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Research Article

Innovative approaches and modified criteria to improve a thermodynamic efficiency of trigeneration plants

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Abstract: Trigeneration plants (TGP) desired for combined production of electricity, heat and refrigeration are highly flexible to follow current loading. But their highest efficiency might be possible only when heat production coincides with its consumption, which is generally impossible in traditional TGP with applying the absorption lithium-bromide chiller (ACh) converting the heat, released from combustion engine in the form of hot water, into refrigeration. Usually, the excessive heat of hot water, not consumed by ACh, is removed to the atmosphere through emergency radiator. However, the well-known methods of TGP efficiency assessment do not consider those heat losses and give the overestimated magnitudes of efficiency for conventional TGP with ACh. The application of booster ejector chiller (ECh), as an example, for utilization of the residual waste heat, remained from ACh and evaluated about 25%, has been proposed to produce supplementary refrigeration for cooling cyclic air of driving combustion engine to increase its electrical efficiency by 3-4 %. In the case of using the supplementary refrigeration for technological or other needs the heat efficiency of TGP will increase to about 0.43 against 0.37 for typical TGP with ACh as example. The new modified criteria to assess a real efficiency of conventional TGP, based on ACh, are proposed which enable to reveal the way of its improvement through minimizing the heat waste. Such combined two-stage waste heat recovery system of TGP can be considered as the alternative to the use of back-up gas boiler to pick up the waste heat potential for conversion by ACh to meet increased refrigeration needs.

Keywords: *gas engine, absorption lithium-bromide chiller, production, consumption, heat conversion.*

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Nomenclature

Abbreviations	Descriptions	Abbreviations	Descriptions
AECh	absorption-ejector type chiller	*TGP*	trigeneration plant
ACh	absorption lithium-bromide chiller	t_w	temperature of water
c_w	specific heat of water;	Δt	temperature drop
ECh	ejector chiller	η_e	electric efficiency
E	energy referred to unit of time	η_h	heat efficiency
GE	gas engine	η_t	total efficiency
G_w	mass flow rate of water		

1. INTRODUCTION

A waste heat recovery remains as the most efficient trend in enhancing the efficiency of the power plants based on combustion engines of any type: internal combustion engines [1,2], gas turbines [3,4] and gas engines [5,6]. Trigeneration plants (TGP) are desired for combined production of electricity, heat and refrigeration [7,8]. They are able to manage actual loading due to their high flexibility [9,10] and increase practically twice the time of the efficient operation of cogenerative plants due to applying the heat released for production of refrigeration [11,12]. So as refrigeration and heat consumption has seasonal or periodical character it is preferably to use rest excessive refrigeration for cooling engine cyclic air [13,14]. Such in-cycle trigeneration [15,16] makes it possible to keep engine operation at stabilized lowered temperature with high thermodynamic efficiency and produce addition electricity leading to arising electricity ant total efficiency as result.

Different heat exchangers might be used to intensify heat transfer [17,18] in utilizing [19,20] and heat transforming contours [21,22]. Besides, special jet devices [23,24], using high pressure potential, can be applied for circulation of working fluids such as ejectors and thermopressors [25,26] in stationary and transport applications [27,28].

The gas engines are manufactured as cogenerative modules with mounted heat exchangers to extract the heat of engine jacket, lubricating oil, charge air and exhaust gas [29,30]. They best meet electricity needs due to the highest electrical efficiency and the total efficiency accordingly [31,32]. Meantime, the highest heat efficiency is possible in the case of heat production and consumption coincidence. The last is generally impossible in traditional TGP [33,34] with applying the most widespread and efficient absorption chiller (ACh) of lithium-bromide type [35,36] to convert the heat released from gas engine in the form of hot water into refrigeration. The excessive heat of return hot water, not consumed by ACh, is removed to the atmosphere through discharge radiator. The refrigerant ejector chiller (ECh) [37,38] of jet type [39,40] might be easy implemented as a booster stage of absorption-ejector type chiller (AECh) to convert the excess heat left behind the ACh [41,42] for cooling the air sucked by engine [43,44].

