A NEW INTELLIGENT PREDICTIVE SOLAR-GAS TRIGENERATION SYSTEM FOR AIR CONDITIONING INDUSTRIAL SPACES

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ABSTRACT

The Tunisian strategy for energy transition 2014-2030 is a large scale deployment of renewable energy (30%) and energy efficiency (30% energy savings). Cogeneration and trigeneration technologies in the industry and the commercial sector are the most recommended ways to optimize fuel and electrical savings and thus to achieve energy efficiency. Moreover, the benefits of the trigeneration are not limited to the country, especially in the regularization of the load curve which is increasingly affected by the emergence of a new peak due to the cooling of industrial buildings and the increasing demand for industrial refrigeration. Moreover, such installation provides a significant net economic impact for industrial companies. The implementation of an intelligent management system for solar-gas contribution is thus important to maximize the air conditioning predictive control in industrial buildings. This work deals with the retrofitting of an existing industrial cogeneration plant to an intelligent trigeneration system which combines a thermal solar energy contribution through solar collectors integrated into the roof of an industrial building located in the North of Tunis, Tunisia. Indeed, the industry in question plans to generate industrial cold production mode with the principle of trigeneration wich is considered as a new approach in Tunisia.

Keywords: Smart building, predictive model, HVAC, solar-gas trigeneration, industrial building cooling

INTRODUCTION

One of the proposed solutions for the case described in the abstract is to use an absorption refrigeration unit and Organic Rankine Cycle (ORC) arranged in cascade with energy cogeneration unit and solar thermal installation. This refrigeration unit is expected to replace, wholly or partially, an existing compression refrigeration unit and, thus, improve the overall energy efficiency through optimal energy integration. In this paper, we also present the results of an experimental study that we conducted on the existing cogeneration unit. The tests carried out have allowed us to characterize the performance parameters and the structure of a new parametric model associated with the cogeneration part. The experimental study revealed the existence of original correlations between the various operating parameters, such as ambient temperature.

Due to the obtained experimental results and the conceptual analysis involving coverage of chilling requirements and structure, we succeeded in simulating the installation behavior of the projected solar-gas tri-generation according to two possible conceptual variants. The installation should be managed intelligently, taking into account the level of sunlight, ambient temperature, the occupancy rate in staff and the rate of production and storage of industrial products. Our principal goal is to offer the optimal design and predict energy performance in order to allow to best plan achievement of the industry in question.

DEVELOPED CONFIGURATION

In this work, the configuration of the thermal power, the solar energy captured at the collectors and steam generated from the heat recovered from the hot gases coming from the heat engine, are supplied to the Organic Rankine Cycle (ORC) via a buffer tank. The cooling effect is produced by two cycles: firstly, using vapor-compression cycle which is powered by the ORC or an electrical generator when solar gain is low and the second source is the absorption cycle which works on the heat discharged by the ORC [1, 6] or directly from the hot gases coming from the heat engine based on the operation mode. The heat that comes from the ORC to the absorption cycle is either stored or used immediately.

