Dynamic modeling of a Low-Concentration Solar Power Plant: a control strategy to improve flexibility

M. Antonelli*, A. Baccioli, M. Francesconi, U. Desideri

University of Pisa, largo Lucio Lazzarino, Pisa 56125, Italy

Abstract

This paper deals with a dynamic analysis on a low concentration solar power plants coupled with Organic Rankine Cycles (ORC), which can be an alternative to PV systems because of their capability of providing a smoother electricity production due to their thermal inertia. At least within certain restraints, moreover they are able to exploit diffused solar radiation.

The dynamic model of a plant with static compound parabolic collectors and an ORC cycle, using a rotary volumetric expander, was developed using the simulation tool AMESim. All the main components of the plant are modelled: solar collectors field, heat transfer fluid circuit, heat exchangers and the ORC cycle. The plant response to the radiation of different days was analyzed to quantify the daily production and the trend of various plant parameters. Real ambient conditions were employed for the simulations by using data obtained by historical series.

The results showed that the employment of a volumetric expansion device with variable rotating speed allows the plant to operate at different radiations

*telephone number: +39 050 2217133 - fax: +39 050 2217160

Email address: `marco.antonelli@ing.unipi.it` (M. Antonelli)

and ambient temperatures without the need of any storage system or external heat sources. Results can be extended to other applications, such as low temperature waste heat recovery or geothermal systems.
Keywords:
Dynamic modelling; ORC solar power plant; AMESim; control strategy; volumetric expansion device; Compound Parabolic Collectors

1. Introduction

The interest towards solar energy has been increasing in the last years. In the micro-generation field, Photo-Voltaic (PV) systems are widely used due to their installation simplicity, simple management, and low costs of maintenance. However the lack of inertia of these systems and the unprogrammable nature of the source, are causing problems on the electric grid. Low concentration solar plants can limit fluctuations of delivered power because of their thermal inertia. Obviously, since we are talking about systems that are addressed to domestic or small industrial or commercial activities, simple, low cost and small size units have to be developed. Compound Parabolic Collectors (CPC) and volumetric expansion devices can help in the accomplishment of this objective. CPCs have been studied for several years [1, 2] and are characterized by a wide operational flexibility [3]. Because of their wide acceptance angle, CPCs do not need any tracking system, and allow to reach higher temperatures with better efficiencies than flat plate collectors [4]. Volumetric rotary expanders are more suitable than micro-turbines for small power output applications, because of the higher isentropic expansion efficiency, lower rotational speed, lower costs [5–7] and wider possibility of control [8]. The variation of the rotational speed in particular can be easily achieved and keeps the isentropic efficiency of the device almost constant [9]. Using this control, the power output can be varied without the need of a storage system, simplifying the layout, saving space and reducing installation costs. Because of the strong variation of thermal input and the lack of a storage system or integration with an external source, it is important to consider the effective dynamic behavior of the system, in order to properly set parameters, improve performances and management.

Dynamic modelling in facts has become an important tool for solar plants and in general for applications characterized by large variations of the input power. Manenti et al. [10, 11] carried out numerical simulations to perform the start-up operations of Archimede Concentrating Solar Plant in Sicily, using DYNSIM. In their papers they identified the critical aspects of start-up and shut-down operations and optimized the control strategy of the plant. El Hefni [12] employed ThermoSysPro - Modelica in modeling a solar plant with different type of collectors and a solar hybrid combined-cycle power plant with PTC collectors. Rodat et al. [13] simulated the dynamic response of two solar concentrating plants with Fresnel collectors in the Modelica environment. They monitored the temperature of the superheated steam after the cloud passage and highlighted the difficulty to tune a proper control systems to handle both slow and fast phenomena. Other authors focused on the optimization of a part of the plant: Eck et al. [14] studied the superheated steam control system of a PTC loop, Henrion et al. [15] used dynamic simulation in the design of an innovative evaporator, with a particular attention to start-up operations. Quoilin et al. [16] showed the possibility of controlling and optimizing a small power output Waste Heat Recovery system through the variation of the speed of a scroll expander.