There are many methods applied to optimize the heat loads on exhaust heat utilization and air-cooling systems [45,46] in order to meet actual loading [47,48], gain a maximum output [49,50] and improve operation performance of engines [51,52]. They focus to enhance output of engines due to sucked air cooling at varying actual ambient temperatures [53,54]. The fundamental researches in sizing the TGP [55,56] take into account the level of cogenerative engine loading [57,58] regarding the type of thermotransformers [59-61]. But generally, they do not consider the discrepancy of heat production and consumption taking into account the efficiency of transforming the residual heat, left from ACh, to refrigeration in traditional TGP [10].

The aim of research is to develop a design method based on the modified criteria enabling to assess the thermodynamic efficiency of TGP, taking into account the heat loss caused by divergence of heat production and consumption.

2. PROBLEM STATEMENT

Trigeneration plants are considered as the most flexible power plants to follow current loading due to generation of different kinds of energy: electricity, heat and refrigeration, to match actual needs. However, their highest efficiency would be achieved only if heat production coincides with its consumption. The last is generally impossible in traditional TGP based on ACh. The reason is that a hot water temperature drop of about 15 °C, optimal for ACh, is usually less than its value above 20 °C, required to provide a lowered temperature of return cooled hot water, used as a coolant, not higher than 70 °C. The latter constraint ensures engine long time operation at the safe thermal level due to low hot water temperature at the engine entrance. The excessive heat of hot water, not consumed by ACh, is removed to the atmosphere through emergency discharge radiator. However, the well-known methods of TGP efficiency assessment do not consider those heat losses and give their unproved increased magnitudes for conventional TGP with ACh.

Issuing from the mentioned above, the criteria of thermodynamic efficiency of TGP [55,56] have to consider not only the efficiency of heat production of cogenerative engine, but the efficiency of converting heat into refrigeration without waste of over generated heat too. Therefore, a design method has to apply the criteria enabling to compare the thermodynamic efficiency of the power plant functioning in cogeneration and trigeneration modes by heat η_h and total η_t efficiency accordingly.

The new modified criteria in addition to assess a real efficiency of conventional TGP, based on ACh, will enable to reveal the way of its improvement through minimizing the heat waste. The application of booster ejector chiller (ECh), as an example, for deep utilization of the residual waste heat, remained from ACh and evaluated about 25%, can be proposed to produce supplementary refrigeration for cooling cyclic air of driving combustion engine to increase its efficiency. Such combined two-stage waste heat recovery system of TGP might be considered as the alternative to the use of back-up gas boiler to pick up the waste heat potential for conversion by ACh to meet increased refrigeration needs.

The new modified criteria to assess a real efficiency of conventional TGP, based on ACh, which enable to reveal the way of its improvement through minimizing the heat waste are proposed and corresponding methodology for estimating the efficiency of heat loss conversion has been developed.

3. RESEARCH METHODOLOGY

The principal feature of the main approach to modify generally accepted criteria is to correlate the thermodynamic efficiency of TGP option based on ACh to consider heat loss $E_{h.loss}$, left behind ACh and rejected to the atmosphere by emergency radiator while converting the heat $E_{h.cog}$ released from cogenerative GE in the form of hot water with temperature of about 90°C: $E_{h.loss} = E_{h.cog} – E_{h.A}$, where $E_{h.cog}$ – heat consumed by ACh.

The heat loss is caused by discrepancy between optimal for ACh hot water temperature drop of about 15°C and its available value of about 20°C, which provides the temperature of returned cooled hot water at the entrance to GE not higher than 70°C. The latter ensues safe operation of GE without overheating. The heat consumed by ACh in a traditional TGP is limited by hot water temperature drop Δt_w in ACh of about 15°C:

$$E_{h.A} = G_w\, c_w\, \Delta t_{wA} \,, \qquad (1)$$

where G_w – water mass flow rate; c_w – water specific heat; $\Delta t_w = t_{w1} – t_{w2}$ – hot water temperature drop in ACh; t_{w1} and t_{w2} – hot water temperatures at the inlet and outlet of ACh; $E_{h.A}$ – heat consumed by ACh referred to unit of time.

