Turbine Intake Air Combined Cooling Systems

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Abstract. The application of absorption lithium-bromide chillers (ACh) for turbine inlet air cooling (TIC) is very effective in hot climatic conditions due to enlarged ambient air temperature drops and fuel reduction. But in temperate climatic conditions, the efficiency of TIC by ACh of a simple cycle is considerably reduced decreased ambient air temperature drops cause that. The last is limited by a comparatively raised temperature of chilled water of about 7 °C that makes it unable to cool ambient air lower than 15 °C. The application of low boiling refrigerants as a coolant enables deeper turbine inlet air cooling to 10 °C and lower. Therefore, the low boiling refrigerants can be used for subsequent cooling air after its pre-cooling in ACh. A refrigerant ejector chiller (ECh) is the most simple in design and cheap and can be applied for subcooling air from 15 °C to 10 °C. Such deep cooling air to 10 °C in combined absorption-ejector chiller (AECh) provides about twice the annual fuel reduction in temperate climate compared with conventional TIC to 15 °C by ACh. The method to determine rational refrigeration capacity of AECh and distribute it between ACh and ECh that provides practically maximum annual fuel reduction at reduced design refrigeration capacity by about 20% is developed. With this current excessive refrigeration, capacities are used to cover peaked loads.

Keywords: Energy efficiency · Gas turbine · Fuel efficiency · Inlet air · Chilled water · Refrigerant

1 Introduction

The fuel efficiency of combustion engines and especially gas turbines (GT), is strictly influenced by ambient air temperature at their inlet [1, 2]. The application of absorption lithium-bromide chillers (ACh) [3, 4] for turbine inlet air cooling (TIC) is very effective in hot climatic conditions due to high ambient air temperatures and enlarged their drops and fuel reduction as a result [5, 6]. But in temperate climatic conditions, the efficiency of TIC by ACh of a simple cycle is much lower than is caused by decreased ambient air temperature drops [7, 8]. The last is limited by a comparatively raised temperature of chilled water of about 7 °C that makes it unable to cool ambient air lower than 15 °C. The application of low boiling refrigerants as a coolant enables deeper turbine inlet air cooling to 10 °C and lower [9, 10]. Therefore the low boiling refrigerants can be used for

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subsequent cooling air after its pre-cooling in ACh. A refrigerant ejector chiller (ECh) is the most simple in design and cheap and can be applied for cooling air from 15 °C to 10 °C [11, 12]. Such deep cooling air to 10 °C in combined absorption-ejector chiller (AECh) provides about twice the annual fuel reduction in temperate climate compared with conventional TIC to 15 °C by ACh. The efficiency of ECh is very sensitive to thermal load changes. Ambient air pre-cooling to 15 °C in ACh practically covers thermal load fluctuations and provides operation of ECh at about stable loading.

The operation of ACh at variable current loads is accompanied by the formation of excess refrigeration capacity that can cover peaked thermal loads. A rational refrigeration capacity distribution within the range of fluctuated thermal loads enables to reduce a design refrigeration capacity of ACh and the overall AECh. A corresponding method to determine a rational refrigeration capacity of AECh in the whole and its distribution between ACh and ECh is to consider the actual current thermal loads and yearly effect gained due to TIC, for instance, as annual fuel saving.

2 Literature Review

A lot of research is focused on enhancing the efficiency of combustion engine inlet air cooling by waste heat recovery [13, 14]. The exhaust heat utilization can be improved by the application of fuel afterburning and exhaust gas boilers with low-temperature heating surfaces [15, 16] that enlarges the available heat to be converted to refrigeration for TIC to lowered temperature of 10 °C and less as compared with conventional TIC to 15 °C in ACh. The advanced system to utilize the exhaust heat by jet technics [17, 18] for cooling cyclic engine air was developed [19]. Some modern simulation methods such as ANSIS [20–22] can be applied for rational designing heat exchangers to match actual operation conditions.

A lot of publications were devoted to combined cooling, heating, and power (CCHP) generation [23, 24] or trigeneration [25, 26].

Practically all the analyses focus on enhancing engine fuel efficiency due to inlet air cooling through rational loading [27, 28]. Many of those methods are based on cooling degree-hour (CDH) numbers and modified methods of their calculation [29, 30] to match current cooling demands in respect to actual climatic conditions [31, 32] and thermal management [33, 34] proceeding from various criteria [35, 36]. The research to determine the input ambient air data for estimating TIC [37].

Most of the TIC system designing methods are based on the approach to cover the maximum yearly thermal loads [38, 39]. Such assumption inevitable leads to overestimating the design refrigeration capacity of TIC system and its oversizing.

