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A STUDY OF EXHAUST WASTE HEAT RECOVERY IN INTERNAL COMBUSTION ENGINES

Abstract: *The efficiency of exhaust heat recovery in typical integrated energy plant on the base of reciprocating gas engines with absorption lithium-bromide chiller for combined electricity, heat and refrigeration supply of the factory Sandora–PepsiCo Ukraine is analyzed. The reserves of decreasing the heat exhausted into atmosphere are revealed on the base of monitoring data and their realization through conversion into refrigeration for cooling the engine cyclic air is proposed. Some scheme decisions of improved and innovative exhaust heat recovery systems providing deep heat conversing into refrigeration for engine cyclic air cooling are developeded.*

Keywords: *energy plant, trigeneration, exhaust heat recovery, combined electricity, heat and refrigeration*

Introduction

The integrated energy plants (IEP) for combined refrigeration, heat and power supply (trigeneration) have growing application [1, 2]. The reciprocating gas fueled engines are used as prime engines [3, 4]. A widespread application of gas engines in IEP for combined supply of electricity, heat and refrigeration is due to well matching current duties [5, 6]. The gas engines are manufactured as cogeneration engine modules equipped with heat exchangers for producing hot water or steam by using the heat of exhaust gas, intake air and charged gas-air mixture of engines, engine jacket and lubricant oil cooling water [7, 8].

With rise in intake air temperature the efficiency of gas engines and IEP reduces: electricity decreases and specific fuel consumption increases [9, 10]. Therefore, the heat released from the engine and conversed into refrigeration can be used for cooling engine cyclic air [11, 12].

The most widespread absorption lithium-bromide chillers (ACh) of a simple cycle enable to provide cooling air to the temperature of about 15°C with a high coefficient of performance: COP of 0.7 to 0.8 [13, 14]. The most simple in design and cheap are jet devices: thermopressors [15, 16] and ejector chillers (ECh) [17, 18]. The refrigerant ejector chillers (ECh) are able to provide cooling air to the temperature of 10°C and lower but with less COP of 0.2 to 0.35 [19, 20] that requires inlarged heat.

In order to encrease the heat converted into refrigeration the advanced technologies of deep exhaust heat utilization can be used [21, 22] with applying low temperature condensing surfaces [23, 24].

The ECh consist generally of heat exhangers with phase change of refrigerant. So, their efficiency can be improved by intensification of heat transfer in evaporators [25-27] including compact minichannels

[28-30] and condensers [31, 32], by application of advanced coolant (refrigerant) circuits with injector [33] and two-stage cooling by heat conversion in combined chillers [34, 35].

The analysis of the IEP efficiency reveals the presence of large heat losses caused by discrepancy of temperature conditions for efficient performance of ACh and gas engine. So, issuing from the condition of engine maintenance at the appropriate thermal rate that provides its reliable operation, the temperature of a return hot water as a coolant entering the engine cogeneration system from ACh, is limited to design value of 70°C [3-5]. If it is exceeded, a surplus heat of return hot water is rejected to atmosphere.

The excessive heat of return hot water rejected to atmosphere in conventional practice of IEP operation can be converted into refrigeration by ejector chillers.

The purpose of the work is increasing the efficiency of conversing the gas engine exhaust heat into refrigeration to match the performance of absorption chiller and gas engine.

Methodology

The problem of increasing the efficiency of conversing the gas engine recoverable heat into refrigeration is solved for a IEP for combined energy supply of factory Sandora–PepsiCo Ukraine (Nikolaev, Ukraine). The trigeneration plant, equipped with two cogeneration Jenbacher gas engines JMS 420 GS-N.LC (electric power N_e = 1400 kW, heat power N_h = 1500 kW) and a single-stage ACh.

The ACh recovers the heat of engine jacket and lubricant oil cooling water, high temperature charged gas-air mixture and engine exhaust gas to produce a chilled water for technology process cooling and conditioning of air in engine room.

The scheme of the existing system of conversing a gas engine recoverable heat into refrigeration by ACh is presented in Figure 1.