As a result, the heat loss $E_{h.loss}$ remained after ACh and rejected to environment is evaluated as about 25% of the heat $E_{h.cog}$ released from cogenerative GE [4, 57]. This heat loss $E_{h.loss}$ is considered as a potential heat for its additional conversion in booster ECh. Therefore, the heat efficiency $\eta_{h.A}$ of the conventional TGP with ACh, consumed only the part $E_{h.A}$ of the overall available heat from cogenerative GE $E_{h.cog}$, is evaluated as;

$$\eta_{h.A} = E_{h.A} / E_f \,. \tag{2}$$

Accordingly, the modified criteria $\eta_{t.A}$ of the total heat and electric efficiency of TGP with ACh is calculated as $\eta_{t.A} = \eta_{h.A} + \eta_e$, which is considerably less than that for cogenerative plant $\eta_{t.cog} = \eta_{h.cog} + \eta_e$, usually determined proceeding from all the heat released E_h , (i.e. without waste heat):

$$\eta_{h.cog} = E_h / E_f \tag{3}$$

The heat loss $E_{h.loss}$ can be converted into refrigeration by booster ECh with thermal efficiency:

$$\eta_{h.E} = E_{h.loss} / E_f \,, \tag{4}$$

which leads to increased total efficiency $\eta_{t.trig}$ of TGP with ACh and ECh:

$$\eta_{t.trig} = \eta_{h.A} + \eta_{h.E} + \eta_e \,. \tag{5}$$

Furthermore, the additional refrigeration gained by converting the heat loss $E_{h.loss}$ by ECh might be used for cooling the air at the inlet of GE to produce supplementary electricity and boost electrical and total efficiency of TGP accordingly. In order to evaluate the efficiency of conversion of the residual (lost) heat into refrigeration by booster ECh (as example) with COP_E compared to high efficient ACh with COP_E the modified heat efficiency of TGP with ECh $\eta_{h.trig}$ is calculated by using the reduced residual heat $E_{h.loss.red}$ according to correlation between COP_E and COP_A as;

$$\eta_{h.trig} = E_{h.loss.red} / E_f \,, \tag{6}$$

where,

$$E_{h.loss.red} = E_{h.loss} \, COP_E / COP_A \tag{6}$$

Such approach enables to correlate the efficiency of heat loss conversion into refrigeration by booster ECh (as example) with its conversion by high efficient ACh.

The application of booster ECh, as an example, for deep utilization of the residual waste heat remained from ACh can be considered as the alternative to the use of backup gas boiler to pick up the waste heat potential to be converted by ACh to meet increased refrigeration needs.

A thermodynamic efficiency of the cogenerative GE is analyzed for cogenerative power plant of enterprise "Sandora"–"PepsiCo Ukraine". The cogenerative plant involves two GE JMS 420 with electric power 1400 kW and heat productivity 1500 kW for each GE (Fig. 1).

Figure 1. Gas engine cogenerative module JMS GE Jenbacher

A scheme of a typical cogenerative plant based on GE is plotted in Fig. 2.

