

The 3rd International Conference on Sustainable Energy Information Technology
(SEIT 2013)

Gases as working fluid in parabolic trough CSP plants

Roberto Cipollone¹, Andrea Cinocca², Angelo Gualtieri³.

^{1,2,3}*Department of Industrial and Information Engineering and Economy,
University of L'Aquila, L'Aquila, 67100, Italy
E-mail: roberto.cipollone@univaq.it, andrea.cinocca@univaq.it, angelo.gualtieri@univaq.it.*

Abstract

The energetic dimension of actual economy is massively oriented towards the use of fossil fuels: they cover a share of 87 % of the energy needs and the trend of this share is increasing, in spite of the commitments adopted by almost all the Countries in the World. Most crucial concern is CO₂ levels in the atmosphere and the positive feedback between Earth's temperature increase and carbon. Actual technologies which make use of renewable sources seem to be not fully suitable to invert this continuous increase of fossil fuels.

Concentrated Solar Power plants (CSP) have had, recently, a huge attention as a technology able to give, in the mean future, a strong contribution to the electrical energy generation. CSP technology has an intrinsic superiority with respect to the other renewable plants but actual plants suffer of many drawbacks which slow down a massive diffusion: these aspects increase costs and do not insure the reliability levels required to make the investments profitable.

Gas as heat transfer fluid inside solar receiver in a CSP Parabolic Trough (PT) type plant is discussed in this paper: this would simplify actual technology in the conversion section, downstream the solar energy collecting phase. The use of gases calls for a new conversion section discussed in this paper based on a direct expansion in gas turbine plants.

The success of this concept is related to the possibility to increase the fluid (gas) temperature above the actual operating maximum values. The paper discusses the performances of a new gas cycle, the performances of actual receivers when fed with gas and introduces and discusses an optimization design parameter which allows a cost decrease and industrial reliability improvement.

© 2013 The Authors. Published by Elsevier B.V.
Selection and peer-review under responsibility of Elhadi M. Shakshuki

Keywords - Solar Energy, Concentrated Solar Power, Parabolic-trough, Heat transfer fluid, Gas turbine.

1. Introduction

Energy saving in final uses, CO₂ reduction and energy production from renewable sources represent the three cornerstones of the energetic and environmental commitments of all the Countries in the World.

In spite of the *politically correct* announcements, in 2011 the global energy consumption grew by 2.5% following the historical trend, but well below the 5.1% seen in 2010, [1]. Fossil fuels still dominate energy consumption, with a market share of 87%. Oil's share is 33% of global energy consumption reaching a 88 million of barrel/day (b/d), while natural gas consumption grew reaching a rate of 8,8 million of m³/d, being responsible of 23.6% of global energy consumption. At the same time, coal consumption reached a rate of 10.2 million of toe/d covering for 30.3% of global energy consumption, [1].

The CO₂ emissions represent another important concern of this so un-balanced fossil fuel based economy. The scientific community agrees about a positive feedback between climate change and the carbon emission: the most important issue is the magnitude of this feedback which is at the center of the scientific debate. Based upon current understanding, the stabilization of CO₂ at 450 ppm will likely result in a global equilibrium warming of 1.4°C to 3.1°C, with a best guess of about 2.1°C: this would require a reduction of current annual greenhouse gas emissions by 70-80% by 2100. Actual CO₂ concentration ranked at an unfortunate level of 395.55 ppm in 2013, so a very urgent intervention should be in the agenda of policy makers.

Non fossil fuel energy generation accounts for only 13%. Excluding large hydro and nuclear, on a worldwide base, *remaining renewables accounted for 3.9% of global power generation*. This discouraging result calls for new conversion technologies based on renewables with greater potential and with a strong industrial feasibility: a new concept which share *energy property and territorial needs* has to be found.

Concentrated solar power (CSP) technologies seem to have these issues and could represent, if duly supported, a real renewable energy breakthrough in the sector of power generation. Making reference to the Parabolic Trough (PT) technology, a heat carrying fluid at high temperature (450-550°C) which moves inside solar receivers acts as high temperature source, suitable to feed almost conventional thermoelectric power plants. So, CSP-PT technology matches downstream conventional generation technologies having upstream a section of capturing solar energy, concentrating it by means of parabolas, to reach a high temperature heat carrying fluid. The possibility to make reference to proven conversion components increases industrial interest, reliability and financial viability of the plants.