This paper shows the numerical modelling of a 25 kW ORC solar plant by means of the AMESim simulation tool, showing the capability of the model of highlighting the optimal working condition of the plant from the point of view of the solar field parameters (concentration and tilt). This paper clearly indicates the need for a dynamic simulation which was able to evaluate the influence of warm-up period on the electrical production of the plant.

This work also demonstrates the effectiveness of the control strategy based on the rotating speed of the expander, which proved to be able of operating under variable radiation conditions, without the need for any storage system or integration with external heat sources.

The novelty which is introduced in this work consists in the application of this kind of simulation and control strategy in a small-size power plant, which employes non-tracking, low concentration collectors, whose parameters have been chosen in order to optimize the overall production along several working days. The conditions which have been taken as a reference were both ideal conditions (fully sunny day) and real ones, derived from historical series.

Nomenclature

a	Azimuth angle (°)
A	Exchange area (m^2)
C	Concentration
G	Global incident radiation (W/m^2)
i	Incident angle (°)

I_{bn} Ground direct radiation (W/m^2)

I_{d0} Ground diffuse radiation (W/m^2)

$\dot{m}$ Mass flow rate (kg/s^{-2})

p Pressure (bar)

r Ambient reflectivity (–)

t Time (s)

T Temperature (K)

u Specific internal energy (J/kg)

U Internal energy (J)

V Volume (m^3)

$\dot{V}$ Volume flow rate (m^3/s)

$\dot{W}$ Power (kW)

subscripts

c collector

el electrical

exp expander

is isentropic

mec mechanical

p pump

ad admission

sat saturation

sh superheating

HTF Heat Transfer Fluid

r receiver

Greek

α Solar height (°)

β Collectors tilt angle (°)

η Efficiency

λ heat exchange coefficient (W/m^2K)

ρ Density (kg/m^3)

Acronyms

PV Photovoltaic

CPC Compound Parabolic Collectors

2. System description and fluids

The studied system consists of a non-tracking CPC field, an HTF circuit and an ORC (fig. 1). The cycle is composed by a pump, an evaporator, an expansion device, a recuperator and an air cooled condenser. Superheating and regeneration are employed because in a previously published work [17] they proved to improve the overall efficiency of the plant. The choice of the heat transfer fluid and of the working fluid is critical. In fact the heat transfer fluid should have good thermal properties to efficiently transfer the heat, high density and low viscosity to limit the pumping power loss. Since the maximum temperature of this system is expected to be about 160 °C, pressurized water was chosen as heat transfer fluid. The working fluid is R-600a since it gave the best results in the stationary analysis of the plant [4].

INSERT FIG. 1 ABOUT HERE

The CPCs employed evacuated pipes to suppress convection losses as shown in a previous paper [4]. The number of collectors was chosen to provide the thermal input needed by the plant when the expansion device rotated at its maximum speed (3000 rpm). CPCs were arranged in arrays composed of 9 collectors linked in series, and each array was in parallel with the other, as reported in fig. 2. A schematic view of an array tilted by a generic angle is reported in fig. 3. In fig. 4 the efficiency of the collectors provided by manufacturers is reported. The collector field outlet temperature was controlled by the circulating pump speed. The collectors were disposed in the East-West direction, for the sun rays to be incident on the CPC aperture within the acceptance angle [18].

INSERT FIG. 2, 3 and 4 ABOUT HERE

The expander displacement and introduction grade, defined as in [5], were respectively 316 cm^3 and 0.2 and the rotational speed was varied in the range 500-3000 rpm. The velocity of the expander was used to control the evaporating pressure set point. An inverter is therefore needed to connect the plant to the grid. Condensing temperature was 15 °C higher than the ambient temperature and therefore was variable during the day. The choice of a variable condensing temperature was possible since the expander is volumetric and the only restriction on the pressure ratio is given by over-expansion phenomena [19], which should be avoided by means of an appropriate value of saturation pressure [9].

3. Numerical model

The numerical model of the plant was developed with AMESim v.12, a 1-D multi-physics commercial code. Elements of the thermal-hydraulic, thermal and two-phase flow libraries were used to model the system. An overview of the model is reported in fig. 5.