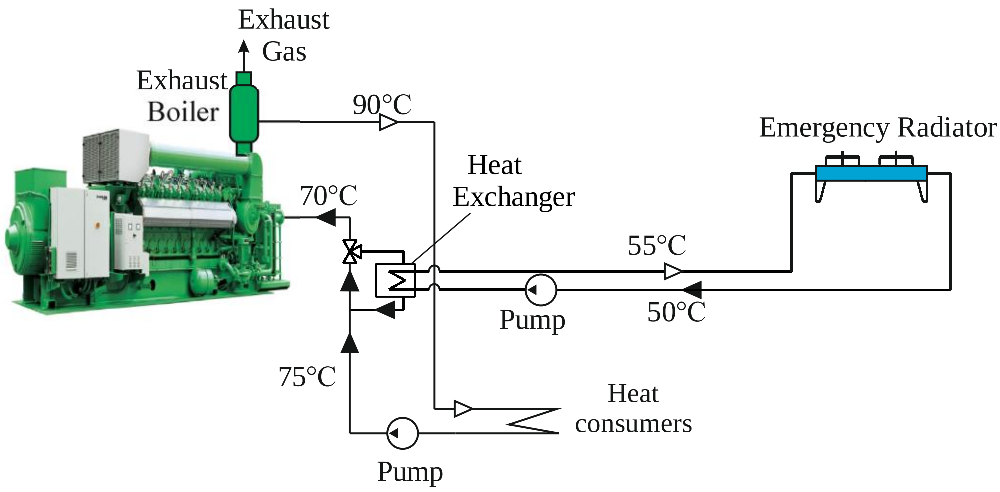

Figure 2. A circuit of traditional cogenerative power plant based on the gas engine.

The heat released from the engine is used to produce hot water with temperature about 90°C.

4. RESULTS AND DISCUSSIONS

The values of energy introduced by fuel E_f , electric output E_e and thermal output E_h referred to time unit with temperatures of GE intake air t_a based on monitoring data during a day for a cogenerative GE module JMS 420 are plotted in Fig. 3.

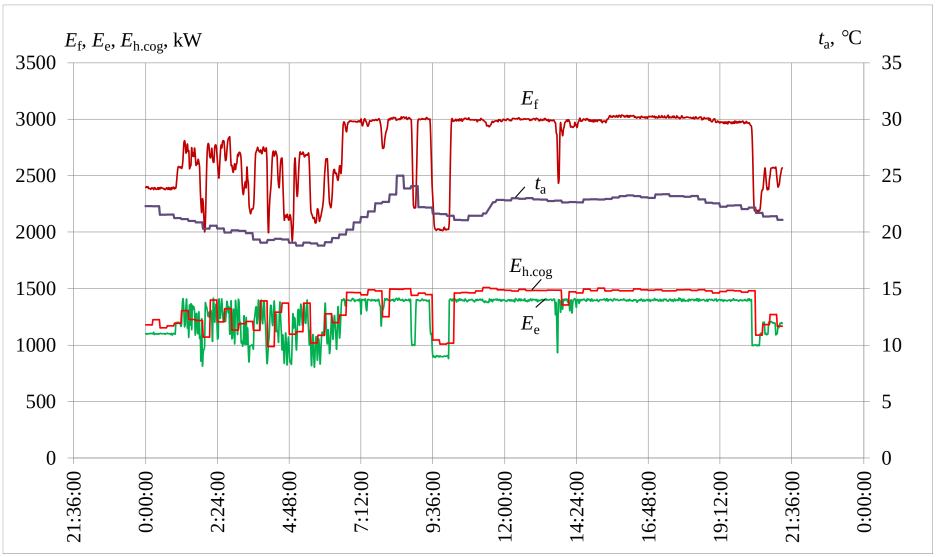

Figure 3. Time series of fluctuations in energy introduced by fuel E_f, electric output E_e and thermal output $E_{h.cog}$ for GE JMS 420 with temperatures of GE intake air t_a during a day.

As Fig. 3 shows, the thermal output E_h of GE JMS 420 referred to time unit as the heat released from GE in the form of hot water is about 1500 kW, as well as electricity production E_e of GE is about 1400 kW and energy introduced by fuel E_f is about 3000 kW. Corresponding values of heat $\eta_{h.cog}$, electric η_e and total $\eta_{t.cog}$ efficiency of typical cogenerative plant based on GE are presented in Fig. 4.

