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Energy Procedia 69 (2015) 1100 – 1112

Energy Procedia

International Conference on Concentrating Solar Power and Chemical Energy Systems, SolarPACES 2014

Techno-economic optimization of low temperature CSP systems based on ORC with screw expanders

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Abstract

Small Organic Rankine Cycles (ORC) coupled with low temperature parabolic collectors can be an affordable solution for the rural electrification of many remote areas worldwide. The aim of this work is to investigate the feasibility of this concept investigating the capabilities of different plant layouts and the use of volumetric screw devices as expander. Thirty working fluids are considered as possible candidates and all the solutions are optimized from a techno-economic point of view minimizing the specific cost of the plant. Finally a sensitivity analysis is carried out varying solar field specific cost and solar collector pressure drops.

Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG

Keywords: ORC; Low Temperature CSP; Screw Expanders; Techno-Economic Optimization; Rural Electrification

1. Introduction

A field of particular interest for ORCs is their use in rural areas and isolated villages where the population doesn't have access to electricity. Most of these contexts are located far from the big cities and the connection to the national grid entails prohibitive installation and maintenance costs. From IEA Energy Outlook 2011 [1] more than 1.317 billion of people live without electricity leading to a poor development of many regions worldwide and limiting the increase of life quality. In these contexts it is possible to install stand-alone power systems also called RAPS (Remote Area Power Supply) connected to an off-the grid electricity system. These stand-alone grids are

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Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG
doi:10.1016/j.egypro.2015.03.220

usually characterized by small utilities, like a water pump, an osmosis system for the water potabilization, a refrigerator for various purposes and a minimal domestic and public illumination. In most of the installed systems a diesel internal combustion engine (ICE) generator is used as primary generator while in several studies the integration between different renewable resources is investigated in order to diversify the energy resources and to guarantee the grid stability. Research projects have been focused on the integration between solar photovoltaic technology (PV) and wind turbines (WT) [2; 3], while in other studies an ICE [4] and a small hydropower system are introduced [5]. Among the renewable energy sources, solar energy is certainly the most suitable one in contexts characterized by low energy consumption and high values of irradiation all along the year. Concentrating Solar Power (CSP) technology is extremely interesting since it allows for a thermal storage (i) which is more efficient and economical than an electrical one based on batteries and because it does not require a high level technology (ii) with the possibility to promote the transfer of knowledge and the manufacturing on site of cheap collectors with the cooperation of local community. On the other hand, CSP technology entails a more complicated plant layout [6], it requires a more frequent and expensive maintenance and the presence of skilled operators on site. In the case of small area solar fields or low concentration factor collectors, steam Rankine cycle cannot be used since a number of difficulties arises affecting the overall plant efficiency and cost [7; 8]. These issues can be solved with the use of a suitable working fluid whose thermodynamic properties allow obtaining an easy design of turbomachinery and a competitive cost of electricity produced. Fluorinated refrigerant fluids, hydrocarbons, siloxanes and mixtures of them can be used depending on both the plant size and the thermal level of the heat source. The definition of the best combination of plant layout and working fluid is the result of a techno-economic optimization. Experimental activities in this field are carried out by STGinternational [9] which is focused on the design of small ORCs for developing countries using low cost concentrating parabolic collector and a scroll expander.

Nomenclature

Symbols

Q	Thermal Power, kW_{th}
s	specific entropy, kJ/(kgK)
T	Temperature, °C
V	Volume flow rate, m^3/s
Vr	Volume ratio
W	Power, kW_{el}
η	efficiency

Subscripts

cond	Condenser
eva	Evaporator
HP	High pressure
LP	Low pressure
out	outlet condition
pp	pinch point
rec	Recuperator
SF	Solar field
sh	superheating

2. Investigated solutions and methodology

The present study is oriented to the techno-economic optimization of small ORCs with a size of about 100 kW_{el}. Axial flow or radial inflow turbines can be used but they results having a very small dimension and they must rotate at very high rotational speeds for this power output range. Magnetic bearings and a fast generator, directly joined to the turbine, are generally used with a power electronic system to eventually correct the current frequency. This solution is adopted by some ORC producers [10; 11] and it is used mainly for waste heat recovery from biogas ICE. Another option is using a positive displacement device which can reach competitive performances for power outputs ranging from few to hundreds of kW_{el} [12]. According to the reference power output, screw expanders are considered in this work while scroll devices are more indicated for applications up to 10 kW_{el} [12; 13]. Unfortunately, the developing of ad hoc screw expanders is still limited while volumetric compressors can benefit by the large market and they can exploit scale economies, moreover they are reversible devices allowing a reverse operation with minor efficiency losses. Nowadays, only two companies on the market propose screw expanders for energy recovery from high pressure steam (Heliex Power [14]) or ORC for small biomass and small WHR applications (Electra-Therm [15]) but their market share is still small respect to other competitors. Main advantages in using a screw expander compared to high rotational speed mini turbines are: (i) the low component cost, (ii) the low rotational speed and the possibility of a direct coupling with the generator, (iii) the capability to adjust the volume ratio with the use of a slide valve in order to maximize the device efficiency in off-design conditions [16; 17] and (iv) the possibility to handle expansion in presence of liquid droplets in the two phase flow region [18; 19; 20]. This last point is of particular interest since it allows designing new cycle configurations, as the triangular and the flash triangular cycle [21; 22] which cannot be explored if a turbine is used. Main disadvantage of screw expanders, and in general of volumetric devices, is their small internal volume ratio which usually ranges between 3 and 7, values which are a way lower than those generally adopted in commercial ORC.

