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Comparison between s-CO2 and other supercritical working Fluids (s-Ethane, s-SF6, s-Xe, s-CH4, s-N2) in Line-Focusing Solar Power Plants with supercritical Brayton power cycles

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Abstract

Thermosolar power plants with linear solar collectors and Rankine or Brayton power cycles are maturing as a competitive solution for reducing CO_2 emissions in power plants as an alternative to traditional fossil and nuclear fuels. In this context, nowadays a great effort is being invested in supercritical Carbon Dioxide Brayton (s-CO_2) power cycles for optimizing the line-focusing solar plants performance and reducing the cost of renewable energy. However, there are other working fluids with similar properties as s-CO_2 near critical point. This researching study was focused on assessing the solar plants performance with alternative supercritical working fluids in the Balance Of Plant (BOP): Ethane, Sulfur Hexafluoride, Xenon, Methane and Nitrogen, see [1, 2, 3]. The integration between linear solar collectors (Parabolic or Fresnel), Direct Moten Salt (MS) as Heat Transfer Fluids (HTF) and a Simple Brayton cycle with Recuperation and ReHeating were studied in this paper.

Main innovation in this researching study is the Brayton power cycle parameters optimization at Design-Point via the Subplex algorithm as proposed in John Dyreby Thesis [4]. After obtaining the optimum reheating pressure, compressor inlet pressure, recompression fraction, and other optimized variables, the solar power plants performances were simulated and detail designed with Thermoflow software [5], providing a first approach about the Solar Fields (SF) effective areas and investment costs.

As main conclusion, we deducted the importance of heat exchangers conductance (UA) for increasing the Brayton power plants efficiency and reducing the SF effective area and investment cost. The pinch point at recuperators exit is the main constrain for increasing the UA in s-CO_2 cycles. This limitation is overcome with the other working fluids proposed in this study providing higher plant efficiency but requiring higher UA in the recuperators. In future studies the heat exchangers detailed design constitute a great challenge for increasing the UA and optimizing these equipments cost. The material corrosion and equipments dimensions and cost is another key issue discussed for selecting the optimum energy transfer fluid in Brayton power cycles.

Keywords: Thermosolar power plants, Brayton power cycles, supercritical fluids.

1. Introduction

Climate change represents one of humanity's greatest challenges to the peaceful, prosperous and sustainable development of society. The world needs a new model of growth that is safe, durable and beneficial to all. Recognizing that sustainable development, universal energy access, and energy security are critical to the shared prosperity and future of our planet. For ensuring the promotion of green, clean and sustainable energy, and to draw on the beneficence of the Sun, the solar thermal energy will play an important role for accelerating the transition from fossil and nuclear fuel to renewable electricity sources.

In this context this paper studied alternative supercritical working fluids (Xenon, Ethane, Sulfur Hexafluoride, Methane and Nitrogen) in Brayton power cycles for power generation in line-focusing solar power plants. The integration between the supercritical Brayton power cycles and linear solar collectors (Parabolic and Fresnel) is an important effort for making competitive solar renewable energy and optimizing the cost of electricity produced in the solar power plants.

The supercritical Brayton cycle has a very long history, the oldest reference about Brayton cycles found is from 1948, when Sulzer Bros patented a partial condensation CO_2 Brayton cycle [Sulzer Patent, 1948]. Nowadays the Brayton cycles equipments technology is already under development. A biennial Symposium about s-CO_2 Brayton power cycles leaded by the SouthWest Research Institute in United States of America is being organized since 2007 for boosting Brayton power cycles deployment at industrial scale. The advantage of CO_2 fluid was quickly realized and investigation of supercritical CO_2 cycles was carried on in many countries: by ok in Italy [Angelino, 1968], [Angelino, 1969]. E.G. Feher selected the CO_2 as the optimum working fluid in the supercritical thermodynamic power cycles. CO_2 critical pressure is one third that of water, allowing lower operating pressures. Second, it is known to be a stable and inert material throughout the temperature range of interest. Third, there is a considerable body of literature on the properties of carbon dioxide, hence cycle analysis is based on reasonably firm data. And finally, carbon dioxide is abundant, non-toxic and relatively

