UDK 621.444:629.5.03-8

Analyzing the efficiency of moderate and deep cooling of air at the inlet of gas turbine in various climatic conditions

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The efficiency of deep cooling air at the inlet of gas turbine unite to the temperature of 10 ℃ by waste heat recovery combined absorption-ejector chiller was analyzed in climatic conditions at Kharkov site, Ukraine, and Beijing site, China, and compared with the moderate cooling to the temperature of 15°C in traditional absorption lithium-bromide chiller. The refrigerant ejector chiller is chosen as the most simple and reliable in operation chiller. It was used as the low-temperature stage for subcooling the air precooled in absorption lithium-bromide chiller to the temperature about 15 °C. Both waste heat recovery absorption lithium-bromide chiller and ejector chiller use the heat of gas turbine unite exhaust gas to produce a cooling capacity. Air cooling at the inlet of gas turbine unite was investigated for varying climatic conditions during the year. The current values of temperature depression with cooling ambient air to different temperatures of 10 °C and 15 °C and corresponding cooling capacities required were calculated. The comparison of the effect due to gas turbine unite inlet air cooling was performed by annual fuel saving and power production growth. With this the current values of turbine power output increase and specific fuel consumption decrease due to cooling inlet air from current varying ambient temperatures to the temperatures of 10 °C and 15 °C were calculated. It was shown that annual fuel saving and power production growth have increased by 1,8 times for Kharkov (Ukraine) site climatic conditions and by 1,6 times for Beijing (China) site due to deep cooling air to the temperature of 10 °C by absorption-ejector chiller as compared with cooling inlet air to the temperature of 15 °C by absorption lithium-bromide chiller.

Keywords: *Cooling; Ambient air; Inlet air; Gas turbine unite; Temperature depression; Climate*

doi: https://doi.org/10.15673/ret.v55i1.1351

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1. Introduction

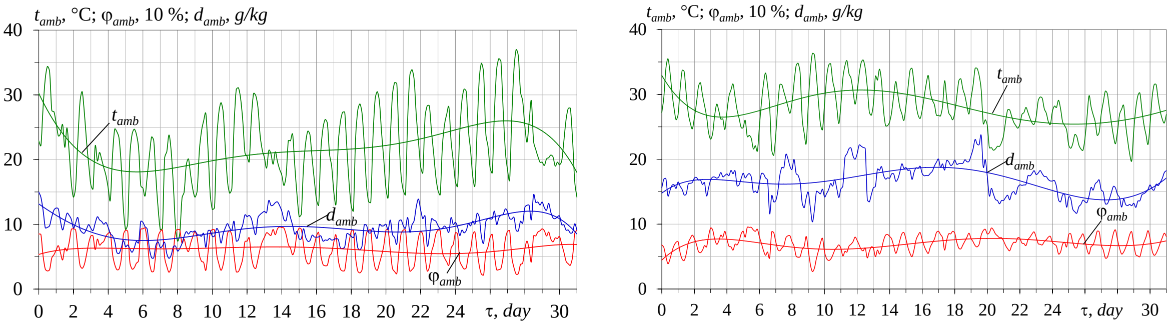
The gas turbine unit (GTU) fuel consumption increases and the efficiency and power output decreases as the temperature at the inlet of the GTU increases [1, 2]. Thus the GTU GE 9351FA (General Electric) power decreases by 0.61...0.65% or by 1600...1700kW and specific fuel consumption b_e increases by 0,35 g/(kW·h) with increasing ambient air temperature t_{amb} at the inlet on 1°C [3]. So, the use of exhaust gases heat for GTU inlet air cooling provides an increase in GTU efficiency at increased ambient air temperatures t_{amb}. The application of waste heat recovery chillers, using the GTU exhaust gas heat for inlet air cooling is the most widespread method to increase turbine efficiency. Traditionally, absorption lithium-bromide chillers (ACh) which provide cooling ambient air down to about 15°C are used [4, 5]. However, deeper GTU inlet air cooling compared with its cooling in the ACh will obviously lead to a greater growth of GTU efficiency. For cooling ambient air from the temperature of 15°C down to 10°C and lower refrigerant ejector chillers (ECh) could be used in such two-stage combined absorption-ejector chiller (AECh) [6]. However, it is necessary to estimate the GTU inlet deep cooling efficiency for actual site operation climatic conditions.

