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Gas turbine unite inlet air cooling by using an excessive refrigeration capacity of absorption-ejector chiller in booster air cooler

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Abstract. Two-stage Gas turbine unite (GTU) inlet air cooling by absorption lithium-bromide chiller (ACh) to the temperature 15 °C and by refrigerant ejector chiller (ECh) to 10 °C through utilizing the turbine exhaust gas heat for changeable ambient air temperatures and corresponding heat loads on the air coolers for the south Ukraine climatic conditions is analysed. An excessive refrigeration capacity of combined absorption-ejector chiller (AECh) exceeding the current heat loads and generated at decreased heat loads on the air coolers at the inlet of GTU can be used for covering increased heat loads to reduce the refrigeration capacity of AECh. The GTU inlet air cooling system with an ambient air precooling booster stage and a base two-stage cooling air to the temperature 10 °C by AECh is proposed. The AECh excessive cooling capacity generated during decreased heat loads on the GTU inlet air coolers is conserved in the thermal accumulator and used for GTU inlet air precooling in a booster stage of air cooler during increased heat loads. There is AECh cooling capacity reduction by 50% due to the use of a booster stage for precooling GTU inlet ambient air at the expense of an excessive cooling capacity accumulated in the thermal storage.

1 Introduction

Gas turbine unit (GTU) inlet air cooling by waste heat recovery refrigeration machine (HRRM) which transforms the exhaust gas heat into the cold is one of the main trends in increasing GTU efficiency. Gas turbine inlet air can be cooled to the temperature $t_{a2} \approx$ 15 ºC by transformation of waste heat into the cold with a high efficiency in the most widespread absorption lithium-bromide chiller (ACh). Its coefficient of performance is $\zeta = 0.7...0.8$ [1, 2]. Deeper air cooling to the temperature t_{a2} = 10 ºC and below is possible in refrigerant ejector chiller (ECh). The efficiency of transformation of waste heat into the cold by ECh is much less: $\zeta = 0.2...0.3$ [3]. Therefore it is rational to use two-stage air cooling at the GTU inlet: to t_{a2} = 15...20 ºC in the ACh and to t_{a2} = 7...10 ºC in the ECh, that is in the combined absorption-ejector chiller (AECh) [4, 5]. The heat load on the air cooler (AC) at the GTU inlet changes significantly according to the current ambient air temperature t_{amb} and relative humidity φ_{amb} that leads to adequate change of AECh cooling capacity. A cooling capacity reserve (AECh installed excessive heat load value compared with current heat loads) is conserved during reduced heat loads. It is expedient to cover the deficit of cooling capacity at high loads, thereby reducing the ACh installed cooling capacity and it cost.

Objective: reduction of the installed absorption chiller cooling capacity by conserving an excessive cooling capacity at low current heat loads on the air cooler at the inlet of GTU and using the reserved cooling capacity for ambient air precooling at increased current heat loads.

2 Results of investigation

The GTU inlet air cooling efficiency can be conveniently estimated by the annual temperature-hour potential, $\prod_\Sigma$,°C·h, which represents the air temperature drop Δt_a at the GTU inlet and the duration τ of GTU operation at reduced temperatures [4]

$$\prod_\Sigma = \sum(\Delta t_a \cdot \tau).$$

To determine the specific cooling capacity of two-stage AECh as the total cooling capacity related to the unit of air flow (G_a = 1 kg/s)

$$q_0 = Q_0/G_a,$$

it is necessary to analyze the annual temperature-hour potential $\prod_\Sigma$° dependence on specific cooling capacity q_0 . The specific cooling capacity is calculated as

$$q_0 = \xi \cdot c_{ma} \cdot (t_{amb} - t_{a2}), \text{ kW/(kg/s), or kJ/kg},$$

where ξ is the moisture coefficient; t_{amb} – ambient air temperature, °C; t_{a2} – air temperature at the air cooler outlet, °C; c_{ma} – moist air specific heat, kJ/(kg·K).

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The project (installed) specific cooling capacity q_0, on the one hand, should cover the GTU inlet air cooling need for as long time as possible during the year, which would have the greatest effect in the fuel saving. On the other hand, it should not be overestimated so that for most of the year the AECh was operated at thermal loads close to the project value, otherwise there would be an AECh operation at partial loads far from the project value. And on the contrary, with the lowered project q_0 there will be undercooling of the GTU inlet air at high ambient temperatures t_{amb} .

