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Comparative Analysis of Energy Efficiency Between Installations with Absorption and Mechanical Vapor Compression in Trigeneration

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Abstract: - Trigeneration is an attractive option in situations where all three needs exist, such as in manufacturing processes with cooling requirements. Trigeneration has the greatest benefits when scaled to fit buildings or building complexes where electricity, heating, and cooling are constantly needed. Such installations include, but are not limited to: data centers, manufacturing facilities, universities, hospitals, military complexes, and colleges. Localized trigeneration has additional benefits, as described by distributed generation. Power redundancy in essential applications, lower energy usage costs, and the ability to sell electricity back to the local utility are some of the major benefits.

This paper analyses a comparative solution between cooling equipment with absorption respectively with mechanical vapor compression and draws conclusions regarding the energy efficiency.

Key-Words: - trigeneration, absorption, mechanical compression, energy efficiency, consumers.

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1 Introduction

In a trigeneration system, the high-temperature heat supply first drives a gas or steam turbine-powered generator, and the resulting low-temperature waste heat is then used for water or space heating. Such systems can achieve higher overall efficiencies than cogeneration or traditional power plants and can offer significant financial and environmental benefits.

Trigeneration extends cogeneration by employing waste heat from cogeneration systems to drive vapor absorption refrigeration systems, thus simultaneously providing heat and cooling from a single fuel source [1] The heat produced by cogeneration can be supplied through various media, including hot water (e.g. for space heating and hot water systems), steam, or hot air (e.g. for commercial and industrial uses). Etymologically, corresponding to "cogeneration", which means the simultaneous production of two forms of energy (electricity and heat), trigeneration represents the simultaneous production of three "energy products": heat, electrical energy and cold. This will be the meaning of the notion of trigeneration, used in this work, as indeed by most energy specialists. However, a broader meaning to the notion of trigeneration could be the simultaneous production of:

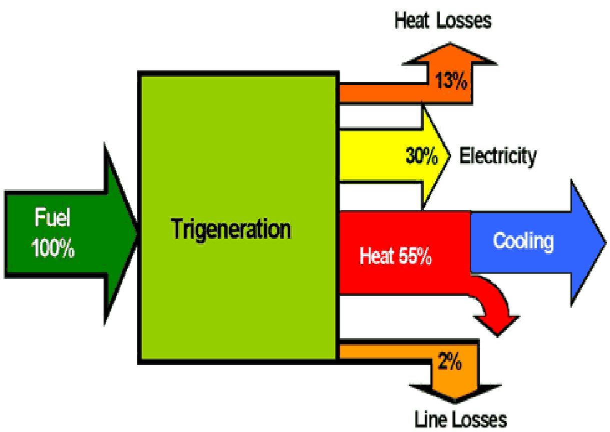

Fig. 1. Trigeneration

– heat, electrical energy and specific chemical streams, which actually integrate a cogeneration plant into a chemical product production complex;

– heat, electrical energy and combustible products (gases), through coal gasification;

– electrical energy, liquid and gaseous fuel [2];

– heat, electrical energy and hydrogen or oxygen.

This interpretation of the notion of trigeneration, as follows from the above, actually represents the association of cogeneration with the production of fuels or chemical products, which in their vast majority are still superior fuels compared to conventional ones.

However, as was shown from the beginning, in this paper the notion of trigeneration will be used, characterized mainly by the production of electricity, heat and cold, abbreviated as "CTG" [3] . The heat from cogeneration can be distributed through various media like hot water, steam, or hot air for different applications. Trigeneration, similar to cogeneration, involves the simultaneous production of electricity, heating, and cooling. This paper explores trigeneration primarily in the context of these three energy forms, although a broader interpretation could include chemical stream production, gasification, and hydrogen or oxygen production. Despite these broader definitions, the paper focuses on the traditional interpretation of trigeneration—producing electricity, heat, and cooling, referred to as "CTG" [3].

Similar to cogeneration, trigeneration must meet the specific conditions for combined energy production, especially since it presupposes the existence of cogeneration. However, some conditions have specific aspects related to the installations that produce the cold and the simultaneity of the consumption of cold, with those in the form of heat and electricity. These conditions are:

the production of heat and electricity takes place in the same installations

– cogeneration installations (ICG) – while the cold is produced in special installations

– refrigeration installations (IF);

the simultaneity of the production of heat and electricity is a condition imposed by cogeneration, while the cold may or may not be produced simultaneously with them, depending on the type of cold consumer (technological cold)

– in industry – or to ensure microclimate conditions in premises

– for air conditioning;

the primary energy used for the production of heat, electricity and cold is the same in the case of cold produced from heat or electricity coming from cogeneration installations;

peak consumption of cold may or may not use the same form of primary energy as the cold produced by heat or electricity produced by cogeneration plants.

