine cyclic air cooling the annual fuel reduction is applied as criterion [57,75] to determine the rational capacities to achieve maximum output.

Thus, the annual fuel reduction ΣB_e due to TIAC is accepted as a primary criterion and calculated according to hour-by-hour summary procedure all the year round:

$$\Sigma B_e = \sum(\Delta t_a \cdot \tau \cdot b_{et} \cdot P_e\, 10^{-3}),\text{t},$$

where: Δt_a – actual value of drop in the temperature of ambient intake air, $\Delta t_a = t_a - t_{a2}$, K or °C; P_e – power output of GT, kW; τ – time period, h; $b_{et} = b_e / \Delta t_a =$ – specific fuel decrease for $\Delta t_a =$ 1K or 1°C, accepted as 0.35 g/(kWh·K).

As an example, the efficiency of application of developed TIAC system was investigated for GTU GE 9351FA, nominal power 260.68 MW.

The results of annual fuel reduction ΣB_e calculation are presented in relative values for unit power of GT ($P_e = 1$ kW): $\sum b_e = \sum B_e / P_e$, kg/kW.

The cooling capacity is also presented in relative values as specific cooling capacity q_0 and calculated as the absolute value Q_0 referred to unit of air mass flow rate $G_a = 1$ kg/s: $q_0 = Q_0 / G_a$ or

$$q_0 = \xi \cdot c_{ma} \cdot \Delta t_a,\ \text{kW/(kg/s) or kJ/kg}.$$

where: ξ – specific heat ratio; c_{ma} – humide air specific heat, kJ/(kg·K).

The optimal values $q_{0.15\text{opt}}$ and $q_{0.10\text{opt}}$ of cooling capacity for ambient air cooling to 15 °C and 10 °C accordingly are defined according to maximum value of the ratio $\Sigma b_e / q_0$ within the whole range of Σb_e as the first, global, maximum of cumulative characteristic $\Sigma b_e = \text{f}(q_0)$. In its turn, rational values $q_{0.15\text{rat}}$ and $q_{0.10\text{rat}}$ of cooling capacity are defined according to the second maximum value of the ratio $(\Sigma \text{b}_\text{e} - \Sigma b_{\text{e.opt}})/\text{q}_0$ within the range of $(\Sigma b_\text{e} - \Sigma b_{\text{e.opt}})/\text{q}_0$ beyond the first maximum of cumulative characteristic $\Sigma b_e = \text{f}(q_0)$, where $\Sigma b_\text{e} > \Sigma b_{\text{e.opt}}$. Thus, the ratio $\Sigma b_e / q_0$ is used as an indicator to define a maximum of cumulative characteristic $\Sigma b_e = \text{f}(q_0)$. The optimal cooling capacity $q_{0.\text{opt}}$ makes it possible to achieve a maximum rate of summarized annual effect increment $\Sigma b_e / q_0$ due to TIAC, as well as the rational value of design cooling capacity $q_{0.\text{rat}}$ enables to reach practically maximum annual effect in fuel reduction, however without oversizing: $q_{0.\,\text{rat}} < q_{0.\text{max}}$.

Conclusions. The TIAC systems with two-stage chillers of combined type including ACh for ambient air precooling to 15 °C by chilled water and ECh for further cooling air lower than 15 °C by refrigerant are considered as a novel perspective trend in enhancement of GT fuel and environmental efficiency in subtropical climate.

A general approach to designing the innovative two-stage combined AECh TIAC system for the subtropical climate consists in defining the optimum value providing the maximum rate of thermal loading and minimum sizes of the AECh accordingly with increased its value for ACh by about 5 to 8 kJ/kg or kW/(kg/s). A such approach simplifies the calculation and raises the accuracy simultaneously.

A developed TIAC system for cooling air to 10 °C in AECh provides a reduction in specific fuel consumption by 2 to 3 % of the overall specific fuel consumption and carbon emission accordingly for GT without TIAC and by 15 to 20 % compared to their values gained due to cooling intake air to 15 °C by ACh in subtropical climate. Thus, the fuel efficiency of two-stage TIAC has been approved for subtropical climate.

References

1. Radchenko, A.; Trushliakov, E.; Kosowski, K.; Mikielewicz, D.; Radchenko, M. Innovative turbine intake air cooling systems and their rational designing. Energies 2020, 13(23), 6201. https://doi:10.3390/en13236201

2. Yang, Z.; Radchenko, M.; Radchenko, A.; Mikielewicz, D.; Radchenko, R. Gas turbine intake air hybrid cooling systems and a new approach to their rational designing. Energies 2022, 15, 1474. https://doi.org/10.3390/en15041474