Three plant layouts are investigated in this paper: two of them are subcritical binary cycles with a HTF loop between the solar field and the ORC, while in the third case the working fluid flows directly into the concentrating collectors allowing for a more compact and economical plant layout:

- *Subcritical binary cycle with a single stage expansion*: it is the most simple cycle layout and it consists in five main components as shown in Fig. 1.a where the T-Q and T-s diagrams for R245fa fluid are reported in Fig. 1.b and Fig. 1.c respectively. In this plant configuration a single expander unit is used with a strong limitation on the maximum exploitable volume ratio and a consequent influence on cycle optimization.

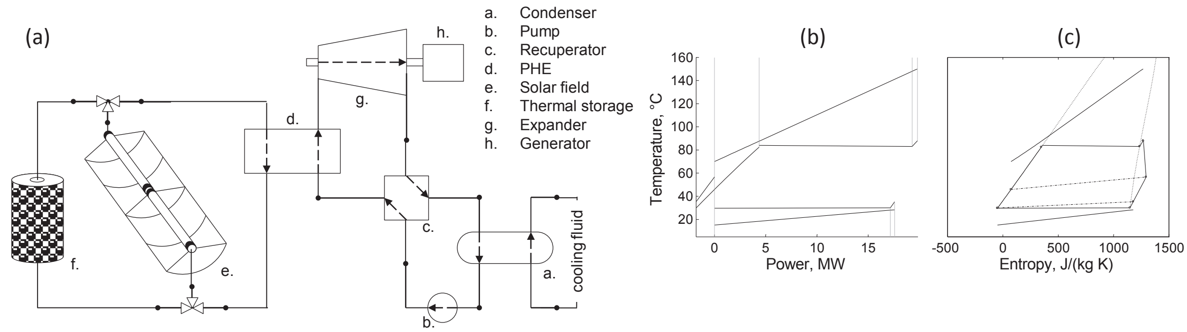

Fig. 1 – (a) Plant layout for the subcritical binary cycle with a single stage expansion and (b) T-Q, (c) T-s diagrams for R245fa in this configuration

- *Subcritical binary cycle with a double stage expansion*: For some fluids, characterized by medium-large volume ratios, the use of a two stage (tandem expansion) can be profitable. This solution consists in two expanders in series, each one with a volume ratio equal to the square root of the global one, with the possibility to notably increase the volumetric expander efficiency for those solutions characterized by large, but not extreme, volume ratios. The two expanders are connected in series and they elaborate a different volumetric flow rate. In a tandem screw compressor the two pair of helical rotors usually rotates at the same velocity and so they have different sizes, while another option is to use a gearbox in order to limit the size of the low pressure device, but introducing additional losses. An efficiency increase around 11-13% is claimed by a two stage compressors producer [23]. It is important to notice that the same expansion handled with a tandem screw configuration is intrinsically more expensive since the low pressure expander cost is approximately the same than the single screw case and an additional cost must be accounted for the high pressure expander. Nevertheless, if the adoption of a tandem expansion allows achieving a higher efficiency and exploiting a larger pressure drop, it might be profitable even from an economic point of view.
- *Flash trilateral cycle*: The main peculiarity of this cycle configuration consists in a heat introduction process without phase transition which allows designing an advanced system characterized by the use of

the working fluid in the solar field and in the thermal storage. This configuration reduces the cost of the system since the HTF loop and the heat exchanger between the HTF and the ORC are not required. On the other hand the flash trilateral cycle shows a higher ORC pump consumption since the working fluid flows directly into the solar collectors tubes, which are characterized by a high pressure drops, and it requires two expanders and a more complicated plant layout with a higher weight of BOP cost. The proposed solution consists in an almost triangular two pressure levels cycle. Plant layout is reported in Fig. 2.a while the T-Q and the T-s diagram for trans-butene are reported in Fig. 2.b and Fig. 2.c respectively.

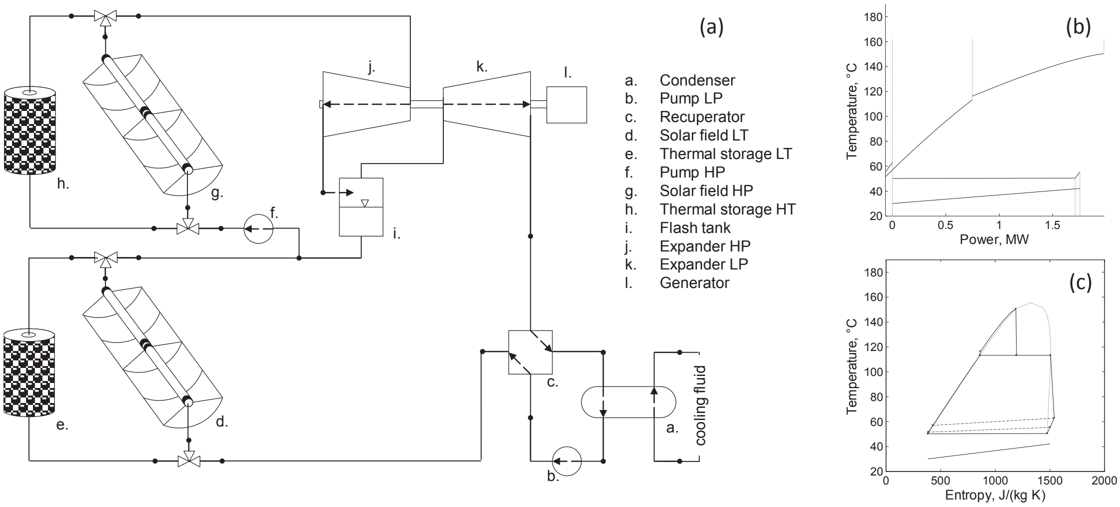

Fig. 2 - (a) Plant layout for the flash trilateral cycle and (b) T-Q, (c) T-s diagrams for trans-butene in this configuration