The purpose of the research is to evaluate the efficiency of GTU inlet air deep cooling (below 15°C) in comparison with traditional cooling ambient air to 15°C by ACh for actual site climatic conditions.

2. Results of investigation

The ambient air parameters change considerably during GTU operation. Fluctuations of ambient air temperature t_{amb}, relative φ_{amb} and absolute humidity d_{amb} during July 2017 for Kharkov, Ukraine, and Beijing, China, are presented in Fig. 1.

The GTU operation climatic conditions at the Beijing site, China, are characterized by large relative humidity φ_{amb} and, respectively, absolute humidity d_{amb} of the ambient air at high its temperatures t_{amb}. This causes a large heat load (chiller cooling capacity required) on the GTU inlet air cooling system because of significant condensation latent heat to be removed during ambient air cooling. The annual GTU specific fuel savings $\Sigma\Delta b_e$ (for 1 kW of GTU power) due to inlet air cooling from ambient temperatures t_{amb} to t_{a2}= 10 and 15ºC by chillers with various design specific cooling capacity q_0 (for air flow G_a = 1 kg/s) are presented in Fig. 2.



a **b**

Figure 1 *– Ambient air temperature t_{amb}, absolute humidity d_{amb} and relative humidity φ_{amb} profiles for July 2017:* ***a*** *–Kharkov, Ukraine;* ***b*** *– Beijing, China*

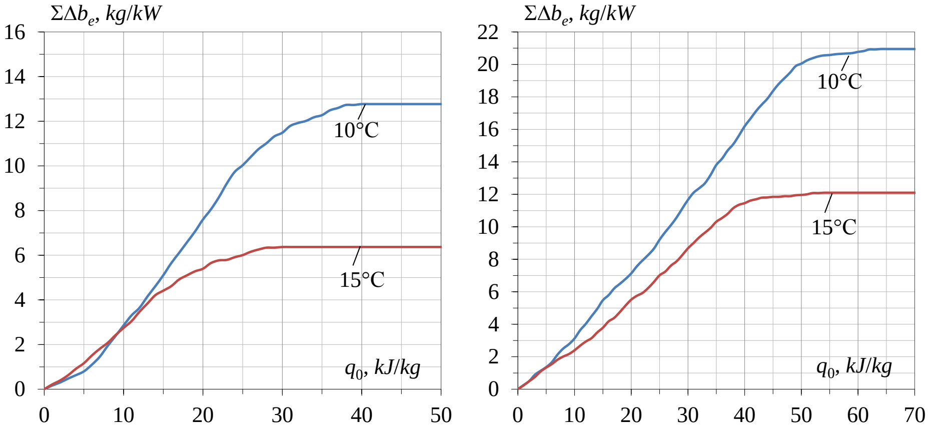


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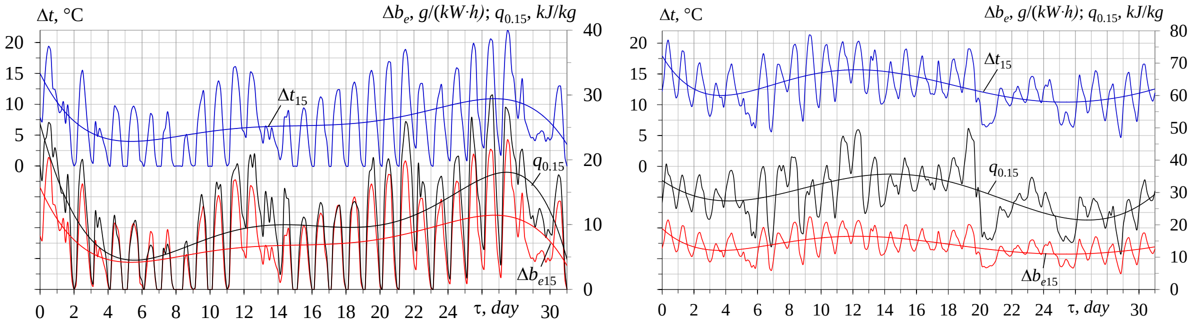
Figure 2 *– The annual values of specific fuel saving $\Sigma\Delta b_e$ versus a design specific cooling capacity q_0 (air flow G_a = 1 kg/s) at different temperatures of cooled air t_{a2}: 10 ºC – in the AECh; 15 ºC – in the ACh for July 2017:* ***a*** *–Kharkov, Ukraine;* ***b*** *– Beijing, China*