INSERT FIG. 5 ABOUT HERE

3.1. CPCs model

Collectors were modelled in order to take into account the main thermal exchange phenomena, as reported in fig. 4 and table 1.

INSERT FIG. 4 ABOUT HERE

INSERT TABLE 1 ABOUT HERE

The interaction with solar radiation was simulated through an appropriate sub-model of the thermal library, which allows to calculate the solar radiation on a planar surface, according to eq. 1 - 3, using as input the solar altitude, the azimuth, the ground radiation, the collector azimuth and the tilt angle.

$$G = I_{bn}\cos(i) + \frac{I_{d0}}{C}\cos^2\left(\frac{\beta}{2}\right) + \left[I_{bn}\sin(\alpha) + I_{d0}\right]\, r\, \sin^2\left(\tfrac{\beta}{2}\right) \tag{1}$$

$$C = \tfrac{A_c}{A_r} \tag{2}$$

$$\cos(i) = \cos\left(a - a_w\right)\cos(\alpha)\sin(\beta) + \sin(\alpha)\cos(\beta) \tag{3}$$

where a_w is the angle formed between the normal of the panel and the south direction on the horizontal plane. Since no data were available about the diffuse and reflected radiation, only ground direct radiation was considered, neglecting the diffuse and reflected component. The effect of the acceptance angle of the concentrator and of the panel was taken into account by cutting radiation data off the range of the acceptance angle. Thermal inertia of the panels was computed by introducing the mass and the material properties of various components. The receiver was modelled as an evacuated pipe consisting of two glass envelopes and a single inner copper pipe. The heat transfer within the enclosure was calculated using radiative, convective and conductive resistances according to fig. 6 available in the software. The value of each resistance was evaluated by referring to literature data [20, 21]. The efficiency of the collector was finally computed as the ratio between the useful heat and the incident radiation, and its trend was validated by the manufacturers specification, as shown in fig. 7. The whole solar field heat flow rate was calculated by multiplying the mass flow rate of a single array by the total number of arrays.

INSERT FIG. 7 ABOUT HERE

3.2. HTF circuit

The HTF circuit was modelled as an open loop which receives the heated fluid from the solar field. Whithin the loop the HTF heated the working fluid of the ORC and then it was sent back to the solar field by means of a variable speed circulating pump, which controlled the collectors outlet temperature through a proportional control. Pressure loss of the circuit were taken into account through various punctual orifices. A pressurized expansion tank was inserted to compensate the volumetric expansion of the heat transfer fluid.

3.3. Heat exchangers

The preheater, the vaporizer and the superheater were modelled as distinct elements, each of one was divided into several nodes to account for HTF and working fluid temperature variation. All the heat transfer sections were modelled as shell and tube exchangers. The HTF flows inside the tubes, while R-600a flows inside the shell. In order to model the HTF, the elements of thermo-hydraulic library were used, while the elements of the two phase flow library were adopted for the working fluid.

For each node and for each fluid the code computed the variation of internal energy using the first law of thermodynamics applied to an open system:

$$\frac{dU}{dt} = \sum_{i=1}^{n} \dot{m}_i \cdot h_i + \frac{d\dot{Q}}{dt} = \rho V \frac{du}{dt} + u V \frac{d\rho}{dt} \tag{4}$$

$$\frac{dQ}{dt} = \lambda \cdot A \cdot \Delta T \tag{5}$$

The heat transfer coefficient were evaluated by the numerical code by using built in correlations. For the HTF side, the Nusselt number was evaluated by using the Sieder and Tate correlation [23]. For the two phase side, the heat transfer was modelled using correlations for pipes and adding several chambers to take into account the major volume of the shell, since the software does not allow to model the shell of an heat exchanger.

On the R600a side, the Gnielinski and VDI (Verein Deutscher Ingenieure) correlations were used in single phase turbulent regime and when the fluid boils in horizontal tubes respectively [24].

A sensitivity analysis about the influence of the two phase flow correlation was carried out by using constant heat transfer coefficients and the results showed that these coefficients did not provide any important variation on production and on plant behavior, being one order of magnitude larger than the HTF heat trasnfer coefficient.

The total volume of the chambers used to model the shell was about 100 liters, as a result of the heat exchanger design calculation.