Comparing the conditions that define the notion of cogeneration with those for trigeneration, the following contradictions appear, from the point of view of combined production:

a) cold production plants are separate from those that produce electricity and heat;

b) demand in the form of cold may not be simultaneous with that of electricity and heat, which are simultaneous;

c) as a form of energy, cold is also heat, but at a different thermal level, so from a thermodynamic point of view, trigeneration defined above is also a bi-energy system, similar to cogeneration;

d) trigeneration necessarily presupposes the prior existence of cogeneration.

Regarding the structure of a trigeneration plant (CTG), starting from the above, it results that it is characterized by the existence of two groups of installations:

A. installations specific to the cogeneration plant, with:

– cogeneration installations (ICG), for the cogeneration production of electricity and heat;

– peak thermal installations, for the production of heat only;

B. installations, additional to CCG, specific to the trigeneration plant, through:

– cooling installations (IF) for the production of cold in cogeneration mode, based on the heat and/or electricity produced in cogeneration (IF can be with absorption – IFA – or/and with mechanical vapor compression – IFC –);

– cooling installations for its production in peak mode, generally using IFC, driven by electricity from the electric power system or produced by ICG but in monogeneration mode. In some situations, depending on the structure of the installed peak thermal capacities (ITV), compared to that of the simultaneous heat and cold demands, with peak IF it may appear technically and economically efficient to use IFA driven by heat produced by these installations (ITV).

2 Advantages of the Trigeneration Solution

Trigeneration is particularly advantageous in contexts requiring simultaneous electricity, heating, and cooling, such as manufacturing processes with cooling needs. It offers significant benefits when applied to buildings or complexes with continuous energy needs, including data centers, universities, hospitals, and military bases. Localized trigeneration, similar to distributed generation, enhances power redundancy, reduces energy costs, and allows selling excess electricity to the grid [4].

Most industrialized countries generate the majority of their electricity needs in large centralized facilities with high electricity generation capacity.

Centralized electricity generation in large facilities often results in transmission losses and environmental impacts due to long-distance electricity transport [5].

Large plants can use cogeneration or trigeneration systems only when there is sufficient need in the immediate geographical vicinity for an industrial complex, an additional power plant or a city. An example of cogeneration with trigeneration applications in a major city is the New York steam system. The city of Sydney has embarked on an ambitious trigeneration plan to reduce greenhouse gas emissions by 70% by producing 477 MW of local energy using trigeneration systems.

One of the technologies that has the best performance to be integrated into a trigeneration system is the fuel cell. Systems that operate on fuel cell technology can convert the energy of a chemical reaction into electricity, heat and water. Its main practical applications range from the bulk production of electricity and heat to its use in sectors such as aerospace, maritime or surface transport and portable devices.

The advantages of trigeneration over separate production are similar to those highlighted in the case of cogeneration. They are based on the favorable effects from a technical, economic and environmental point of view, compared to separate production, which are:

– the overall energy efficiency of energy production increases;

– for the same amounts of energy produced, a primary energy saving is achieved;

– by concentrating the production of the three forms of energy and due to the savings in total primary energy consumed, compared to separate production, unit production costs decrease;

– by reducing primary energy consumption, direct and indirect environmental pollution is reduced, with the respective consequences in terms of ecotaxes, therefore of the unit costs of energy delivered by CTG.

3 Hybrid refrigeration plants – IFA/IFC – in industry

In industrial scenarios, hybrid refrigeration systems combining IFA and IFC can be economically and technically beneficial, depending on the available primary energy. For example, when high-pressure steam is available, coupling an IFC with a turbocharger and an IFA with BrLi solution is cost-effective for cooling outputs below 3500 kWf. Such systems utilize steam from the backpressure of a compressor drive turbine, enhancing efficiency [6]. Hybrid systems can also be applied in meat processing plants, where steam is used in turbines before returning to steam generators, optimizing energy use. This approach reduces steam consumption relative to refrigeration capacity, achieving significant energy savings. Hybrid systems can also leverage waste heat in chemical processes, utilizing it for cooling needs, as seen in the petrochemical industry.