A techno-economical comparison between the different cycle configurations is not trivial since it requires the definition of different parameters which can greatly affect the final solution like the solar field cost, the pressure drops in the solar collector loops and the expander efficiency. The analysis is carried out comparing the performances of several working fluids in both subcritical and flash trilateral cycle configurations. A sensitivity analysis is proposed varying the cost of the solar field and the pressure drops into the solar loops with the aim to obtain more robust results. All the plants are optimized from a techno-economic point of view with the approach already adopted in previous author's works [7; 8]. Depending on the cycle layout, a different number of optimization variables is considered as reported in Table 1. Every variable produces different and opposite effects on the plant specific cost and the optimal value is always the result of a trade-off analysis. Thirty fluids have been considered selecting them among pure linear and cyclic alkanes, refrigerant fluids and light siloxanes. Very high critical temperature fluids are excluded a priori since they are the less suitable ones for the exploitation of low temperature heat sources, especially with volumetric devices which are negatively affected by large expansion volume ratios. For each working fluid the three plant layouts without solar multiplier are optimized and the results are compared in terms of plant specific cost since it is roughly proportional to the Levelized Cost of Electricity (LCOE) if the exploitation of the energy source entails operational cost negligible respect to the capital investment as in the case of CSP technology.

Table 1 - Optimized variables for the two investigated cycle configurations

	Binary cycle	Flash Trilateral cycle
T_{cond}	X	X
$\Delta T_{pp,cond}$	X	X
$T_{x,LP}$	X	X
$\Delta T_{sh,LP}$	X	-
$\Delta T_{pp,rec,LP}$	X	X
$T_{x,HP}$	-	X
$T_{out,HTF}$	X	-
n vars	6	5

3. Screw expander efficiency

The assumption of constant screw expander efficiency, independent of the expansion volume ratio and the device size, may lead to misleading results with unfeasible final solutions far from the optimal one. An efficiency map as function of some characteristic parameters is required with the aim of considering volumetric expanders in a numerical code for ORC optimization. Performance maps of maximum attainable efficiencies are not available in literature for either compressors or expanders and most of the studies in literature are oriented to the performance characterization of selected device with the aim to calibrate models helpful for off-design and dynamic simulations [24; 25]. These models are limited to a single machine and they do not provide any information about the attainable efficiency of any other device with a different design (i.e. a larger size or a different volume ratio). This limit can be overcome thanks to the European normative EN12900 which requires to the manufactures the definition of validated correlations for mass flow rate and power consumption in the whole operative range of evaporation and condensation temperatures at nominal rotational speed. Among the European producers, Bitzer [26] provides complete information for a huge number of screw compressor models allowing studying the attainable performances for different machines working with different fluids. Data of overall maximum efficiency as function of external volume ratios (V_r) and volumetric flow rate (V_{out}) are collected and regressed in Gretl [27] for more than 100 open screw compressors. The result is displayed in Fig. 3 together with the values calculated from producer data represented by cross markers while the proposed efficiency correlation is reported in eq. 1. As expected the overall efficiency decreases for high volume ratios while benefits are obtained with bigger machines and higher swept volumes. Furthermore, it is important to underline that the values of efficiency obtained is comparable with the experimental data from references [28; 29; 30]

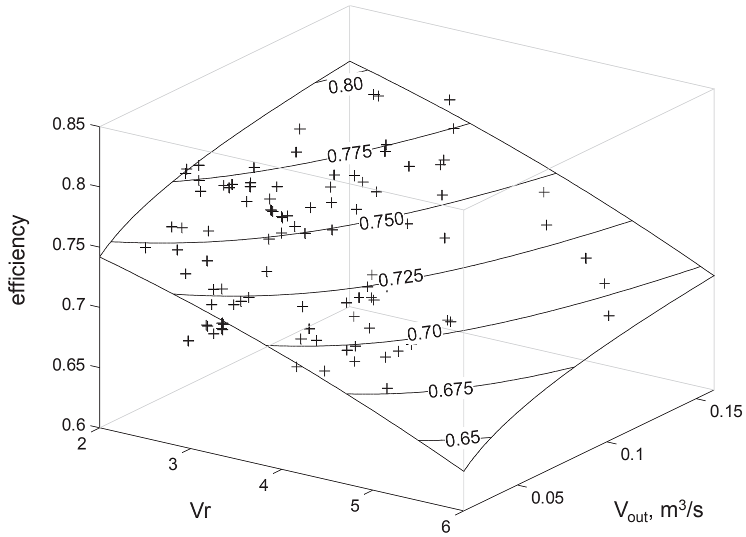

Fig. 3 – Map of efficiency for Bitzer open screw compressors. Cross markers are representative of single device performances