3.4. Expansion device

The expansion device was modelled by using, the ”two phase turbine” model, which uses several look-up tables to calculate the volumetric flow rate and isentropic efficiency as a function of the pressure ratio and of the rotational speeds. These data were gathered from the results of the numerical model of the expansion device [4–6]. The fitted surface of the volumetric flow rate is shown in fig. 8.

INSERT FIG. 8 ABOUT HERE

The expander speed was controlled in order to keep the saturation pressure at the set point value. The value of the speed was controlled in the range of 500-3000 rpm in order to keep the value of saturation pressure at the set point if the exchanged heat is enough to warm up the fluid up to the temperature corresponding to the set point saturation pressure. In other cases the device rotates at its minimum speed. The mechanical efficiency (0.95) and the electrical efficiency (0.85) were considered constant and average for similar applications. Output power was calculated as:

$$\dot{W}_{exp} = \rho_{ad} \cdot \dot{V} \cdot \Delta h_{is} \cdot \eta_{is} \cdot \eta_{mec} \cdot \eta_{el} \tag{6}$$

3.5. Feed Pump

The pump was modelled as a volumetric fixed displacement pump with a constant efficiency ($\eta_p = 0.8$) and its work consumption was calculated as:

$$\dot{W}_p = \frac{\dot{m} \cdot \Delta p}{\rho \cdot \eta_p} \tag{7}$$

The pump rotational speed controlled the superheating temperature.

3.6. Condenser

The condenser was modelled as a two phase flow separation chamber with set internal temperature, variable over time. The internal temperature was kept 15 °C above the ambient temperature to ensure the heat transfer between the working fluid and the air. The air condenser consumption was calculate by multiplying the specific consumption by the condensing thermal power. The value of the specific consumption was 17 W/kW_{th}, obtained from state of the art commercial equipments.

3.7. Recuperator

The efficiency of the recuperator was assumed as constant and equal to 0.85.

3.8. Control System

Three control loops was defined in this model:

1. control of the outlet temperature of the collector field at the set point value, by changing the rotational speed of the circulating pump;
2. control of the evaporating pressure, by changing the expander speed;

3. control of the superheating temperature, by changing the feed pump speed.

   This control strategy allows to operate the plant at the best thermodynamic conditions which are very near to the conditions studied in the stationary analysis [17]. If the temperature of the HTF fluid were not controlled and the pump were kept at constant speed, on one hand there would be the risk of choosing a too low flow rate, which can cause water vaporization when irradiation occours, and on the other there would be the risk to operate with a too low temperature, which reduces the termodynamic efficiency of the ORC. The saturation pressure of 28.4 bar and the superheating temperature of 150 °C gave the best results in terms of overall efficiency.

4. Boundary conditions

The model was simulated in different conditions of radiation and for several consecutive days using data from historical series for the city of Pisa, available in [22]. This data provided ground irradiation and air temperature hour by hour for every day of the year.

Air temperature was used both to calculate the condenser temperature ($T_c = T_a + 15$), and to calculate convection and radiation losses of the collectors.

Since the acceptance angle of the concentrators is 60°, the tilt angle of the panel was varied in the range 35-50°. Larger values prevent the collection of sun rays in the middle of the day, when the solar altitude is maximum during the summer period, whereas lower values prevent the collection of sun rays when the solar altitude is lower, i.e. in winter and shortly after the sunrise and before the sunset.

Solar altitude and azimuth were provided to the model to calculate the incidence angle with the glass cover of the collectors. The number of panel was set in order to provide the maximum thermal power of about 150 kW to the plant ($P_{sat} = 28.4\,bar$, $T_{sh} = 150^oC$, $T_{HTF} = 160^oC$) on the 21th of June. Mutual shading between the various rows was calculated as a function of the tilt angle, of the solar altitude angle and of the distance between the rows.

5. Simulations and Results

5.1. Clear sky conditions

A first simulation with clear sky conditions and on the 21st of June (fig. 9) was performed to set up the control parameters of the plant. The efficiency of the recuperator was set to 0.85. Lower values lead to lower performances, despite the increase of the temperature of the HTF at the collectors inlet, which lowered their efficiency.