In literature, a huge interest has been reversed in recent years toward CSP and, more in particular, to PT technology. In [2] is clearly evidenced that the technical potential of PT-CSP is much greater than the real electricity consumption of the World, [3]. In fact, several important studies [4, 5, 6, 7, 8] agreed about the possibility to have by 2050 50% of electricity produced by CSP. An important social aspect this generation which gives consistency to the sustainability concept is that the production of electricity must match important territorial needs i.e. fresh water production, electrification of rural and well irradiated solar areas, drying processes for agriculture, methane reforming, etc...

However, this CSP interests have not been followed in scientific literature by an engineering industrial improvement [9, 10, 11] and this represents today the weakest point of the CSP-PT technologies. Actual technology considers as Heat Transfer Fluid (HTF) thermal oil and the majority of the plants under construction [12] still make use of this fluid in spite of the significant drawbacks: oil is pollutant, toxic, explosive, difficult to be managed, with a maximum working temperature is 400-450°C and this limits the conversion efficiency.

A step ahead will be done by molten salts (MS) as HTF [13, 14]. As most important aspect, actual MSs reach higher maximum temperatures with respect to thermal oil, till to 550°C: this allows a downstream electricity conversion section with higher efficiency, so a greater profitability. This temperature increase allows also to align thermoelectric power plants toward most advanced layouts, making profit of all the proven technologies available in the sector. Some weakness points which reduce reliability and financial interest are still on the way: the solidification of the MS at temperature below than 290°C requires engineering care during plant operation: the management of daily transients is difficult and all the auxiliary components (pumps, seals, etc...) must have a fail-safe behavior to avoid internal salt solidification. Moreover, energy storage systems are more critical in terms of reliability and

efficiency; conventional alloys cannot be used for chemical compatibility and cross coupled effects from a thermo-mechanical point of view prevent the use of available proven components (bellows, connectors between parabolas, deformable pipes, joints, sealing components, etc...). A great research is under development with the aim to solve important engineering and operational aspects: the fluid sealing systems, the connection solution between parabolas and single receivers, as well as the improvement of solar receivers reliability. Plant size is oriented toward large power stations, of the order of hundreds of MW and this doesn't facilitate the territorial diffusion. The presence of a condensing section in the thermoelectric plant introduces some limitations, mainly in desert areas: it is not surprising that the most important large scale CSP plants, are placed in the coastal areas where sea water is available to condense steam [15].

A real breakthrough could be represented by the use of gases as HTF, [16, 17, 18]. Many components will take benefit of this choice including simplicity and HTF availability. Plant size could be really reduced and several operational aspects would be simplified, being more conventional with respect to the molten salt use (sealing, connection, material compatibility, etc...). The use of gases call for new conversion sections with respect to those actually considered.

The use of gas intrinsically reduces the thermal capacity of the HTF, so its ability to carry heat and to store it inside thermal storage reservoirs for the night-time production. Some efforts have been presented [17] increasing the pressure of the gas as HTF till to 100 bar, but at so high pressure levels reliability decreases and the overall management of the thermal energy collection section increases in complexity and design. In fact, receiver's design at high pressure and temperature is unconventional for the high levels of thermo-mechanical stresses and strains; the need to enhance convective heat transfer between HTF and receiver in order to reduce metal temperature call for new advanced receiver set up (for example, finned receiver from the gas side, [19]).

Therefore, the use of gases as HTF calls for new conversion sections downstream the solar collection. One interesting possibility is offered by expanding it inside gas turbines, without exchanging the concentrated solar heat collected to another fluid. Solar fields and expanding machines, as well as compressors (which restore maximum working pressure), would be fully integrated without separating the two sections (heat collection and electricity conversion). Considering that maximum temperature is limited by mechanical constraints and pressure, the conventional Joule cycle can't be considered as reference plant's cycle. Efficiency can be improved if the compression phase will be done in several stages, intercooling the gas among stages and also expansion phase, re-heating gases inside solar fields. When these two transformations would be isothermal, the cycle is that of the Ericsson and, when fully regenerated, its efficiency is that of the Carnot's cycle. Considering that only a fixed (and limited) number of compressions and expansions can be done, the corresponding cycle has been named as DEC, Discrete Ericsson Cycle, [20]. This new plant layout calls for a system approach in order to select best operating parameters.

A contribution in this direction has been offered by the Authors recently, [21]. The result has been a comprehensive mathematical modeling which has as input the solar radiation and as output the temperature of the HTF. The model takes benefits from previous studies and privileges a global approach, [22]: all the design parameters of a CSP solar field can be setup and the HTF's properties can be calculated, considering thermal oil, molten salt, gases. Thermal efficiency prediction of receivers is a key point when the receiver temperature is increased in order to favor a direct expansion.