The research focuses on developing the advanced TIC system with combined AECh to provide deep TIC and the method to define a rational refrigeration capacity that enables practically maximum annual fuel reduction and distributes it between ACh and ECh matching current loading.

3 Research Methodology

A developed method of designing the TIC system focuses on determining the refrigeration capacity of AECh to achieve practically maximum annual fuel reduction and rational distribute it between ACh and ECh according to actual thermal loads to reduce design refrigeration capacities of the chillers.

The annual GT fuel reduction ΣB_e due to (TIC) is considered a primary criterion when defining a rational refrigeration capacity Q_0 of the TIC system. The current fuel savings B_e is yearly summarized to calculate the annual value:

$$\Sigma B_e = \sum(\Delta t_a \cdot \tau) \cdot b_{et} \cdot N_e \cdot 10^{-3}, \text{ t}, \tag{1}$$

where: $\Delta t_a = t_{amb} - t_{a2}$– current air temperature drop at GT inlet, °C; t_{amb} and t_{a2} – temperatures of ambient air at the entrance and cooled air at the exit of the cooler at the GT intake, °C; N_e – GT power, kW; τ – time interval, h; b_{et} – specific fuel reduction for 1 °C turbine intake air temperature drop, accepted as 0.7 g/(kWh·K) for turbine UGT10000 (power 10000 kW) [40].

A refrigeration capacity Q_0 for air mass flow G_a, kg/s:

$$Q_0 = G_a \, \Delta t_a \quad \xi \cdot c_{ma}, \text{kW}, \tag{2}$$

where: ξ – specific heat ratio; c_{ma} – specific moist air heat, kJ/(kg·K); $G_a = 40$ kg/s – total air mass flow for UGT10000.

Specific refrigeration capacity q_0 referred to unit air mass flow rate 1 kg/s:

$$q_0 = Q_0 / G_a, \text{kW/(kg/s) or kJ/kg}. \tag{3}$$

The variations in the current turbine fuel reduction B_e are taken into account by the rate of their annual increment in relative value $\Sigma B_e/Q_0$ related to required refrigeration capacity Q_0.

So the relative annual fuel reduction increment $\Sigma B_e/Q_0$ is applied as an indicator to determine a maximum rate of yearly fuel-saving increment, and its maximum corresponds to optimum refrigeration capacity $Q_{0.\text{opt}}$.

The optimum refrigeration capacity $Q_{0.\text{opt}}$ corresponds to the minimum sizes of the chillers and TIC system accordingly.

4 Results

A circuit of the developed TIC system with AECh is presented in Fig. 1.

Current specific thermal loads $q_{0.10}$ and $q_{0.15}$ for cooling air to 10 and 15 °C during 2017 in Mykolayiv, southern Ukraine, are presented in Fig. 2.

As seen, large variations in current specific thermal loads q_0 for cooling ambient air make it problematic to determine a design refrigeration capacity of TIC system providing maximum annual fuel reduction ΣB without overestimating.

According to the advanced proposed method, the variations of the current required refrigeration capacity q_0 (for 1 kg/s) and Q_0 (for $G_a = 40$ kg/s, UGT10000) and corresponding fuel-saving B_e are considered the relative annual fuel reduction increment $\Sigma B_e/Q_0$ related to the required refrigeration capacity Q_0.