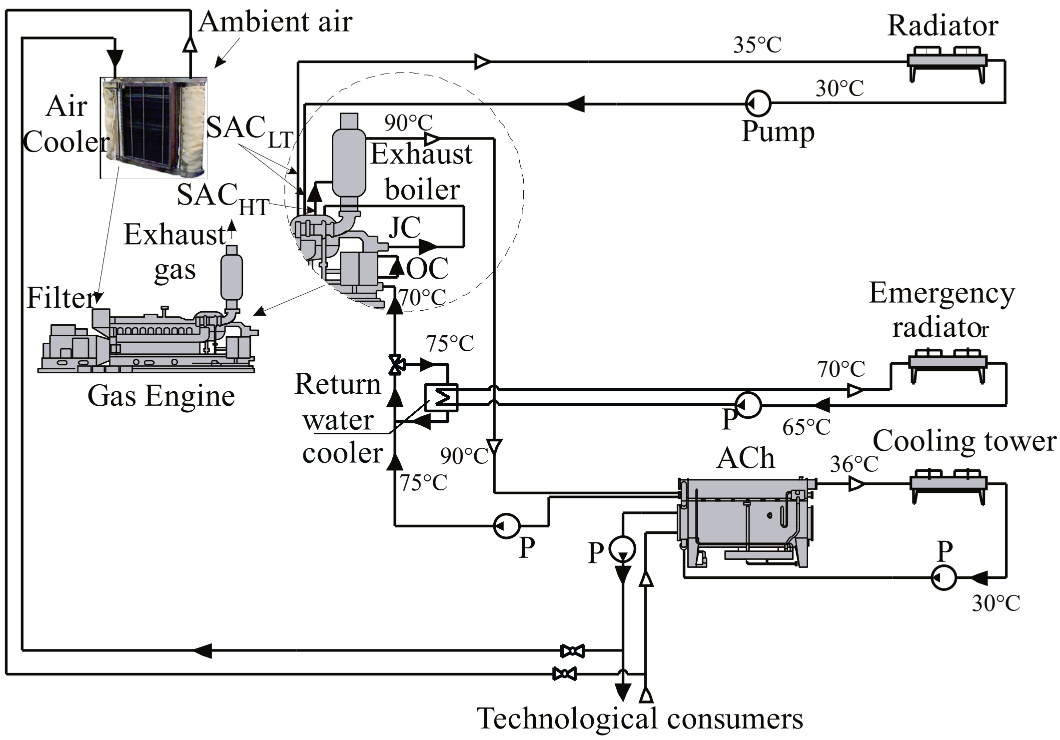

FIGURE 1. The scheme of the existing system of conversing gas engine recoverable heat into refrigeration by ACh: OC – oil cooler; JC – jacket cooler; SAC$_{LT}$ and SAC$_{HT}$ – low- and high-temperature scavenge air coolers (of charged gas-air mixture)

According to the conventional scheme in Figure 1 the temperature of return hot water from ACh t_r is about 75°C to 80°C, i.e. above its design value of $t_{r.sp}$ = 70°C at the inlet of heat exchangers of cogeneration engine module, providing appropriate engine thermal rate. Therefore, a part of return water is cooled in a return water cooler (RWC) with rejecting excessive heat by emergency radiator into the atmosphere.

Return of excessive heat to a single-stage absorption chiller is impossible because of its temperature t_r = 75°C, ..., 80°C lowered than design temperature of the supply hot water for a single-stage absorption chiller: $t_{h.sp}$ = 90°C, ..., 95°C. Fall of the supply hot water temperature would cause dropping the efficiency of transforming a gas engine recoverable heat into a refrigeration in a single-stage absorption chiller – decrease in coefficient of performance (COP) from nominal (design) value of about 0.7 to 0.5 and lower.

In order to estimate a magnitude of excessive heat rejected to the atmosphere and to reveal the reserves for its reduction through returning the heat exhausted to the exhaust heat recovery cycle to produce the additional refrigeration, the analyses of the data on hot water temperatures t_w, received during monitoring of IEP parameters, have been made.

The temperatures of supply hot water t_{w1} to ACh from cogeneration engine module, of return hot water after ACh t_{w4} (before return water cooler RWC for rejecting excess heat by emergency radiator to the atmosphere) and of return hot water, cooled by rejecting excessive heat to the atmosphere (after RWC), i.e. hot coolant at the inlet of gas engine module t_{w5} are given in Figure 2.