Fig. 2 shows that in order to achieve the maximum potential annual specific fuel saving $\Sigma\Delta b_e$ in Beijing climatic conditions it is necessary to use a considerably larger specific cooling capacity q_0 in comparison with the Kharkov climatic conditions, which confirms the need for elevated design cooling loads of the chiller because of a larger ambient air relative humidity φ_{amb} and absolute humidity d_{amb} , respectively, at its high temperatures t_{amb} for Beijing climatic conditions. This results in a greater fuel saving in Beijing climatic conditions due to cooling GTU inlet air from the higher ambient air temperatures and with larger temperature depression $\Delta t = t_{amb} - t_{a2}$. The current values of the specific fuel consumption reduction Δb_{e15} due to GTU inlet air cooling from t_{amb} to t_{a2}=15ºC with temperature reduction of Δt_{15} in the ACh, as well as the value of Δb_{e10} when the air is cooled from t_{amb} to t_{a2}=10ºC with temperature depression of Δt_{10} in the combined absorption-ejector chiller (AECh) for Kharkov and Beijing climatic conditions in July 2017 are presented in Fig. 3 and 4. The calculations are carried out for the GTU GE 9351FA (N_{eISO} =260MW), for which the air temperature reduction Δt_a by 1°C leads to a decrease in the specific fuel consumption Δb_e by 0,35 g/(kW·h) [3].



a **b**

Figure 3 *– Current values of the GTU inlet ambient air temperature decrease Δt_{15} when cooling to 15 ºC in the ACh, corresponding GTU specific fuel consumption reduction Δb_{e15} and specific cooling capacity $q_{0.15}$ for July 2017:* ***a*** *–Kharkov, Ukraine;* ***b*** *– Beijing, China*

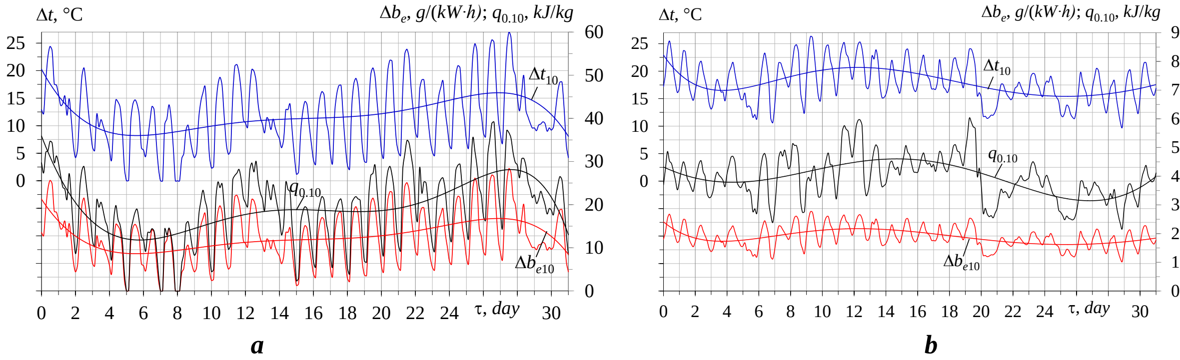


Figure 4 – *Current values of the ambient air temperature decrease Δt_{10} when cooling to 10 ℃ in the AECh, corresponding specific fuel consumption reduction Δb_{e10} and specific cooling capacity $q_{0.10}$ for July 2017:* ***a*** *–Kharkov, Ukraine;* ***b*** *– Beijing, China*

Comparing the values of specific heat loads when cooling the ambient air to 15°C $q_{0.15}$ and to 10°C $q_{0.10}$ in Fig. 5 it can be seen that despite the need to use more cooling capacity for cooling the air at the inlet of the GTU in Beijing climatic conditions, compared with the conditions in Kharkov, the specific heat load on the refrigerant ejector chiller for air subcooling from 15°C to 10°C, determined as heat load difference $\Delta q_{0.10\text{–}15}$, is about 10 kJ/kg for both cases, so as the heat load difference in various climatic conditions falls on relatively high temperature range of cooling air from ambient air temperatures t_{amb} to 15°C in ACh as the high temperature cooling stage of combined two-stage AECh.