This correlation cannot be used at volume ratios higher than 7 which is the maximum volume ratio for the set of commercial devices here considered. For higher external volume ratios, a post expansion correction factor must be considered in order to take into account off-design effects. Useful information about this aspect can be obtained from two publications realized by Mycom [31] and Steidel [32] where the off-design performances of different screw expanders having built in volume ratios between 2 and 5.2 are compared. The results are reported in Fig. 4.a and Fig 4.b in absolute and relative axes and they are regressed by a logarithmic trend line function. The correction factor to be used for V_r higher than 7 is reported in eq. 2.

$$\eta = c[0.9403305 + 0.0293295 \ln(V_{out}) - 0.0266298\, V_r] \quad (1)$$

$$c = 1 - 0.264 \ln(V_r/7) \text{ for } V_r > 7 \quad (2)$$

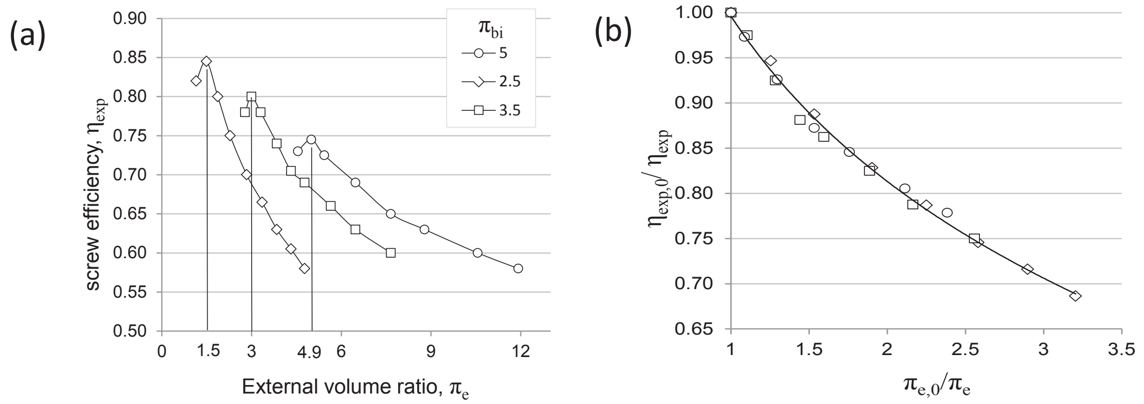

Fig. 4 – (a) absolute and (b) relative efficiency penalization for post expansion effect

The correlation of efficiency obtained and the correction factor for post expansion are a first attempt for the definition of a correlation of efficiency for screw compressors operated in reverse mode as expanders as function of both device size and volume ratio. No other examples are available in literature and further improvement will be certainly possible when new experimental data or detailed numerical models will be available. What is important to highlight is that this correlation is able to catch the effect of the two independent parameters and it allows for a more realistic techno-economic optimization.

4. Model assumptions

The thermodynamic cycle is modelled considering fixed pressure drops in heat exchangers with values of 50 kPa (absolute) and 0.02 (relative to inlet pressure) for liquid and vapor streams respectively. Pumps efficiencies are set to 0.75. The ambient temperature is 30°C and the nominal DNI is 800 W/m^2. Other assumptions are related to solar collector maximum temperature (160°C) and pressure drops (1.5 bar). A reference cost, equal to 100 USD/m^2, is assumed considering different sources [9; 33] while the nominal overall efficiency is set to 60% [33; 34; 35; 36]. All the plants are designed with a collected thermal power equal to 2 MW$_{th}$.

The cost of the heat exchangers and the pumps are evaluated with correlations of cost already used by the authors in previous works [7; 8]. An exponential correction factor equal to 0.67 is used for the extrapolation to value below 25 m^2 (heat exchangers) and 1 kW$_{el}$ (pump). Screw device cost correlation is derived from the cost of more than 100 commercial compressors in the range between 3.7 and 184 kW$_{el}$. Data are fitted with a linear function of the swept volume of the machine since it is the parameter which mainly affects the size and the cost of these devices. The effect of volume ratio on component cost is not taken into account because usually this parameter does not change the actual size of the device. Different volume ratios can be obtained with a different shape of the intake or discharge ports with a non-relevant impact on the device design and cost. The cost correlation is reported in eq 3 as function of the volumetric flow rate at the end of the expansion in m^3/s

$$C_{screw} = 3143.7 + 217423\, V_{out} \quad (3)$$

5. Results

5.1. Single screw

Results for single level subcritical cycles are proposed in Fig. 5.a in terms of plant specific cost for different class of fluids. A single screw expander is considered and it is interesting to note that for alkanes, cycloalkanes and fluorinated fluids there is always an optimal fluid which has a critical temperature around 160°C. Relevant differences can be highlighted for lower and higher critical temperature fluids.

