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Dynamic analysis of off-grid systems with ORC plants adopting various solution for the thermal storage

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Abstract

Real time matching of electric power generation is a crucial aspect in off-grid systems as well as in case of use of renewable intermittent sources. In this paper, with reference to 1 MW_{el} Turboden biomass ORC plants operating in off-grid systems, we study the possibility to store thermal energy in the form of sensible heat within a storage composed by a bunch of steel or cast iron pipes with variable thickness and different coating materials. Thermal power is taken in and out of the storage by a flow of thermal oil, heated by a biomass furnace, and eventually supplied and converted into electricity by the ORC plant running in an off-grid area. Starting from steady state conditions at 30% of the nominal power of the furnace, we assume an instantaneous increase to 100% of the electric power demand and we study the transient of the system in correspondence of the furnace power ramp. To this purpose, we developed a dynamic finite difference model, for the system composed by the furnace, the ORC plant, the furnace inlet and outlet piping and the thermal storage. It comes out that with a storage system properly designed as function of the furnace power ramp, it is possible to run the ORC at 100% during the analyzed transient, thus allowing a real time matching of the power demand.

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Keywords: Off-grid systems; Organic Rankine Cycles; Dynamic analysis

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1. Introduction

Electrification through off-grid systems is generally the preferred choice whenever the grid connection is difficult to achieve for technical and/or economic reasons. Typical cases can be found in small villages located in remote areas or in developing countries. In such situations, the electricity generation should normally rely on local renewable primary resources like wind and solar energy or the heat produced by biomass combustion. Though, the real time coupling with the electric demand can be rather challenging in case of electricity generated by intermittent resources, thus requiring the use of some storage technologies. These may include batteries [1], hydrogen as energy carrier [2] and particularly for large scale applications, pumped hydro storage (PHS) and compressed air energy storage (CAES) [3]. Moreover, high temperature thermal energy storage (TES) such as molten salt are often considered in solar applications. However, the relatively high costs and risk of salt freezing have so far limited their diffusion. Also in a few cases, the combination of thermal storage with ORCs has been explored in solar electricity generation [4,5]. To this respect, the availability of biomass as fuel in external combustion power plant like ORC or gas cycles may carry some advantages given the possibility to control the furnace power in accord to the electric power demand [6,7,8,9]. Nonetheless, even in this case the real time matching of the electric power generation is still difficult owing to the comparatively slow load change transient of both the furnace and the other components of the power cycle, thus requiring the use of one of the storage solution mentioned above.

In this paper, we study the transient of an off-grid system in case of a single step change of the power demand, by means of dynamic simulations carried out in Aspen Custom Modeler. The power plant is based on the available operating data of 1 MW_{el} Turboden biomass ORC. The system includes a thermal energy storage composed by a bunch of steel or cast iron pipes. The effectiveness of this solution will be analyzed and optimized in different cases, defined as function of the considered storage material, the diathermic oil maximum temperature and the position of the storage.

2. System description

The system considered in this analysis is shown schematically in Figure 1. It consists of an ORC power plant fed by the diathermic oil provided by a boiler heated by the exhausts of a biomass furnace, through a supply and a return piping. The following temperature can be evidenced:

- $T_{in,\ boiler}$: inlet boiler temperature, corresponding to the outlet temperature of the return piping
- $T_{out,\ boiler}$: outlet boiler temperature, corresponding to the inlet temperature of the supply piping
- $T_{in,ORC}$: inlet ORC temperature, corresponding to the outlet temperature of the of the supply piping
- $T_{out,ORC}$: outlet ORC temperature, corresponding to the inlet temperature of the return piping

In nominal conditions, the boiler generates about 5 MW_{th} that are converted into about 1 MW of electricity by the ORC plant. Nominal operating conditions and main geometric data of the considered system are reported in Table 1. Physical properties for diathermic oil and carbon steel employed for the piping are taken from [10,11]

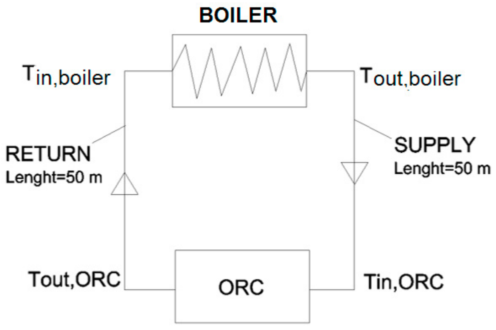

Fig. 1. Layout of the considered system.

Table 1. Nominal operating conditions and main geometrical and material properties data of the system shown in Figure 1.