In this paper the Authors reinforce from a theoretically point of view the validity of the use of gases in CSP- PT and of the DEC based conversion section, discussing the gas choice and main operating plant parameters. The prediction of the overall receiver length and of the operating conditions of the various receiver branches as a function of the free parameters (maximum pressure and temperature, speed's constraints, heat transfer coefficients i.e. metal temperatures, etc...) allows engineering optimizations and a support for design choices. An interesting parameter given by the power produced by the plant per unit of receiver length has been introduced and discussed: it seems among the most adequate to decrease cost and increase reliability, so plant profitability. When gases operate inside CSP-PT plant, the plant size can

be reduced and this, when compared with conventional CSP-PT using thermal oil as HTF, gives greater flexibility and opens the way to a number of not-only energetic applications.

2. Solar receiver modeling

In a concentrated solar power plant the device which plays a role of primary importance is undoubtedly the solar receiver, responsible for collecting the solar power. The solar receiver is done by a metal tube absorber, surrounded by a glass tube co-axial to the previous one: this positioning has been made in order to increase the amount of solar energy collected, combining high values of the absorption coefficient of solar radiation (short wavelengths) with low values of emissivity in the temperature range corresponding to the one in which the surface emits (long wavelengths). This means that the glass tube behaves as transparent for the incoming solar radiation, but as anti-reflective for wavelengths which are relative to the thermal emission of the internal metal; the glass tube and the corresponding vacuum inside also protects metal from contact with external air, so from oxidation. Differential thermal expansion between glass and metal is compensated by the use of bellows positioned therein.

Heat Collector Element (HCE) is radiated from the concentrated solar power produced by the parabolas, which produces a series of processes which ultimately heat up the working fluid. The inner and outer surfaces of the glass and metal tube show differences in temperature related to the conduction that occurs inside them, while the internal convection is inhibited by the vacuum. Therefore, the solution of the equations that describe all these processes leads to the calculation of the following thermal states: a) the temperatures of HTF, considered uniform on the tube's cross section; b) the temperature of the metal on the fluid side; c) the temperature of the metal from vacuum side; d) the temperature of the glass from vacuum side; e) the temperature of the glass facing the external air.

Inside the metal tube and glass, a good approximation is to consider thermal fields purely radial. In this way, all the above mentioned temperatures changes only with the length of the receiver.

A detailed description of the model used in this paper is in [18, 20, 21, 22].

As HTF moves inside the receiver, its temperature increases due to the heat received by the metallic tube, this modifies the temperature along receiver length. Pressure drops due to friction can be evaluated according to specific correlations as a function of mass flow rate, receiver length, diameter of the receiver and density, [16, 18]. The most important property of the HCE is the thermal efficiency which is given by the ratio of the thermal power reaching the HTF and the solar power radiated by the Sun.

3. Energy conversion section using gas turbine

This paper introduces a gas as working fluid, which is directly expanded inside a series of gas turbines. So, the HTF, is also the working fluid inside a gas turbine plant. With respect of the conventional conversion sections, there is no storage of thermal energy neither the introduction of an additional fluid (water) which is used, as working fluid, inside a thermoelectric plant. Gas turbine cycles (and plants) of the Joule's type, require higher maximum temperature (with respect to the Rankine cycle) in order to have comparable efficiency. Such temperatures (1300°C – 1400°C) cannot be reached inside solar receiver, due to mechanical constrains of the inner tube.

The Authors introduced already DEC (Discrete Ericsson Cycle) in which the isothermal compression is approximated by a sequence of adiabatic inter-cooled compressions. Similarly, the isothermal expansion is done by a sequence of adiabatic re-heated expansions, [23].

Making reference to three compression and expansion stages, the plant layout is in *Figure 1a*: solar fields (SF) use is limited to the high temperature transformation once regeneration (R) is considered.

Solar fields after the expansions act as re-heating units while the inter-cooling needs are fed by external air. In the figure, solar receivers are operated in parallel to limit maximum speed inside them. In fact, proceeding inside the receiver, the gas is accelerated because of the temperature increase and

pressure decrease.