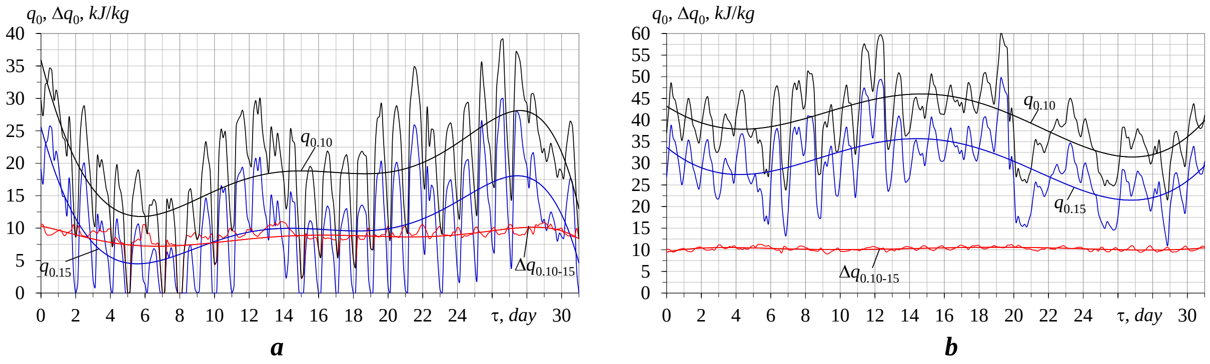


Figure 5 *– Current values of the specific cooling loads $q_{0.10}$ for a design GTU inlet air temperature of 10 ℃ cooled by AECh, $q_{0.15}$ – for a design GTU inlet air temperature of 15 ℃ cooled by ACh and their difference $\Delta q_{0.10\text{–}15}$ as the ECh cooling load for July 2017:* ***a*** *–Kharkov, Ukraine;* ***b*** *– Beijing, China*

The current values of increment in the GTU power output ΔN_{e15} due to cooling inlet air from varying ambient temperatures t_{amb} to t_{a2}=15ºC with temperature depression of Δt_{15} in the ACh and power output increment ΔN_{e10} due to cooling air from t_{amb} to t_{a2}=10ºC with temperature depression of Δt_{10} in combined AECh for the Kharkov and Beijing climatic conditions are given in Fig. 6.

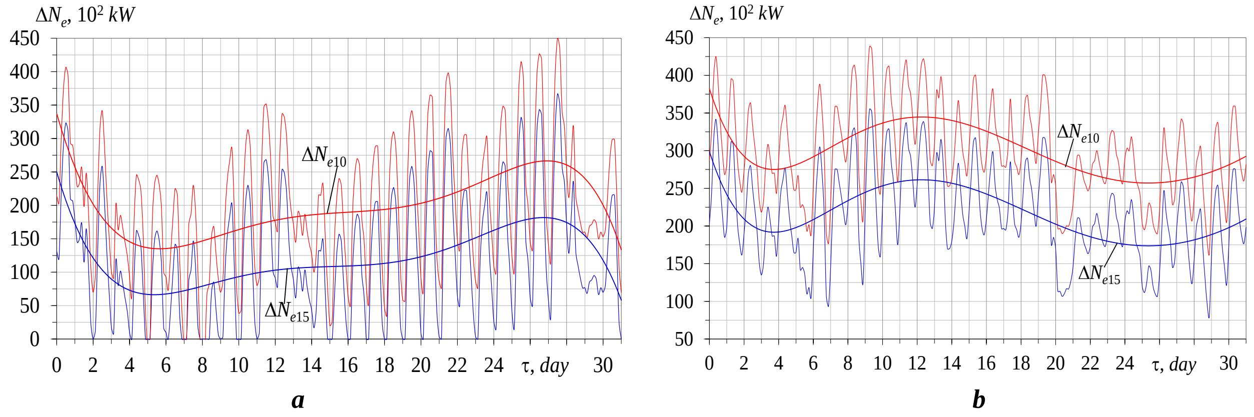
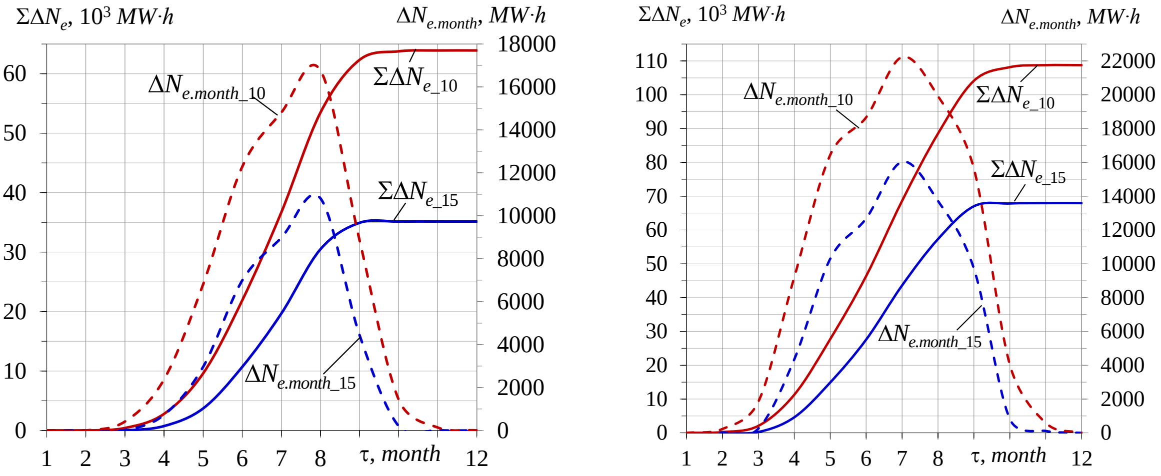