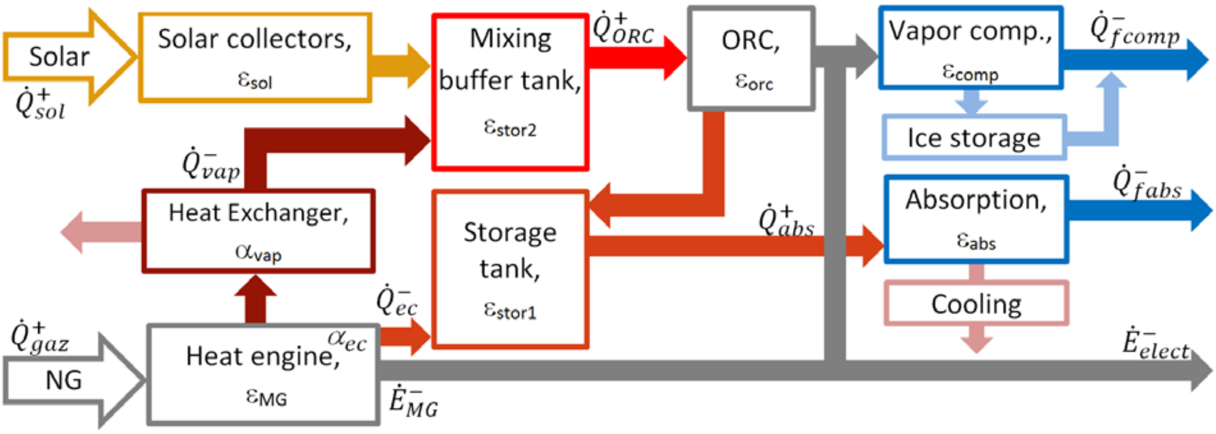

Figure 1 : *A schematic disgram for the principle of type Sunlife 3 installation.*

A NEW PREDICTIVE MODEL

The change in internal energy is assumed to be zero. The system is therefore evolving in quasi-stationary operating conditions.

Overall Efficiency Model: Type Sunlife3

The ratios, shown below, are used to simulate energy balance and the overall efficiency of trigeneration under the different assumptions.

The solar contribution, (τ_{sol}) is the ratio of the solar gain at the solar collectors to the total heat input of solar gain and the primary heat from natural gas:

$$\tau_{sol} = \frac{\dot{Q}^{+}_{sol}}{\dot{Q}^{+}_{sol}+\dot{Q}^{+}_{gaz}} \tag{1}$$

The ratio of the net electrical utility produced to the sum of the electrical power produced by the ORC and the heat engine is given by:

$$\tau_{elect} = \frac{\dot{E}^{-}_{elect}}{\dot{E}^{+}_{MG}+\varepsilon_{orc}.\dot{Q}^{+}_{ORC}} \tag{2}$$

The overall efficiency of the given configuration (dual input solar-gas with the heat engine cogeneration) is based on two assumptions:

Assumption 1 : The system is considered to mainly produce both cooling and electricity and for which the following expression is developed :

$$\varepsilon_{g-cog.trigen} = \frac{\dot{Q}^-_{fabs} + \dot{Q}^-_{fcomp} + \dot{E}^-_{elect}}{\dot{Q}^+_{sol} + \dot{Q}^+_{gaz}}$$

$$\begin{aligned}
&= \varepsilon_{abs}.\varepsilon_{stor1}.\varepsilon_{stor2}(1-\varepsilon_{orc}).\left(\tau_{sol}.\varepsilon_{sol} + \alpha_{vap}.(1-\tau_{sol})\right) \\
&+(1-\tau_{sol}).\left(\varepsilon_{abs}.\varepsilon_{stor1}.\alpha_{ec} + \tau_{elect}.\left(\varepsilon_{MG} + \varepsilon_{stor2}.\varepsilon_{orc}.\alpha_{vap}\right)\right) \\
&+\varepsilon_{comp}.(1-\tau_{elect}).\left(\tau_{sol}.\varepsilon_{orc}.\varepsilon_{sol}.\varepsilon_{stor2} + \left(\varepsilon_{stor2}.\alpha_{vap}.\varepsilon_{orc} + \varepsilon_{MG}\right).(1-\tau_{sol})\right) \\
&+\tau_{elect}.\tau_{sol}.\varepsilon_{orc}.\varepsilon_{sol}.\varepsilon_{stor2}
\end{aligned} \tag{3}$$