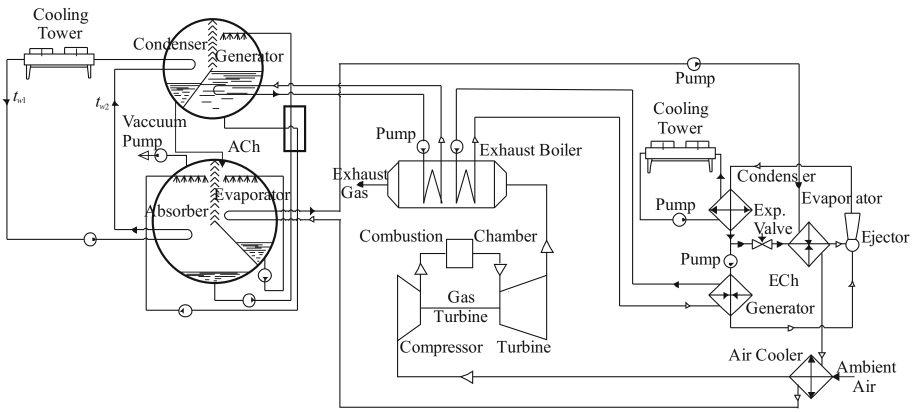


Fig. 1. A circuit of developed TIC system with AECh

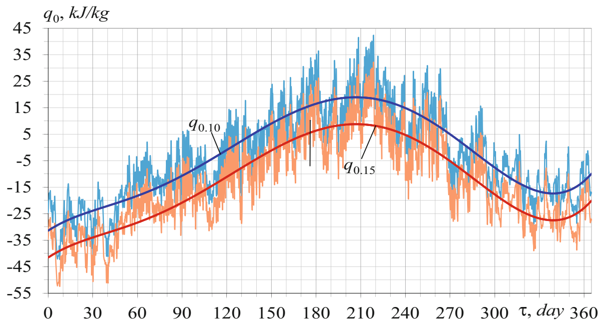


Fig. 2. Current values of ambient air temperature t_{amb}, specific thermal loads $q_{0.10}$ and $q_{0.15}$ for cooling ambient air to t_{a2} = 10 and 15 °C during 2017

The results of the calculation of optimum design refrigeration capacity $Q_{0.\text{opt}}$ that enables a maximum rate of annual fuel saving $\sum B_e/Q_0$ for gas turbine UGT 10000 are presented in Fig. 3a.

As seen, a maximum rate of annual fuel saving increment $\sum B_e/Q_0$ for t_{a2} = 10 °C occurs at the optimum refrigeration capacity $Q_{0.10\text{opt}}$ of about 1050 kW and corresponding $\sum B_{10\text{opt}}$ of about 140 t (Fig. 3a).

To determine a reasonable value of design refrigeration capacity $Q_{0.\text{rat}}$, enabling practically maximum annual fuel saving $\sum B_e$ it is necessary to define the next maximum value of annual fuel saving rate $\sum B_e$ above the first one: $Q_0 > Q_{0.\text{opt}}$ and $\sum B_e > \sum B_{e\cdot\text{opt}}$ (Fig. 3b).

A maximum value of annual fuel saving rate $\sum(B_e - B_{e\cdot\text{opt}})/Q_0$ above the $\sum B_{f\cdot\text{opt}}$ = 140 t corresponds to $Q_{0.\text{opt}}$ = 900 kW and occurs at the rational value $Q_{0.\text{rat}}$ about 1400 kW and enables annual fuel saving $\sum B_{e\cdot\text{rat}}$ = 150 t about the maximum value 160 t but at a reduced design refrigeration capacity $Q_{0.\text{rat}}$ = 1400 kW less than $Q_{0.\text{max}}$ = 1800 kW by about 15%.

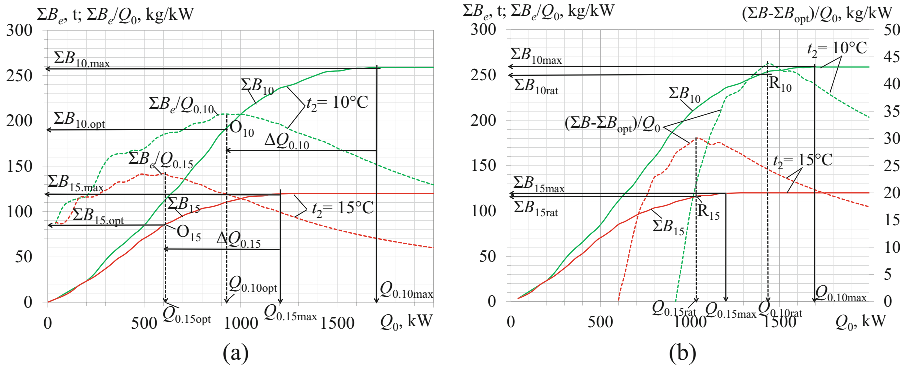


Fig. 3. Annual fuel-saving $\sum B_{e,}$ and its relative increment $\sum B_e/Q_0$ (a), annual fuel saving $\sum B_e$ and relative values $\sum(B_e – B_{e\cdot opt})/Q_0$ above the optimum ones $\sum B_{e\cdot opt}$ and $Q_{0.opt}$ (b) versus refrigeration capacities Q_0 required for cooling ambient air to 10 and 15 °C

The optimum designing of TIC systems enables reduction of the chillers refrigeration capacities by $\Delta Q_{0.10,15}$, i.e., 15 to 20% compared with their maximum values $Q_{0.10,15max}$, received in typical designing (Fig. 3b).

Deeper turbine intake air cooling to 10 °C in AECh compared with typical cooling air to 15 °C in ACh provides practically twice the increase in annual fuel saving $\sum B_{10max}$ compared with $\sum B_{15max}$ for ACh in temperate climatic conditions (Fig. 3b).