Fig. 1 shows the value of annual specific fuel saving b_e depending on the specific cooling capacity values q_0 (with $G_a = 1$ kg/s) for ambient air cooled to the temperatures $t_{a2} = 15$ ºC in ACh and to $t_{a2} = 10$ ºC in two-stage AECh for 2017 year, Yuzhnoukrainsk city, Mykolaiv region, Ukraine.

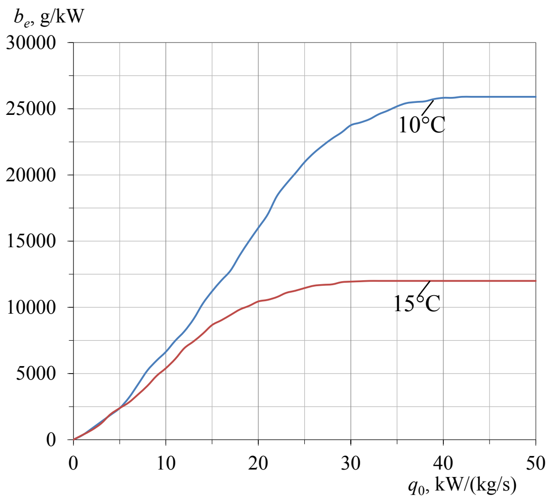

Fig. 1. The value of annual specific fuel saving b_e depending on the specific cooling capacity values q_0 (with $G_a = 1$ kg/s) for cooling an ambient air to the temperatures $t_{a2} = 10$ ºC in AECh and to 15 ºC in Ach.

As can be seen from Fig. 1, for the climatic conditions of the GTU operation in the Yuzhnoukrainsk city, Mykolaiv region, 2017, a specific cooling capacity $q_0 = 34$ kW/(kg/s) (for $G_a = 1$ kg/s) can be considered as rational project AECh specific cooling capacity for cooling ambient air at the inlet of GTU to the temperature $t_{a2} = 10$ ºC at which the annual specific fuel saving b_e is kept closed to the maximum value at high enough rate of its increment. When air is cooled to t_{a2}°=15 ºC in ACh the rational project AECh specific cooling capacity is respectively $q_0 = 24$ kW/(kg/s). Proceeding from the rational specific cooling capacity q_0 the total installed cooling capacity of AECh in accordance with the air flow G_a through the GTU is chosen as

$$Q_0 = G_a \cdot q_0, \text{ kW}.$$

Since a decrease in the rate of the annual specific fuel saving increment b_e at high cooling capacity indicates that there is an excess of cold, it is advisable to determine the cooling capacity, which ensures its maximum build-up rate, which will be less than $q_0 = 24$ kW/(kg/s) for $t_{a2} = 15$ ºC for ACh, as shown in Fig. 1.

To determine the cooling capacity, which provides a maximum build-up rate, it is necessary to analyze the annual specific fuel saving b_e related to the specific cooling capacity q_0, b_e/q_0, in dependence on the specific cooling capacity values q_0 (Fig. 2) for the cooled air temperatures $t_{a2} = 10$ and 15 ºC.

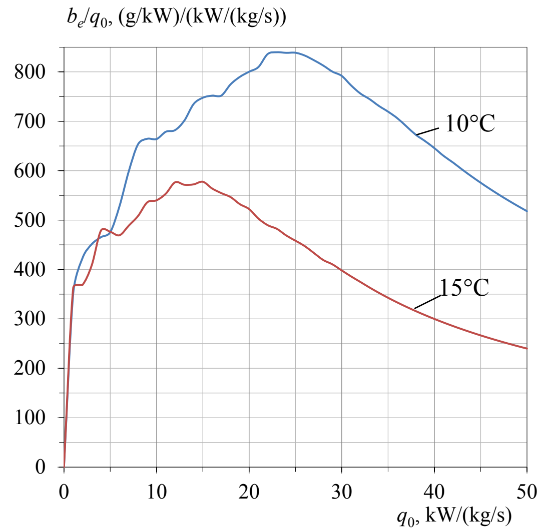

Fig. 2. The values of annual specific fuel saving related to the specific cooling capacity b_e/q_0 in dependence on the project specific cooling capacity q_0 for the cooled air temperature $t_{a2} = 10$ and 15 ºC.