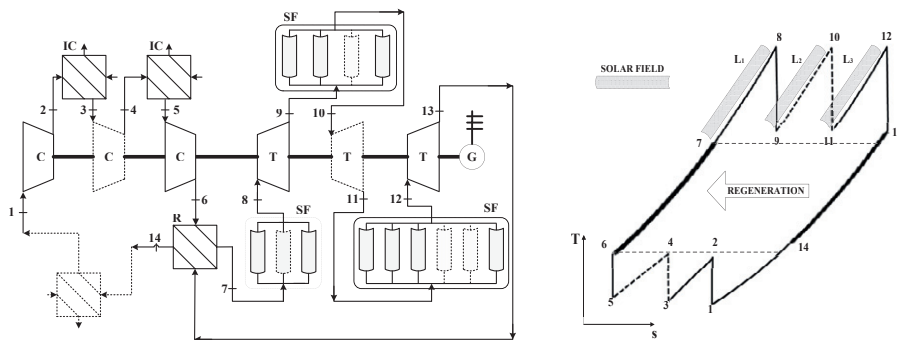


Fig. 1. Gas turbine plant layout (1a) and T-s diagram of DEC cycle (1b) for three expansions and three compressions.

Figure 1b demonstrates the concept of having a series of intercooled compressions: the final temperature of HTF is reduced with respect to the one which happened if a single compression stage would be done. Similarly, the reheated expansions lead the working fluid to a greater temperature compared to the value which occurred if only one expansion stage is considered: this high value calls for a regeneration between the two streams (gas exiting the last compression stage and gas exiting the last expansion) with a sensible benefit in terms of cycle efficiency (and plant). So, a great part of the heating of HTF is done internally, leaving to the high temperature part the role of the solar fields.

The mathematical model of the HCE and that which represents DEC (real compressions, expansions, heat exchanges, etc...), have been integrated and through an iterative procedure, the performances of the plant can be calculated and those of the solar fields.

4. Results

In literature, the use of gases as HTF has been limited to CO_2 and air [16, 17, 18]. When using CO_2 , the plant layout (Figure 1a) must consider, after the regenerator (R), a heat exchanger which “closes” the cycle. The use of air can be simpler thanks to the possibility of a direct discharge into atmosphere. So, the two fluids have advantages and drawbacks when compared each other.

When the gas as HTF is expanded inside gas turbines, many parameters must be observed, and some of them are not directly referred to the HCE performances. Pressure drops, for instance, plays an important role with respect to the case when diathermic oil and molten salts are used. The second parameter is mass flow rate, which significantly changes with the gas type and operating pressure. HTF speed is another parameter which has a significant variation inside receiver, dependent on gas type and operating conditions, strongly influencing pressure losses. So, if gases are used as HTF, several other parameters have to be taken into consideration, and the operating conditions choice becomes more complex and deserves more attention. Before discussing the performances of DEC and with the aim of going deep inside operating conditions and gas choice, a preliminary analysis has been done in order to compare CO_2 and air.

Figure 2 reports the performances of air and CO_2 inside a solar receiver having same inlet temperature and speed of gases. This last condition has been fixed considering that speed inside solar receiver has to be limited to a maximum value: in fact, as the HTF proceeds inside the receiver, temperature increases, pressure decreases and density decreases for both these two reasons. This produces a continuous speed increase to keep initial mass flow rate. A maximum fixed value (25 m/s) avoids pressure losses out of control, noise appearance, macroscopic vibrations, etc... : when this occurs, the fluid has to be split in two parallel branches and it proceeds inside receivers of the same geometry. The phenomena repeat till to the reaching of the same limiting value and flow rate split is done again. Considering that the different

solar fields operate at very different initial pressure levels due to the presence of expansions, the speed control (and flow rate split) has to be carefully managed.

The properties are plotted versus receiver length. All the geometrical data of the HCE have been fixed according the current technology. Three pressure initial levels have been considered, equal to 2 MPa, 5 MPa and 10 MPa. Initial HTF speed has been fixed to 12 m/s. The following considerations apply:

- a. concerning pressure drops, CO₂ demonstrates higher values, so air as should be preferred;
- b. speed increase is lower for CO₂ when compared with air: therefore CO₂ is preferred even if the differences are negligible. When the maximum speed is reached, mass flow rate must be divided in parallel branches;
- c. heat transfer coefficient remains more or less constant inside receiver and it is greater for CO₂: this justifies the lower difference in temperature between metal tube and fluid. Absolute values strongly depend on operating pressure;
- d. HTF temperature increases almost linearly inside solar receiver with a slight deviation for lower operating pressures. CO₂ temperature increases are lower than the corresponding values when using air. So, longer receiver must be used.