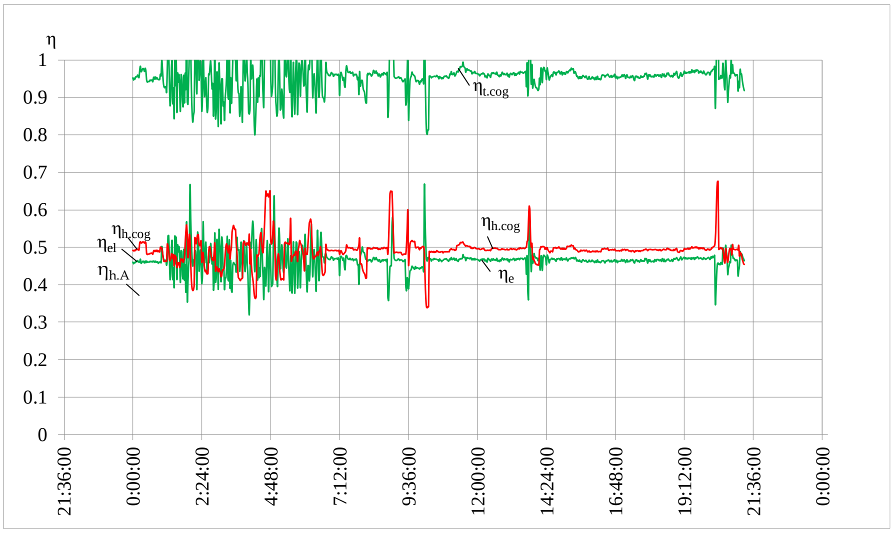

Figure 4. Time series of fluctuations in heat $\eta_{h.cog}$, electric η_e and total $\eta_{t.cog}$ efficiency of cogenerative GE JMS 420 : $\eta_e = E_e / E_f$; $\eta_{h.cog} = E_{h.cog} / E_f$; $\eta_{t.cog} = (E_e + E_{h.cog}) / E_f$.

As can be seen from Fig. 4, the electric efficiency η_e is about 0.45, heat efficiency $\eta_{h.cog}$ is 0.5 and total efficiency of cogenerative GE $\eta_{t.cog}$ is close to 0.95, that practically corresponds rated values. However, the difference between heat production, as the heat released from GE, and its consumption, especially evident when it is converted into refrigeration by ACh in TGP of enterprise "Sandora"–"PepsiCo Ukraine" when the cogenerative plant operates in trigeneration mode (Figs. 5 and 6), requires a modification of the above criteria to consider their discrepancy between the heat mentioned.

Figure 5. Absorption chiller AR-D500L2 applied in the considered TGP.