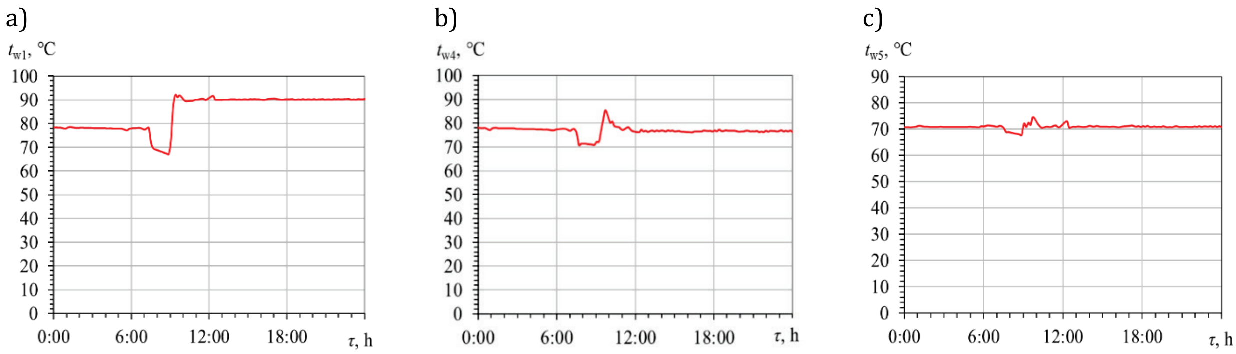

FIGURE 2. *Temperatures of supply hot water t_{w1} to ACh (a); return hot water after ACh t_{w4} (b) and cooled return hot water at the inlet of gas engine t_{w5} (c)*

Temperature difference of supply hot water to ACh and return hot water after it, i.e. temperature drop of hot water in the ACh, $t_{w1} - t_{w4}$, and temperature difference of return hot water from ACh and cooled return hot water at the inlet of gas engine, i.e. temperature drop of return hot water due to rejecting excessive heat to the atmosphere, $t_{w4} - t_{w5}$, are given in Figure 3.

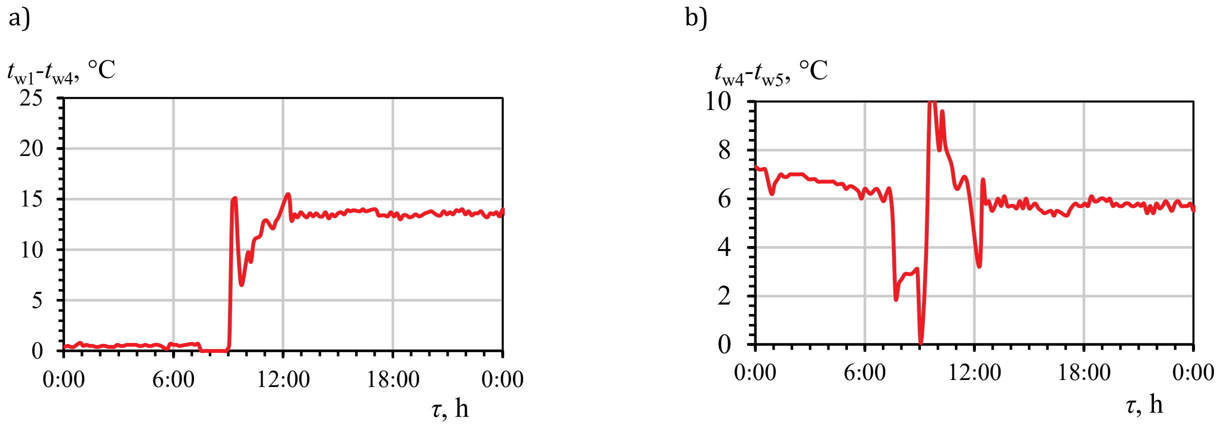

FIGURE 3. *Temperature drops of hot water in ACh $t_{w1} - t_{w4}$ (a) and of return hot water due to rejecting excessive heat to the atmosphere $t_{w4} - t_{w5}$ (b)*

As Figure 3 shows, that temperature drops of hot water in the absorption chiller, $t_{w1}-t_{w4}$, are closed to their design value of 15°C. Meanwhile, the temperature drops of return hot water caused by rejecting excess heat to the atmosphere are rather essential: $t_{w4}-t_{w5}\approx 5$°C, that testifies to considerable heat wasted.