The data correspond to different flow rates: the CO₂ one is greater so if the solar field goal is to reach a maximum temperature, the use of CO₂ will require necessarily longer receivers. In fact, CO₂ will require a greater thermal power from the Sun and this is possible only using longer receivers (the specific solar irradiation on the parabolas is the same). This aspect is not the only one present: when using air, metal temperatures are higher and thermal efficiency tends to decrease, so the receiver length tends to increase in order to recover a lower efficiency. But this aspect is not the dominant one and, definitively, the use of CO₂ will require longer receivers. It should be observed that when using CO₂ a greater electrical power is produced by the plant.

Definitively, thermal efficiency represents the most important parameter. The use of CO₂ leads to better efficiencies. The superiority increases when operating pressure decreases: at 2 MPa, after 200 m, thermal efficiency when using air is below 60% while CO₂ shows an efficiency close to 65%. This is clearly due to the higher metal temperature which increases the radiation losses. When the operating pressure increases, the differences between the two fluids are negligible even if CO₂ can be still preferred. Moreover, there are not important differences between 5 MPa and 10 MPa, while undoubtedly the lower pressure is safer and more reliable from an engineering point of view. Observing the other properties in *Figure 2*, there is no need to go over 5 MPa as maximum pressure. Mass flow rate of CO₂ is 1.43 times than that of the air. In conclusion, observing the results in *Figure 2*, there are no important reasons to prefer CO₂ or air: an eventual reason has to be searched beyond the receiver performances.

The opinion of the Authors is that a parameter which allows to make a choice between gases is the electric power produced per unit receiver length and in what follows this parameter has been focused. According to the plant layout in *Figure 1a*), a first analysis has been done in order to evaluate the optimum number of compression and expansion stages. It is clear that when this number increases, the performances of the plant increases but they must have an asymptotic value given by those of the Ericsson cycle. *Figure 3* reports the specific work and the efficiency of the plant when the number of compressions and expansions is increased. Suitable values have been fixed in order to reproduce real values (compressors and expanders efficiency, heat exchanger pinch points, pressure losses inside components, etc...) as well as all the parameters affecting receiver performances. All these data refer to the actual best technology. Maximum HTF temperature is 650°C and pressure has been set at 5 MPa. Intercooling during compression is done using external air a 40°C. The fluid considered for this analysis is CO₂. Intermediate pressures during compression or expansion have been calculated considering a fixed ratio calculated as equal to the root of the overall compression/expansion (ratio) having the order equal to the number of stages. HTF flow rate is equal to 1.43 kg/s. Inlet pressure and temperature are 40°C and 0.1 MPa, solar irradiation equal to 900 W/m².