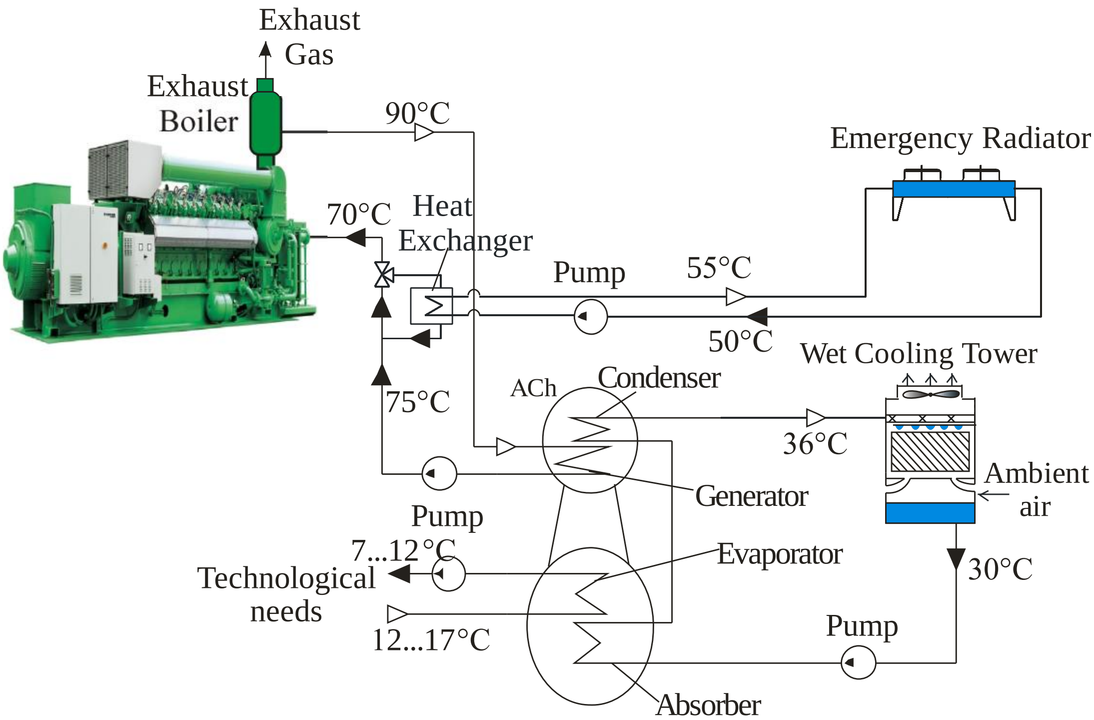

Figure 6. A circuit of a TGP at the enterprise "Sandora"–"PepsiCo Ukraine" with two GE and ACh.

The heat released from two engines (jacket cooling water and lubricating oil, scavenge air-gas mixture and exhaust gas) is used to produce hot water with temperature of about 90 °C which feeds the ACh AR-D500L2 Century. The latter produces a chilled water of 7 °C to 12 °C, spent for technological and conditioning needs. Because the return cooled hot water leaving ACh is used as a coolant in GE heat extracting circuit, its temperature has to be kept at the level not higher than 70 °C satisfying engine safe thermal operation. The excessive return heat, not consumed by ACh, is traditionally removed to environment through emergency radiator (Fig. 6).

The loss of heat $E_{h.loss}$ discharged into the atmosphere is about 25 % of the total heat $E_{h.cog}$ released from cogenerative GE and the heat consumed by ACh $E_{h.A}$ calculated according to Eq. (1) is about 75 % (Fig. 7).

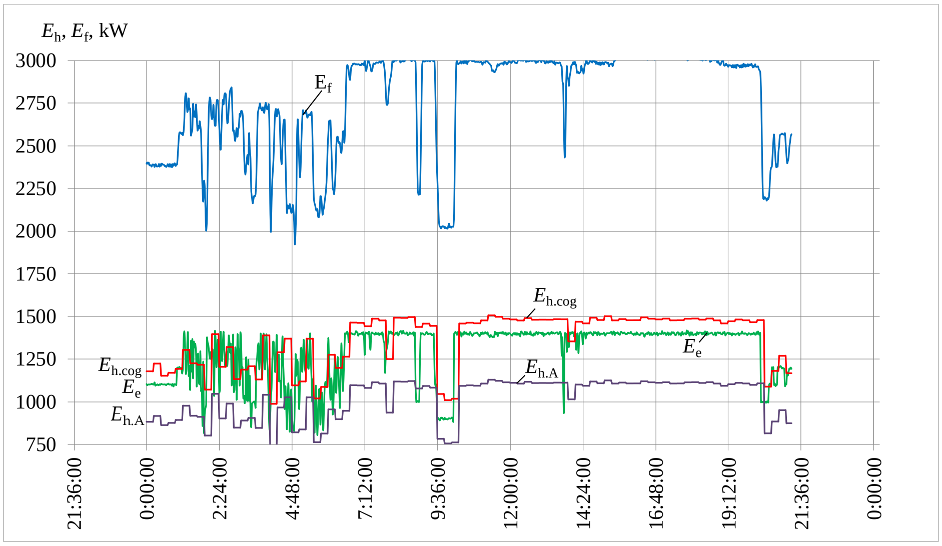

Figure 7. Fluctuations in energy introduced by fuel E_f, electric output E_e and thermal output $E_{h.cog}$ of GE JMS 420 and heat consumed by ACh referred to time unit.