The results for propane, butane and nonane are reported in Table 2 while T-Q diagrams are displayed in Fig. 5.b.1-3. With propane, the cycle is limited by the critical temperature and a superheating is necessary in order to increase cycle efficiency. However the power production is relatively low because of the limited mean logarithmic temperature of heat introduction and the optimization algorithm imposes a large $\Delta T_{pp,PHE}$ in order to reduce the cost of this component. The plant cost is lower than in the other cases because of the smaller cost of both the PHE and the screw expander. Propane, due to its low critical temperature, shows a high pressure of condensation and a small expansion volume ratio (~2.5) with a high efficiency screw expander. In addition, thanks to the high density of the discharged fluid the isentropic volume flow rate is small leading to a lower cost of the expander. For butane the lowest specific cost is achieved thanks to a better match between the hot stream and the working fluid in the PHE. The evaporation temperature is higher than for propane since there is no limitation due to the proximity of critical point, the condensation temperature is slightly higher than the previous case because of the trade-off between a larger volume ratio and lower screw efficiency. The total absolute cost is higher but the larger power production leads to a reduction of specific cost. Finally, nonane is considered as representative of a non-suitable working fluid for this application. The high critical temperature involves very large volume flow rate at expander outlet and a non-feasible volume ratio with a condensation temperature similar to the other fluids. For this fluid the expander is largely the most expensive component and the techno-economic optimization acts increasing the condensing temperature with the aim of reducing the cost (function of the volume flow rate) and increasing the screw expander efficiency (function of both size and volume ratio). The optimized volume ratio is slightly above 7, which corresponds to the point where the efficiency starts to be corrected by the off-design efficiency reduction factor. The optimized cycle has a very expensive PHE but more than 83% of the total power block cost is represented by the screw expander which has to handle a huge mass flow rate.

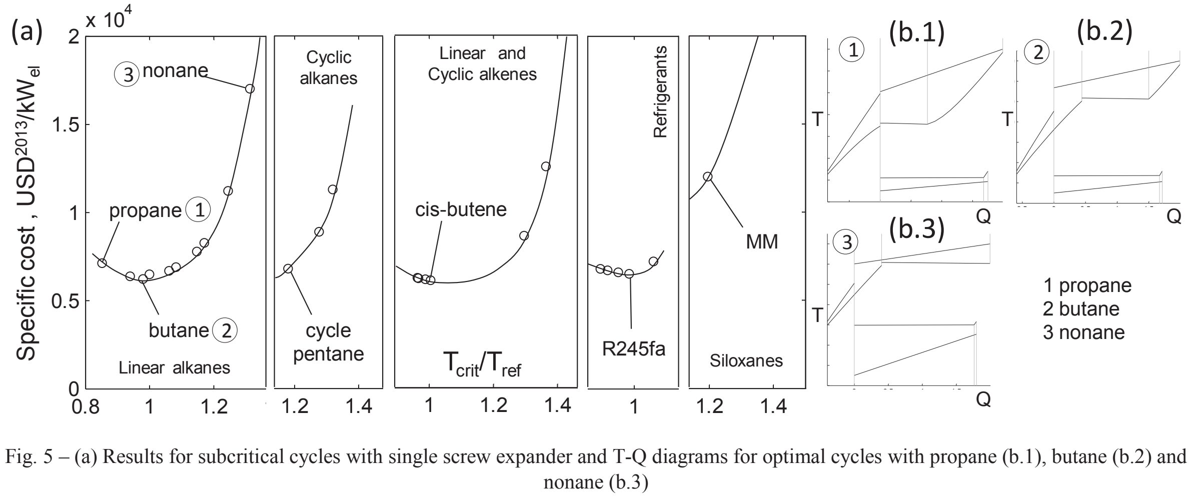

Fig. 5 – (a) Results for subcritical cycles with single screw expander and T-Q diagrams for optimal cycles with propane (b.1), butane (b.2) and nonane (b.3)

This example is important to underline two aspects related to the use of volumetric expanders which are not always taken into account in other publications on the topic:

- the use of a fixed efficiency in thermodynamic optimization entails misleading results since the important effects of the volume ratio and off-design effects are not considered. In most of the publications about the use of volumetric expanders usually a fixed efficiency is assumed with a maximum value of volume flow ratio depending on the device type. Only in one paper [35] the effect of size and volume ratio is considered for a 3 kW_{el} scroll expander for ORC.

- considering a fixed cost for the volumetric expander, or using a cost correlation dependent on the shaft power, in the techno-economic optimization lead to optimized solution far to be reliable. In fact, depending on the working fluid, machine with comparable power output but dramatically different dimensions can be obtained. For high critical temperature fluids, screw expanders can be operated at higher velocity but additional losses should be taken into account for (i) the higher friction in the machine and (ii) the mechanical losses of the gearbox or (iii) the electrical dissipation in the power electronics system.

Table 2- Results for the optimal subcritical cycles with propane, butane or nonane.

	propane	butane	nonane
General results			
W_{net}, kW_{el}	184.38	228.14	163.80
plant efficiency	9.22%	11.41%	8.19%
Cost PB, $kUSD^{2013}$	686.6	767.0	4915.5
Cost TOT, $kUSD^{2013}$	1309.3	1413.8	3460.6
Cs PB, USD^{2013}/kW_{el}	3723.9	3362.0	21127.5
Cs TOT, USD^{2013}/kW_{el}	7100.8	6197.0	30009.5
$W_{pump\ SF}$, kW_{el}	8.59	12.70	16.95
Optimized parameters			
T_{cond}, °C	42.25	47.21	80.00
T_{eva}, °C	91.18	122.49	140.66
ΔT_{sh}	65.86	33.89	0.00
$\Delta T_{pp,rec}$	3.00	3.13	3.14
$T_{out,HTF}$, °C	120.97	133.57	140.17
$\Delta T_{pp,cond}$	4.00	6.26	10.00

	propane	butane	nonane
Power block cost breakdown			
Cond	29.06%	21.72%	3.43%
Des	7.09%	3.81%	0.59%
Rec	11.29%	8.68%	1.69%
Eco	-	12.85%	3.10%
Eva	15.92%	17.51%	7.43%
Sup	22.56%	15.74%	-
Screw	8.14%	15.22%	83.16%
Pump	3.46%	2.45%	0.29%
Others	2.49%	2.01%	0.32%
Screw expander			
η screw	83.23%	78.76%	72.42%
Vr	2.4966	4.9706	7.348
Vout, m^3/s	0.2426	0.52249	13.221
Cost,kUSD	55.89	116.74	2877.80