Two typical examples of such combinations are presented below.

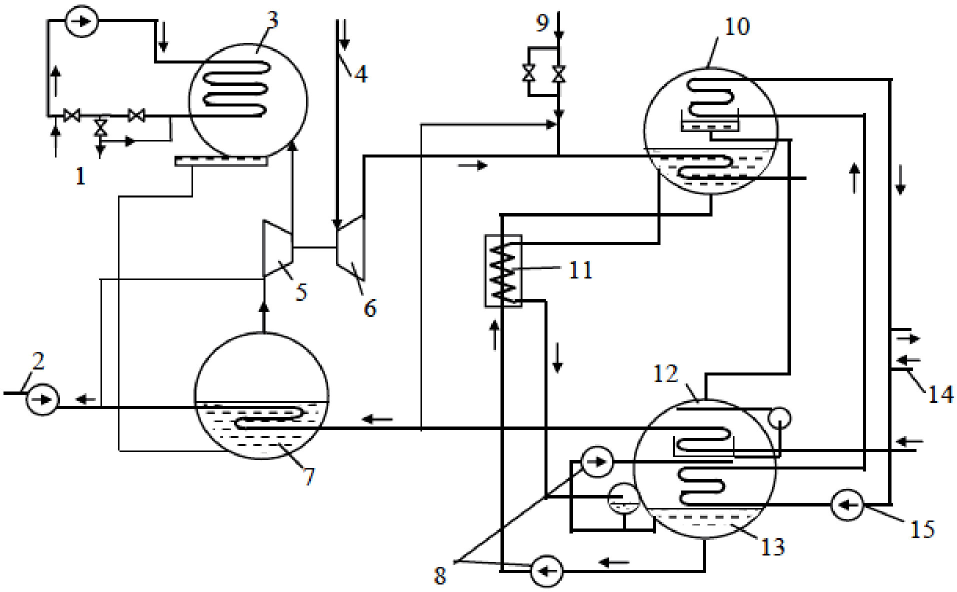

Fig.2 Schematic diagram of a combination of an IFC with a turbocharger driven by a backpressure steam turbine, the backpressure steam of which is used in the steam generator of a BrLi IFA

1 - cooling water; 2 - chilled water for the air conditioning system; 3 - condenser; 4 - high-pressure steam; 5 - turbocharger; 6 - backpressure steam turbine; 7 - evaporator; 8 - solution pumps; 9 - low-pressure steam; 10 - low-pressure steam generator; 11 - heat exchanger - regenerative; 12 - evaporator; 13 - absorber; 14 - cooling water; 15 - cooling water pump

When high-pressure steam (8...42 bar) is available, it is possible to couple an IFC with a turbocharger and an IFA with BrLi solution, shown in Fig. 2.

Depending on the condition of the live – high pressure – steam available, it is possible to use it first in the turbine and then in the steam generator.