INSERT FIG. 9 ABOUT HERE

As an example, the results of the calculations with $\beta = 35^o$ are reported in fig. 10 and 11in terms of radiation, thermal input, delivered electrical output and HTF temperatures. As expected, without any storage system, the mechanical output followed the trend of the incident radiation, but with a slight delay due to the thermal inertia of the system. After the sun set on collectors the plant continued to operate for almost an hour. The trend of production is slightly wrinkled because of the daily variation of the condensing pressure which is bounded by the ambient air temperature. The delay after the sun rised in collectors was due to the time which was needed to warm up the HTF and to produce vapor with a unit vapor quality. The circulating pump speed was kept at the minimum during warm-up and it was increased as the temperature approached the set-point (160 °C).

INSERT FIG. 10 ABOUT HERE

INSERT FIG. 11 ABOUT HERE

As shown in fig. 12, the variation of the expander rotating speed was an effective mean to control the evaporating pressure; the superheating temperature also proved to be quite constant along the day (fig. 13). The global data regarding the collected radiation, the electrical production and the average efficiency of the plant are reported in tab. 2. In this case the plant was able to follow the variations of radiation and set point value were retained during operations.

INSERT FIG. 12 ABOUT HERE

INSERT FIG. 13 ABOUT HERE

INSERT TAB. 2 ABOUT HERE

5.2. Real conditions

The plant was simulated in real sky conditions to verify its operational flexibility. On the basis of the analysis described in the previous paragraph, the tilt angle of the panels was increased to 45° to collect more radiation and consequently the sunrise angle of the panel decreased to 15°. To limit the ground occupied surface, mutual shading was accepted and the closest rows to the ground saw the sun when its altitude was higher than 25°.

Because of the different incidence angle the number of concentrators was increased to 666, to collect the same maximum thermal power of 150 kW, with a surface of the panels of $197\,\mathrm{m}^2$ and an occupied area of $656\,\mathrm{m}^2$. If mutual shading is avoided the occupied ground surface of the collectors field raises up to $1480\,\mathrm{m}^2$, reducing the plant specific energy production per unit of ground surface.

Five consecutive days on the month of October were simulated (fig. 14). These days were chosen since they are representative of different radiation conditions, as reported in fig. 15, both for the lowest collector (the closest to the ground) and for the highest.

INSERT FIG. 14 ABOUT HERE

INSERT FIG. 15 ABOUT HERE

As expected, because of the absence of the storage, collectors heat output and mechanical output (fig. 16) followed the trend of solar radiation with a later start up after the sunrise and a later shut down after the sunset. Under a certain radiation value production did not start-up, since the useful heat was not enough to compensate thermal losses and warm-up. Shut-down occurred an hour after the collectors did not see the sun (fig. 15).

INSERT FIG. 16 ABOUT HERE

INSERT FIG. 17 ABOUT HERE

Mutual shading of some rows of collectors has a negative impact on the production start-up and shut-down, increasing the start-up and decreasing the shut-down delay. In fact shaded rows do not collect useful heat and moreover behave as a radiator, wasting heat in convection and radiation losses and lowering the temperature at the inlet of the solar field. As a result, the heat-ing process is slower and the temperature of HTF does not quickly reach values at which the system may be started-up, delaying start-up. On the other hand, during shut-down the HTF is cooled by the shaded rows and useful heat is wasted, reducing plant inertia. This effect is particularly evident analyzing the HTF temperature at the collectors outlet at the beginning of day 2 (fig. 18) and the collectors radiation at the same time (fig. 13, 15).

INSERT FIG. 18 ABOUT HERE

Superheat temperature was kept constant at about 150 °C by the feeding pump acting on the liquid level of the evaporator (fig. 17) while the trend of temperature at the evaporator inlet was wrinkled by the effect of condensing temperature and by the effect of expander speed variation (fig. 19). Saturation pressure was kept at its set-point value (fig. 20). Obviously the lack of a thermal storage cause strong fluctuations in power generation. However a constant (or almost constant) power generation means that the expander rotates at constant speed at its design point (1500 rpm in the case of this analysis), requiring thermal storage, a larger solar multiple and therefore a larger collector field or an integration with an external heat source. Without the storage the production is not able to follow the radiation trend, but it allows to reduce the size of the solar field which is designed for the maximum plant power output when the expander rotates at 3000rpm. Due to the flexibility of the volumetric expander the plant can adapt itself to the variation of the boundary conditions.