A further improvement can be achieved for some low critical temperature fluids by using a supercritical configuration. In the next sections both the configurations are considered and so the result displayed for a certain fluid is the minimum specific cost attainable with a subcritical or a supercritical cycle configuration.
It is finally interesting to note that R245fa fluid used from STGi international for a smaller (3 kW_{el}) application is the best fluid even in this case where a subcritical superheated single level cycle with a single screw expander is used.

The value of specific cost of the whole plant cannot be really validated because this is a niche application and studies on this topic do not consider techno-economic optimization of the system or they refer to plant sizes notably smaller or bigger. The specific cost of the power block is around 3300 USD^{2013}/kW_{el}, a value which is confirmed by a personal communication with a ORC producer which claims a cost close to 3000 €/kW_{el} for a 130 kW_{el} WHR unit receiving heat from a loop of pressurized water.

5.2. Tandem screw

The decrement of the specific cost attainable with a two stage expansion is reported in Fig. 6.a for all the investigated fluids. This specific cost reduction is relevant for fluids with critical temperatures between 140 °C and 200°C while for low critical temperature fluids (e.g. propane), the use of a tandem expansion is not really profitable because the expansion is already characterized by small volume ratio and so the advantages in terms of a higher power output are levelled off by the expander cost increase. For very high critical temperature fluids, a similar consideration can be done since the overall efficiency increases notably but also the high pressure expander cost increases significantly, with a detrimental effect on the specific cost of the plant.

A comparison between supercritical cycles with iso-butane is reported in Table 3. The first case is optimized using a single expander while the other one with a tandem expansion. The power output increases by more than 19% with the tandem configuration since the condensing temperature is reduced by 5 °C and a higher enthalpy drop is available in expansion. The expander inlet condition is almost constant since the maximum temperature and pressure are constrained by the cost of the PHE. The overall volume ratio is increased from 6.4 to 7.3 but the overall efficiency is increased by 8.8 percentage points, partially confirming the over mentioned producer's data. The two screw expanders in series have the same volume ratio equal to 2.7 and they have an efficiency of 81.2% and 84.13% respectively for the high pressure and the low pressure device and the difference in performance is due to the larger size of the second expander, leading to smaller leakage losses. The cost of the power block increases, as well as the share of screw components on the total cost (from 13.9% to 19.2%). As result, both the power block specific cost and the total plant specific costs decrease thanks to the higher power production. Finally, it is interesting to note that the cost of the heat exchangers (PHE, recuperator and condenser) covers more than 70% of power block cost while screw expander share is around 14% for optimized solutions. This fact is not surprising since in this study the cost of commercial screw compressors is used, a component which is characterized by a large market in several different applications with the possibility to exploit relevant scale economies thanks to the standardization of the production process.

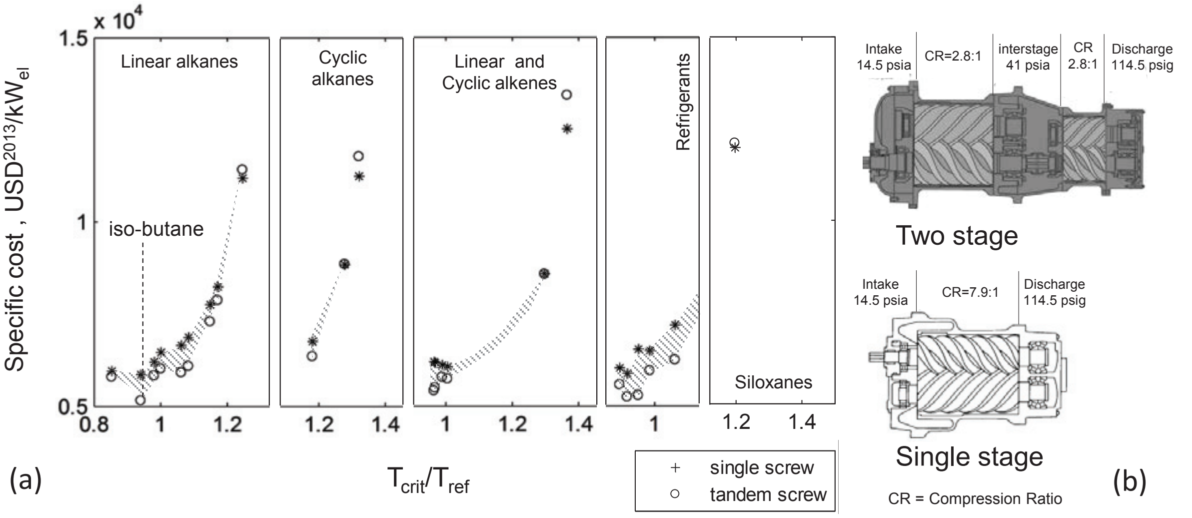

Fig. 6 – (a) Comparison between optimal solution attainable with a single screw or a tandem expansion. The shaded area highlights the decrement of plant specific cost. (b) Comparison between a commercial two stage air compressor (2.8+2.8) and single stage air compressor (7.9) produced by Sullair [23]