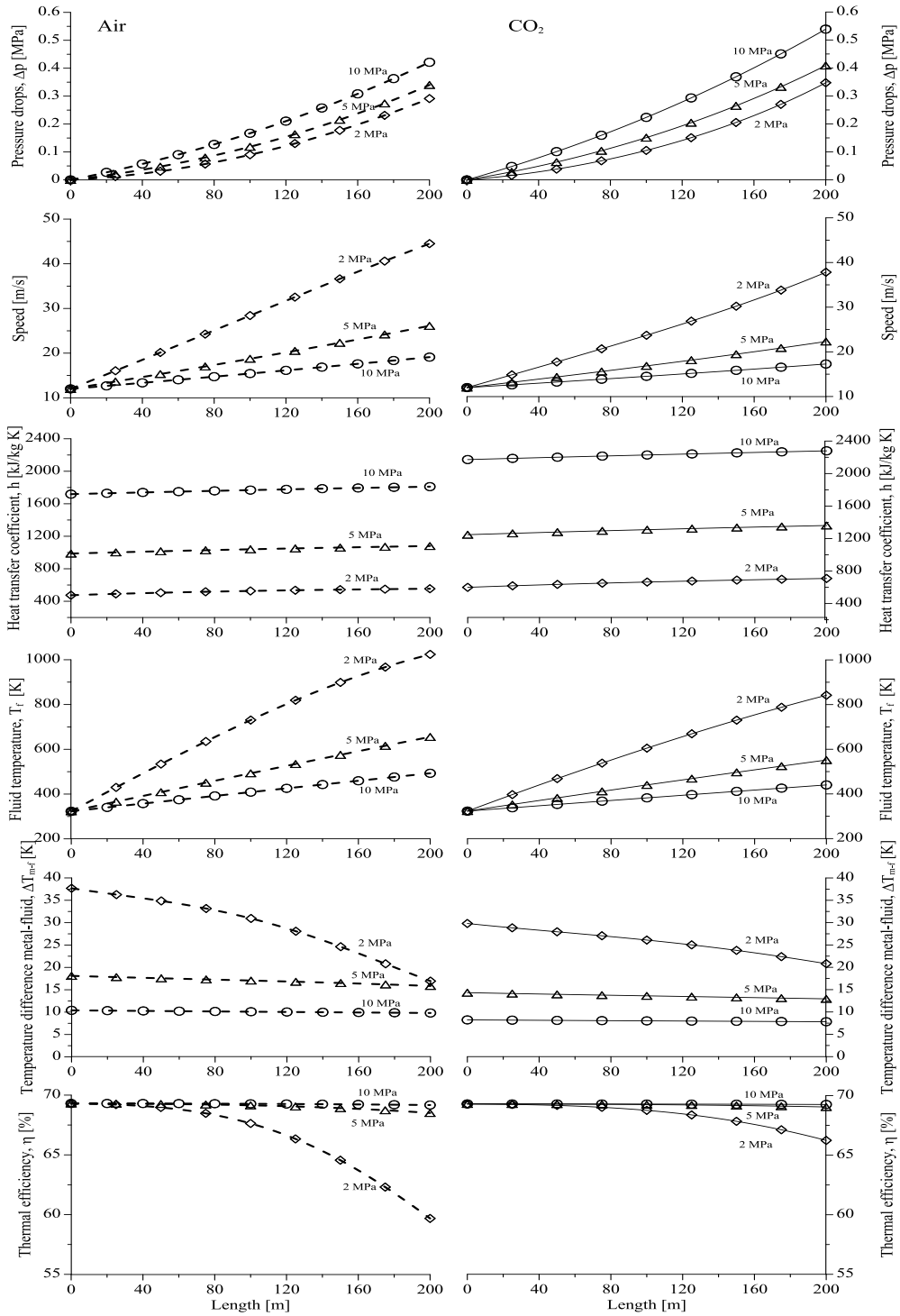


Fig.2. Variation of thermo-fluid dynamic parameter along the receiver length.

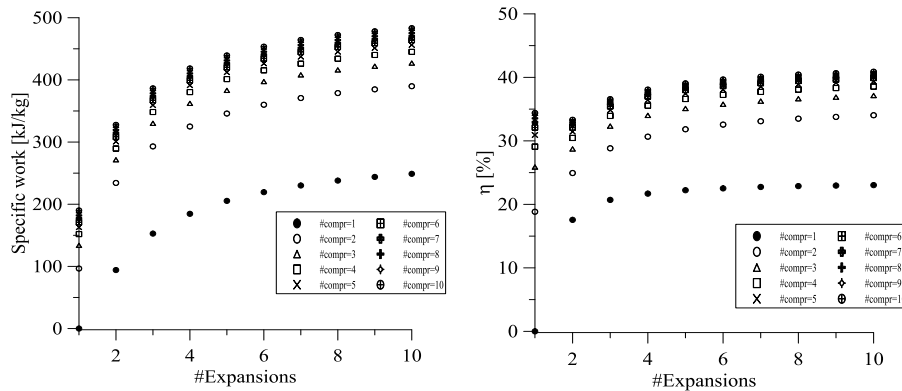


Fig.3. Specific work and efficiency of DEC plant when number of compression and expansion stages increase – a)right, b) left–

The two graphs (Figure 3a and 3b) demonstrate asymptotic values, so from an engineering point of view it is not useful to increase the number of stages beyond a given value. In the Figures, the number of expansions is on the abscissa, while the number of compressions is fixed for each curve. For a fixed number of compressions, there is no need to increase the number of expansions beyond four: from this point on, the additional benefits are lower and the complexity (and costs) of the plant. Same consideration applies when considering, for a fixed number of expansions, the effects of an increasing number of compressions: the curves tend to collapse (in vertical direction) towards a single common curve and, for a number of compressions greater than four, no additional benefits take place. Limiting to four the compression and expansion stages, very interesting and promising values are shown for the efficiency close to 37-38% and for specific work close to 400 kJ/kg. Concerning the efficiency, the values are greater than those obtained in the conventional thermoelectric power plants which make use of diathermic oil or molten salt as HTF. Concerning the specific work, the value obtained opens the way towards a smaller power range of CSP-PT and also this represents an advantage, being possible a wider territorial diffusion.

Limiting the compression and the expansion stages at four, an optimization has been done in terms of power plant per unit receiver length. The cost of the plant, in fact, is dominated by the cost of the solar collection and concentration section. The highest ratio approaches to the condition of the minimum investment cost per unit energy produced.