The refrigeration capacities $Q_{0.15}$ required for cooling air to 15 °C, values of rational cooling capacities $Q_{0.10rat}$ and $Q_{0.15rat}$ for cooling air to 10 and 15 °C, the basic refrigeration capacity as difference $Q_{0.10\text{-}15} = Q_{0.10} - Q_{0.15}$, required for cooling air from 15 °C to 10 °C and the rest boost refrigeration capacities $Q_{0.b10–15}$ were calculated for temperate climatic conditions in Mykolayiv region, southern Ukraine, July 2017 (Fig. 4).

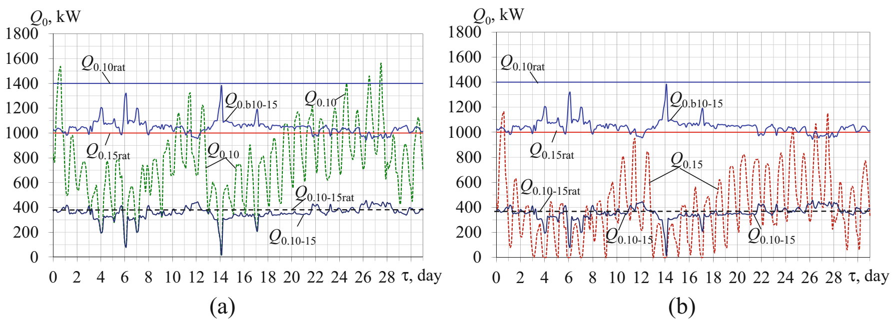
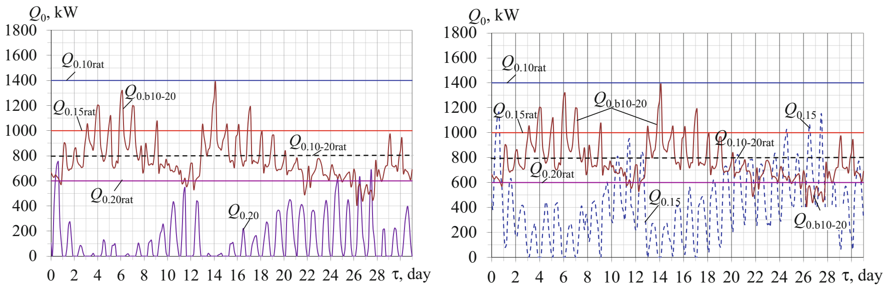


Fig. 4. The refrigeration capacities $Q_{0.10}$ (a) and $Q_{0.15}$ (b) for cooling air to 10 and 15 °C, rational refrigeration capacities $Q_{0.10rat}$ and $Q_{0.15rat}$ for 10 and 15 °C, capacities differences $Q_{0.10\text{-}15}$ for subcooling air from 15 °C to 10 °C, boost refrigeration capacity $Q_{0.b10\text{-}15}$ for 15 °C: $Q_{0.b10\text{-}15} = Q_{0.10rat} - Q_{0.10\text{-}15}$, where $Q_{0.10\text{-}15} = Q_{0.10} - Q_{0.15}$

Such significant variations in the current thermal loads $Q_{0.15}$ when cooling the ambient air to 15 °C indicates to considerable excess of refrigeration capacities. But when subcooling air from 15 °C to 10 °C, the thermal load variations $\Delta Q_{0.10\text{-}15} = Q_{0.10} - Q_{0.15}$ is small. The boost part of $Q_{0.10\text{rat}}$ is used for pre-cooling ambient air to 15 °C and calculated as $Q_{0.\text{b}10\text{-}15} = Q_{0.10} - \Delta Q_{0.10\text{-}15}$. The boost cooling capacity $\text{Q}_{0.\text{b}10\text{-}15}$ completely covers current loads $\text{q}_{0.15}$ for cooling air to $\text{t}_{\text{a}2} = 15$ °C (Fig. 4b).

Further enhancing the efficiency of TIC due to advanced design method is possible through shearing the unstable boost range of refrigeration capacity $Q_{0.\text{b}10\text{-}15}$ in two parts: $Q_{0.\text{b}10\text{-}20}$ and $\Delta Q_{0.15\text{-}20}$ (Fig. 5).