Table 3 - Comparison between iso-butane supercritical cycles based on a single screw or a tandem screw expansion

	single	tandem
General results		
W_{net}, kW_{el}	203.48	244.65
plant efficeincy	10.17%	12.23%
Cost PB, $kUSD^{2013}$	595.34	648.79
Cost TOT, $kUSD^{2013}$	1190.61	1260.10
Costs PB, USD^{2013}/kW_{el}	2925.79	2651.92
Costs TOT, USD^{2013}/kW_{el}	5851.21	5150.61
Optimization parameters		
T_{cond}, °C	50.18	45.01
T_{eva}, °C	135.66	135.66
ΔT_{sh}	21.609	21.109
$\Delta T_{pp,rec}$	4.107	3.9076
$T_{out,HTF}$, °C	136.16	135.97
$\Delta T_{pp,cond}$	8.0853	5.8836

	Single	tandem
Prower block cost break down		
Cond	25.53%	26.60%
Des	5.96%	5.97%
Rec	10.03%	8.76%
PHE	37.85%	33.16%
Screw	13.89%	19.17%
Pump	4.23%	3.82%
Others	2.50%	2.51%
Screw expansder		
$\eta_{screw,eq}$	74.07%	82.85%
Vr	6.390	7.291
Vout, m^3/s	0.366	0.396
Cost, kUSD	82.70	124.40

5.3. Flash Trilateral Cycle

Finally the flash-trilateral cycles are investigated: two screw expanders are used in series separated by a flash tank where the two phases are separated. The maximum temperature of the fluid is set to 160 °C a value usually reached if the limit due to the proximity of the critical point is not activated. The flash trilateral cycles can be even more efficient than the single level cycles with tandem screw expander if the maximization of the power output is the goal of the study. However in this case, the techno-economic optimization leads to less efficient solutions compared to binary cycles. This can be explained considering that flash trilateral cycles do not require the PHE which is the most expensive component (~35% of power block cost) of binary cycles. In Fig. 7 a comparison between single screw, tandem screw and flash-trilateral cycles is proposed and it is possible to note that the use of this latter cycle configuration allows achieving for many fluids a lower plant specific cost. For each group of fluids, the optimal one has a critical temperature higher than in the previous case because low critical temperature fluids can reach lower inlet temperatures at the high pressure screw intake with a limitation of cycle efficiency. Fluids with a critical temperature higher than the maximum achievable in the solar collectors are less constrained and they can reach a lower overall specific cost. A comparison between single screw, tandem screw and flash trilateral cycles with trans-butene is reported in Table 4.

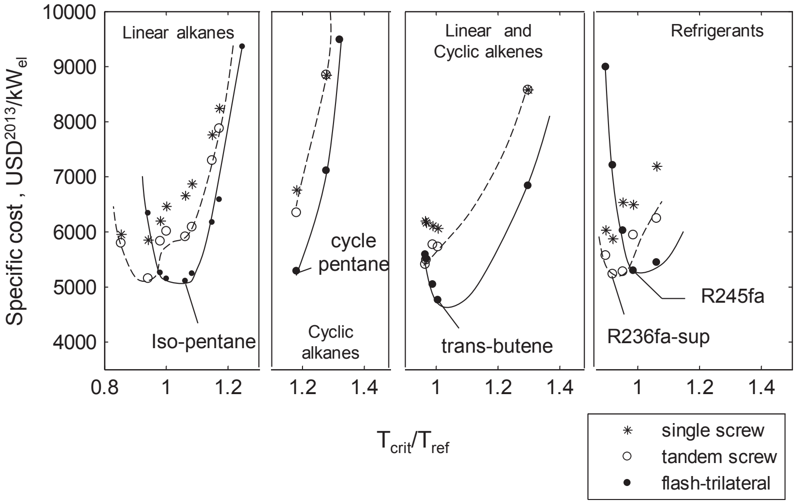

Fig. 7 - Comparison between single screw binary cycles, tandem screw binary cycles and direct flash-trilateral systems

Table 4 - Optimal results for trans-butene with a single level-single screw binary cycle, with a tandem screw and for a flash trilateral cycle

	Single	Tandem		Flash	
General and economic results					
Wnet plant, kW_{el}	227.77	258.56		190.61	
plant efficiency	11.39%	12.93%		9.53%	
Cost PB, $kUSD^{2013}$	749.66	826.29		375.82	
Cost BOP, $kUSD^{2013}$	224.90	247.89		169.12	
Cost SF, $kUSD^{2013}$	416.67				
Cost TOT, $kUSD^{2013}$	1391.22	1490.84		961.60	
Specific Cost PB, USD^{2013}/kW_{el}	3291.35	3195.71		1971.67	
Specific cost BOP, USD^{2013}/kW_{el}	987.41	958.71		887.25	
Specific cost SF, USD^{2013}/kW_{el}	1829.36	1611.48		2185.98	
Specific Cost TOT, USD^{2013}/kW_{el}	6.11	5.77		5.04	
Expansion results					
		1stage	2 stage	LP	HP
η screw	78.86%	82.69%	85.28%	80.06%	77.24%
Vr	4.936	2.522	2.522	4.281	3.828
Vout	0.5146	0.2060	0.5210	0.4161	0.1052

It can be noticed that the flash trilateral configuration allows achieving a notable specific cost reduction mainly because the cheaper power block, while the net power output of the system is lower respect to both the single screw and the tandem screw configuration but it is due to cross effects related to the economic optimization. In the flash trilateral cycle the two screw expanders work with a similar volume ratio but the High Pressure (HP) one has smaller rotor diameter than the Low Pressure (LP) one even if it expand the whole mass flow rate. For this reason its efficiency is lower than the LP expander which is less affected by leakage and friction losses.