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inexpensive. In 2004 V.Dostal MIT published a Thesis considered a reference in this matter and the beginning of the s-CO_2 technology renaissance. Recently, an important innovation in this matter has been published in [1, 2, 3] proposing other supercritical working fluids for Brayton power cycles in solar power plants for low and medium enthalpy values, and with similar properties as CO2 near critical point, optimizing the power cycle exergy and minimizing compressor work. In this paper we continue researching in the same way, selecting six working fluids (Ethane, Methane, Sulfur Hexafluoride, Xenon, Nitrogen and Carbon Dioxide) as potential candidates for the new generation solar power plants with linear solar collectors and supercritical Baryton power cycles. In the Table 1 are summarized the supercritical fluids critical properties for predicting the power cycles performance. One of the most important issues to be taken into account when selecting a supercritical working fluid is the ultimate heat sink temperature in the power plant. The target is minimizing the difference between the ambient temperature and the working fluid critical temperature. At first look the Carbon Dioxide and the Ethane present a critical temperature around 32ºC. This critical temperature is suitable for adopting the dry-cooling, air cooling heat exchangers, in locations where the water is scarce resource, despite the important penalty due to air fans electrical consumption. Same behavior will show the Sulfur Hexafluoride with a critical temperature around 45ºC. Nevertheless, Xenon has a critical temperature around 16.5ºC, for this reason this working fluid is most suitable for a wet cooling ultimate heat sink, as cooling water from the sea. But for compensating the higher Compressor Inlet Temperature (CIT) we should increase the compressor inlet pressure and the recuperator heat exchanger conductance, as proposed in reference [4]. Other important factor to be considered when selecting a supercritical working fluid is the critical pressure. The pressure at compressor inlet is a key variable to be considered, the compressor pressure ratio should comply the technical requirements available in the market for these equipments. The water has a critical pressure around 22.064 MPa, a high value reducing the pressure ratio at the turbines expansion stages. The critical density is directly related to the turbo-machines efficiency and required energy for compressing the fluid before being heated and expanded in the turbines. Also the supercritical density is very important for reducing the turbo-machines volumes and cost.

***Table 1**. Critical constants of working fluids.*

Name	Formula	Critical Temperature (ºC)	Critical Pressure (MPa)	Critical Density (kg/m^3)
Water	H_2O	373.95	22.064	322.0
Carbon Dioxide	CO_2	30.98	7.38	467.6
Ethane	C_2H_6	32.172	4.8722	206.18
Methane	CH_4	-82.586	4.5992	162.66
Sulfur Hexafluoride	SF_6	45.573	3.755	742.3
Nitrogen	N_2	-146.96	3.3958	313.3
Xenon	Xe	16.583	5.842	1102.9

The Turbine Inlet Temperature (TIT) is a very important parameter for defining the thermodynamic power cycle performance. The maximum TIT for operation with the different working fluids due to the risk of chemical decomposition, explosion, autoignition, corrosion and other considerations impacting negatively in the Brayton cycles performance. In the following Table 2 we explained the TIT upper limits for a safe and optimum operation, and explaining the physical phenomenon predicted and constraining higher TIT values.

***Table 2**. Recommended Maximum TIT limit for supercritical working fluids.*

Working Fluid	TIT limiting reasons
s-CO2	Chemical decomposition, Corrosion.
s-Ethane	Chemical decomposition, Explosion risk, Corrosion. Lack of experiments for confirming the fluid properties.
s-SF6	Chemical decomposition, Corrosion.
s-CH4	Chemical decomposition, Corrosion, Explosion risk.
s-N2	Corrosion.
s-Xe	Lack of experiments for confirming the fluid properties.

2. Methodology

The Brayton power cycles were simulated with a modified Fortran code for the Recuperated Simple Brayton cycle with ReHeating configuration, provided in John Dyreby Thesis [4], for optimizing the cycle's main performance variables at Design-Point. The Subplex algorithm was integrated in this Fortran code for obtaining the optimum performance operational parameters (reheating pressure, compressor inlet pressure, recompression fraction, low temperature recuperator conductance, etc). Subplex is a subspace-searching simplex method for the unconstrained optimization of general multivariate functions. Like the Nelder-Mead simplex method it generalizes, the Subplex method is well suited for optimizing noisy objective functions. The number of function evaluations required for convergence typically increases only linearly with the problem size, so for most applications the Subplex method is much more efficient than the Simplex method [4]. Subplex was developed by Tom Rowan for his Ph.D. Thesis: "Functional Stability Analysis of Numerical Algorithms (University of Texas at Austin)". Regarding the solar fields aperture area and cost were designed with Thermoflow [5]. The supercritical fluids properties were provided by REFPROP database developed by NIST in USA, and already integrated in Thermoflow and in the optimization software adapted from Dyreby Thesis [4].

