

Innovative combined in-cycle trigeneration technologies for food industries

Andrii Radchenko¹, Dariusz Mikielwicz², Mykola Radchenko^{1*}, Serhiy Forduy¹, Oleksandr Rizun¹ and Viktor Khaldobin¹

¹Admiral Makarov National University of Shipbuilding, 9 Heroes of Ukraine Avenue, Mykolayiv, Ukraine

²Gdańsk University of Technology, 11/12 Gabriela Narutowicza Street, 80-233 Gdansk, Poland

Abstract. The majority of integrated energy systems (IES) for combined electricity, heat and refrigeration generation, or trigeneration, are based on gas engines. The fuel efficiency of gas engines are strictly influenced by intake air temperatures. Practically in all IES the absorption lithium-bromide chillers (ACh) are applied for converting the heat removed from the engine into refrigeration in the form of chilled water. The peculiarity of trigeneration in food industries is the use of chilled water of about 12°C for technological needs instead of 7°C as typical for ACh. This leads to a considerable great potential of engine intake air deeper cooling not realized by ACh, that can be used by ejector chiller (ECh) as the low temperature stage of two-stage absorption-ejector chiller (AECh) to provide engine cyclic air deep cooling and enhancing engine fuel efficiency. To evaluate the effect of gas engine cyclic air cooling the data on fuel consumption and power output of gas engine JMS 420 GS-N.L were analyzed.

1 Introduction

The gas engines (GE) [1, 2] found a widespread application in integrated energy systems (IES), trigeneration or systems for combined cooling, heat and power (electricity) generation (CCHP) [3, 4]. With a rise in intake air temperature a thermodynamic efficiency of GE essentially decreases: electric power output decreases and specific fuel consumption increases. A refrigeration capacity, generated by absorption lithium-bromide chiller (ACh), that recovers the heat released from the engine, can be used (in addition to technological or other needs) for engine intake air cooling (EIAC) as in-cycle trigeneration [5, 6]. This provides not only improvement of engine fuel efficiency, but also prolong the time of efficient operation of trigeneration plant [7, 8], since cooling demands for technological needs have, as a rule, periodic character.

The peculiarity of trigeneration in food industries is the use of chilled water of about 12°C for technological needs instead of 7°C as typical for ACh. This leads to a considerable great potential of engine intake air deeper cooling not realized by ACh, that can be used by ejector chiller (ECh) as the low temperature stage of two-stage absorption-ejector chiller (AECh) to provide engine cyclic air deep cooling and enhancing engine fuel efficiency [9, 10].

A conventional method of chilling all the ambient air, coming into the engine room, from where it is sucked by engine turbocharger (TC), is non-effective because of heat influx from surroundings to the air stream

sucked, that results in increased air temperature at the inlet of turbocharger and enlarged cooling capacity required [11].

2 Literature review

Many researches deal with improving the performance efficiency of trigeneration plants based on combustion engines for space conditioning [12, 13], technological and other needs. A lot of publications are devoted to enhancing the fuel efficiency of engines by cooling cyclic air with application of waste heat recovery chillers [14-16]. The absorption lithium-bromide chillers (ACh) are the most widely used and provide cooling air to about 15 °C with a high coefficient of performance (COP = 0.7–0.8) [17, 18]. The jet devices as thermopressors [19-21] and ejector chillers (ECh) [22, 23] are the most simple. The ECh enable to provide cooling air to 10 °C and lower but with a low COP of 0.2 to 0.3 and are quite suitable for marine applications [24, 25].

The efficiency of cooling systems and chillers can be improved due to intensification of heat transfer in evaporators [26] and condensers [27], advanced scheme decisions [28, 29], deep utilization of exhaust heat [30-32] with low temperature condensation [33, 34] to enhance the heat for conversion into refrigeration.

Various methods including ANSIS [35-37], statistical methods for processing monitoring data and ambient air parameters [38, 39] can be used for optimizing the thermal loads of ambient air cooling systems to match actual climatic conditions and provide

* Corresponding author: nirad50@gmail.com

maximum effect gained [40-42]. The most of well-known concepts of increasing the efficiency of trigeneration plant are limited to engine out-cycle use of refrigeration capacity and issue from conventional trigeneration with ACh [17, 18]. A realization of in-cycle concept of EIAC would broaden the applicability of trigeneration even without enough cooling demands.

