Rational Loading on Combined Waste Heat Recovery Cooling System

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Abstract. Combined cooling, heat and power (CCHP), or trigeneration, systems based on gas engines as driving engines, are among the main prosperous trends in energy-saving technologies. Addition reserves of enhancement of such integrated energy systems efficiency increase fuel efficiency of their basic gas engines by cyclic air cooling. The processing of the monitoring data on gas engine fuel efficiency has proved inefficient operation of traditional cooling all the engine room incoming air in the central conditioner fed by chilled water from absorption lithium-bromide chiller using engine exhaust heat. An advanced system of gas engine inlet air two-stage deep cooling by combined absorption-ejector chiller with absorption chiller as a high-temperature stage and ejector chiller as a low-temperature stage has been developed. The method of rational loading of the proposed engine inlet air cooling system proved annual fuel reduction by about 50 % higher than traditional cooling by absorption chillers in temperate climatic conditions.

Keywords: Combined cooling · Heat · Power · Combustion engine · Ejector · Absorption chiller

1 Introduction

The combined cooling, heat, and power (CCHP) gained widespread applications [1, 2]. Such trigeneration is considered as the main trend in energy-saving technologies [3, 4]. As driving engines in CCHP, gas engines (GE) are widely used [5, 6]. A large power augmentation is gained in gas turbines (GT) [7, 8]. The fuel efficiency of basic engines can be increased by cyclic air cooling [9, 10]. In a typical GE intake air cooling system, all the ambient air incoming engine room is cooled in a central conditioner fed by chilled water from absorption lithium-bromide chiller (ACh) using exhaust heat [11, 12]. Because of the large incoming air volume and heat influx to air in the engine room from where it is sucked into the engine turbocharger, the intake air temperature is considerably increased. It results in falling engine fuel efficiency.

In order to provide deeper engine cyclic air cooling in addition to ACh the refrigerant is to be used [13, 14]. To evaluate the cooling effect, GE fuel consumption and power output data at varying ambient air temperatures can be received by treating GE fuel efficiency monitoring [12, 15].

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The study's goal is to improve the fuel efficiency of the gas engine of the CCHP plant by combined inlet air cooling in a two-stage absorption-ejector chiller utilizing exhaust heat and rationally designed to provide close to maximum annual fuel reduction.

2 Literature Review

An enhancement of fuel efficiency of combustion engines is possible by cooling cyclic air in waste heat recovery chillers [16, 17]. The ACh are the most widely used in CCHP plants and provide cooling air to about 15 ºC with a high coefficient of performance (COP is 0.7 to 0.8) [18]. The refrigerant vapor-compression chillers consume electrical energy to drive compressors and provide cooling air practically to any low temperature [13]. The most simple in design refrigerant ejector chillers (ECh) can cool air to 5-10ºC but with low COP of 0.2 to 0.3 [12, 13].

The efficiency of waste heat recovery cooling is especially high for the engines with the combustion of water-fuel emulsion [19, 20]. It is achieved due to the application of low temperature condensing surfaces [21, 22] providing deeper exhaust gas heat utilization that leads to additional heat converted in refrigeration. For cooling cyclic air of combustion engines, Jet technologies have a growing application [23]. They can be used for cooling scavenge air in internal combustion engines (ICE) [24, 25]. Jet cooling is especially effective in GT [26]. The high-efficiency heat exchangers should be applied to reduce cooling system sizes [28, 29].

3 Research Methodology

The efficiency of gas engine inlet air cooling was investigated for the CCHP plant of combined energy supply at the "Sandora"–"PepsiCo Ukraine" (Nikolaev, Ukraine). The CCHP plant is equipped with two cogenerative Jenbacher gas engines, JMS 420 GS-N.LC (rated electric power output P_{eISO} = 1400 kW, heat power Q_h =1500 kW of each engine). The heat of exhaust gas, scavenge air-gas mixture, engine jacket cooling water, and lubricating oil is used for heating water to about 90 °C. The hot water is used in AR-D500L2 Century absorption Li-Br chiller to produce chilled water of 7 to 12 °C, which is spent for technological needs and feeding to the central air conditioner that provides cooling ambient air incoming the engine room, from where it is sucked into the engine turbocharger.