INSERT FIG. 19 ABOUT HERE

INSERT FIG. 20 ABOUT HERE

5.2.1. *Influence of Concentration*

All these results were collected when $C = 2$. The results collected with this concentration were shown because this configuration provided the best performances, despite the limited acceptance angle.

As a comparison, the same analyses were performed with C=1.25. The number of collectors was increased to 1161 in order to provide the same maximum thermal power to the ORC cycle (150 kW), and the tilt angle was set at 45°.

As well known, a lower concentration results in a larger acceptance angle (106 versus 60 degree in this case); this fact in theory would allow the collectors to collect the solar heat for a larger number of hours per day, however in practice the mutual shading between the rows makes ineffective this advantage. In facts, when C=2, only the lower row is shaded as long as α is lower than 25° (fig. 21), while when C=1.25, all the three rows are shaded as long as α is respectively lower than 25, 15 and 5° (fig. 22).

INSERT FIG. 21 ABOUT HERE

INSERT FIG. 22 ABOUT HERE

Other effects make disadvanteous the use of C=1.25 instead of C=2, since the electrical output proved to be more sensitive to variations of radiation: not only the collectors have a lower lower efficiency, but also a larger quantity of HTF fluid is needed due to the larger solar field, which led to a further increase in the plant warm-up period. As a result, on the fourth and fifth day production did no longer follow the solar radiation in the earliest hours of the days. Due to the longer warm-up period, the set point temperature (160°) was reached when the ORC cycle had already reached the set point evaporating pressure (28,4 bar), as shown in fig. 23. The variation of HTF mass flow rate to keep the temperature at its set point caused a strong variation of thermal power input to the ORC cycle, emphasized by the higher slope of collectors efficiency [20]; in turn the expander speed increased in order to keep the evaporating pressure at its set point causing a fluctuation of the electrical output (fig. 24).

INSERT FIG. 23 ABOUT HERE

INSERT FIG. 24 ABOUT HERE

Even in this case, mutual shading of collectors along with low concentration was the cause of a long delay in the warm-up phase; the simulations showed the difficulty to properly tune the control system to handle fast phenomena, as reported by [13].

As a comparison, the results using the two different concentrations are summarized in tab. 3.

INSERT TAB. 3 ABOUT HERE

6. Conclusions

In this work, the dynamic model of a low concentration CPC power plant has been developed. The plant has been modelled in all its main parts and was controlled by the expander speed variation without the need of any storage system or integration with external heat source.

Simulations were carried out at different conditions of radiation. A first simulation was realized with clear sky conditions and a concentrating factor of collectors equal to 2, to set up parameters and showed the capacity of the plant of following solar radiation. Then five consecutive days of the month of

October were simulated. These days were representative of different radiation conditions and data were furnished by historical series.

Despite the low efficiency value, typical of these systems, the control strategy has proved to be suitable and even in various working conditions the plant has managed to follow the load variations and to keep all control parameters at their set point. Mutual shading of collectors was taken into account. Eventually results were compared to those obtained with C=1.25 collectors. Besides the lower overall efficiency, the slowness of warming up and the higher slope of the efficiency curve of the collectors stressed the control system, which was able to keep operative parameters at their set point value, but production has not been able to follow solar radiation. The use of higher concentration collectors coupled with a simple tracking system, may reduce warm up lag, increase efficiency of the system, and reduce the number of collectors on the field.

The model has shown the potential of volumetric expanders to be a valid alternative to the use of thermal storage or integration with external sources and this type of regulation can be adopted in several low power application (waste heat recovery or low temperature geothermal systems) where thermal power input is variable over time.

References

[1] Rabl A, Goodman NB, Winston R. Practical design considerations for CPC solar collectors. Solar Energy 1979; 22 (4): 373-381.

[2] Mills DR, Basset IM, Derrick GH Relative cost-effectiveness of CPC re-

flector designs suitable for evacuated absorber tube solar collectors. Solar Energy 1986; 36 (3): 199-206.