All the combinations among compression and expansion stages have been calculated considering air and CO₂ as HTF, discussing the sensitivity of the compression/expansion number of machines on power plant per unit receiver length. Calculations have been done respecting the condition that at the inlet of the first solar field (after the regeneration) air and CO₂ must have the same speed: this implies a difference between the two flow rates. When using air, the flow has been set at 1 kg/s while for CO₂ flow rate is equal to 1.43 kg/s. Nine plants have been simulated with air and nine with CO₂: all the thermodynamic properties of the relevant points in Figure 1b) have been calculated and this required the calculation of the HTF thermodynamic states inside receivers. So, the overall receiver length for each plant has been calculated as well as the specific work for each cycle and, therefore, the corresponding power. Overall receiver length resulted adding all the branches needed (in series and in parallel when flow rate has to be split), independently from the pressure level. Table 1 shows absolute values of the power plant per unit receiver length expressed in kW/m: higher values are obtained when using CO₂ and compression stages increase is more important than expansion stages increase on the ratio under discussion. For a fixed number of compressions, the ratio decreases if the number of expansions increases and this is more pronounced for a higher number of compressions.

The highest ratio is obtained for a plant having 4 compressions and 2 expansions reaching the value of 0.96 kW/m. On the contrary, the highest efficiency is obtained for a plant with four expansions and compressions – *Figure 3* – but this requires an overall greater receiver length and the observed ratio decreases to 0.84 kW/m. Limiting the analysis to plants having the same number of compressions and expansions equal to 3 and 4, *Figure 4* shows how the receiver length is distributed among different solar fields.

Table.1. Power plant per unit receiver length (kW/m) as a function of the number of compression/expansion stages

		Air			CO ₂		
#Expansions	#Compressions	2	3	4	2	3	4
	2		0.58	0.78	0.86	0.79	0.91
3		0.63	0.78	0.84	0.78	0.87	0.91
4		0.62	0.74	0.79	0.73	0.81	0.84

For air, the respective total length is 373m for the 3x3 case and 449 m for the 4x4 case. For CO₂ the corresponding lengths are 536 m and 635 m.

The fourth solar field is characterized by a high number of parallel branches – *Figure 4b* – each of one is very short, 10 m – *Figure 4a*). This situation has a very limited engineering interest and data explains the reduction of the power per unit receiver length ratio. Similar conclusion applies for plant which have three compression and expansion stages: the high number of the short (20 m) branches in parallel produces an overall excessive increase of the receiver length.

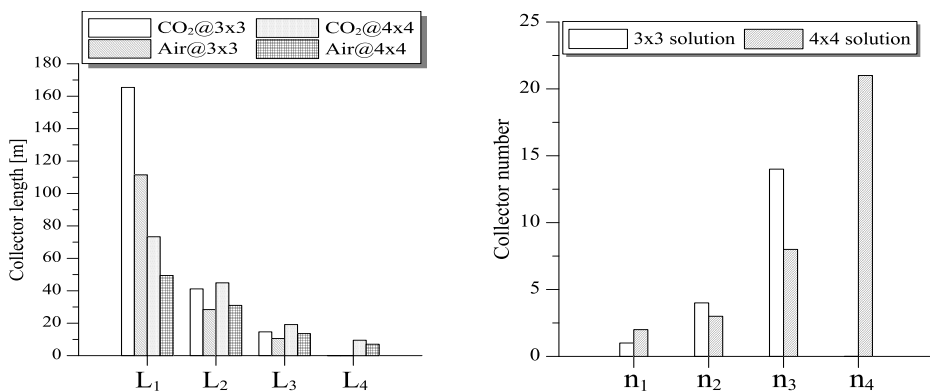


Fig. 4. Collectors length for the plant that use air and CO₂ as HTF.

5. Conclusions

The paper discusses CO₂ and air as working fluid inside CSP-PT plants. Considering the lower thermal capacity of the gas when compared with diathermic oil or molten salt, a new conversion section downstream the solar collection and concentration is presented. The gas is directly expanded across gas turbine stages and, among these stages, a reheating process is done by means of solar fields. In order reduce compression work, intercooling is done using external air. Thanks to the low temperature of the gas after compression and to the high temperature after the last expansion, a regeneration stage has been included, leaving to the solar fields only the role to increase temperature to a specified value. The sequence of the thermodynamic transformations (DEC) approaches an Ericsson cycle.

DEC demonstrates very interesting performances in terms of efficiency, greater than the actual conversion sections based on a thermoelectric power plants. The resulting specific work allows a high

flexibility in terms of power plant which is reduced with respect to conventional plants, so a higher territorial diffusion is possible considering the lower power range that can be reached. To make a DEC, gas inside receiver requires slightly higher temperatures with respect to the actual values: this would decrease receiver efficiency which has been predicted thanks to complete physical consistent model. Receiver modeling and the calculation of plant performances have been integrated and the overall modeling has been used as design tool; receiver length of the different solar fields has been calculated.