Figure 6 – *Current values of the GTU power output increment ΔN_{e15} due to ambient inlet air cooling to 15 ℃ in the ACh and power increment output ΔN_{e10} due to ambient inlet air cooling to 10 ℃ in the AECh for July 2017:* ***a*** *–Kharkov, Ukraine;* ***b*** *– Beijing, China*

As can be seen from the results, deeper GTU ambient inlet air cooling to the temperature t_{a2}=10°C provides a current specific fuel consumption reduction Δb_{e10} of 10...15 g/(kW·h) (Fig. 4,***a***) and the GTU power output increment ΔN_e of 15...25 MW (Fig. 6,***a***) for Kharkov site climatic conditions and 17...22 g/(kW·h) and 25...35 MW for Beijing site climatic conditions (Fig. 4,***b*** and 6,***b***). However, actual fuel savings will be slightly lower because of spending some power output to overcome the air cooler aerodynamic resistance at the inlet of the GTU, with addition fuel consumption respectively.

The power production growth ΔN_e per month and during 2017 year for GTU GE 9351FA (nominal power output 260 MW) due inlet air cooling from varying current ambient air temperatures t_{amb} to cooled air temperatures t_{a2} = 10 and 15°C for Kharkov, Ukraine, and Beijing, China, climatic conditions are presented in Fig. 7.



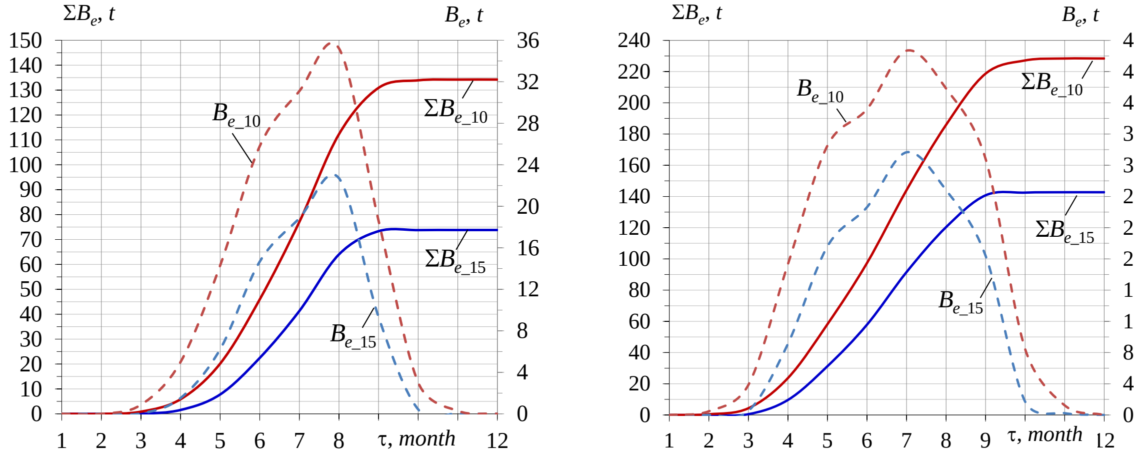
a ***b***

Figure 7. *– The values of the monthly power production* growth $\Delta N_{e.month}$ *for GTU GE 9351FA and power production* growth $\Sigma\Delta N_e$ *during 2017 year for different cooled air temperatures* t_{a2}*:*
10 ºC – the AECh; 15 ºC – the ACh in 2017; ***a*** *–Kharkov, Ukraine;* ***b*** *– Beijing, China*

