Partial load efficiency analysis of a CCHP plant with RICE and H₂O-LiBr absorption chiller

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Abstract. This paper presents a model for calculating and analyzing the global efficiency of a trigeneration system (CCHP) using 3 reciprocating internal combustion engines (RICE) as prime mover for heat and electric loads. RICE operate simultaneously and at the same load. The CCHP plant delivering energy for the office buildings of an economic operator includes also 2 absorption chillers with water-lithium bromide solution for air conditioning. The system has been analyzed for RICE partial load operation mode, linking the thermal energy output to the cooling power generation. The amount of thermal energy production is influenced by the required energy for cooling. The total cooling load in the summer is determined by both the indoor office-rooms cooling load and the data center cooling load (the energy dissipated by the data center's components and electrical circuits). An vaporcompression chiller is operated for cooling peak load. During yearly thermal load variation, RICE are switched on or off, operate at nominal capacity or in partial load mode. The thermal efficiency of each engine changes according to the demanded heating load, determining the global efficiency variation of the trigeneration system.. The electrical efficiency of the system is also dependent on the RICE operating load that leads the electric generators. The EER factor for the absorption chillers results accordingly at partial or nominal load operating mode. The functioning graphics for each system equipment were developed based on the thermal load curve of the RICEs and the global efficiency variation graph of the trigeneration system was plotted. Finally, conclusions resulted regarding the optimal functioning of the studied trigeneration system.

1 Introduction

Trigeneration technologies are already known for decades, they mean the combined production of electricity, heating and cooling, using a single fuel source. The trigeneration system (CCHP) may have a complex structure which depends on available technologies of prime mover. According to the prime mover the following technologies can be identified [1]: steam turbines, gas turbines, microturbines, combined cycle gas turbines, reciprocating internal combustion engines (RICE) and new emerging technologies such as organic rankine cycle, Stirling engines, fuel cells.

Regarding RICE, the literature mentions the main benefits: works at low fuel consumption at nominal powers, long life and high efficiency, quick start for fast electrical network balancing (about 3 min.), wide range of capabilities (from 50 kW to 9.5 MWel), the ability to operate at partial loads, the ability to operate at relatively low natural gas pressures (about 50 mbar) [2].

2 The CCHP plant scheme

The CCHP plant, Fig. 1, analyzed in the present paper belongs to an economic operator and provides heat, electricity and air conditioning to the offices and to the data center, on the summer season. As the main equipment, the CCHP plant consists of 3 RICE for the production of the thermal agent and electrical energy, a hot water boiler for the peak thermal load, two absorption chillers for air conditioning and a vaporcompression chiller for cooling peak load. As secondary equipment are: plate-heat exchangers, hot and chilled water storage tanks, open cooling towers with fans.

The three internal combustion engines are supplied with natural gas, have a thermal output of 1675 kW and a electrical power output of 1500 kW. Engines can operate at any load capacity between 50% and 100% of their rated capacity without significant impact on their efficiency. Manufacturers of RICE prohibit the use below 50% of rated capacity. If the consumer demand for thermal power is below 50% of rated capacity, the engine is switched off and the load is taken over by a hot water boiler. In a previous study [3], operation of RICE was simulated in 3 different operation modes. The study concluded that the simultaneous operating mode at the same partial load without the boiler's intervention brings the best benefits. Also the informations from the technicians operating the considered plant say that the engines discharge the useful heat in the same percentage. The simultaneous operating mode, previously specified, has been considered in the present work, regarding engines operation.

The low pressure hot water boiler, supplied with natural gas, has a thermal output of 850 kW. The hot water boiler will come into operation after the three engines achieve nominal capacity (100%), at the same time.

The two absorption chillers use working fluid LithiumBromide-Water, lithium bromide solution is acting as absorber and water is acting as refrigerant. The absorption chillers have a cooling capacity of 1500 kW. For the peak cooling load, in the summer, the CCHP plant have an vapor-compression chiller of 1500 kW cooling capacity, whose function is not studied in the present work.



Fig. 1.The CCHP plant scheme

3 Water lithium bromide absorption chiller

Two types of installation are known for the production of cooling energy by absorption: the vapour absorption refrigeration plant on Ammonia-Water and on Water-Lithium Bromide solution. The first type can be used in refrigeration, for the ammonia condensation temperature below zero degrees, and the second type may be used in air conditioning, considering that the condensation temperature of the water can not fall below zero degrees. The energy efficiency ratio (EER) of an H₂O-LiBr absorption chiller, in one stage, is between 0.65 and 0.75 [4].