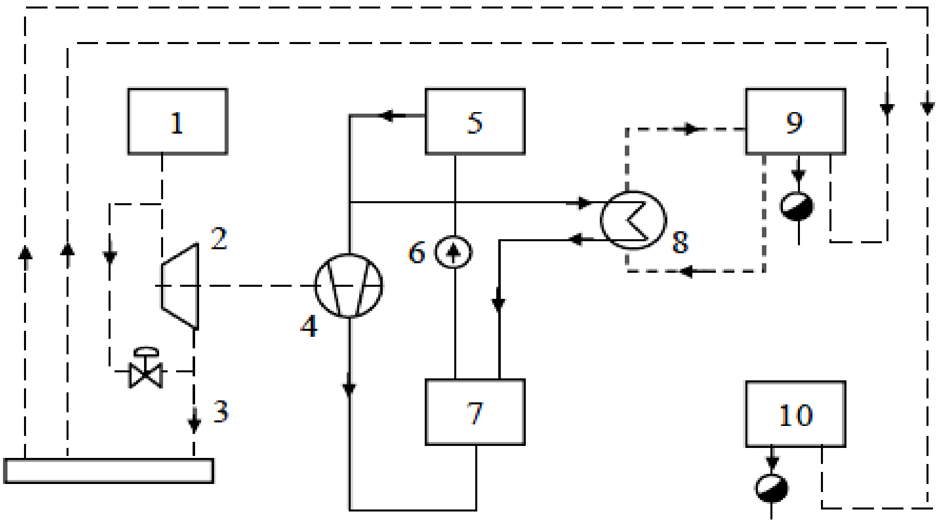

Fig. 3. Schematic diagram of the coupling of an IFA with an IFC, for a meat processing plant:
1 - steam generator at 40 bar/450°C; 2 - steam turbine, with backpressure; 3 - steam at 3 bar; 4 - turbocharger with R22 freon; 5 - cold consumer; 6 - pump for R22; 7 - IFC with R22 turbocharger, at –10/+35°C; 8 - condensate cooler; 9 - IFA, at –15/+40°C; 10 - steam consumer for technological purposes.

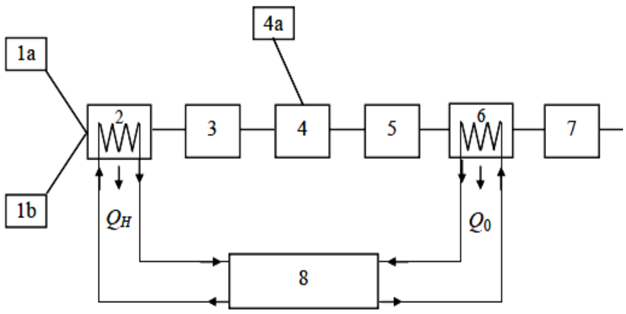

Fig. 4. Schematic diagram of an IFA operating with waste heat from a technological process
1a, 1b - raw materials; 2 - exothermic reactions that heat the IFA steam generator; 3, 4, 5 - intermediate technological stages; 6 - technological stage that requires the cold produced by the IFA evaporator; 7 - final stage of the technological process; 8 - IFA.

This reduces the specific steam consumption, in relation to the refrigeration capacity of the machine, as follows (for a nominal refrigeration capacity of 1000 kWf):

Heating steam parameters steam flow rate:

- 8 bar, 275°C..................................1700 kg/h;
- 32 bar, 400°C................................1500 kg/h;
- 42 bar, 430°C................................1400 kg/h

In such a mixed operation of IFC with IFA, the refrigeration productions of IFC + IFA are combined to such an extent that the steam turbine produces the share of steam that would otherwise not be used. The distribution of the total cold production between the two types of IF is: 35%/65% – at low pressure and 45%/55% – at high pressure.

In the case of plants that self-produce their electricity, the use of an IFA allows, in most cases, an interesting operation in terms of technical and economic performance, in the form of trigeneration: heat/mechanical work/cold. Thanks to such an installation, for each ton of steam consumed by the IFA, an additional amount of electricity is produced upstream of it, which allows reducing the consumption of electricity from the SEE, to power the electric motors required by the IFC (its compressor). In this way, a double energy gain is achieved, allowing a faster depreciation of the IF [7].

It is found, for example, that for a nominal refrigeration capacity of 1160 kWf and an evaporation temperature of - 15°C, at a cooling water temperature at the consumer of + 35°C, an IFA needs 29 kWe, and an IFC, 380 kWe.

If an IFA powered by 40 bar, 450°C steam is used, coupled with a steam turbine, an additional electrical power of 430 kWe will be available. If the parameters of the live steam available are 18 bar, 350°C, the power gain decreases, but still remains at an important value of 300 kWe.

There are also numerous cases in which an IFA powered by waste steam from an IFC driven by a steam turbine can be directly coupled, as in the schematic diagram in Fig. 3. This represents a particularly rational use of heat for the production of cold. In the example of IFC and IFA comparison, each have a refrigeration capacity of 2150 kWf. The steam consumption is only 1400 kg/h for 1000 kWf, which means a significant gain compared to the hybrid installation presented in fig. 2.

In particular, in the chemical industry, it is currently sought to increase the profitability of various manufacturing processes by using waste heat, converting it into cold demand – as shown in Fig. 4.

This is the case of the petrochemical industry, where large amounts of waste heat (at 170°C) are used, which can be used to cover cooling demands at temperature levels of - 30 ... - 45°C.

3.1 Construction of central cooling stations (SCF)

Central cooling stations typically use IFC due to their high COP, employing modern components like plate heat exchangers and efficient controls. While electric motors are common energy sources, centralized systems may use steam, gas turbines, or alternative engines. IFA is often preferred based on local energy costs. Designing SCF involves determining total cooling capacity, linking components under technical and cost constraints, and considering future expansions. Multiple cold water production plants can enhance safety, flexibility, and cost control by optimizing temperature, flow rate, and energy sources.