As can be seen from Fig. 7, the heat consumed by ACh $E_{h.A}$ is about 1100 kW that is considerably less than the cogenerative GE thermal output $E_{h.cog}$ practically equal to 1500 kW, that leads to much heat loss $E_{h.loss}$ of about 400 kW. Thus, the heat loss $E_{h.loss}$ of about 25% not consumed by ACh and discharged into the atmosphere has been considered as a heat potential for enhancing the thermodynamic efficiency of typical TGP.

The heat loss $E_{h.loss}$ discharged into the atmosphere leads to reduced heat and total efficiency of TGP evaluated by corresponding modified criteria $\eta_{h.A}$ and $\eta_{t.trig}$ (Fig. 8 and 9).

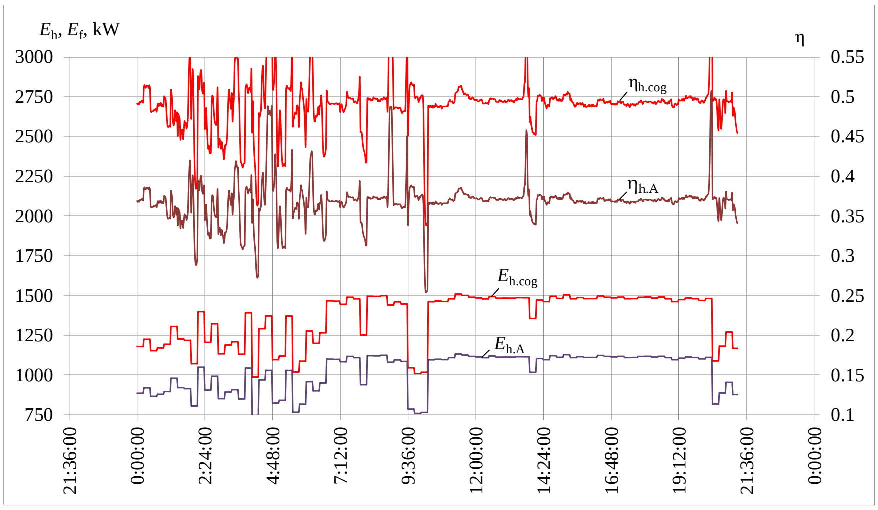

Figure 8. Fluctuations in thermal output $E_{h.cog}$ of GE JMS 420 and heat $E_{h.A}$ consumed by ACh referred to time unit and corresponding heat efficiency $\eta_{h.cog}$ of cogenerative plant and heat efficiency $\eta_{h.trig}$ of trigeneration plant: $\eta_{h.cog} = E_{h.cog} / E_f$, $\eta_{h.A} = E_{h.A} / E_f$.

As it is seen, the real heat efficiency $\eta_{h.A}$ of TGP taking into account the heat lost is about 0.37 against its value $\eta_{h.cog}$ of about 0.5 traditionally estimated without considering the heat waste.