Assumption 2: The system is assumed to mainly provide both cooling and electricity with the cooling is the only recognized final output. The following expression is given for this scenario:

$$\varepsilon'_{g-cog.trigen} = \frac{\dot{Q}^-_{fabs} + \dot{Q}^-_{fcomp}}{\dot{Q}^+_{sol} + \dot{Q}^+_{gaz}}$$

$$\begin{aligned}
&= \varepsilon_{abs}.\varepsilon_{stor1}.\varepsilon_{stor2}(1-\varepsilon_{orc}).\left(\tau_{sol}.\varepsilon_{sol} + \alpha_{vap}.(1-\tau_{sol})\right) + (1-\tau_{sol}).(\varepsilon_{abs}.\varepsilon_{stor1}.\alpha_{ec}) \\
&+\varepsilon_{comp}.(1-\tau_{elect}).\left(\tau_{sol}.\varepsilon_{orc}.\varepsilon_{sol}.\varepsilon_{stor2} + \left(\varepsilon_{stor2}.\alpha_{vap}.\varepsilon_{orc} + \varepsilon_{MG}\right).(1-\tau_{sol})\right)
\end{aligned} \tag{4}$$

Both models have the advantage which is not involving any performance parameters other than those used for the energy component in the considered configuration. However, the feasibility and the optimization of such configuration must be validated at the design phase using process integration methods such as pinch technology [2, 3, 5, 6 ,7]. The goal here is to verify the consistency of the heat exchange surfaces used [3, 4].

Parametric Representation Model of Power Outputs

By identifying the following terms:

$$\dot{Q}^+_{ORC} = \varepsilon_{stor}.\left(\dot{Q}^+_{sol}.\varepsilon_{sol} + \dot{Q}^-_{vap}\right) \tag{5}$$

$$\dot{Q}^+_{gaz} = \dot{Q}^+_{sol}.\left(\frac{1-\tau_{sol}}{\tau_{sol}}\right) \tag{6}$$

$$\dot{Q}^-_{vap} = \alpha_{vap}.\dot{Q}^+_{gaz} \tag{7}$$

$$\dot{Q}^-_{ec} = \alpha_{ec}.\dot{Q}^+_{gaz} \tag{8}$$

$$\dot{E}^-_{MG} = \varepsilon_{MG}.\dot{Q}^+_{gaz} \tag{9}$$

In this work, the following parametric presentation has been developed :

$$\dot{Q}^-_{fabs} = \varepsilon_{abs}.\left(\varepsilon_{stor1}.\varepsilon_{stor2}.\tau_{sol}.\varepsilon_{sol}.(1-\varepsilon_{orc}) + \varepsilon_{stor2}.\alpha_{vap}.(1-\tau_{sol}).(1-\varepsilon_{orc}) + \varepsilon_{stor1}.\alpha_{ec}.(1-\tau_{sol})\right).\left(\frac{\dot{Q}^+_{sol}}{\tau_{sol}}\right) \tag{10}$$

$$\dot{Q}^-_{fcomp} = \varepsilon_{comp}.\left(\tau_{sol}.\varepsilon_{orc}.\varepsilon_{sol}.\varepsilon_{stor2}.(1-\tau_{elect}) + \left(\varepsilon_{stor2}.\alpha_{vap}.\varepsilon_{orc} + \varepsilon_{MG}\right).(1-\tau_{sol}).(1-\tau_{elect})\right).\left(\frac{\dot{Q}^+_{sol}}{\tau_{sol}}\right) \tag{11}$$

$$\dot{E}^-_{elect} = \left(\tau_{elect}.(1-\tau_{sol}).\left(\varepsilon_{MG} + \varepsilon_{stor2}.\varepsilon_{orc}.\alpha_{vap}\right) + \tau_{elect}.\tau_{sol}.\varepsilon_{orc}.\varepsilon_{sol}.\varepsilon_{stor2}\right).\left(\frac{\dot{Q}^+_{sol}}{\tau_{sol}}\right) \tag{12}$$

Experimental Model Representing Heat Engine with Cogeneration

For the considered experimental model, the following expression is used based on the electrical power generated by the cogenerative heat engine:

$$\varepsilon_{MG} = \frac{\dot{E}_{MG}^{-} + \dot{Q}_{ec}^{+} + \dot{Q}_{vap}^{+}}{\dot{Q}_{gaz}^{+}} = \varepsilon_e + \alpha_{ec} + \alpha_{vap} \tag{13}$$