3. Assumptions

The most important design parameters and constrains for simulating the linear solar power plants with Brayton cycles are summarized in the Table 3 to 7. In all the plant models and simulation the gross power output was fixed to 50 MWe.

Table 3. *Brayton BOP parameters.*

Turbine Efficiency:	93 %
Compressor Efficiency:	89 %
Recuperator Conductance UA:	Fixed
Pressure Drop across Heat Exchangers:	No
Turbine Inlet Temperature (TIT):	550ºC
Turbine Inlet Pressure:	250 bar
Reheating Pressure:	Optimized
Compressor Inlet Temperature (CIT):	32 ºC
Compressor Inlet Pressure :	Optimized
Auxiliary BOP (%Gross Power):	1 %
Generator Efficiency (Design-Point):	98.23 %

Table 4. *Location and Ambient conditions.*

Location:	Dagget,CA, USA.
Latitude:	34.86 º
Longitude:	-116.8 º
Hourly zone:	-8
Time:	11:30 hr
DNI:	986 W/m^2
Ambient temperature:	25 ºC
Altitude:	588 m

Table 6. *Receiver parameters.*

Outer Diameter:	70 mm
Wall Thickness:	4.191
Material:	Stainless Steel
Vacuum between outer glass tube	
Roughness:	0.0457
HTF Solar Salt	

Table 5. *LF solar collectors parameters.*

Collector type:	SuperNova 1 (Novatec)
Module Dimensions:	16.56 m x 44.8 m
Aperture area:	513.6 m^2/per Module
Optical Efficiency:	0.647
Thermal losses:	$0.15\ \Delta T + 7.15\cdot 10^{-9}\ \Delta T^4$

Table 7. *PTC solar collectors' parameters.*

Collector type:	EuroTrough II
Aperture Width:	5.77 m
Focal Length:	1.71 m
Cleanliness	0.96
Optical	0.75
Thermal Losses:	$0.18\ \Delta T + 7.15\cdot 10^{-9}\ \Delta T^4$

4. Brayton power cycles configurations

In the Figure 1 is illustrated the supercritical Brayton power cycle equipments layout considered in the present study. The Turbine is splitted with an intermediate ReHeating stage for heating the working fluid after the first turbine exit with the energy transferred from a Reheating SF. The main advantage in the Simple Brayton is the simplicity and the reduced number of equipments, providing an economical and low volume equipments arrangement.

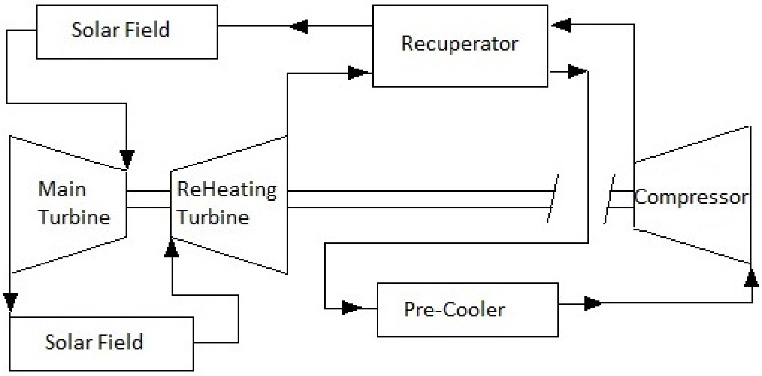


Figure 1. *Simple Brayton power cycle with Recuperation and Reheating.*

5. Balance Of Plant performance at Design-Point

The heat exchangers conductance UA is one of the most important variables in the supercritical Brayton power cycles impacting directly in the net plant efficiency and performance. Following the methodology established in references [3, 4], in this study in order to characterize the Simple Brayton cycle illustrated in Fig. 1, we fixed the recuperator conductance UA for different Turbine Inlet Temperatures (TIT) from 300ºC to 550ºC. The results obtained for the different BOP working fluids (s-CO$_2$, s-Ethane, s-SF$_6$, s-CH$_4$, s-N$_2$ and s-Xe) are illustrated in the Figs. 2 to 9. As first conclusion deducted, if recuperator UA is increased the net plant efficiency keep constant above a determined UA threshold value due to the minimum pinch-point temperature difference limit in recuperator. The UA threshold values for sCO$_2$ UA = 10000 kW/K, Ethane UA threshold = 15000 kW/K, SF$_6$ UA threshold = 30000 kW/K, s-Xenon UA threshold = 5000 kW/K, s-CH$_4$ y s-N$_2$ UA threshold above 30000 kW/K.