Results

The results of calculations of the heat Q_w rejected to the atmosphere were compared with heat Q_{hA} used by ACh (Fig. 4).

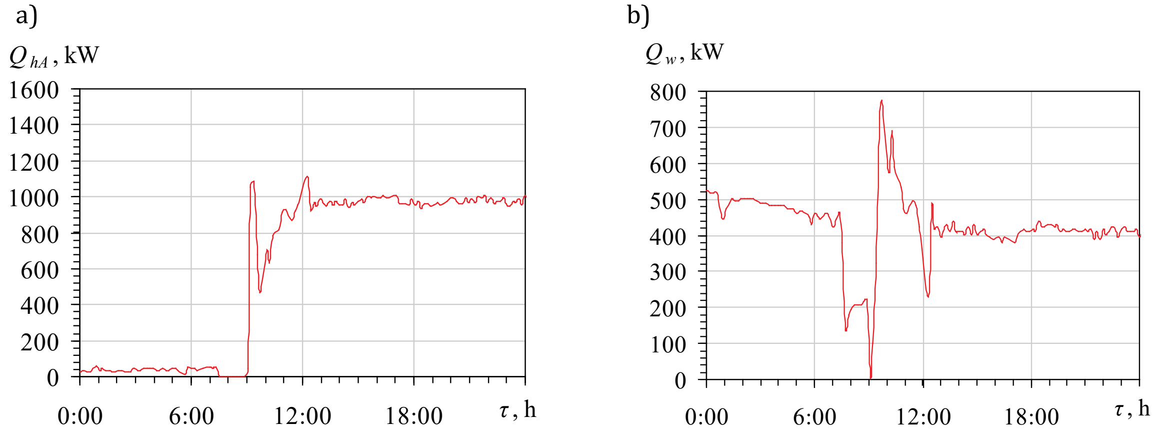

FIGURE 4. *Valueses of heat used by absorption chiller Q_{hA} (a) and heat rejected to the atmosphere Q_w (b)*

The share of heat rejected to the atmosphere Q_w caused by necessity to maintain the temperature of cooled return hot water (hot coolant for gas engine) at the input of gas engine module at the rate of 70°C, is about 40% of heat consumed by ACh and actually third of cogeneration engine module thermal capacity 1400 kW.

The heat recovery system with using the excessive heat (normally rejected to the atmosphere) in ejector chiller (ECh) to produce addition cold for gas engine cyclic air cooling was developed and its efficiency was estimated based on the monitoring data.

It is possible to avoid heat losses inherent in the typical heat recovery system by increasing a temperature rate of excessive heat (normally rejected to the atmosphere) up to design value of 90°C, ..., 95°C to be used as activation heat source for ACh. A gas boiler, normally available at any factory as booster boiler, can be applied to heat up the return hot water. So, an additional return hot water circulating contour with booster gas boiler might be integrated into the existing heat recovery system (Fig. 5).

Actual refrigeration capacities of ACh using the currently available heat excluding heat losses caused by rejecting excessive heat to the atmosphere (without heating up the return hot water) Q_{0A} and additional refrigeration capacities Q_{0w} due to recovering excessive heat boosted by gas boiler Q_w are given in Figure 6.

As one can see, due to recovering excessive heat Q_w, normally rejected to the atmosphere, it is possible to maximize the recovery of the available thermal energy and to increase refrigeration capacity of the actual trigeneration plant by Q_{0w} = 300 kW, picking it by about 50% up to design refrigeration capacity of a trigeneration Jenbacher gas engine module JMS 420 GS-N.LC: $Q_{0A}+Q_{0w}$ = 1000 kW.

First of all it should be noted, that the approach to transform the gas engine exhaust heat into refrigeration by ACh of a simple cycle through increasing a temperature rate of excessive heat of return hot water (excessive heat normally rejected to the atmosphere) up to desirable value (Fig. 5) is the most efficient for multi engines IEP with at least two ACh. In this case the addition heat is used for boosting the heat feeding to the second ACh thereby increasing the refrigeration capacity and the flexibility of the trigeneration plant operation in the whole. The increased refrigeration capacity can be used for gas engine cyclic air cooling to enlarge the engine power output and electricity production as a result, accompanied by reduction of specific fuel consumption.