The hourly experimental measurements were taken for one year from the cogeneration heat engine at a food processing plant in Tunisia. The results obtained has yielded the following correlations for α_{ec} and α_{vap}:

$$\alpha_{ec} = -0.0006\, \dot{E}_{MG}^{-} + 19.978 \tag{14}$$

$$\alpha_{vap} = -0.0042\, \dot{E}_{MG}^{-} + 17.533 \tag{15}$$

For a typical day, the following values are considered in the simulation:

$$\varepsilon_{MG} = 41\%;\ \varepsilon_{cogen} = 74\%;\ \alpha_{ec} = 22\%;\ \alpha_{vap} = 17\%$$

Experimental Model Representing the Efficiency of the Absorption Machine

The absorption refrigerator exchanges heat with three sources given by three levels of temperatures denoted by T_{m0}, T_{m1} and T_{m2}, which are those of the evaporator, the cooling tower and the generator.

We propose an empirical model that has been widely validated using both dimensional and dimensionless analysis and it was inspired by two basic expressions of COP.

$$\varepsilon_{abs} = c_{0}.\cdot\left(\frac{T_{m0}}{T_{m2}}\right)^{c1}\cdot\left(\frac{T_{m2} - T_{m1}}{T_{m1} - T_{m0}}\right)^{c2} \tag{16}$$

The empirical model we developed has been validated through an experimental study in 2015; with our experience in the field, we were able to identify its parameters c_o, c_1 (explaned in the appendix). The experiments were conducted on the absorption chiller (dual solar-gas) with an output of 175 kW used to cool the industrial premises in one of our agro-industry partners in Tunisia.

Experimental Model Representating the ORC Efficiency

The structure of the cycle has a single volumetric turbine stage involving an organic fluid with the high temperature kept constant while the lower temperature is variable. The condensation of the organic fluid does not take place at ambient temperature but at a temperature higher than that required by the absorption machine [1, 3, 4, 5] and it is also subject to the average ΔT_{pinch}. The efficiency can be expressed by the following model where parameters d_o and d_1 are determined experimentally.

$$\varepsilon_{ORC} = d_0.(T_{ORC} - T_{m2})^{d1}.(T_{ORC})^{-1} \tag{17}$$

The Efficiency Model of The Solar Field

After a thorough analysis of the most appropriate solar collectors and the selected temperature ranges, we selected the following model:

$$\varepsilon_{sol} = F'.(\tau\alpha) - \frac{F'.U_{L0}}{E_n}.(T_{m-sol} - T_a) - \frac{F'.U_{L1}}{E_n}.(T_{m-sol} - T_a)^2 \tag{18}$$

This model has been extensively validated in numerous studies involving several experimental works [1, 8].

SIMULATING TYPE 3 SUNLIFE CONFIGURATION

Power Simulation

For $\tau_{sol} = 0.3$, the solar collector surface is 1200 m^2 using vacuum tube collectors.

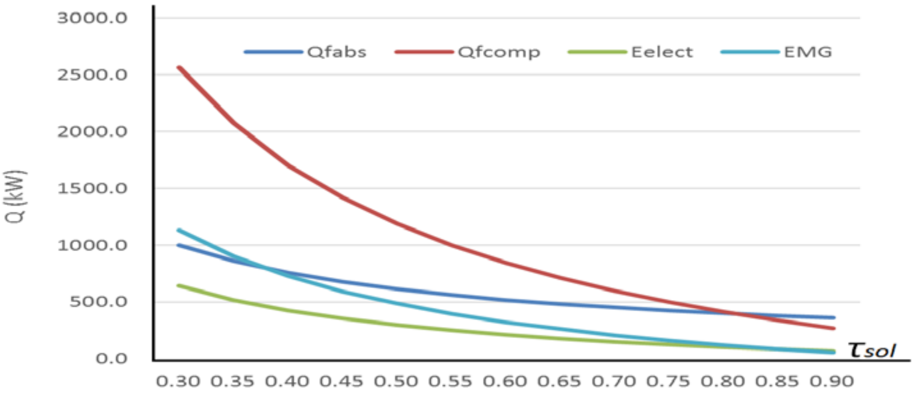

Figure 2: Simulation for the different refrigeration and electrical outputs (Type Sunlife 3).