In order to stabilize engine intake air temperature a new concept of combined two-stage EIAC in ACh and ECh can be proposed [43, 44]. With this chilled water from ACh is used as a coolant in the high-temperature stage of engine inlet air cooler and boiling refrigerant of ECh – in the low-temperature stage.

The purpose of research is to estimate the enhancement of fuel efficiency of gas engine due to combined two-stage inlet air cooling on the base of monitoring data.

3 Research methodology

The efficiency of cooling air at the inlet of gas engine (GE) was investigated for trigeneration plant of "Sandora"-"PepsiCo Ukraine" (Nikolaev, Ukraine). It is equipped with two Jenbacher gas engine modules JMS 420 GS-N.LC (rated electric power $P_{elSO} = 1400$ kW and heat $Q_h = 1500$ kW) and ACh AR-D500L2 Century.

The heat removed from GE is used for heating the water, used by ACh for producing a chilled water with temperature of about 12°C. Chilled water is used for technological needs and by central conditioner for cooling engine room intake air, from where cooled air is sucked by engine turbochargers (Fig. 1).



a



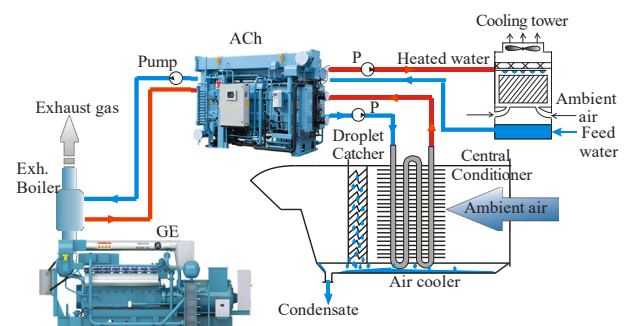
b



c

Fig.1. Cogeneration gas engine JMS GE Jenbacher (a), absorption chiller AR-D500L2 Century (b) and central conditioner for cooling engine room intake air (c).

Such a conventional scheme of GE inlet air cooling system is presented in Fig. 2. Because of heat influx from the engine room environmental to cooled air flow the temperature of engine intake air t_{in} is more higher than its value t_{HT} at the outlet of high-temperature air cooler AC_{HT}: $t_{in} = t_{HT} + \Delta t_{ER}$, where Δt_{ER} – air temperature increment, caused by heat influx from the engine room (Fig.2,b). This proves a non-effective operation of conventional EIAC system (Fig.2, a).



a

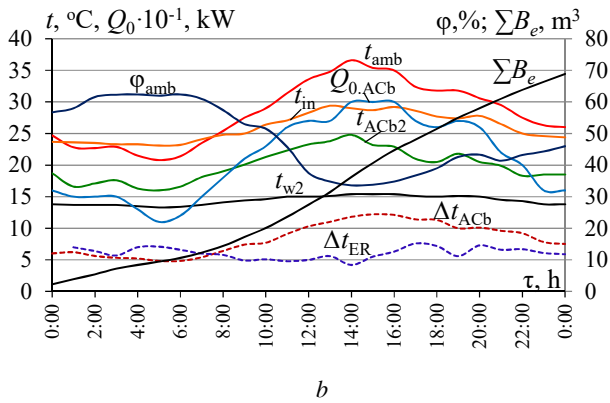


Fig. 2. A conventional system of gas engine inlet air cooling in the air cooler of the central conditioner by chilled water from ACh (a) and daily variation of temperature t_{amb} and relative humidity φ_{amb} of ambient air, temperature of air at the inlet of gas engine turbocharger t_{in} , at the outlet of high-temperature air cooler AC_{HT} t_{HT} : $\Delta t_{HT} = t_{amb} - t_{HT}$; $\Delta t_{ER} = t_{in} - t_{HT}$.