As can be seen from Fig. 7, cooling air at the inlet of GTU GE 9351FA to the temperature of 15°C provides the annual power production growth ΔN_{e_15} about 35000 MW·h for Kharkov climatic conditions (Fig. 7, *a*), whereas for the Beijing climate (Fig. 7, *b*) – about 68000 MW·h. At the same time, deeper ambient air cooling down to 10 °C provides obtaining a much larger gain of the GTU annual power production growth ΔN_{e_10}: about 64000 MW·h (Fig. 7, ***a***) and 109000 MW·h (Fig. 7, ***b***) respectively.

Attention should be paid to the considerable increase in the GTU power production growth ΔN_{e_10} due to deeper inlet air cooling to the temperature t_{a2} = 10°C compared with its cooling to t_{a2}=15°C in 1.8 times for Kharkov climatic conditions and 1.6 times for Beijing.

The fuel savings due to traditional inlet air cooling to the temperature of 15°C and a deeper cooling to 10°C for the climate of Kharkov site, Ukraine, and Beijing site, China, for 2017 is presented in Fig. 8.



a ***b***

Figure 8. *– The values of the monthly fuel saving* B_e *and fuel saving* ΣB_e *during 2017 year due to inlet ambient air cooling to different temperatures* t_{a2}*: 10 ºC – in the AECh; 15 ºC – in the ACh;* ***a*** *– Kharkov, Ukraine;* ***b*** *– Beijing, China*

As can be seen from the results in Fig. 8, the fuel saving ΣB_e per 2017 year as well as the GTU annual power production growth $\Sigma\Delta N_e$ is increased by 1.8 times for Kharkov site climatic conditions and by 1.6 times for Beijing site while comparing with the moderate cooling to 15°C (ΣB_{e_15} and $\Sigma\Delta N_{e\_15}$) by the ACh with a deep cooling to 10°C (ΣB_{e_10} and $\Sigma\Delta N_{e\_10}$) by the AECh. However, it should be taken into account that because of spending some power output to overcome the air cooler aerodynamic resistance at the inlet of the GTU, with addition fuel consumption respectively, the actual effect will be somewhat lower.

3. Conclusions

The efficiency of deep air cooling (down to 10 °C) at the inlet of the GTU with waste heat recovery two-stage combined absorption-ejector chiller (AECh) for the climatic conditions at Kharkov site, Ukraine, and Beijing site, China, has been analyzed.

It has been shown that deep inlet air cooling to the temperature *of* 10 °C by AECh provides an increase in the GTU annual power production growth $\Sigma\Delta N_e$ as well as the annular fuel saving ΣB_e per 2017 year in 1.6...1.8 times (for Beijing and Kharkov climatic conditions respectively) as compared with traditional moderate cooling to 15°C by the absorption lithium-bromide chillers ACh.

References

1. **Farouk, N., Sheng, L., Hayat, Q.** (2013) Effect of Ambient Temperature on the Performance of Gas Turbines Power Plant. *International Journal of Computer Science Issues*, 10 (1), 439–442.
2. **Kumar Tiwari, A., Muzaffarul Hasan, M., Islam, M.** (2013) Effect of ambient temperature on the performance of a combined cycle power plant. *Transactions of the Canadian Society for Mechanical Engineerin*g, 37(4), 1177–1188. Doi: https://doi.org/10.1139/tcsme-2013-0099
3. General Electric. Available at: https://www.ge.com/power/gas/gas-turbines/6b-03#0: GE PG9351FA. (Accessed 20.11.2018)
4. **Popli, S., Rodgers, P., Eveloy, V.** (2013) Gas turbine efficiency enhancement using waste heat powered absorption chillers in the oil and gas industry. *Applied Thermal Engineering*, 50, 918–931. Doi: https://doi.org/10.1016/j.applthermaleng.2012.06.018
5. **Popli, S., Rodgers, P., Eveloy, V.** (2012) Trigeneration scheme for energy efficiency enhancement in a natural gas processing plant through turbine exhaust gas waste heat utilization. *Applied Energy*, 93, 623–636. Doi: https://doi.org/10.1016/j.apenergy.2011.11.038
6. **Radchenko A. N., Kantor, S. A.** (2015) The method of evaluation of rational heat load on absorption-ejector thermotransformer for cooling regenerative GTU intake air of compressor stations. *Aerospace technics and technology*, no. 5 (122), 61-64.