The energy sources for the operation of IF are most often electric motors, but in the case of centralized cold supply systems, other efficient solutions are often used as forms of energy consumed. These can be steam – with various origins – gas turbines, or other drive engines.

In such situations, IFA is often preferred, the choice being also determined by the local costs of the energy consumed.

The design of a centralized cold production station – SCF – means, in addition to establishing its total cold production capacity, also the way to realize–link–the various necessary components under various technical restrictions and low costs, including those related to investments and long-term maintenance expenses. These are taken into account in the conditions of future expansions, including from the point of view of possible future changes of the solutions.

In a network system, there can be several cold water production plants, including accumulation facilities, which increase the safety and flexibility of distribution.

When the demand for cold increases, this may require an increase in capacity in the existing networks.

The existence of several sources of cold production can also ensure a better connection for the operational control of the various parameters and a reduction in costs, due to [8]:

– avoiding unnecessary cost increases;

– regulating the supplied temperature and flow rate on each plant;

– possibly, choosing the appropriate type of primary energy source for each plant;

– integrating some of the cooling plants for peak production;

– integrating existing cooling plants into the system, in order to limit the investments related to a possible new IF.

3.2 Series and/or in parallel solution

Refrigeration plants for centralized cold supply systems need variable load operation, achievable through series, parallel, or combined connections. Series connections offer multi-level water cooling but have power limitations. Parallel connections mix cooled water from each plant before distribution, providing flexibility and cost efficiency. A series-parallel arrangement allows optimal adaptation to demand variations, accommodating additional modules as needed.

For example, the air cooling process in the France-England tunnel operates with a system consisting of three open IFs, supplemented by an IFC, which cool the water to the required temperature.

However, this technique has limited power: when the demand is too high, it cannot be ensured with only one refrigeration plant.

The most widely used system is the one with parallel connection of IF. In these conditions, the cooled water from each IF is mixed in a collector, before being sent to the cold water network. Such a system is realized, for example, in the shopping center "Les Halles" in Paris, composed of 10 IF in parallel: 9 are IFC with centrifugal compressors and one with a screw compressor.

A series-parallel combination can offer superior flexibility to adapt to the variation of demand.

In this situation, with the increase in demand, independent modules with capacities between 70 and 84.5 MWf could be installed.

4 Refrigeration systems in trigeneration solutions

Refrigeration systems require external energy sources for condenser cooling and operation, provided as mechanical work for IFC or heat for IFA. Trigeneration systems leverage cogeneration to supply energy for refrigeration, with technical integration depending on the cogeneration plant's thermal agent and consumer energy requirements. Optimal integration balances technical and economic factors, considering energy demands, cogeneration plant specifics, and external economic influences.

On the other hand, the trigeneration solution assumes the existence of the cogeneration solution, which provides the refrigeration system with the energy necessary to "drive" it.

Depending on the nature and parameters of the thermal agent delivered by the cogeneration plant, simultaneously with the ratio between the quantities of energy in the form of heat, electricity and cold, which must be provided to consumers over time through the trigeneration solution, the technical modalities for the practical inclusion of the IF in cogeneration plants (CCG) result, achieving the concrete trigeneration solutions. The respective inclusion must be decided following technical and economic optimization calculations at the level of the entire trigeneration solution. A series of characteristic aspects and some results of these optimizations are presented below.

4.1 Combining IFA with IFC in a CCG, directly using the heat produced by fuel combustion

Cold production systems can utilize combustion processes as hot sources, employing two-stage absorption refrigeration cycles where heat from high-temperature stages powers low-temperature steam generators. In cogeneration cycles, mechanical work drives the IFC compressor, while exhaust heat powers IFA steam generators [9]. The system delivers mechanical work and heat, dissipating excess heat into the environment. Thermodynamic efficiency is calculated based on input and output heat and work. Economic analysis compares real-world scenarios, assessing investment recovery based on mechanical work consumption, cooling demand, and specific fuel consumption. Flexibility and heat source options influence IFA integration, with two-stage IFA offering high COP. Single-stage IFA may require high temperatures, while two-stage IFA can use various heat sources. The choice between single and two-stage IFA depends on available heat and economic considerations, with steam turbines and hot exhaust gases providing suitable heat sources.