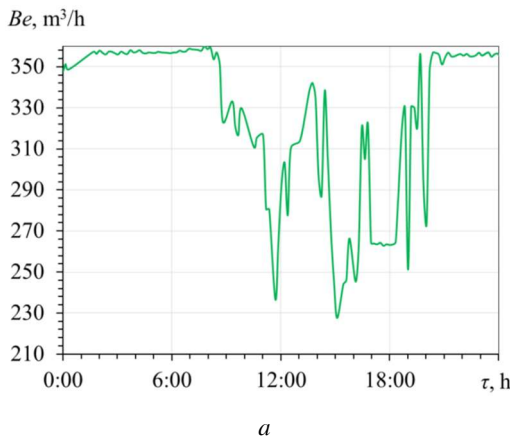
In order to evaluate the effect of GE inlet air two-stage cooling, compared with conventional conditioning all the ambient air coming into the engine room, the data of gas engine JMS 420 GS-N.L fuel efficiency monitoring were used.

The results of monitoring a gas engine fuel efficiency were presented in the form of data sets on dependence of fuel consumption $B_e = f(t_{in})$, power output $P_e = f(t_{in})$ and specific fuel consumption $b_e = B_e / P_{el}$, as a result, upon the air temperatures t_{in} at the inlet of the engine turbocharger. A method for processing the monitoring data on fuel consumption and power output of gas engine was developed [6-8].

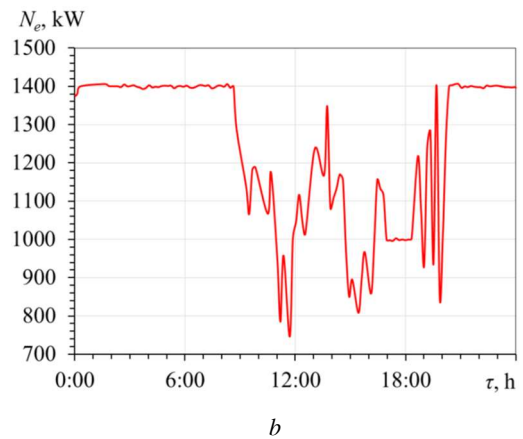
The goal of processing the monitoring data sets $P_e = f(t_{in})$, $B_e = f(t_{in})$ and $b_e = f(t_{in})$ was to calculate the value of the change in specific fuel consumption Δb_e caused by the change in the engine inlet air temperature t_{in} by 1 °C, as $\Delta b_e / \Delta t_{in}$, to evaluate the fuel saving effect due to application of advanced two-stage air cooling [6-8].

4 Results

The results of monitoring daily variation of volume gas consumption B_e and electric power output P_e of engine JMS 420 GS-N.LC are presented in Fig. 3-5.



a



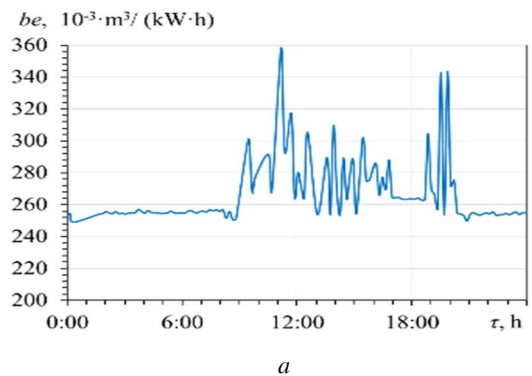
b

Fig.3. Daily variation of volume gas consumption B_e (a) and electric power output P_e (b) of gas engine with time τ .

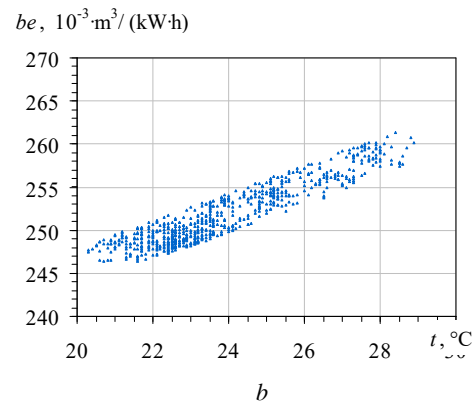
In summer hot day time interval $\tau = 9 \dots 20$ h the ambient air temperatures are high: $t_{amb} = 30 \dots 35$ °C, that makes impossible reliable cooling the scavenge gas-air mixture by radiator to appropriate temperature level of about 40 °C. This results in automatically reducing gas supply to engine followed by decreasing load (Fig.3).

A performance of gas engine in part load modes at arising intake air temperature t_{in} ($\tau = 9 \dots 20$ h) is followed by increase in specific gas consumption b_e by $(20 \dots 30) \cdot 10^{-3} \text{ m}^3 / (\text{kW} \cdot \text{h})$ (Fig. 4,a), i.e. 8...12 % compared with engine full loading at ambient air temperatures t_{amb} and corresponding t_{in} lower then 25 °C ($\tau = 2 \dots 9$ h).