The schematic cooling cycle of the H2O-LiBr absorption chiller is shown in Fig. 2, [5]. The chilled water is prepared in the evaporator E. Cooling takes place at the evaporator temperature, 4+5 °C. Chilled water (useful flow) can be obtained at temperatures between 6÷10 °C. The heating agent is hot water at 95 °C that comes from the RICE via the plate heat exchanger into the generator G. The heat of the absorber A and condenser C is removed to the outside - to the open cooling towers with fans - by means of the cooling water system whose circuit is in series. In the absorber, the cooling water enters at temperature of 29 °C and exits from the condenser at 37 °C. The dilute solution H₂O-LiBr is obtained in absorber as a result of the absorption of water vapor from the evaporator inside the strong solution. The dilute solution is taken up, at the physical state point 5th, by the pump P which increases the pressure from the lowest level (in the absorber) to the generator and condenser pressure. In the generator is

boiling the refrigerant - superheated water vapor, at the physical state point 1st, passes into condenser C where condensation occurs under the action of cooling water. The strong solution leaves generator G, with the physical state point 8th. The strong solution passes in the solution heat exchanger SHX to heat the dilute solution, eliminating the danger of crystallization. The strong solution is sprayed into the absorber, the physical state point 10th, and the cycle is resumed. The refrigerant, water, condenses in condenser C at 35 °C and passes through the refrigerant expansion valve, ER, shrinking its temperature and pressure, then it is sprayed into the useful flow of chilled water in the circuit to the consumer.



Fig. 2. Schematic of a H₂O-LiBr system (model [5])



Fig. 3. The numerical model of efficiency of CCHP plant

4 Numerical model

In order to create a model, Fig. 3, for calculating and analyzing the overall efficiency of considered trigeneration plant, we started from the numerical model of the simultaneous operating mode, we have added the operating mode of absorber chillers and the domestic hot water supply (DHW) and we have studied the behavior of the entire trigeneration system in partial load (PL) operating conditions of engines, respectively at 50%, 75% and 100% PL.

The thermal efficiency at partial load of RICE is given by the equation of Sanaye S. et al. [6]. The variation graph of PL of the three engines at different thermal load required by the consumer is presented in Fig. 4. At the total thermal load provided by CCHP plant, the hot water boiler capacity was also considered and added, as can be seen in the last segment of the graph.

The electrical power supply by each engine was calculated with ASHRAE equation (2008) [7] for electrical efficiency of the electrical generator combined with the method of calculating the energy requirements and the system efficiency in SR EN 15316 [8], [9].

Domestic hot water is provided with heating agent from the engines via a plate-heat exchangers with a heat transfer efficiency of 98%. The heat required for DHW demand in offices, at 60 $^{\circ}$ C to avoid the risk of legionella, is 85 kW.

The operating model of H_2O -LiBr absorption chiller took into account chilled water system, cooling water system, hot water system and the power of pumps. From the water and steam properties tables, specific densities and specific heats corresponding to the average temperature on each circuit have been introduced in the model, as well the flow rates measured in CCHP plant. For chilled water at 6 °C, an EER of 0,687 was found. The energy efficiency ratio value is assumed to keep invariable during the process. The amount of heat that comes in the generators of two absorption chillers, provided by engines, is shrinking first with amount of heat required for DHW preparation.

From the reverse calculation of the thermal and electrical efficiency together with the useful thermal power and useful electrical power on each engine, the fuel input power was calculated. The values of global efficiency resulted by dividing the sum of useful powers to the input power delivered by the fuel. The input power of the boiler fuel have been taken into account too. The values of global efficiency of CCHP plant, under the described conditions, ranged between 69.3% and 73.3%.



Fig. 4. Variation of PL with total thermal load provided



Fig. 5. The useful powers provided of CCHP plant

5 Results and analysis

The useful power streams provided by the CCHP plant are represented in Fig. 5. DHW production is constant, at 85 kW, according to the water demand for offices. The useful electrical power supplied is starting from 750 kW during first engine operation at 50% PL and is reaching to 4500 kW when all three engines are functioning at 100% operation load, Table 1. The boiler's intervention obviously does not add anything to the electrical output. The cooling power supply is starting from 521 kW during first engine operation at 50% PL and is reaching to 3982 kW when all three engines and the boiler are functioning at 100% operation load.

Table 1. Results of useful powers depending on PL

PL	engines in function	cooling supply (kW)	DHW supply (kW)	electrical supply (kW)
50%	1	521	85	750
	2	1096		1500
	3	N/A		N/A
75%	1	809	85	1125
	2	1672		2250
	3	2535		3375
100%	1	1096	85	1500
	2	2247		3000
	3	3398		4500
	3+boiler	3982		4500

The global efficiency of trigeneration plant has a variation between 69,32% and 73,30%. We notice a very small abbreviation (4%) of the global efficiency of such a trigeneration system (with RICE) at the wide variation of operation load. The minim value of global efficiency, 69,32%, is recorded at the time of changing from one engine to two engines. This is done when one extra kilowatt of useful power requires to pass from one engine operating at 100% capacity to two engines operating at 50,03% PL. Losses on two engines are greater, thermal efficiency at PL [6] are lower, so global efficiency will be lower. The higher value of global efficiency, 73,30%, is recorded at the time of achieving 100% of capacity by first engine. The explanation is the reverse of the precedent: one engine at full load has lower losses and better efficiency then two or three engines at partial load. The variation of global efficiency with the total thermal load provided is shown in Fig. 6.