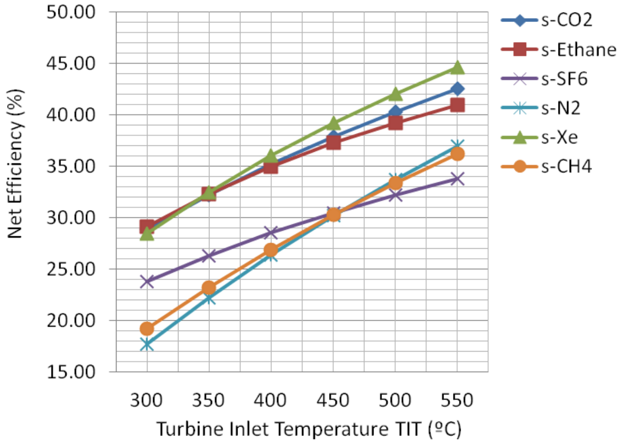


***Figure 2**. Net Efficiency & TIT. UA = 3000 kW/K.*

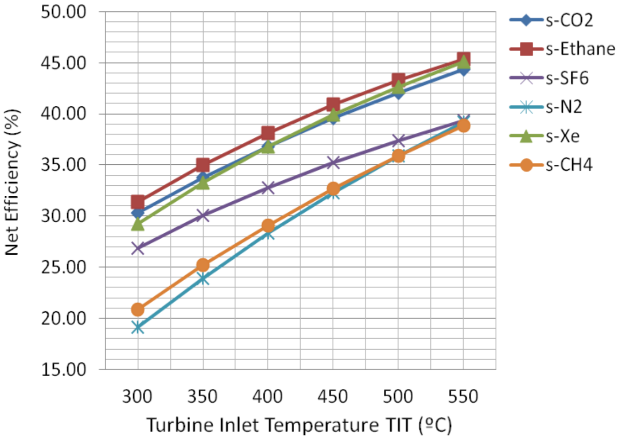


***Figure 3**. Net Efficiency & TIT. UA = 5000 kW/K.*

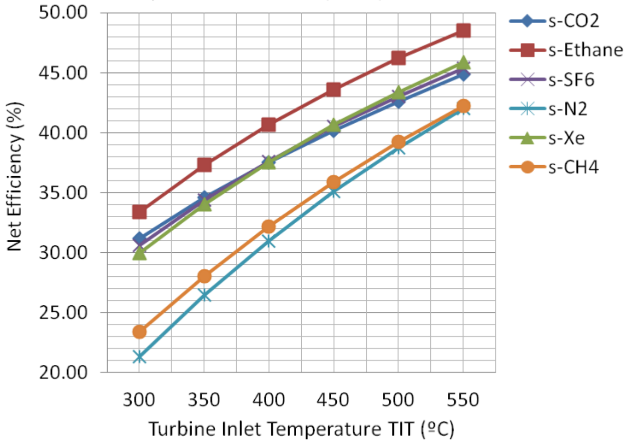


***Figure 4**. Net Efficiency & TIT with UA = 10000 kW/K.*

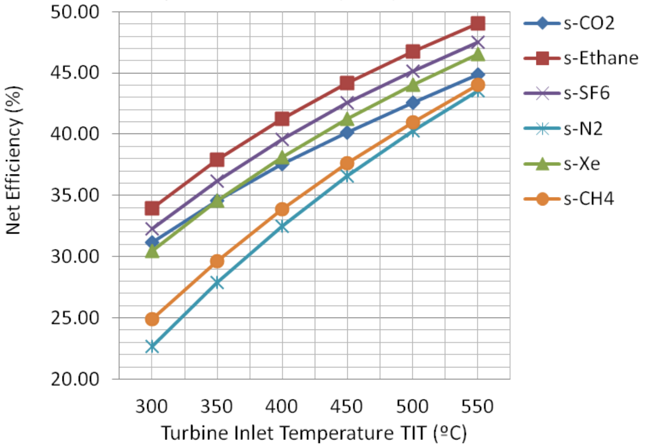