As can be seen from Fig. 2, for the climatic conditions of the GTU operation, the maximum rate of increment in the annual specific fuel saving b_e/q_0 due to cooling (maximum of the graph) for the temperature of air $t_{a2} = 15$ ºC cooled in the ACh takes place at the project specific cooling capacity values q_0 = =12…16 kW/(kg/s), and when air is cooled to $t_{a2} = 10$ ºC in two-stage AECh q_0°=°22…26°kW/(kg/s). The corresponding total project (installed) cooling capacities,

$$Q_0 = G_a \cdot q_0, \text{ kW}.$$

provide the maximum rate of the annual specific fuel saving increment.

Since the project (installed) specific cooling capacity values q_0, which ensure the maximum rate of increment in the annual specific fuel saving b_e/q_0 (Fig. 2) are less than their values determined in accordance with the maximum annual specific fuel saving b_e in Fig. 1, then at an increased ambient air temperature t_{amb} there will be a deficit of cooling capacity, while at low ambient air temperatures t_{amb}, on the contrary, its excess. The excess of cooling capacity, generated during reduced heat load periods, is expedient to accumulate in the cold storage and use during increased heat loads in the pre-cooling air booster stage AC_B of air cooler.

With this the reserve of ACh cooling capacity, generated during current reduced heat loads, is defined as its excess compared with the current heat load on the basic high-temperature stage AC_{HT} and the pre-cooling air booster stage AC_B, that is, on the heat exchanger

"AC_{HT} + AC_B". The ECh cooling capacity reserve is also defined as the project ECh heat load excess over the current heat loads on the low-temperature stage AC_{LT} of air cooler and the total cooling capacity reserve of AECh is the sum of ACh and ECh reserves.

The total project heat load on the AC_{HT} is defined as

$$Q_{0.HT16pr} = q_{0\cdot HT16pr} \cdot G_a = 16\cdot 40 = 640 \text{ kW}$$

and is based on the AC_{HT} project specific heat load $q_{0\cdot HT16pr}$ = 16 kW/(kg/s). With this the project heat load on the AC_{HT} with pre-cooling air booster stage AC_B:

$$Q_{0.HT24pr} = q_{0.HT24pr} \cdot G_a = 24\cdot 40 = 960 \text{ kW},$$

where $q_{0.HT24pr}$ = 24 kW/(kg/s) – the total specific heat load on both AC_{HT} and AC_B, that provides the maximum annual fuel saving due to GTU inlet air cooling to the temperature $t_{HT2} \approx 15$ ºC in ACh according to Fig. 1 [3]. The air consumption is G_a = 40 kg/s. The project heat load on the AC_{LT} is defined as

$$Q_{0.LT10pr} = q_{0.LT10pr}\cdot G_a = 10\cdot 40 = 400 \text{ kW},$$

and based on the project specific heat load on the AC_{LT} $q_{0.LT10pr}$ = 10 kW/(kg/s) according to the maximum annual effect (Fig. 1).

In determining the ACh cooling capacity reserve, the current heat load on the AC_{HT} with booster AC_B is compared with the project heat load

$$Q_{0.HT24pr} = 24\cdot 40 = 960 \text{ kW},$$

where $q_{0.HT24pr}$ = 24 kW(kg/s).

Partial replacement of high-temperature stage AC_{HT} by pre-cooling air booster stage AC_B with corresponding reduction of the project cooling capacity of ACh is possible if there is a reserve of the ACh cooling capacity, accumulated in the cold storage, which exceeds its spending for the ambient air precooling in the AC_B. In accordance with this, the ACh excessive cooling capacity (reserve) is defined as

$$Q_{0.HT16exc} = Q_{0.HT16pr} - Q_{0.HT24} = 640 - Q_{0.HT24}, \text{ kW},$$

and its deficit is respectively:

$$Q_{0.HT16def} = Q_{0.HT24} - Q_{0.HT16pr} = Q_{0.HT24} - 640, \text{ kW}.$$

The ECh excessive cooling capacity (its reserve):

$$Q_{0.LT10exc} = Q_{0.LT10pr} - Q_{0.LT10} = 400 - Q_{0.LT10}, \text{ kW},$$

and its deficit:

$$Q_{0.LT10def} = Q_{0.LT10} - Q_{0.LT10pr} = Q_{0.LT10} - 400, \text{ kW}.$$

The total excessive cooling capacity (total reserve) is

$$Q_{0.ACexc} = Q_{0.HT16exc} + Q_{0.LT10exc}, \text{ kW},$$

and the total deficit:

$$Q_{0.ACdef} = Q_{0.HT16def} + Q_{0.LT10def}, \text{ kW}.$$

These balances coincide for properly selected the sum of project heat load on the basic high-temperature stage AC_{HT} and the booster stage AC_B for precooling air at the expense of the ACh cooling capacity reserve, as well as on the low-temperature stage AC_{LT} at the expense of the ECh cooling capacity reserve. Of course, the cooling capacity reserve depends on the climatic conditions. The same can be said about its rational choice, taking into account the excess (reserve) of cooling capacity accumulated during a certain period. The convergence of cooling capacity excess with its deficit proves rational choice of project (installed) cooling capacity.

An example of implementing the approach to determine the booster stage AC_B project heat load and a value of fuel saving due to pre-cooling air in the booster stage AC_B with decreased basic high-temperature stage ACh project (installed) cooling capacity during 3 days (10-12.07.2017) is shown in Fig. 3.

As can be seen from Fig. 3, with the project heat loads 320 kW for pre-cooling air booster stage AC_B, 640 kW for high-temperature stage AC_{HT} and 400 kW for low-temperature stage AC_{LT}, the spending of excessive cooling capacity accumulated over 3 days eliminates the ACh cooling capacity deficit, as it is proved by the change in the summarized total value of cooling capacity deficit: from $\Sigma Q_{0.ACdef}$ = 2500 kW·h to $\Sigma Q_{0.ACAcdef} = 0$. The presence of cooling capacity significant excess after covering the deficit $\Sigma Q_{0.ACAcexc}$ confirms the correct approach to choose a reduced project heat load for the basic high-temperature stage AC_{HT}, and respectively the total heat load 1040 kW on the high-temperature stage AC_{HT} and low-temperature stage AC_{LT} (cooling capacity of ACh and ECh) with the use of a cooling capacity reserve for the booster stage AC_B in comparison with the initial project cooling capacity 1360 kW of ACh and ECh (without use of the booster stage AC_B), as well as the availability of a cooling capacity reserve for further reduction of the project ACh cooling capacity.

In order to increase the efficiency of using the cooling capacity reserve, an option with a larger reduction of the project load on the high-temperature stage AC_{HT} to 480 kW is calculated, which is half as much as the output of 960 kW, with an increase in the load on the pre-cooling air booster stage AC_B to 480 kW while maintaining its value on the low-temperature stage AC_{LT} (respectively on the ECh) 400 kW.

As can be seen from Fig. 3, with the project heat loads 320 kW for pre-cooling air booster stage AC_B, 640 kW for high-temperature stage AC_{HT} and 400 kW for low-temperature stage AC_{LT}, the spending of excessive cooling capacity accumulated over 3 days eliminates the ACh cooling capacity deficit, as it is proved by the change in the summarized total value of cooling capacity deficit: from $\Sigma Q_{0.ACdef}$ = 2500 kW·h to $\Sigma Q_{0.ACAcdef} = 0$. The presence of cooling capacity significant excess after covering the deficit $\Sigma Q_{0.ACAcexc}$ confirms the correct approach to choose a reduced project heat load for the basic high-temperature stage AC_{HT}, and respectively the total heat load 1040 kW on the high-temperature stage AC_{HT} and low-temperature stage AC_{LT} (cooling capacity of ACh and ECh) with the