From a thermodynamic point of view, the energy efficiency of the whole of this installation is given by:

$$COP = \frac{T_e}{T_c - T_e} \cdot \frac{T_1 - T_c}{T_1} \tag{1}$$

Which also can be written:

$$COP = COP_{CC} \cdot \eta_{cpe} \tag{2}$$

where,

$$COP_{CC} = \frac{T_e}{T_c - T_e} \tag{3}$$

is COP equivalent of cooling proecess, and

$$\eta_{cpe} = \frac{T_1 - T_c}{T_1} \tag{4}$$

is the efficiency of the work production cycle.

Under these conditions, the maximum value of COPCC, for an infinite number of stages, represents the efficiency of the reversible Carnot cycle:

$$COP_{MAX} = \frac{T_e}{T_{ac} - T_e} \tag{5}$$

Starting from these aspects, a comparative economic analysis is presented between four real situations:

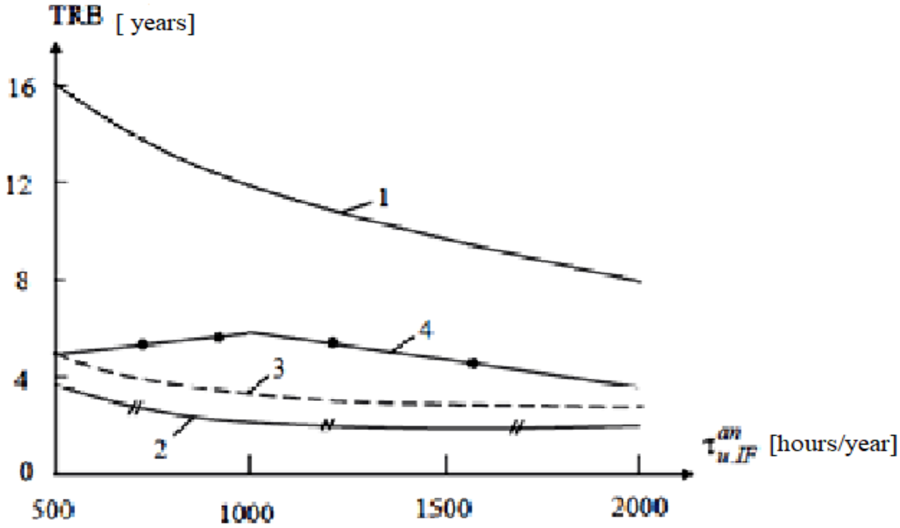

Fig. 5. TRB variation depending on the annual duration of use at the nominal capacity of the installation:
1 - TG+IFC+IFA with steam in 2 stages; 2 - MAI+IFC+IFA with hot water in one stage; 3 - MAI+IFC; IFA with direct combustion, in 2 stages

a) the “engine” cycle with a gas turbine (GT), with an IFC with centrifugal compressor, plus two stages of IFA, with steam for the steam generator;

b) the “engine” cycle with an internal combustion engine (IC) and a single-stage IFA, using hot water in the steam generator;

c) the “engine” cycle with an internal combustion engine and an IFC with centrifugal compressor;

d) a two-stage IFA, with direct combustion.

Except for case (d), all the others have the same mechanical work consumption of 1050 kWe (produced under ISO conditions, either with TG or with IFA) and a cooling demand of approx. 5800...7600 kWf.

The results of the technical and economic calculations, based on the criterion of the gross recovery period – TRB – of the investment, are presented in Fig. 5. It is found that, in this respect, the most efficient is variant (b), where TRB = 1...4 years, closely followed by variant (c). Variant (a) has the highest TRB values of approx. 9...16 years, followed by variant (d), with TRB = 4...6 years.

Regardless of the variant analyzed, increasing the annual duration of use of the nominal capacity of the ensemble leads to an increase in its economic efficiency (TRB decreases) [10].

If a comparative analysis were made in terms of specific fuel consumption, then variant (b) is the one that leads to the lowest value (1.02...1.07) and a COP value of 5.5 - 6, while in variant (c) - without IFA - the specific fuel consumption reaches 1.14...1.19.