As Fig. 4 shows, arising intake air temperature t causes considerable increase in specific volume gas consumption b_e .



a



b

Fig. 4. Specific volume gas consumption b_e variation with time τ during a day (a) and with intake air temperature t (b).

As Fig. 5 shows, with decreasing engine inlet air temperatures t_{in} the mass specific fuel consumption b_f reduces by 0.25 to 0.27 g/(kWh) for 1 °C increment of engine inlet air temperature $\Delta t_{in} = 1$ °C.

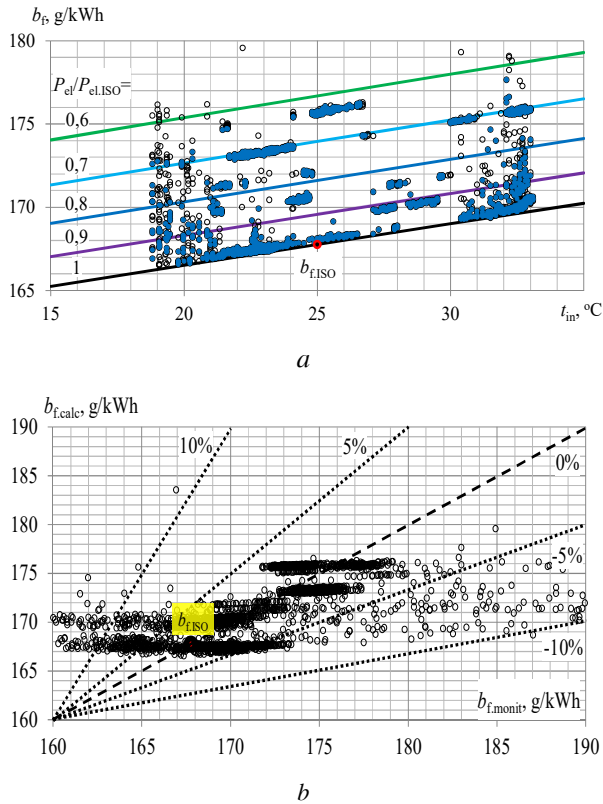


Fig. 5. Variation of mass specific fuel consumption b_f versus inlet air temperature t_{in} at various loads $P_{el}/P_{el,ISO} = 0.6 \dots 1.0$ (a) and calculated values of mass specific fuel consumption $b_{f,calc}$ compared with monitoring data $b_{f,monit}$ (b).

Proceeding from decrease in specific fuel consumption b_f with lowering engine inlet air temperatures t_{in} a concept of addition subcooling intake air compared with its conventional cooling in ACh with chilled water temperature of about 12 °C, used for technological needs, is proposed (Fig. 6).

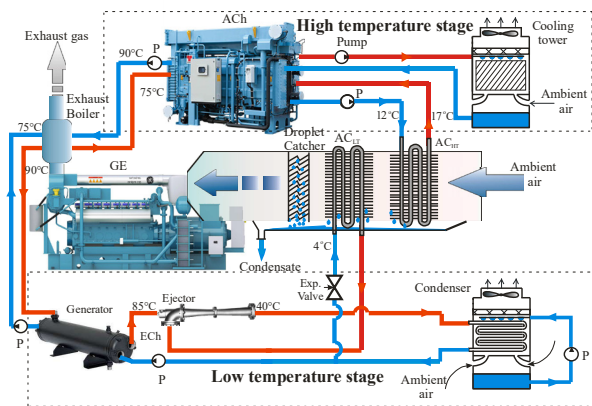


Fig. 6. The two-stage absorption-ejector (AECh) gas engine inlet air chilling system: AC_{HT} – high-temperature air cooler; AC_{LT} – low-temperature air cooler; GE– gas engine; P– pump.

The results of calculation of heat loads $Q_{0,HT}$ – on the high-temperature stage AC_{HT} and $Q_{0,LT}$ – on the low-temperature stage AC_{LT} and $Q_{0,AC}$ – on the developed

two-stage air cooler based on measured air temperatures at the inlet of gas engine turbocharger t_{in} effecting the engine fuel efficiency shows decreases in current specific fuel consumption b_e and daily summarised absolute volume gas saving ΣB_e due to intake air cooling in high-temperature stage AC_{HT} by ACh and low-temperature stage AC_{LT} by ECh and the overall value for two-stage AECh (Fig. 7, b).