6. Sensitivity analysis on solar field cost and collectors pressure drops

All the results achieved in the previous analysis are obviously affected by the specific cost of the solar field and the pressure drops in the tubes of the parabolic collectors. Increasing the pressure drops for direct flash trilateral cycles entails a larger and more expensive pumping station with a higher consumption resulting in a lower net power output. For binary cycles instead, higher pressure drops in HTF loop leads to a lower minimum temperature of the oil, in order to reduce its mass flow rate and solar field pump consumption. Since the PHE is a relevant share of the total plant cost, the pinch point temperature difference in the evaporator cannot be strongly reduced leading to a slightly lower evaporation and condensation pressures in order to maintain a good thermodynamic cycle efficiency. These contrasting effects result in a higher specific cost for all the three solutions with a higher penalization for single screw binary cycle and flash trilateral one. Assuming 3 bar of pressure drop an increase of specific plant cost equal to 3.60%, 3.47% and 3.57% is obtained for the three investigated cycles working with trans-butene. This variation compared to the gap between the specific costs in the previous case is not so relevant to modify the previous considerations. High critical temperature fluids in flash trilateral cycles are more penalized by higher pressure drops since they work with a small absolute pressure differences between condensation and maximum pressure and so an absolute off-set has a stronger impact on final performances.

Specific solar field cost is instead a relevant share (around 30%-50% in the reference case) of the total plant cost and an increase of this parameter leads to more efficient optimal solutions since the economic optimization favors those solutions with higher power outputs. With a specific cost of the solar field twice than the reference one it is possible to highlight an increase of average specific plant cost of the optimal solutions close to 35%. The advantages in using flash trilateral cycles become negligible comparing the different optimal solutions since they are the cycle layout with the lower power output. For some classes of fluid the advantage is still relevant (i.e. cycle alkanes and alkenes) and the use of direct cycles allows reducing the total plant cost while, if flammable fluids cannot be used, the optimal solutions are supercritical recuperative cycles with a two stage expansion.

7. Conclusions and future works

A small solar thermal power plant coupled with an ORC is investigated. The system is based on low-cost and low-temperature parabolic collectors with a maximum temperature of 160 °C and three different cycle configurations are analyzed. Main results are listed:

- The use of well calibrated correlations for the efficiency and the cost of volumetric expander is crucial for thermodynamic and techno-economic optimizations. A fixed efficiency, even considering a limit on maximum volume ratio, is far from the reality and, for high critical temperature fluids, it pushes the optimal solution always toward the upper limit of volume ratio;
- The use of two stage tandem expansion can be really profitable, allowing an increase of power production and a reduction of specific cost for those fluids which can take advantage from the repartition of the expansion in two devices;
- The use of flash trilateral cycles is really interesting since it entails a lower power block cost and the possibility to perform a direct storage with the working fluid. This is an innovative concept and so far no experimental activities have been carried out since this niche market is nowadays more oriented to conventional and low risk solutions;
- A sensitivity analysis on the pressure drops in the solar collectors and on the specific cost of the solar fields has highlighted two main conclusions. (i) An increase of pressure drops in solar collectors penalizes all the cycle configurations in a similar way. A higher specific cost increase is obtained for single screw and flash trilateral

cycles but different assumptions on this parameter wouldn't affect the choice of the best combination of working fluid and cycle configuration. (ii) For a higher cost of the solar field flash trilateral cycles are penalized due to their lower power output, nevertheless they are still competitive even with a price of 200 USD/m^2.

Future works related to this concept will be focused on:

- A better description of the solar field with a model of solar collectors in order to link the thermal efficiency and the pressure drops to the HTF thermodynamic properties. Simplified and detailed models are available in the literature for the numerical characterization of parabolic trough technology [35; 37] and their implementation will probably advantage flash trilateral cycles where a lower mass flow rate flows into the solar field with a lower average temperature. A preliminary design of the solar field should be considered as well in order to account reliable pressure drops in the headers;
- A more detailed bibliographic review of cost correlations for heat exchangers different from the S&T ones is required. Especially for smaller application, the extrapolation with an exponential law to very small heat transfer surfaces would entail a non-realistic increase of heat exchanger specific cost. Other heat exchangers types, like plate fins or brazed plate heat exchangers, can be considered with the aim of reducing the power block cost;
- The off-design simulation of these plant configurations in order to highlight differences in efficiency and power production for one year of operation, in particular for plants without or with limited thermal energy storage.
- A comparison among the use of volumetric devices and fast axial turbines for application in a range of power outputs between few kW and 100 kW.

Acknowledgements

The author wishes to thank Professor Ennio Macchi of Energy Department of Politecnico di Milano for his inspiring assistance during this work.

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