The cooling capacity Q_0•spending for ambient air cooling is calculated according to heat balance on coolant (chilled water from ACh):

$$Q_0 = c_w(t_{w1} - t_{w2})G_w, \tag{1}$$

where c_w – specific heat of water [kJ/(kg·K)]; $t_{w1}$and t_{w2} – measured temperature of water at the inlet and outlet of air cooler [°C]; G_w – water mass flow rate [kg/s].

The values of current volume fuel consumption $B_{e.v}$, m^3 /h, and electrical power output P_e, kW, of gas engine JMS 420 GS-N.LC was taken by treating corresponding monitoring data on $B_{e.v}$ and P_e in dependence on the air temperature at the engine inlet t_{a2}. Specific volume fuel consumption is calculated as $b_{e.v} = B_e / P_e$, m^3 /kWh, and specific mass fuel consumption as $b_e = b_{e.v}\, \rho_g = \rho_g B_e / P_e$, kg /kWh, where ρ_g – density of fuel gas, kg/m^3.

The results of monitoring data processing were used as a decrease in specific fuel consumption Δb_e due to engine intake air temperature drop Δt by 1 °C, i.e., $\Delta b_e / \Delta t$.

The values of rational design cooling capacities needed for cooling air in ACh to t_{a2} = 15 °C and in ECh to t_{a2} = 7 and 10 °C were calculated according to the developed method [10] with taking into account current effect in fuel reduction ΔB, kg/h, due to cooling engine intake air at varying actual ambient air temperatures t_{amb} and relative humidities φ_{amb}.

The yearly varying real weather data collected in the weather datasets of the meteorological center were used by applying the "online" program "mundomanz.com".

The current fuel-saving B, kg, for hour time duration τ, h, due to cooling engine intake air with temperature decrease Δt_a, °C, is calculated according to correlation:

$$\mathrm{B} = \Delta t_a \cdot \tau(\Delta b_e/\Delta t_a) \cdot P_e, \tag{2}$$

where $\Delta t_a = t_{amb} - t_{a2}$ – decrease in air temperature [°C]; t_{amb} – ambient air temperature [°C]; t_{a2} – air temperature at the air cooler outlet [°C].

The annual fuel saving $\sum$B, kg, is calculated by summarizing current fuel reduction B on step by step (hour by hour) basis as $\sum$B:

$$\sum \mathrm{B} = \sum [\Delta t_a \cdot \tau(\Delta b_e/\Delta t_a) \cdot P_e] \tag{3}$$

The annual fuel saving $\sum$B in response to its consumption is used as a primary criterion for assessing engine intake air cooling system efficiency yearly operation.

The values of cooling capacities Q_0 spent for intake air cooling with temperature decrease Δt_a are calculated as

$$Q_0 = (c_a\, \xi\, \Delta t_a) G_a, \tag{4}$$

where: c_a –specific heat of moist air [kJ/(kg·K)]; ξ – specific heat ratio of total heat, including sensible and latent heat, to sensible heat rejected from the air during to its cooling; $\Delta t_a = t_a - t_{a2}$ – decrease in air temperature [°C]; t_a – ambient air temperature [°C]; t_{a2} – air temperature at the air cooler outlet [°C]; G_a – air mass flow rate [kg/s].

A rational design cooling capacity $Q_{0.rat}$ is determined to exclude its unproductive expenses caused by overestimating (oversizing chiller) without obtaining a noticeable effect in increasing the annual fuel saving $\sum$B.

With this, the values of refrigeration capacity $Q_{0.15}$ for cooling ambient air from its current temperature t_{amb} to the temperature t_{a2} = 15 °C and $Q_{.10}$ for cooling ambient air t_{a2} = 10 °C have been calculated for current site climatic conditions.

4 Results

The scheme of a typical gas engine inlet air cooling system with an absorption chiller is presented in Fig. 1.