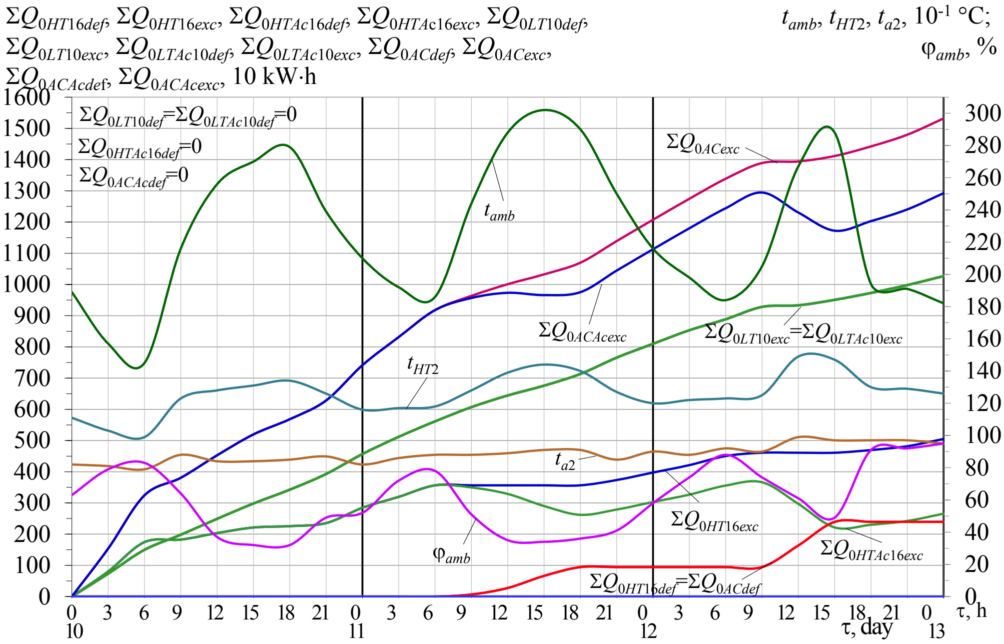

Fig. 3. The current values of the ambient air temperature t_{amb}, the temperature after AC_{HT} t_{HT2}, after AC_{LT} t_{a2}, relative humidity of the ambient air at the inlet φ_{amb}, the total deficit $\Sigma Q_{0HT16def}$ and the excess $\Sigma Q_{0HT16exc}$ of the ACh cooling capacity (without using the cooling capacity reserve in the booster stage AC_B of air cooler), the total deficit $\Sigma Q_{0HTAc16def}$ and the excess $\Sigma Q_{0HTAc16exc}$ of the cooling capacity of the ACh (with using the cooling capacity reserve in the booster stage AC_B), the total deficit $\Sigma Q_{0LT10def}$ and the excess $\Sigma Q_{0LT10exc}$ of the cooling capacity of the ECh (without using the cooling capacity reserve in the booster stage AC_B), a total deficit $\Sigma Q_{0LTAc10def}$ and the excess $\Sigma Q_{0LTAc10exc}$ of the cooling capacity of the ECh (with using the cooling capacity reserve in the booster stage AC_B), the total deficit ΣQ_{0ACdef}, and the excess ΣQ_{0ACexc} of the cooling capacity of two-stage air cooler (without using the cooling capacity reserve in the booster stage AC_B), and the total deficit $\Sigma Q_{0ACAcdef}$, and the excess $\Sigma Q_{0ACAcexc}$ of the proposed air cooler cooling capacity (with using the cooling capacity reserve in the booster stage AC_B) within 3 days (10–12.07.2017).

use of a cooling capacity reserve for the booster stage AC_B in comparison with the initial project cooling capacity 1360 kW of ACh and ECh (without use of the booster stage AC_B), as well as the availability of a cooling capacity reserve for further reduction of the project ACh cooling capacity.

In order to increase the efficiency of using the cooling capacity reserve, an option with a larger reduction of the project load on the high-temperature stage AC_{HT} to 480 kW is calculated, which is half as much as the output of 960 kW, with an increase in the load on the pre-cooling air booster stage AC_B to 480 kW while maintaining its value on the low-temperature stage AC_{LT} (respectively on the ECh) 400 kW.

The results of air cooling with project loads 480 kW for booster stage AC_B, 480 kW for high-temperature stage AC_{HT} and 400 kW for low-temperature stage AC_{LT} 400 kW with using excessive cooling capacity accumulated at low heat loads for pre-cooling air in the booster stage AC_B in the times of increased heat loads are presented in Fig. 4.

As can be seen from Fig. 4, with the project heat load 480 kW on the booster stage AC_B, 480 kW for high-temperature stage AC_{HT} and 400 kW for low-temperature stage AC_{LT}, the spending of cooling capacity reserve, accumulated over 3 days, eliminates the ACh cooling capacity deficit, as evidenced by a change in its value: from $\Sigma Q_{0.ACdef} = 9500$ kW·h to $\Sigma Q_{0.ACdef} = 0$. Accordingly, there is a reduction in the cooling capacity reserve after eliminating the deficit $\Sigma Q_{0.ACAcexc}$ to about 15% of the initial version without the use of booster stage AC_B, which confirms the possibility of reducing the half of the initial ACh project cooling capacity through the accumulation of excessive cooling capacity during reduced heat loads on the high-temperature stage AC_{HT} with its subsequent use for booster stage AC_B at high heat loads with practically the constant heat load on the low-temperature stage AC_{LT} and the reduced total cooling capacity 880 kW of the ACh and ECh compared to the initial value 1360 kW (without the using the booster stage AC_B of air cooler at the GTU inlet).