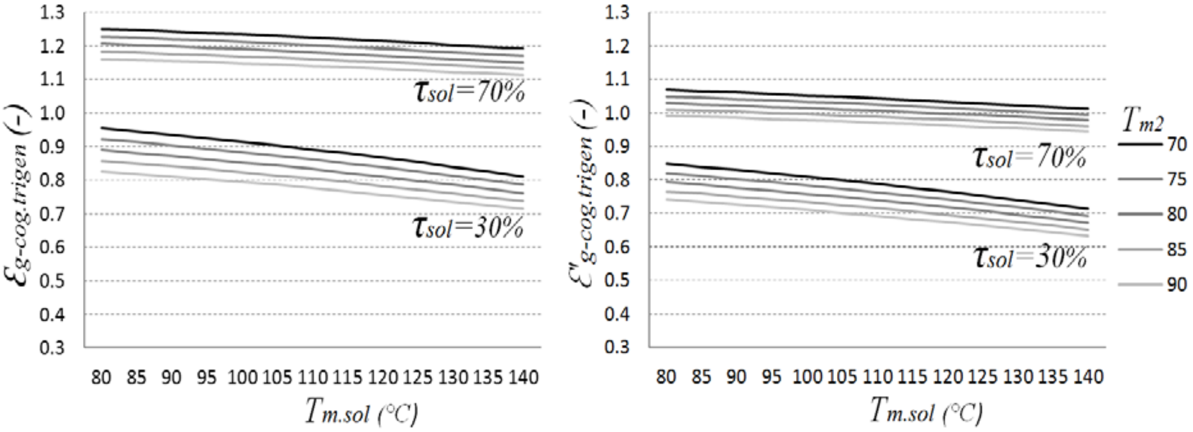

Figure 3: Simulation at Different Effciency Levels around the Nominal Design Point.

MAIN RESULTS

The performance of the trigeneration system (based on the field of solar collectors, heat engine cogeneration and ORC cycle which derives its heat from the hot gases released by the engine) is very sensitive to the temperature variation at the solar collector and the generator of the absorption system and also to the changes in solar radiation. For solar contribution of 30% and 70%, the overall efficiency considering both cooling and electricity is 115% and 75% while the overall efficiency when considering cooling only is 98% and 68% respectively. These results were achieved for the following conditions:

T_{m-sol}= 140 °C; T_{m2} = 80 °C (Type 1 and 2); E_n = 900 W/m^2, T_a = 25 °C.

Notice that for a nominal rate $\tau_{sol} = 0.3$, the surface of the solar collectors is 1,200 m^2 with $\dot{E}_{MG}^{-} = 1100\ kWe$.

CONCLUSION

We have demonstrated that the possibility of improving the nouriously power consuming cooling systems through the combination of solar energy and natural gas which has significant advantages, using a design solar contribution between 30% and 70%. Trigeneration system improves energy efficiency in refrigeration systems and can also guarantee supply of cooling, heating and electricity with the operation being reliably adaptable to the condition when the system is in use. By involving thermal storage in the refrigeration process, it is possible to use this new autonomous dual-fuel energy configuration to ensure an intelligent cooling and power supply for industrial buildings with efficiency exceeding 100%.