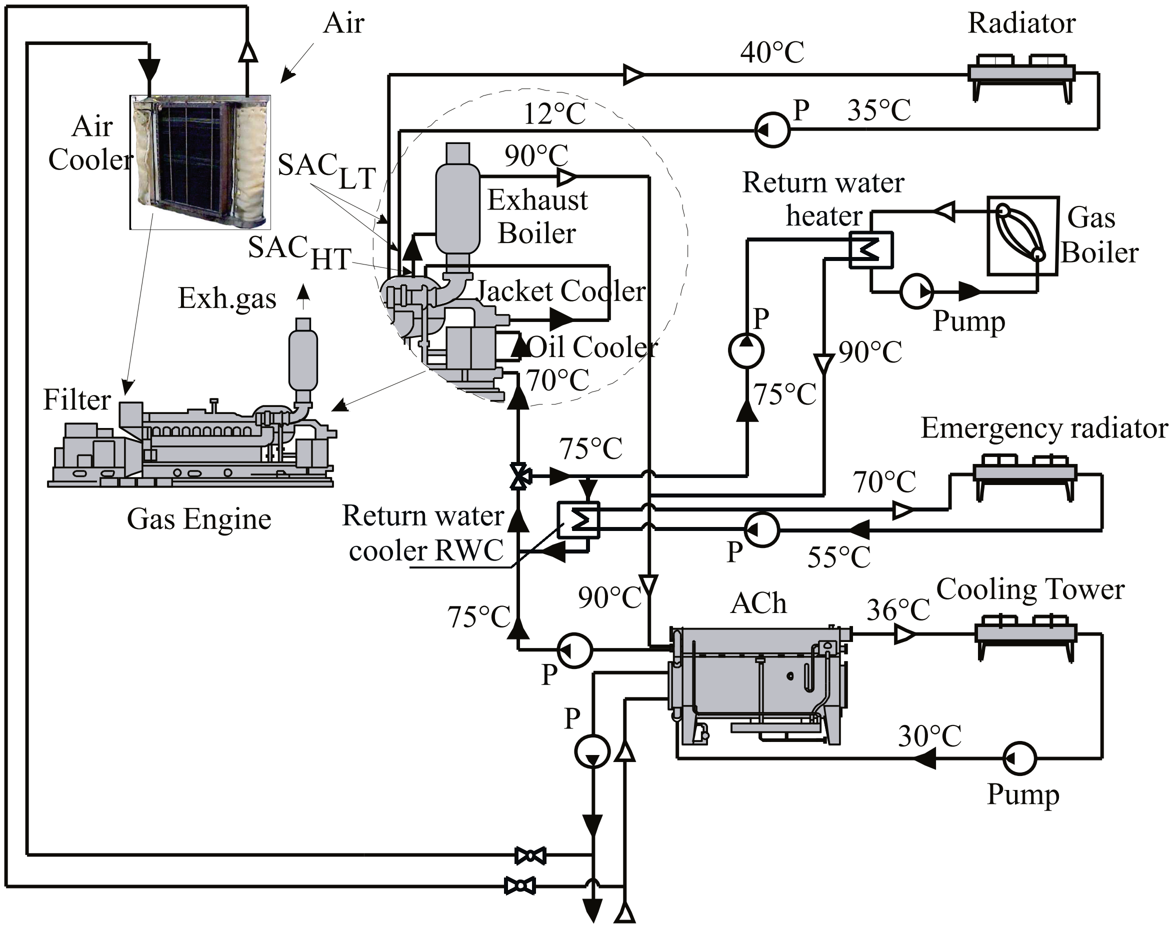

Figure 5. *The scheme of modified system of transforming gas engine recoverable heat into refrigeration by absorption chiller: SAC$_{LT}$ and SAC$_{HT}$ – low- and high-temperature scavenge air coolers of charged gas-air mixture*