***Figure 5**. Net Efficiency & TIT with UA = 15000 kW/K.*

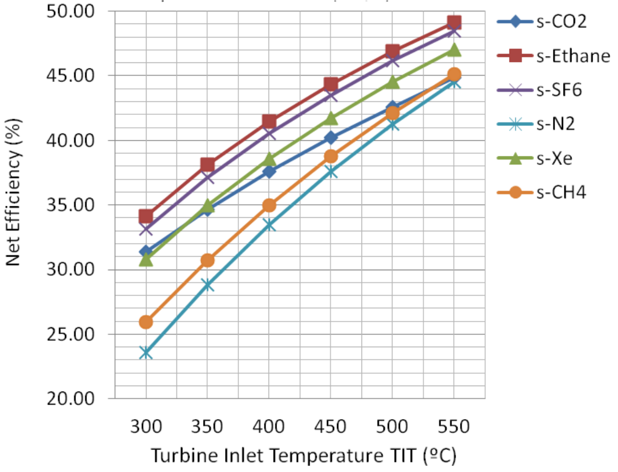


***Figure 6**. Net Efficiency & TIT with UA = 20000 kW/K.*

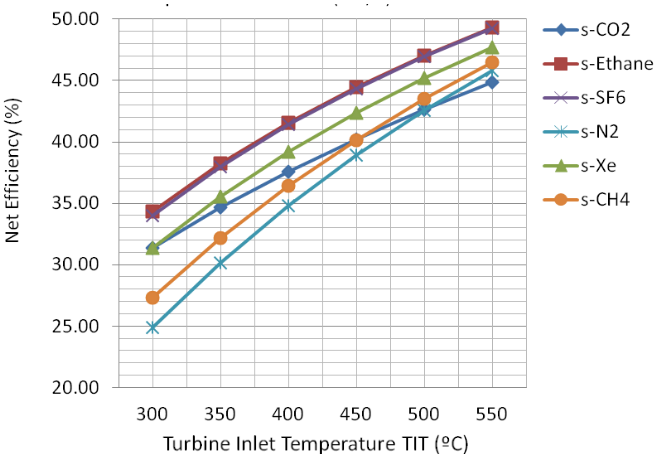
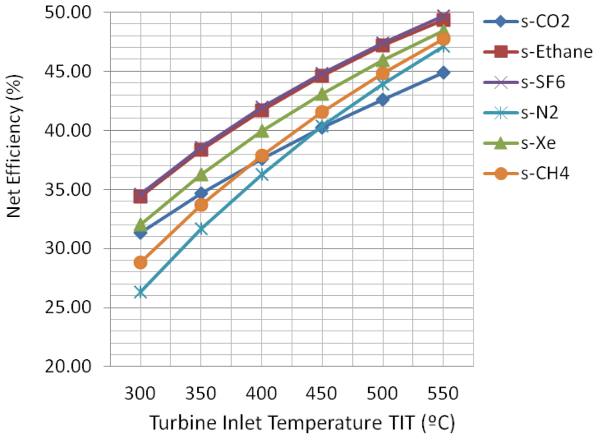


***Figure 7**. Net Efficiency & TIT with UA = 30000 kW/K.*



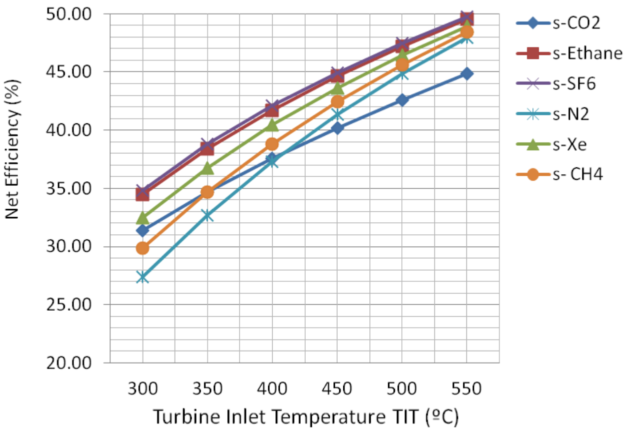
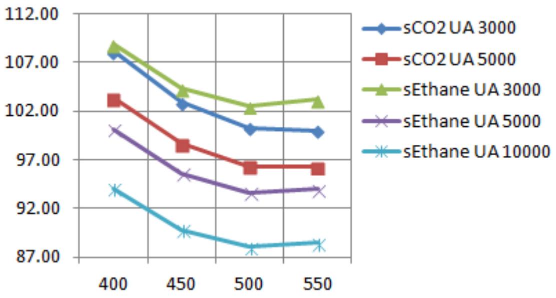