In addition, the following technical aspects related to the CCG in which the IF is integrated are worth noting:

– IFA ensures the greatest flexibility, because the heat required for the steam generator can be provided in various forms, depending on the concrete possibilities of the CCG;

– Two-stage IFA ensures a high COP but, in the case of a single stage, requires a high temperature of the heat used in the steam generator;

– the inclusion of the IFA in a CCG can be achieved in the following ways:

• for a single-stage IFA: with hot water at 80...130°C, or with steam at approx. 1 bar;

• for a two-stage IFA: with steam at 3...9 bar, or with flue gases at 280...800°C;

– although a single-stage IFA can use low-pressure steam, the most common heat source is the cooling assembly of the MAI, where hot water is available, most often, at 70...140°C. Here, however, it must be taken into account that the value of the heat used depends on the flow rate and the temperature difference achieved between the flow and the return and on the fact that the return temperature value itself greatly influences the production capacity of the IF.

Many CCGs with steam turbines use steam with a pressure of 8...15 bar, useful for two-stage IFA designed for 8 bar steam. In the case of TG and MAI, the hot exhaust gases can be used directly for two-stage IFA.

5 Conclusion

Cogeneration plants in a CCG face variable thermal loads based on consumer demands, affecting economic efficiency. Urban consumers typically have lower thermal load flattening, while industrial consumers exhibit higher flattening, influencing cogeneration coefficient values and annual thermal load percentages. Increasing heat demand, especially in summer, enhances cogeneration efficiency by utilizing heat for IFA cold production. The integration of IFA in SACC based on CCG is economically justified by enhanced efficiency and reduced seasonal load gaps. Trigeneration solutions should prioritize IFA-based cold production, with technical and economic optimization determining the optimal mix of IFA and IFC for base and peak loads. Integration depends on energy demand characteristics, cogeneration plant factors, and external economic influences. Industrial energy demands vary with technological processes, influencing IF integration and local secondary energy resource utilization. Urban consumers' seasonal cold and hot water demands affect integration, with cooling water source size and temperature playing a role. Cold temperature requirements differ between industrial and urban consumers, influencing IF choice and limiting IFA applicability for sub-zero cold production.

This situation increases the interest in any heat demand – especially in summer – that could fill the respective gap, so as to increase the average annual thermal load of the ICG, which implicitly determines the increase in the technical and economic efficiency of the entire cogeneration solution.

Or, the heat demand that may appear additionally in summer, for urban consumers, or in various other periods of the year, for industrial consumers, is the heat demand for the production of cold within the IFA. This is the justification for which IFA are so “interesting” for integration into SACC based on CCG.

This also justifies the tendency of specialists to consider that a true trigeneration solution must be based on the production of cold with IFA, at the expense of using for its “training” the heat obtained in the ICG, in cogeneration mode. Of course, from case to case, depending on the results of the technical-economic efficiency calculations, the optimal mixed solution for cold production may appear: IFA for base - semi-base cold consumption and possibly IFC for peak consumption regimes.

The technical solutions adopted for the integration of IFA into SACC based on CCG and their economic efficiency depend on three categories of factors:

A. factors that characterize quantitatively and qualitatively, including the simultaneous annual variation of the demand for heat, electricity and cold - the balance of energy demands - for the consumers in question;

B. technical-economic factors specific to the CCG that may be used;

C. "external" factors, of a technical-economic nature specific to the operation of the ensemble formed by CCG, heat transport and distribution, into which the CCG is to be integrated.

In the case of industrial consumers, the type and especially the variation over time of energy demands depend almost exclusively on the nature of the technological processes.

As a result, the balance of the three main forms of energy consumed (heat, electricity, cold) is characteristic of each specific case. Part of the influence on the integration of IF into CCG is the existence of local secondary energy resources, in the form of heat, which could be used to "train" possible IFAs and waste heat with temperatures of 25...35°C, which could be used for cooling in the IFA absorber and condenser.

In the case of urban consumers, a particular influence is the share – especially in summer – of the demand for cold and hot water, compared to the demand for heating and hot water, in winter, and here, a great influence is the size of the cooling water source and its temperature, depending on its type (cooling tower, water from deep wells, from lakes, etc.).

Between the two large categories of consumers, presented above, there is another specific aspect, related to the thermal level of the necessary cold. Thus, in the case of industry, from case to case it can be cold above 0°C or below 0°C, which completely changes the type of IF that can be used and in any case, for cold 0°C, we can no longer talk about IFA, and especially those with water solution - BrLi. In the case of urban consumers, it is about the consumption of cold for air conditioning in summer, which requires cold at 5 - 10°C, which can currently be achieved with any IFA.

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