[3] Farouk Kothdiwala A, Eames PC, Norton B. Optical performance of an asymmetric inverted absorber compound parabolic concentrating solar collector. Renewable Energy 1996; 9 :576-9.

[4] Antonelli M, Baccioli A, Francesconi M, Lensi R, Martorano L. Analysis of a Low Concentration Solar Plant with Compound Parabolic Collectors and a Rotary Expander for Electricity Generation. Energy Procedia 2014; 45: 170-9.

[5] Antonelli M, Martorano L. A Study on the Rotary Steam Engine for Distributed Generation in Small Size Power Plants. Applied Energy 2012; 97: 642-7.

[6] Antonelli M, Baccioli A, Francesconi M, Desideri U, Martorano L. Operating maps of a rotary engine used as an expander for micro-generation with various working fluids. Applied Energy 2014; 113: 742-750.

[7] Quoilin S, Declaye S, Legros A, Guillaume L, Lemort V. Working fluid selection and operating maps for Organic Rankine Cycles expansion machines. International Compressor Engineering Conference at Purdue 2012.

[8] Badami M, Mura M. Preliminary design and control strategies of a small scale wood waste Rankine cycle (RC) with a reciprocating steam engine (SE). Energy 2009; 34: 1315-1324.

[9] Antonelli, M., Baccioli, A., Francesconi, M., Martorano, L. Experimental and numerical analysis of the valve timing effects on the performances of a

small volumetric rotary expansion device (2014) Energy Procedia, 45, pp. 1077-1086.

[10] Vitte P, Manenti F, Pierucci S, Joulia X, Buzzi-Ferraris G., (2012), Dynamic simulation of concentrating solar plants, Chemical Engineering Transactions, 29, 235-240.

[11] Manenti F, Ravaghi-Ardebili Z. Dynamic simulation of concentrating solar power plant and two-tanks direct thermal energy storage. Energy 2013; 55: 89-97.

[12] El Hefni B. Dynamic modeling of concentrated solar power plants with the ThermoSysPro library (Parabolic Trough collectors, Fresnel reflector and Solar-Hybrid). Energy Procedia 2014; 49: 1127-1137.

[13] Rodat S, Souza JVD, Thebault S, Vuillerme V, Dupassieux N. Dynamic simulations of Fresnel solar power plants. Energy Procedia 2014; 49: 1501-1510.

[14] Eck M, Hirsch T. Dynamics and control of parabolic trough collector loops with direct steam generation. Solar Energy 2007; 81: 268-279.

[15] Henrion T, Ponweiser K, Band D, Telgen T. Dynamic simulation of a solar power plant steam generation system. Simulation Modelling Practice and Theory 2013; 33: 2-17.

[16] Quoilin S, Aumann R, Grill A, Schuster A, Lemort V, Spliethoff V. Dynamic modelling and optimal control strategy of waste heat recovery Organic Rankine Cycles. Applied Energy 2011; 88: 2183-2190.

[17] Antonelli M, Baccioli A, Francesconi M, Desideri U, Martorano L. Electrical Production of a Small Size Concentrated Solar Power Plant with Compound Parabolic Collectors. Renewable Energy 2015. Arcticle in press.

[18] Gudekar AS, Jadhav AS, Panse SV, Joshi JB, Pandit AB. Cost effective design of compound parabolic collector for steam generation. Sol Energy 2013;90: 4350.

[19] V. Lemort, S. Quoilin, C. Cuevas, J. Lebrun. Testing and modeling a scroll expander integrated into an Organic Rankine Cycle. Applied Thermal Engineering 2009; 29: 30943102.

[20] Farouk Kothdiwala A, Norton B, Eames PC. The effect of variation of angle of inclination on the performance of low-concentration-ratio compound concentrating solar collector. Solar Energy 1995; 55 (4): 301-9.

[21] Rabl A. Comparison of solar concentrators. Solar Energy 1975; 18: 93-111.

[22] European rule UNI EN ISO 15927-4

[23] AMESim Thermal Hydraulic Tutorial Guide

[24] AMESim Two Phase Flow Tutorial Guide.