***Figure 8**. Net Efficiency & TIT with UA = 50000 kW/K.* ***Figure 9**. Net Efficiency & TIT with UA = 75000 kW/K.*

6. Conclusion

The solar collectors effective aperture areas estimated in the thermosolar power plant simulations developed with Thermoflow [5] for the different Brayton working fluids: CO2, Xenon, Ethane, Sulfur Hexafluoride, Methane and Nitrogen are summarized in Figures 10 to 19. The Ethane is working fluid with higher net plant efficiency than Carbon Dioxide as recently developed in reference [3]. Also present the advantage of reducing the solar aperture area for conductance UA = 10000 kW/K, as detailed in Figure 10 and 15. But main disadvantages of this working fluid is the potential explosion and chemical decomposition at high temperatures, generating Hidrogen and other subproduct that impact very negatively in the cycle performance. The Sulfur Hexafluoride also present a important advantage about the low corrosion in contact with metals, but further experiments are required in this sense to confirm the corrosion behavior at high pressure and temperatures. The high environmental impact of this working fluid could be compensate by the advantage of decreasing the solar field aperture area for high conductance values as illustrated in Figure 11 and 16. In Figure 12 and 18 are summarized the Xenon results. This working fluid could play an important role in the future, despite higher dimensions in turbomachines compared with Carbon Dioxide, the inert gases present a low corrosion behavior this is an important key issue for saving in the power cycle equipments material cost. Also the heat exchanger dimensions are similar to Carbon Dioxide. Nitrogen presents lower net plant efficiency than Carbon Dioxide for similar working operational parameters. This working fluid was previously experimented by CEA Centre Energie Atomique in France for nuclear power plants with Brayton power cycles. The detailed results obtained for this fluid are in Figures 13 and 17. Also the nitrogen corrosion in contact with metals is another important issue to be assessed for warranting this fluid feasibility in supercritical power cycles.



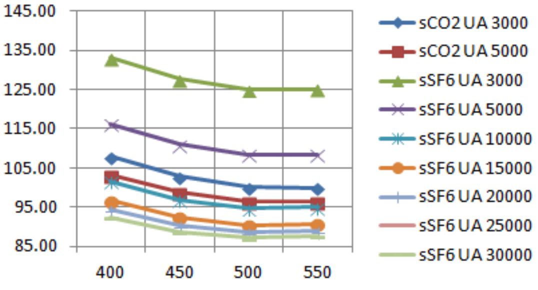
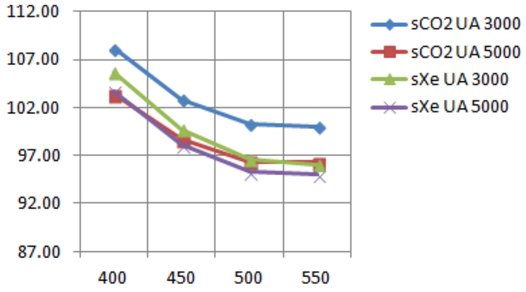


***Figure 10**. PTC cost (Mill. USD)* ***Figure 11**. PTC cost (Mill. USD)*



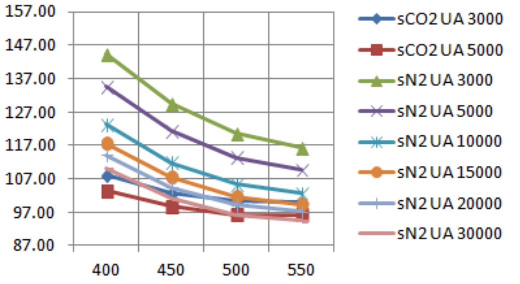


***Figure 12**. PTC cost (Mill. USD)* ***Figure 13**. PTC cost (Mill. USD)*

Finally Methane, is a fluid impacting very much in the international economy due to the shale gas huge production. Due to this fact, and also according to the critical properties, is another candidate for mixing with CO2 or for substituting this gas. In Figures 14 and 19 are illustrated the results obtained from Methane simulations. The same conclusion is deducted as from Nitrogen, for obtaining similar net efficiency as with CO2 are necessary to increase the recuperator heat exchanger conductance a great factor.