Fig. 5 shows the current B_e and the total ΣB_e fuel saving calculation results depending on the climatic conditions during 3 days for such a combined ambient air cooling at the inlet of GTU.

As can be seen from Fig. 5, the high-temperature stage AC_{HT} provides a significantly higher amount of saved fuel, compared with the low-temperature stage AC_{LT} that proves the correct choice of decreased project heat loads of the ACh. So, the results of simulation have shown that an excessive cooling capacity of combined absorption-ejector chiller above current heat loads, generated at the decreased heat loads on the air cooler at the inlet of GTU, can be used for covering the increased heat loads on the air cooler to reduce the cooling capacity of the absorption-ejector chiller installed by about 50%.

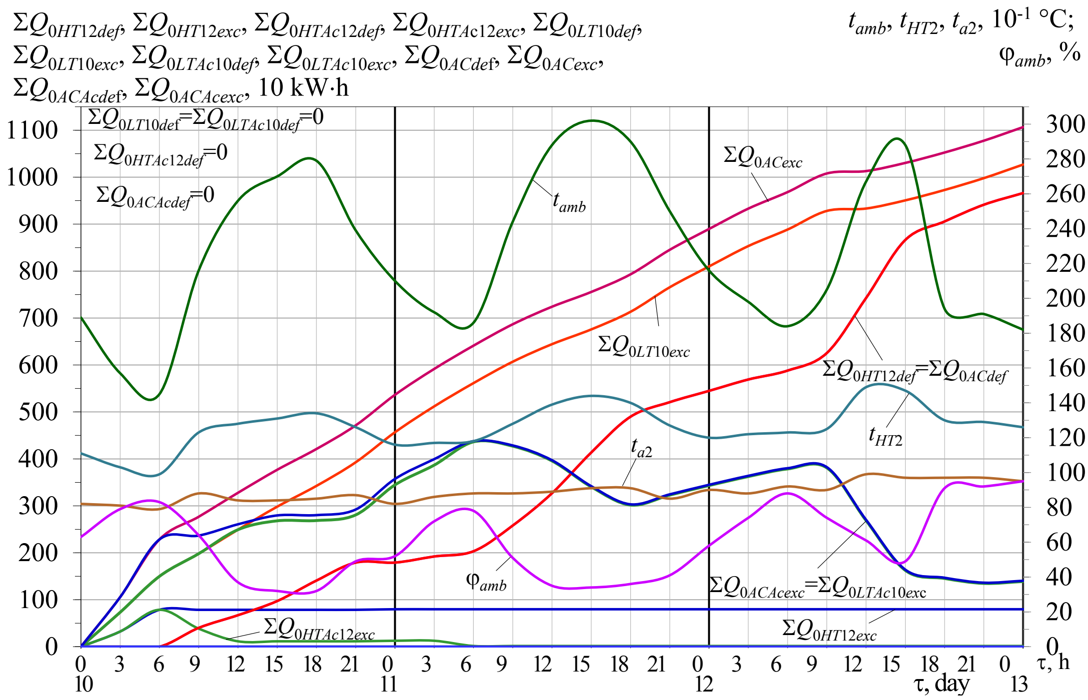

Fig. 4. The current values of the ambient air temperature t_{amb}, after AC_{HT} t_{HT2}, after AC_{LT} t_{a2}, relative humidity of the ambient air at the inlet φ_{amb}, the total deficit $\Sigma Q_{0HT12def}$ and the excess $\Sigma Q_{0HT12exc}$ of the ACh cooling capacity (without using the cooling capacity reserve in the booster stage AC_B), the total deficit $\Sigma Q_{0HTAc12def}$ and the excess $\Sigma Q_{0HTAc12exc}$ of the cooling capacity of the ACh (with using the cooling capacity reserve in the booster stage AC_B), the total deficit $\Sigma Q_{0LT10def}$ and the excess $\Sigma Q_{0LT10exc}$ of the cooling capacity of the ECh (without using the cooling capacity reserve in the booster stage AC_B), a total deficit $\Sigma Q_{0LTAc10def}$ and the excess $\Sigma Q_{0LTAc10exc}$ of the cooling capacity of the ECh (with using the cooling capacity reserve in the booster stage AC_B), the total deficit ΣQ_{0ACdef}, and the excess ΣQ_{0ACexc} of the cooling capacity for two-stage air cooler (without using the cooling capacity reserve in the booster stage AC_B), and the total deficit $\Sigma Q_{0ACAcdef}$, and the excess $\Sigma Q_{0ACAcexc}$ of the cooling capacity for the proposed air cooler (with using the cooling capacity reserve in the booster stage AC_B) within 3 days (10–12.07.2017).