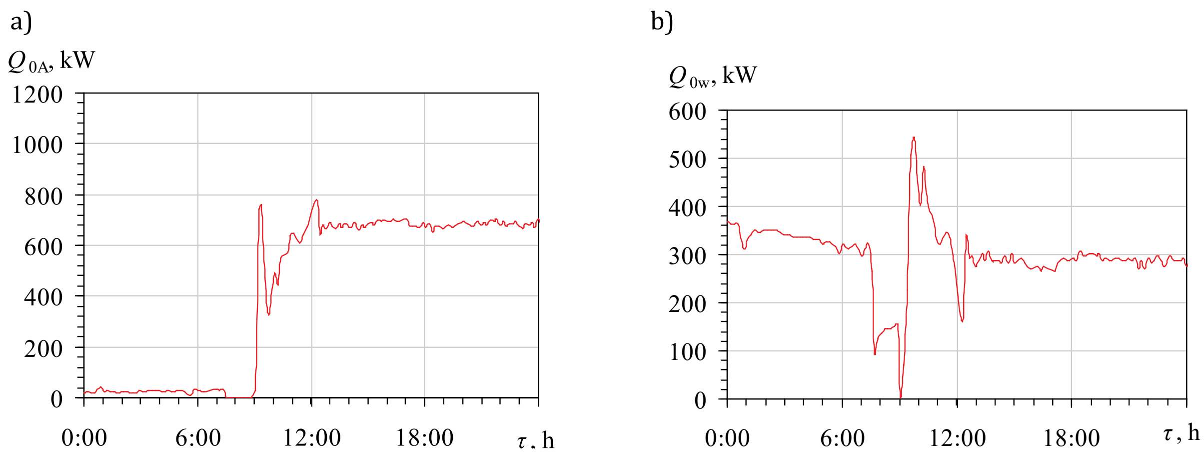

Figure 6. *Refrigeration capacities of ACh without boosting excessive heat Q_{0A} (a) and additional refrigeration capacities Q_{0w} due to recovering excessive heat Q_w (b)*

The simplest in implementation and most expedient solution to recover the relatively low-temperature heat of return hot water from ACh of the rate of 75°C, …, 80°C is the application of ejector chiller (ECh) as a low temperature stage of two-stage absorption-ejector chiller (AECh) with ACh as a high temperature stage [34, 35].

The additional refrigeration capacity, gained due to deep recovering the heat exhausted from the engine, is used for engine cyclic air cooling: intake air at the suction of turbocharger in two-stage air cooler with boiling refrigerant of ECh in the low temperature stage and chilled water from ACh in the high temperature stage of air cooler and scavenge air-gas mixture cooling through using chilled water from ACh for subcooling the scavenge air cooling water, precooled in radiator by ambient air, in booster cooler after radiator (Fig. 7).