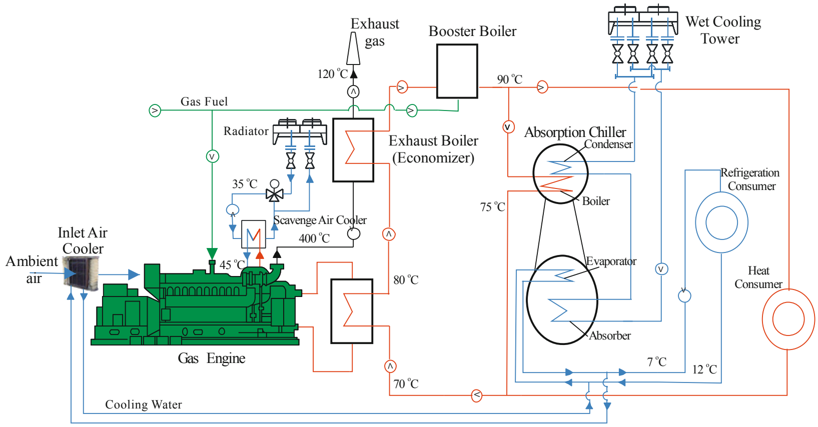

Fig. 1. The scheme of a typical gas engine inlet air cooling system with an absorption chiller.

In a typical gas engine inlet air cooling system, all the ambient air coming into the engine room is cooled in the inlet air cooler of the central conditioner fed by chilled water from the absorption chiller utilizing the exhaust heat of the engines. Because of much more increased volume of incoming ambient air (about twice higher than engine cyclic air mass flow) and heat influx to the cooled air from engine room surroundings the temperature of intake air t_{in} at the entrance of engine turbocharger suctioning it from engine room can be considerably higher than 20 or 25 °C in hot summer days. At the raised ambient air temperatures, the radiators (dry coolers) cannot cool the scavenge air to the required reliable level of its temperature at the outlet of the scavenging air cooler (of about 40 to 45 °C). It causes automatically decreasing the engine gas supply to maintain a charged gas-air mixture temperature at the inlet of engine combustion cylinders at the appropriate level.

Daily changes of specific gas consumption b_e received by treatment of monitoring data on the fuel efficiency of JMS 420 GS-N.LC is presented in Fig. 2.

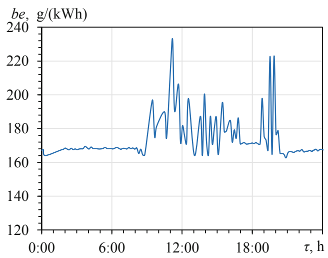

Fig. 2. Daily changes of specific gas consumption b_e of engine JMS 420 GS-N.LC.

A reduction of specific gas fuel consumption b_e is possible by addition decreasing temperature of engine cyclic air with mass flow rate G, fed to the turbocharger directly, as compared with typical cooling all the ambient air (of twice engine cyclic airflow G), coming into the engine room, to the temperature t_{in} of 20 to 25 °C and higher in hot summer days.

The scheme of the developed gas engine cyclic air cooling system with refrigerant ejector and absorption chillers is presented in Fig. 3.

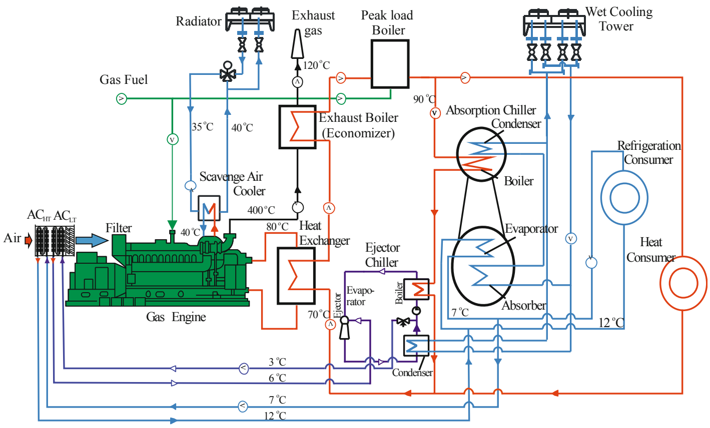

Fig. 3. The scheme of developed gas engine intake air cooling system with absorption and ejector chillers: AC_{HT} – high-temperature air cooler; AC_{HT} – low-temperature air cooler.