(a) (b)

Fig. 5. The refrigeration capacities $Q_{0.20}$ (a) and $Q_{0.15}$ (b) for cooling air to 20 and 15 °C, rational values of refrigeration capacities $Q_{0.10\text{rat}}$, $Q_{0.15\text{rat}}$ and $Q_{0.20\text{rat}}$ for 10, 15 and 20 °C, rational design refrigeration capacity $Q_{0.10\text{-}20\text{rat}}$ for cooling air from 20 °C to 10 °C and capacities $Q_{0.10\text{-}20}$ for cooling air from $t_{a2} = 20$ °C to $t_{a2} = 10$ °C, boost capacity $Q_{0.\text{b}10\text{–}20}$ for cooling air to 20 °C: $Q_{0.\text{b}10\text{-}20} = Q_{0.10\text{rat}} - Q_{0.10\text{-}20}$, where $Q_{0.10\text{-}20} = Q_{0.10} - Q_{0.20}$; $Q_{0.10\text{-}20\text{rat}} = Q_{0.10\text{rat}} - Q_{0.20\text{rat}}$

Comparing the boost refrigeration capacity $Q_{0.\text{b}10\text{-}20}$ with current thermal loads $Q_{0.15}$ indicates that the boost refrigeration capacity $Q_{0.\text{b}10\text{-}20}$ generally covers even the current loads $Q_{0.15}$ (Fig. 5b).

Issuing from this, the hypothesis of reducing a design boost refrigeration capacity $Q_{0.\text{b}10\text{-}15}$ or $Q_{0.15\text{rat}}$ practically twice due to using $Q_{0.20\text{rat}}$ to cover current thermal loads $Q_{0.15}$ has been approved (Fig. 5b).

The installed refrigeration capacity of ACh rational distribution makes it possible to reduce a design boost one by $\Delta Q_{0.15\text{-}20\text{rat}} = Q_{0.15\text{rat}} - Q_{0.20\text{rat}}$ (Fig. 5b and Fig. 6), which is practically twice less as compared with $Q_{0.15\text{rat}}$.

As Fig. 6 shows, rational designing of TIC systems provides a decrease of installed refrigeration capacities of the chillers by $\Delta Q_{0.15,20\text{max-rat}}$, i.e., by 15 to 20% compared with their maximum values $Q_{0.15,20\text{max}}$ received in conventional designing.

In a temperate climate, applying the proposed TIC system with combined AECh enables achieving nearly twice higher annual fuel reduction $\sum \text{B}_{10}$ than $\sum \text{B}_{15}$ for ACh. It can be supposed as a prosperous trend in TIAC.

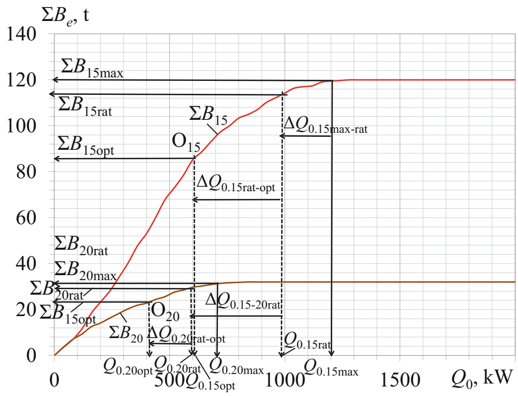


Fig. 6. The annual fuel reduction $\sum B_e$ and refrigeration capacities Q_0 for cooling air at GT inlet to 15 and 20 °C: $\Delta Q_{0.\text{max-rat}} = Q_{0.\text{max}} - Q_{0.\text{rat}}$; $\Delta Q_{0.\text{rat-opt}} = Q_{0.\text{rat}} - Q_{0.\text{opt}}$; $\Delta Q_{0.15\text{-}20\text{rat}} = Q_{0.15\text{rat}} - Q_{0.20\text{rat}}$.

5 Conclusions

A new trend in enhancing TIC efficiency by applying combined AECh is proposed for temperate climatic conditions that provide practically twice higher annual fuel reduction than ACh.

An advanced TIC systems rational designing method is developed to achieve practically maximum annual fuel reduction; moreover, the installed refrigeration capacities are reduced by 15 to 20% compared with conventional designing practice.

The method is based on the rational distribution of design refrigeration capacity of AECh between ACh for ambient air pre-cooling within unstable thermal load range and ECh for further air cooling within a comparatively stable load range.

With this, the annual fuel reduction of GT is assumed as a primary criterion, and the variations of the current values of B_e due to TIC are taken into account by the rate of the annual increment as its value $\Sigma B_e/Q_0$ related to required refrigeration capacity Q_0.

The maximum rate of annual fuel saving $\sum B_e/Q_0$ and minimum sizes of the chillers is achieved at the optimum value of design refrigeration capacity $Q_{0.\text{opt}}$.

The hypothesis of reducing a design boost refrigeration capacity $Q_{0.\text{b10-15}}$ or $Q_{0.15\text{rat}}$ of ACh to $Q_{0.\text{b10-20}}$ or $Q_{0.20\text{rat}}$, id est. practically twice has been approved.

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