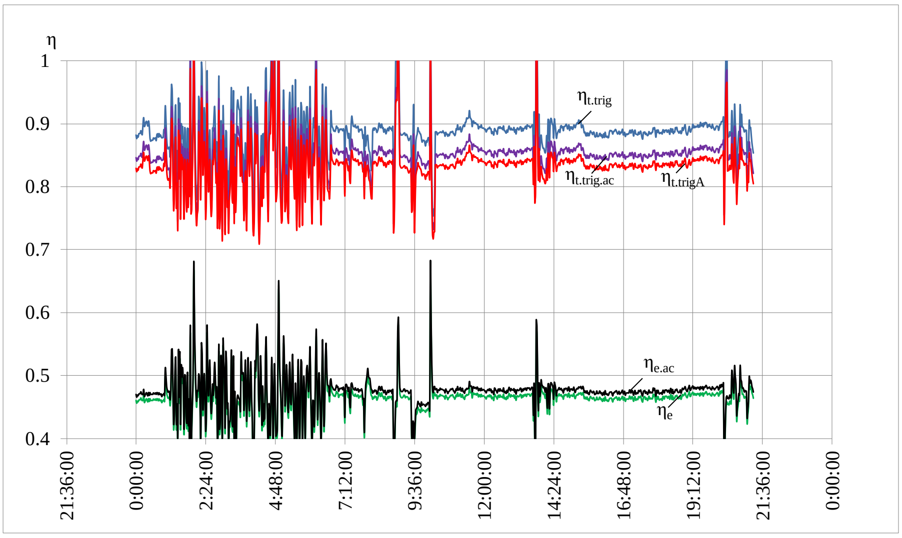

Figure 9. Fluctuations in total efficiency of conventional TGP with ACh $\eta_{t.trigA}$, developed TGP with ACh and booster ECh $\eta_{t.trig}$, developed TGP with ACh and engine intake air cooling by ECh using residual heat $\eta_{t.trig.ac}$, electric efficiency without engine air cooling η_e and with air cooling $\eta_{e.ac}$: $\eta_{t.trig}= \eta_e + \eta_{h.trig}$; $\eta_{t.trig.ac}= \eta_{e.ac} + \eta_{h.A}$; $\eta_{t.trig.A}= \eta_e + \eta_{h.A}$

The real reduced heat efficiency $\eta_{h.A}$ of conventional TGP with ACh of about 0.37 (Fig. 8) leads to the real total efficiency of $\eta_{t.trigA}$ within 0.82-0.83 (Fig. 9) against to $\eta_{t.cog}$ of about 0.95 not taking into account heat waste.

In order to consider the efficiency of conversion of the residual (lost) heat into refrigeration by booster ECh with COP_E of about 0.2 against high efficient ACh (COP_A of about 0.7) the modified heat efficiency of TGP with ECh $\eta_{h.trig}$ is calculated according to correlation Eq. (6) between COP_E and COP_A . Such approach enables to correlate the efficiency of heat loss conversion into refrigeration by booster ECh (as example) with its conversion by high efficient ACh. The calculation results of the efficiency of developed TGP with ACh and ECh against traditional TGP are tabulated below.

Table 1. Efficiency of conventional TGP with ACh and developed TGP with ACh and booster ECh

Efficiency	**Basic TGP with ACh**	**TGP with ACh and booster ECh**	
		without intake air cooling	with intake air cooling
Total efficiency η_t	0.83	0.90	0.85
Heat efficiency η_h	0.37	0.43	0.37
Electrical efficiency η_{el}	0.46	0.46	0.48

Thus, the modified criteria enable to reveal the heat potential of about 25 % usually lost in conventional TGP with ACh and estimate the efficiency of its conversion into refrigeration by booster chiller (ECh as example), thereby to increase the real heat efficiency of TGP $\eta_{h.trig}$ to about 0.43 against $\eta_{h.A}$ of about 0.37 (Fig. 8), as well as total efficiency $\eta_{t.trig} \approx 0.9$ (without engine intake air cooling) and $\eta_{t.trig.ac} \approx 0.85$ (with engine intake air cooling by using residual heat) against $\eta_{t.A} \approx 0.83$.

5. CONCLUSION

New modified criteria for estimation of thermodynamic efficiency of TGP based on ACh are proposed to take into account the heat loss, caused by divergence of heat production by engine and its consumption by ACh. It is shown, that in the case of TGP with gas engine the heat loss is about 25 % of heat production. In contrast to existing criteria, not taking into account the heat, unconsumed by ACh and discharged into the atmosphere in typical TGP, the modified criteria consider also the efficiency of transforming the heat loss in booster chiller evaluated by COP.

In the case of ECh, applied as a booster chiller to transform the heat loss, the heat efficiency of TGP increases to about 0.43 against its value of about 0.37 for typical TGP. The use of supplementary refrigeration for engine intake air cooling enables to increase electricity production and electrical efficiency of TGP to about 0.48 against its value of about 0.46 for typical TGP with ACh, id est. by about 3-4 %. The proposed criteria are quite suitable for primary estimation of thermodynamic efficiency of any TGP based on combustion engine and characterized inevitable discrepancy between heat production by engine and its consumption by ACh.

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