According to this scheme, chilled water from the absorption Li-Br chiller with a temperature of 7 °C is used as a coolant in high-temperature air cooler AC_{HT} as the first stage for cooling ambient air to 15 °C. The further subcooling air to 10 or 7 °C is conducted in low-temperature air cooler AC_{LT} by refrigerant boiling at the temperature of about 2 to 4 °C from ECh as the second stage of the combined two-stage AECh. The chilled air from a two-stage air cooler is directed through air ducting immediately to the suction of the engine turbocharger.

The values of cooling capacities $Q_{0.7,10,15}$ and heat $Q_{h.7,10,15}$ required for cooling engine inlet air to the temperatures 7, 10, and 15 °C are presented in Fig. 4 and Fig. 5.

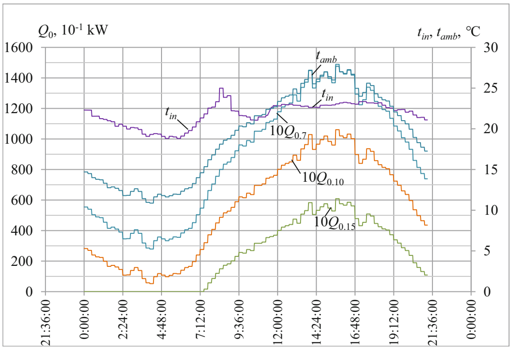

Fig. 4. Daily changes of cooling capacities $Q_{0.7,10,15}$, required for cooling engine inlet air to 7, 10, and 15 °C in the developed cooling system with varying ambient temperatures t_{amb} during time τ.

The values of available exhaust heat Q_{h}, the heat required $Q_{\text{h.7,10,15}}$ for cooling ambient air to t_{a2} = 7, 10 °C (in AECh) and 15 °C (in ACh) in developed engine intake air cooling system (in Fig. 3) and $Q_{\text{h.ACh.in}}$ in a typical existing system ($t_{a2} = t_{in}$) and corresponding remained heat $\Delta Q_{\text{h.7,10,15}}$ in developed and $\Delta Q_{\text{h.ACh.in}}$ in typical systems are presented in Fig. 5.

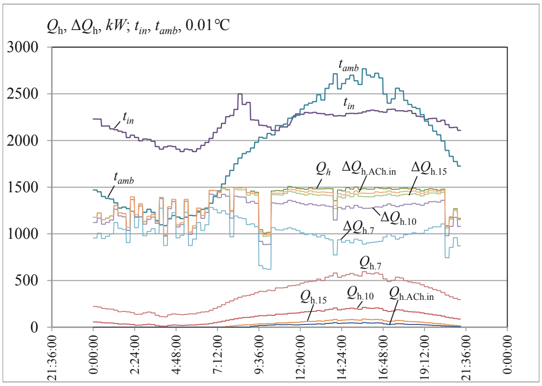

Fig. 5. Daily changes of available exhaust heat Q_{h}, the heat required $Q_{\text{h.7,10,15}}$ for cooling ambient air and remained heat $\Delta Q_{\text{h.7,10,15}}$ in developed engine inlet air cooling system (Fig. 3) and $\Delta Q_{\text{h.ACh.in}}$ in the typical system and the available heat Q_{h}.

The enhancement of gas engine fuel efficiency due to the application of developed intake air cooling system can be estimated by decreasing current specific mass fuel consumption Δb_e and summarized daily values of mass fuel reduction $\sum \Delta B_e$ due to engine inlet air cooling to the temperatures of 7, 10 and 15 °C (Fig. 6).

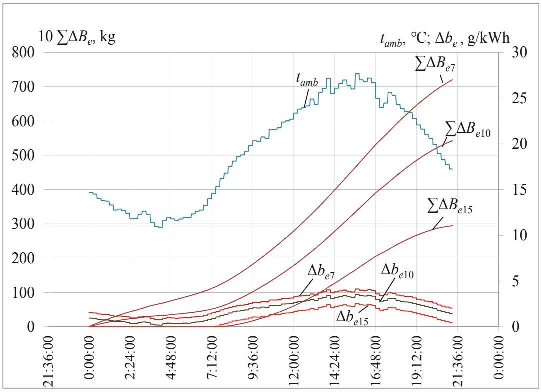

Fig. 6. Daily variation of decrease in current engine specific gas consumption Δb_e and summarized daily values of mass fuel reduction $\sum \Delta B_e$ due to engine inlet air cooling to 7, 10 and 15 °C with a variety of ambient temperatures t_{amb} during time τ.