Received 03.01.2019
Approved 05.02.2019
Available in Internet 03.03.2019

Аналіз ефективності помірного та глибокого охолодження повітря на вході газотурбінної установки в різних кліматичних умовах

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Проаналізовано ефективність глибокого охолодження повітря на вході газотурбінних установок до температури 10℃ шляхом утилізації відпрацьованого тепла комбінованою абсорбційно-ежекторною холодильною машиною в кліматичних умовах м. Харків, Україна та м. Пекін, КНР, і порівняно з помірним охолодженням повітря до температури 15 °С в традиційній абсорбційній бромистолітієвій холодильній машині. Ежекторна холодильна машина обрана як найбільш проста і надійна в експлуатації. Вона використовується як низькотемпературний ступінь для доохолодження повітря, попередньо охолодженого в абсорбційній бромистолітієвій холодильній машині до температури близько 15 °С. Обидві тепловикористовуючі холодильні машини, абсорбційна бромистолітієва та хладонова ежекторна, використовують теплоту відпрацьованих газів газової турбіни для виробництва холоду. Охолодження повітря на вході газотурбінної установки було досліджено для змінних кліматичних умов протягом року. Розраховано поточні значення зниження температури повітря при його охолодженні від показників навколишнього середовища до температур 10 і 15 °С та відповідних необхідних холодильних потужностей. В якості показників оцінки ефективності охолодження повітря на вході газотурбінної установки застосовано показники річної економії палива та зростання виробництва електроенергії. При цьому були розраховані поточні величини збільшення вихідної потужності турбіни та зменшення питомої витрати палива як результат охолодження повітря на вході від поточних змінних температур навколишнього середовища до температур 10 і 15°С. Показано, що річна економія палива та виробництво електроенергії зростають у 1,8 рази для кліматичних умов Харкова та в 1,6 рази для м. Пекін за рахунок глибокого охолодження *повітря до температури 10°C в комбінованій абсорбційно-ежекторній холодильній машині порівняно з традиційним охолодженням повітря на вході до температури 15°C в абсорбційній бромистолітієвій холодильній машині.*

Ключові слова: *Охолодження; Зовнішнє повітря; Повітря на вході; Газотурбінна установка, Зниження температури, Клімат.*

Література

1. **Farouk, N.** Effect of Ambient Temperature on the Performance of Gas Turbines Power Plant [Text] / N. Farouk, L. Sheng, Q. Hayat // International Journal of Computer Science Issues. – 2013. – vol. 10, issue 1, № 3. – pp. 439–442.

2. **Kumar Tiwari, A.** Effect of ambient temperature on the performance of a combined cycle power plant [Text] / A. Kumar Tiwari, M. Muzaffarul Hasan, M. Islam // Transactions of the Canadian Society for Mechanical Engineering. – 2013. – vol. 37, № 4. – pp. 1177–1188.

3. General Electric [Электронный ресурс]. – Режим доступа: https://www.ge.com/power/gas/gas-turbines/6b-03#0: GE PG9351FA. – 20.11.2018

4. **Popli, S.** Gas turbine efficiency enhancement using waste heat powered absorption chillers in the oil and gas industry [Text]/ Sahil Popli, Peter Rodgers, Valerie Eveloy // Applied Thermal Engineering. – 2013. – №50. – pp. 918–931.

5. **Popli, S.** Trigeneration scheme for energy efficiency enhancement in a natural gas processing plant through turbine exhaust gas waste heat utilization [Text] / Sahil Popli, Peter Rodgers, Valerie Eveloy // Applied Energy. – 2012. – №93. – pp. 623–636.

6. **Радченко, А. Н.** Метод выбора рациональной тепловой нагрузки абсорбционно-эжекторного термотрансформатора охлаждения воздуха на входе регенеративных ГТУ компрессорных станций [Текст] / А. Н. Радченко, С. А. Кантор // Авиационно-космическая техника и технология. – 2015. – № 5(122). – С. 61 – 64.

Отримана в редакції 03.01.2019, прийнята до друку 05.02.2019