SYMBOLS

Symbol	Designation	Unit	Symbol	Designation	Unit
$\dot{Q}^{+}_{sol}$	Heat from solar collectors	kW	τ_{sol}	Nominal solar contribution	(-)
$\dot{Q}^{+}_{gaz}$	Primary heat from natural gas fuel	kW	τ_{elect}	Ratio of net electricity produced	(-)
$\dot{Q}^{+}_{ORC}$	Useful thermal power input to ORC	kW	$\varepsilon_{stor1,2}$	Storage tank effciency,1, 2	(-)
$\dot{Q}^{+}_{abs}$	Thermal power provided to the absorption machine	kW	ε_{MG}	Electrical efficiency of the cogeneration heat engine	(-)
$\dot{Q}^{-}_{fabs}$	The cooling load of the absorption machine	kW	ε_{sol}	efficiency of solar collectors	(-)
$\dot{Q}^{-}_{fcomp}$	The cooling load of the vapor compression machine	kW	α_{vap}	efficiency of vapor recovery at heat engine	(-)
$\dot{E}^{-}_{MG}$	Power produced by heat engine	kW	ε_{ORC}	Effciency of ORC	(-)
$\dot{E}^{-}_{elect}$	Net electrical power produced	kW	α_{ec}	Effciency of steam generation at heat engine	(-)
E_n	Solar radiation	W/m^2	ε_{abs}	absorption machine COP	(-)
T_a	Ambient temperature	°C	ε_{comp}	Vapor compression COP	(-)
T_{m-sol}	Average temperature (solar collectors)	°C	ε_{cogen}	Overall effciency of the cogeneration heat engine	(-)
T_{m0}	Temperature (evaporator)	°C	$\varepsilon_{g-cog.trige}$	Trigeneration system overall effciency (assummption 1)	(-)
T_{m1}	Temperature (cooling tower)	°C	$\varepsilon'_{g-cog.trige}$	Trigeneration system overall effciency (assummption 2)	(-)
T_{m2}	Temperature (generator)	°C	$F'.(\tau\alpha)$	Loss factor	(-)
T_{ORC}	High temperature of the ORC	°C	U_{L0}, U_{L1}	Conductivity of solar collectors	W/m^2/°C
T_{e0}, T_{s0}	Inlet, outlet temp. of the evaporator	°C	c_0, c_1, c_2	Absorption machine coffcients	(-)
T_{e2}, T_{s2}	Inlet, outlet temp. of the generator	°C	d_0, d_1	ORC Coeffcients	(-)
$\dot{m}_0, \dot{m}_2$	Mass flow, evaporator & generator	Kg/s	C_{p0}, C_{p2}	Specific heats	J/kg/°C

REFERENCES

1. Henchoz, S., Buchter, F., Favrat, D., Morandin, M., Mercangoez, M.: Thermoeconomic analysais of a solar enhanced Energy storage concept based on thermodynamics cycles. Energy. Vol. 45 (1), PP 358-36, 2012.
2. Alllani, Y., Favrat, D., Von Spakovsky, M.: *CO2,* mitigationtrough The Use Of Hybride Solar-Combined Cycles. Energy Conversion and Management. Vol. 38, PP S661-S667, 1997.
3. Kane, M., Favrat, D., Larrin, D., Allani, Y.: Small hybrid solar power system. Energy. Vol. 28 (14), PP 1247-1443, 2003.
4. Kane, M., Favrat, D., Allani, Y., Larrin, D.: Thermoeconomic Analysis of Advanced Solar-Fossil Combined Power Plants. Int. Journal of Applied Thermodynamics, Vol. 3 (4), PP 191-198, 2000.
5. Kane, M., Zanelli, T., Favrat, D., Allani Y., Glauser, E.: Conception d'une mini-centrale electro-thermo-solaire hybride adaptée aux pays en voie de développement. Proc. of The Inetrnational Conference on Solar Energy and Buildings (CISBAT'99), PP 103-108, Lussane, 1999.
6. Al-Azri, N., Al-Rawahi, N., Allani, Y.: Solar Power Generation and Solar Cooling Cogeneration. Project Report, The RESEARCH COUNCIL (TRC) Sultanate of Oman, 2012.
7. Al-Azri, N., Al-Thubaiti, M., El-Halwagi, M.: An algorithmic approach to the optimization of process cogeneration. Clean Technologies and Environmental Polices, Vol. 11(3), PP.329-338, 2009.
8. Allani, Y.: Caractérisation des convertisseurs héliothermiques par couplage entre modèles physiques et de représentations. Thèse de doctorat, Ecole Polytechnique Fédérale de Lausanne, 1993.