The paper considered air and CO₂ as working gases: comparison between the two gases can't be limited to receiver performances but it has to include their behavior in the conversion mechanical section. The power per unit receiver length has been assumed as parameter able to decrease costs, increase profitability and reliability. When this parameter is adopted, optimum plant choices, according to the actual receiver technology and geometry, orient maximum pressure and temperature at 5 MPa and 650°C, with a number of expansion stages lower than compression stages.

References

- [1] BP, *Statistical Review of World Energy*, June 2012.
- [2] MED-CSP – “*Concentrating Solar Power for the Mediterranean Regional*” – Final Report DLR, April 2005.
- [3] F. Trieb et al. “*Global Potential of concentrating solar power*”, German Aerospace Center, Solar Pace Conference, September 2009.
- [4] T. Mancini “*The Status of CSP Development*”, CSP Program Manager Sandia National Laboratories, USA April 4th, 2011.
- [5] *Global Concentrating Solar Power, Outlook 09 Why renewable Energy is Hot* - IEA Solar Paces, Greenpeace International, ESTELA, 2009.
- [6] PriceWaterHouse Cooper “*Delivering on Earth's Solar Potential. Concentrating Solar thermal power as a solution to the world's Energy challenges*”, September 2009 .
- [7] IEA, *Technology Roadmap Concentrating Solar Power*, 2010.
- [8] Greenpeace, International Solar Paces, ESTELA, CSP Outlook 2010, 2010.
- [9] Cipollone R. “*Renewable energy and new economic outlook*” 4th Italian-Russian Forum: “*Cooperation for the Modernization and Innovation*”. Verona (Italy) 27-28 October 2011.
- [10] Meccanotecnica Umbra Group (various authors). “*Molten salt sealing systems for PT-CSP plants*”. Private communication. December 2011.
- [11] Archimede Solar Energy s.r.l. (various authors). “*Technological advancements for PT-CSP solar receiver*”. Private communication. June 2011.
- [12] CSP Today World Map ©, 2012.
- [13] Montes M.J., Abánades A., Martínez-Val J. M.. “*Thermofluidynamic Model and Comparative Analysis of Parabolic Trough Collectors Using Oil, Water/Steam, or Molten Salts Heat Transfer Fluids*” ASME. Journal of Solar Energy Engineering. MAY 2010, Vol. 132 / 021001-1.
- [14] Fernandez-García A. et al. “*Parabolic-trough solar collectors and their applications*”. Elsevier, Renewable and Sustainable Energy Reviews 14 (2010) 1695–1721.
- [15] Garcia Moreno L. E., “*Concentrated Solar Power (CSP) in Desertec – Analysis of technologies to secure and affordable energy supply*”. 6th IEEE International Conference, 2011.
- [16] Rubbia C., “*Use of gas cooling in order to improve the reliability of the heat collection from the solar concentrators of ENEA design*”, 2004.
- [17] Rodriguez-Garcia M-M. et al., “*First experimental results of a solar PTC facility using gas as the heat transfer fluid*”, CIEMAT. 2009.
- [18] Cipollone R., Cinocca A. “*Un modello matematico di supporto alle tecnologie del solare termodinamico a concentrazione*”. 66° ATI National Congress - Cosenza (Italy). 2011.
- [19] *Tubular heat exchanger, in particular receiving tube of a concentrating solar plant*, Patented by ARC s.r.l, Advanced Research Consulting, PCT/IT2010/000441, Via Andrea Doria, 15, 10123 Torino TO.
- [20] Cipollone R., Cinocca A. “*Integrazione tra turbine a gas e collettori parabolici lineari in impianti solari a concentrazione*”. 67° ATI National Congress - Trieste (Italy). 2012.
- [21] Cipollone R., Cinocca A. “*Integration between gas turbines and concentrated parabolic trough solar power plants*”. ASME 2012 International Mechanical Engineering Congress & Exposition, IMECE 2012, Houston, (TX).
- [22] R. Forristall. “*Heat transfer analysis and modeling of a parabolic trough solar receiver implemented in Engineering Equation Solver*”. Colorado: NREL-U.S Department of energy laboratory, 2003.
- [23] Cipollone R., Cinocca A. “*An innovative gas turbine plant for parabolic trough concentrated solar power plants*”. GSTF Journal of Engineering Technology (JET Vol.2 No.1). 2013.