Fig. 6. Variation of global efficiency with total thermal load provided



Fig. 7. Variation of global efficiency with PL

Compared to the overall upward trend of the global efficiency curve, two moments of drop in efficiency are recorded when the 2nd engine and the 3rd engine enters. After this two moments the rising trend is resumed each time.

Also a decrease of values of global efficiency, from 72.75% to 72.12%, is observed from the moment when the nominal capacity is reached for all three engines and the boiler intervenes. The graph of variation of global efficiency with the partial load is shown in Fig. 7.

The correlation between the useful powers supplied by CCHP plant and the working load, partial or full, was studied. The total electrical power delivered by the system during operation at different loads has a Pearson correlation coefficient of +0.699. This is interpreted as a positive association wich means the increasing of PL involves increasing of the total useful power supplied by the system. Correlation coefficient being in range of 0.50 \div 0.75, there is a moderate relationship between the values of the two variables, PL and total electrical power.

The correlation coefficient between total cooling power supplied by CCHP plant and PL of engines has a value of +0.701, wich is also positive and moderate relationship, respectively the cooling power is growing at moderate speed with the PL operation. There was no question of studying the correlation between DHW and PL, DHW being a constant.

Study of the correlation between global efficiency, η_{global} , and PL reveals a value of correlation coefficient of +0.853. That means a strong positive association between the two range of value, the global efficiency of system is increasing rapidly with increasing of PL.

Regarding on the production of useful cooling power, the possible cooling capacity of the vaporcompression chiller was not taken into account. This equipment is not working with heating agent, hot water coming from the RICE. The vapor-compression chiller will be put into operation under exceptional conditions when a peak cooling load is required. This aspect has not been studied in the present work. Two simulations were conducted assuming first: a variation of hot water inlet temperature in the generator of chiller for boiling the refrigerant and second: a variation of chilled water outlet temperature to the consumer's offices and data center. In first simulation of operating mode of absorber chillers the EER coefficient was found to be descending from 0.84 (for 10 degree Δt) to 0.42 (for 20 degree Δt), Fig. 8. In the second simulation EER coefficient was found to be ascending from 0.51 (for 5 degree Δt) to 0.91 (for 9 degree Δt). Obviously, the variation of cooling water temperature doesn't bring variation of EER coefficient.



Fig. 8. Variation of EER with temperature variation in chiller external circuits

In order to find a mathematical relationship describing the behaviour of global efficiency according to the partial load, PL, and the useful cooling power, Φ_0 , from absorption chillers, we have created a multiple regression model. We have introduced in the data table the sets of 16 values of global efficiency, of partial load and of useful cooling power and we have obtained the Equation (1) expressing the variation of the global efficiency with PL and Φ_0 .

$$\eta_{global} = 0.675 + 0.066 \cdot PL_{COG} - 3.4 \cdot 10^{-6} \cdot \Phi_0 \quad (1)$$

In the ANOVA analysis of a equation the p-value of significance helps us to determine the significance of our results, for the coefficients. A small p-value less than 0.05 indicates we may reject the null hypothesis (which states that there is no relationship between the studied variables).

The p-values of the Equation (1) are: $4 \cdot 10^{-20}$ for the intercept, $3.65 \cdot 10^{-5}$ for PL coefficient and 0.075 for Φ_0 coefficient, wich is relatively close to the cutoff (0.05).

6 Conclusions

The CCHP system has been studied for the summer operation, when the focus is on providing energy for cooling spaces and air conditioning. The study described a new numerical method of quick calculation of the global efficiency of a specific CCHP plant, having RICE as prime mover, in partial load operation. The study is applicable to office buildings with significant energy consumption.

In terms of absorption chillers operation, some interesting observations have been made that contradict the 'common sense'. So, if the output temperature of chilled water increases (Δt chilled water is shrinking) since the generator load is kept constant, the energy efficiency ratio value decreases. We would expect to get

more efficiency delivering chilled water to consumers by 10 degrees instead of 6 degrees, but it is not true, due to the drop in the amount of useful cooling power. In the same sense, decreasing the temperature of the heating agent coming from the engines (Δt hot water is shrinking) since the useful cooling power is kept constant, leads to the increase of the EER coefficient due to the decrease of the amount of heat consumed in the generator.

The value of global efficiency of CCHP plant increases with increasing the partial load of operation on engines. Should be mentioned that there are moments of entry into operation of the 2nd engine and the 3rd engine, when the global efficiency is affected by a decrease of 3.98%, and 1.41% respectively. The upward trend of the global efficiency curve is maintained during operation at variable loads but with each new entry into operation of a first mover the curve descends, 0.55% first new entrance and 0.19 at the second new entrance, Fig. 7.

The Equation (1) of variation of the global efficiency of the CCHP plant at partial loads, depending on the value of the partial load, PL, and the useful cooling power, Φ_0 , found by regression, has coefficients of good significance and may be applied instead of approximate values.

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