Thus, due to minimizing the heat influx from the engine room environments the proposed combined two-stage air cooling system provides engine operation at practically stabilized low intake air temperatures at changeable climatic conditions. This leads to specific fuel consumption reduction by about 3-5 g/(kWh), i.e. about 3% decrease at increased ambient air temperatures t_{amb} (Fig. 7, a) and about 50% increase in the annual fuel saving $B_{f,10}$ due to EIAC in AECh compared with its value $B_{f,15}$ due to EIAC in AECh (Fig. 7, b).

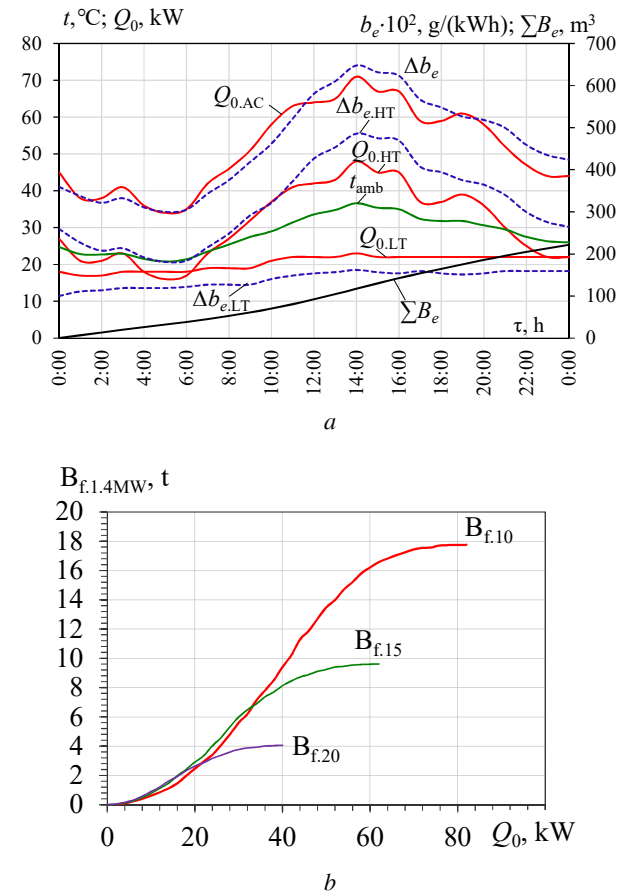


Fig. 7. Daily variation of heat loads $Q_{0,HT}$ on AC_{HT} (ACh), $Q_{0,LT}$ on AC_{LT} (ECh) and $Q_{0,AC}$ two-stage air cooler (AECh) and corresponding decreases in current specific fuel consumption $\Delta b_{e,HT}$, $\Delta b_{e,LT}$, Δb_e and summarised absolute volume gas saving ΣB_e (a) and annual fuel saving B_f against installed cooling capacities Q_0 of chillers for engine inlet air temperatures: $t_{a2} = 15$ and 20 °C in ACh; $t_{a2} = 10$ °C in AECh (Nikolayev, southern Ukraine, 2017).

5 Conclusions

A treatment of monitoring data sets on fuel efficiency of gas engine JMS 420 GS-N.L has proved inefficient conventional cooling the air entering engine room in

ACh with chilled water temperature of 12 °C, used for technological needs.

Proceeding from reducing the specific fuel consumption with lowering the engine intake air temperatures a novel concept of two-stage cooling air at the inlet of gas engines in trigeneration plants for food industries is proposed and corresponding engine intake air cooling (EIAC) system is developed. It includes ACh as the first high-temperature stage of EIAC and ECh as the second low-temperature stage.

The application of combined absorption-ejector chiller (AECh) provides stabilized operation of the engine in the rated mode with high fuel efficiency due to excluding heat influx to intake air flow from engine room environments.

The in-cycle trigeneration with combined two-stage waste heat recovery in the working cycle of the engine itself provides about 50% increase in the annual fuel saving for temperate climatic conditions as compared with conventional absorption EIAC and is very promising for food industries.

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