As Fig. 6 shows, the application of developed engine cyclic air cooling system provides decreasing current specific fuel consumption Δb_e by the values of 2 to 3 g/kWh at increased ambient air temperatures t_{amb}, that leads to their summarized daily values $\sum B_e$ of about 50 kg for gas engine JMS 420 GS-N.L of 1400 kW power output, i.e., practically twice larger than by typical cooling in ACh.

The efficiency of the engine intake air cooling system and a rational value of its design cooling capacity without system oversizing can be determined by a developed method based on annual fuel saving as a primary criterion. With this, the annual fuel saving ΣB is calculated by summarizing all the current fuel reductions B through step by step procedure along with the overall range of cooling capacities Q_0 for a considered temperature of cooled air t_{a2} (Fig. 7).

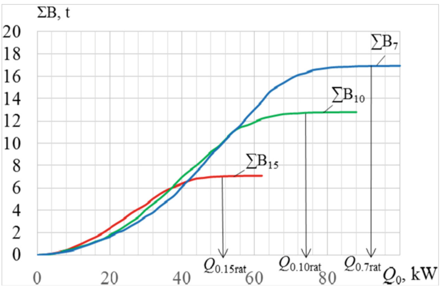

Fig. 7. Annual fuel-saving $\sum B$ due to cooling ambient air at the inlet of a gas engine to t_{a2} = 7, 10 and 15 °C versus cooling capacities Q_0 needed: $Q_{0.7,10,15}$ – rational design values.

As Fig. 7 shows, a developed cooling system with combined AECh of design cooling capacity $Q_{0.10}$ about 70 kW, provides cooling ambient air to t_{a2} = 10 °C with annual fuel saving $\sum B_{10}$ about 12.3 t is closed to a maximum value.

It is seen, although a rate of increment of annual fuel saving $\sum$Babove this value is negligible, the range of cooling capacities Q_0 needed to provide a maximum value of $\sum$B, i.e., to cover the maximum current cooling duties Q_0, is still wide. It approves a considerable oversizing of the cooling system, designed traditionally to cover the maximum current cooling needs Q_0. So, the proper (rational) values of design cooling capacities Q_0 are determined for an appropriately sized cooling system.

As Fig. 7 shows, the application of the developed method of cooling system rational designing allows to reduce the sizes of the system by about 15 to 20% due to rational design cooling capacities Q_{0rat} decreased by $\Delta Q_0 = Q_{0max} - Q_{0rat}$ compared with their maximum values Q_{0max} calculated traditionally.

The method allows estimating the efficiency of applying the proposed advanced cooling system with combined AECh for deeper engine inlet air cooling to t_{a2} = 7 and 10 °C as compared with traditional cooling to t_{a2} = 15 °C in ACh. As Fig. 7 shows, applying a combined engine intake air cooling system to ta2 = 10 and 7 °C in AECh provides annual fuel saving $\sum$B in 1.5 to 2.0 times higher than cooling to t_{a2} = 15 °C in ACh for temperate climatic conditions.

5 Conclusions

The results of processing the monitoring data on the fuel efficiency of driving gas engines in combined electricity, heat, and cooling generation plant have proved inefficient operation of traditional cooling. All the engine room incoming air in central conditioner fed by chilled water from absorption lithium-bromide chiller.

An advanced system of gas engine inlet air two-stage deep cooling by combined absorption-ejector chiller has been developed.

The method of rational loading of the proposed engine inlet air cooling system proved the increment of annual fuel reduction at raised ambient air temperatures by about 50% compared with traditional cooling by absorption chillers.

An advanced cooling system provides decreasing specific fuel consumption by 2.0 to 3.0 g/kWh due to stabilized low temperature of the air at the suction of engine turbocharger at increased ambient air temperatures.

The proposed system does not require considerable additional investments over the existing one, so the ejector chiller generally consists of heat exchangers and can use existing cooling towers to remove rejected heat (Fig. 4).

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