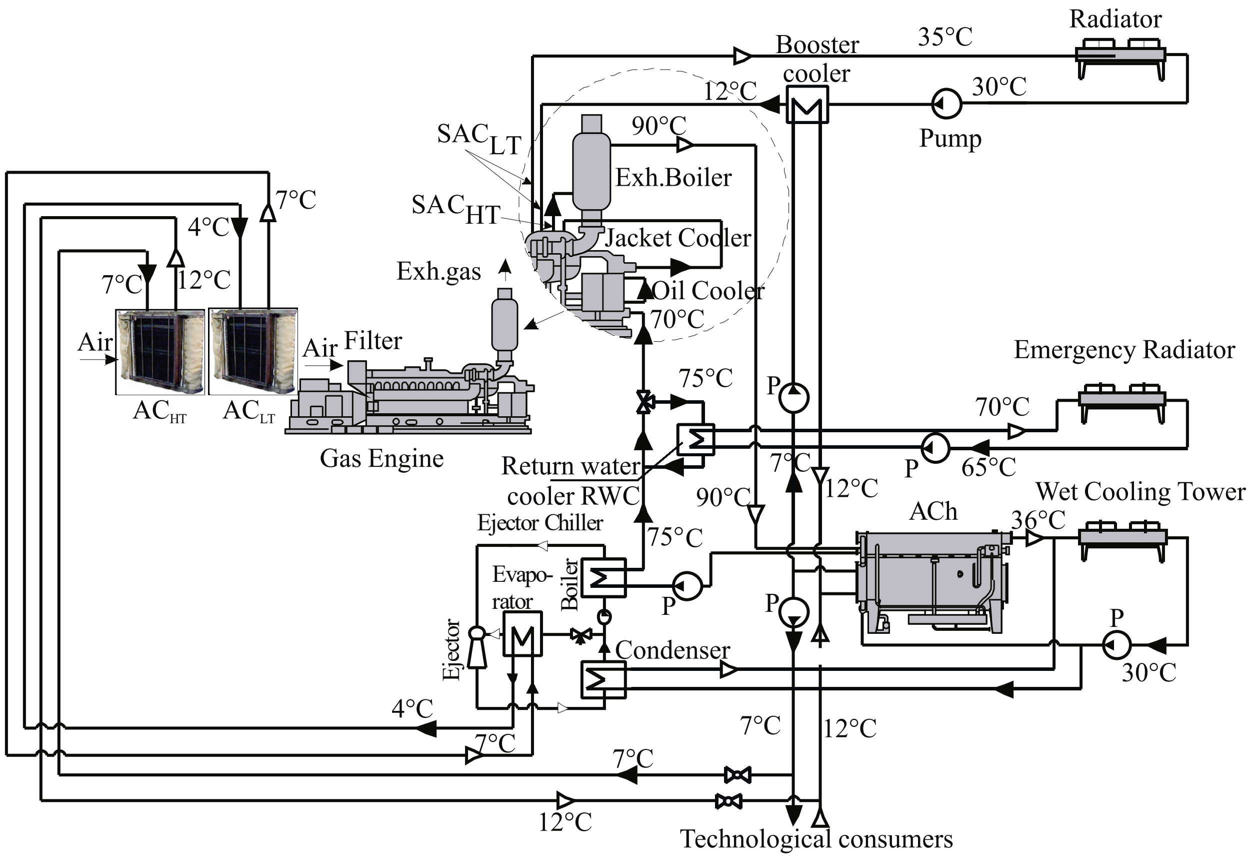

FIGURE 7. *The scheme of innovative system of deep transforming the gas engine exhaust heat by combined AECh: SAC_{LT} and SAC_{HT} – low- and high-temperature scavenge air coolers of charged gas-air mixture; AC_{LT} and AC_{HT} – low- and high-temperature air coolers of engine intake air*

Such engine in-cycle trigeneration provides enhancing engine fuel efficiency and prolong the time of efficient operation of trigeneration plant since cooling demands for technological needs have, as a rule, periodic character.

Conclusions

The analysis of conversing the exhaust heat from gas engine of IEP into refrigeration by ACh, based on monitoring data, has revealed the considerable heat losses of about 40% of ACh heat consumption and actually third of cogeneration engine module thermal capacity 1400 kW, caused by conflicting requirements of temperature conditions for effective performance of ACh and gas engine. So, issuing from the condition of engine maintenance at the appropriate thermal rate that provides its reliable operation, the temperature of a return hot water (as hot coolant for gas engine) entering the engine cogeneration system from ACh, is limited to the value of 70°C. If it is exceeded, a surplus heat of return hot water is rejected to atmosphere.

The approach to transform the gas engine exhaust heat into refrigeration by ACh of a simple cycle through increasing a temperature rate of excessive heat of return hot water (excessive heat normally rejected to the atmosphere) up to desirable value is discussed as the most efficient for multi engines IEP with at least two ACh. With this the addition heat is used for boosting the heat feeding to the second ACh thereby increasing the refrigeration capacity and the flexibility of the trigeneration plant operation in the whole.

The innovative heat recovery system with using the excessive heat (normally rejected to the atmosphere) in ejector chiller (ECh) to produce addition refrigeration capacity for gas engine cyclic air cooling was proposed as the simplest regarding to the implementation and the most expedient solution to recover the relatively low-temperature heat of return hot water from ACh of the rate within 75°C to 80°C.

Two-stage absorption-ejector chiller (AECh) with ejector chiller (ECh) as a low temperature stage and ACh as a high temperature stage is proposed to utilize the advantages of each chiller.

Two-stage gas engine inake air cooling system with boiling refrigerant of ECh in the low temperature stage and chilled water from ACh in the high temperature stage of air cooler.

Therefore it is reasonable to apply ECh as a low temperature stage and ACh as a high temperature stage of two-stage absorption-ejector chiller (AECh). A combined AECh is able to provide engine cyclic air deep cooling and enhance engine fuel efficiency.

Such in-cycle trigeneration provides engine cyclic air deep cooling leads to enhancing engine fuel efficiency and prolonging the time of efficient operation of trigeneration plant, since cooling demands for technological needs have, as a rule, periodic character.

Conflicts of Interest: The author declares no conflict of interest.

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