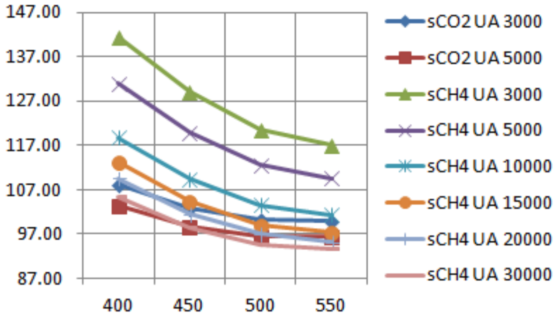


***Figure 14**. PTC cost (Mill. USD)*

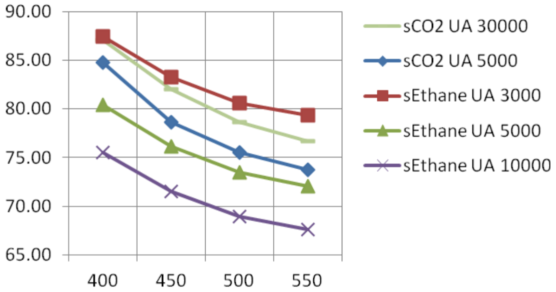


***Figure 15**. PTC cost (Mill. USD)*

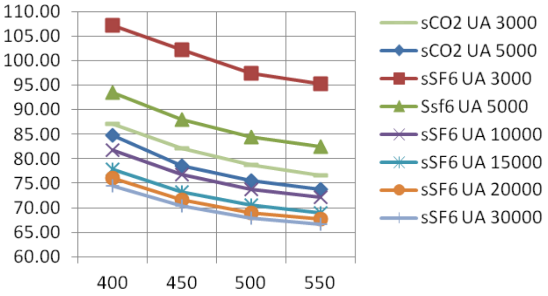
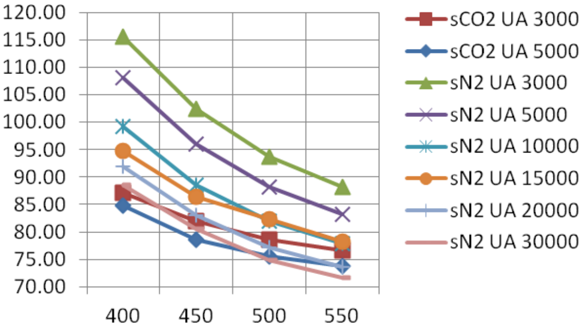


***Figure 16**. PTC cost (Mill. USD)*



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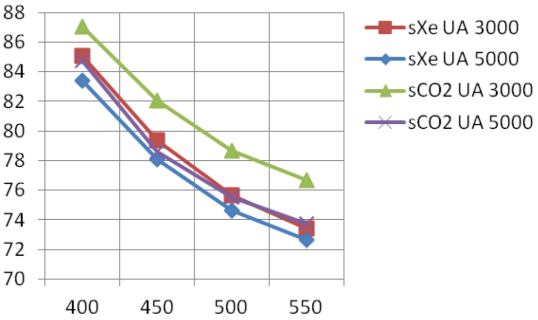

***Figure 18**. PTC cost (Mill. USD)*

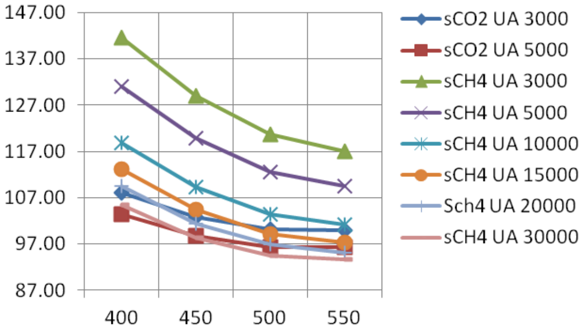

***Figure 19**. LF Cost (Mill. USD)*

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