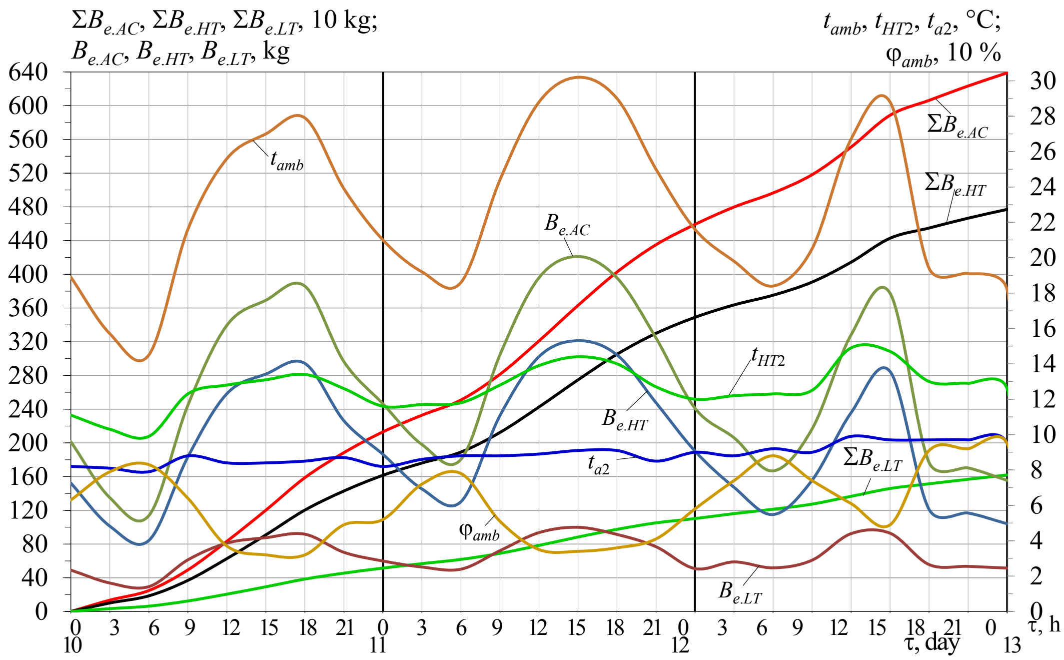

Fig. 5. Current values of the ambient air temperature t_{amb}, the temperature after AC_{HT} t_{HT2}, after AC_{LT} t_{a2}, relative humidity of the ambient air at the inlet φ_{amb}, current fuel saving $B_{e.HT}$ for AC_{HT}, $B_{e.LT}$ – for AC_{LT} and $B_{e.AC}$ – for the whole AC, the total fuel saving for the high-temperature cooling stage $\Sigma B_{e.HT}$, $\Sigma B_{e.LT}$ – for low-temperature cooling stage and the total fuel saving $\Sigma B_{e.AC}$– for the whole air cooler.

3 Conclusions

An improved two-stage GTU inlet air cooling to the temperature 15 °C in the high-temperature stage AC_{HT} of air cooler by absorption lithium-bromide chiller (ACh) and to the temperature 10 °C in the low-temperature stage AC_{HT} by refrigerant ejector chiller (ECh) through utilizing the turbine exhaust gas heat has been proposed.

It is shown the possibility of decreasing the project (installed) cooling capacity of the ACh by using the excessive cooling capacity conserved during reduced current heat loads to cover increased heat loads through precooling ambient air in the booster stage AC_B for two-stage air cooler at the inlet of GTU.

For the south Ukraine climatic conditions the application of ambient air precooling booster stage for two-stage air cooler at the GTU inlet provides a reduction of the installed cooling capacity of ACh by about 50% due to the use of cooling capacity reserve to match the changeable heat loads caused by current climatic conditions.

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