Boiler thermal power	5141 kW
ORC electrical power	1043 kW
ORC efficiency	20.2%
$T_{out,ORC}=T_{in,boiler}$	240 °C
$T_{out,Furnace}=T_{in,ORC}$	300 °C
Diathermic oil mass flow	34.8 kg/s
Diathermic oil velocity in boiler piping	8.2 m/s
Diathermic oil velocity in supply and return pipes	2.3 m/s
Overall equivalent length of the piping in the boiler	240 m
Furnace piping internal diameter / thickness	80 mm / 7 mm
Length of supply and return pipes	50 m
Supply and return pipes internal diameter / thickness	150 mm / 10 mm
Properties of steel employed in pipes:	
Specific heat $c_{p,steel}$/ Density ρ_{steel} / Thermal conductivity k_{steel}	500 J/kgK / 7500 kg/m^3 / 50 W/mK
Properties of the diathermic oil:	
Specific heat $c_{p,oil}$/ Density ρ_{oil} / Thermal conductivity k_{oil}	2500 J/kgK / 840 kg/m^3 / 0.095 W/mK

3. Modeling of the plant components

3.1 Boiler

We consider a biomass furnace that in nominal conditions provides heat to a diathermic oil raising its temperature from $T_{in,Furnace}$=240°C to $T_{out,Furnace}$=300°C (Figure 1). This process is normally carried in a heat exchanger where thermal power is transferred from the biomass combustion products (hot stream) to the diathermic oil (cold stream).

The following assumptions are made:

a) the cold stream of the furnace consists of a single carbon steel pipe with internal diameter and thickness of 80 mm and 7 mm respectively. The length of this piping is determined assuming an overall mass of 1000 kg for the contained thermal oil

$$M_{oil} = \rho_{oil} V = \rho_{oil} \frac{\pi D_{int}^2}{4} L \tag{1}$$

where M_{oil} is the mass of the oil, ρ_{oil} the oil density, V the overall internal volume of the piping, D_{int} the internal diameter and L the equivalent length. Thus, considering and average oil density of 840 kg·m^{-3}, we obtain from Eq.1 L= 240 m.

b) it is assumed for simplicity that the heat is generated by a heat source uniformly distributed through the oil pipe thickness t. The temperature profile along the oil flow and the piping is calculated through a one-dimensional finite difference analysis. In each node, identified by the axial coordinate x, the conservation of energy is applied as follows for the oil and the piping thickness respectively

$$\rho_{oil} c_{p,oil} \frac{\partial T_{oil}(x)}{\partial t} = -u_{oil} \rho_{oil} c_{p,oil} \frac{\partial T_{oil}(x)}{\partial x} + \frac{4U}{D_{int}} \left[T_{steel}(x) - T_{oil}(x) \right] \tag{2}$$

$$\rho_{steel}c_{p,steel}\frac{\partial T_{steel}(x)}{\partial t}=k_{oil}\frac{\partial^2 T_{oil}(x)}{\partial x^2}+\frac{U}{t}\left[T_{oil}(x)-T_{steel}(x)\right]+\frac{\dot{Q}}{\pi D_{int}tL} \tag{3}$$

Notably, the last term on the right end side of Eq.3 represents the heat source within the pipe, which, in accord to our previous assumption, emulates the thermal power generated by the biomass combustion. The heat exchanged between the oil and the internal surface of the piping is determined by the overall heat exchange coefficient U. This is obtained from the Nusselt number, $Nu=0.023Re^{0.8}Pr^{n}$ given by the well-known Dittus-Boelter equation, valid for circular ducts, where n=0.3 for cooled fluids and n= 0.4 for heated fluids [12]. The mathematical problem is closed by the following boundary conditions

$$\begin{aligned}&T_{oil,x=0}=T_{in,Furnace}\\&\frac{\partial T_{steel,x=0}}{\partial x}=0\\&\frac{\partial T_{steel,x=L}}{\partial x}=0\end{aligned} \tag{4}$$

3.1 ORC Plant

In the ORC plant the heat produced by furnace is converted into electricity. Operating data of the ORC plant at both nominal and part load conditions, available from Turboden, are reported in Table 2 and 3. We assumed that the ORC is capable to adapt to different feeding conditions. This can be reasonable, considering the relatively slow variations due to the inertia of the system. It is worth noting that part load conditions can be obtained either varying the oil inlet temperature $T_{in,ORC}$ with fixed oil mass flow (Table 2) or varying the oil mass flow at fixed $T_{in,ORC}$ (Table 3)

Table 2. Part load data of the ORC obtained by varying the inlet oil temperature (Tin.ORC), at rated mass flow of 34.8 kg/s

$T_{in,ORC}$, °C	T_{outORC} °C	Boiler power, kW	ORC power, kW
300	240	5141	1043
280	232	3992	810
260	224	2959	582
240	213	2128	390

Table 3. Part load data of the ORC obtained by varying the inlet oil mass flow with fixed $T_{in.ORC}$ of 300 °C

Oil mass flow, kg/s	T_{outORC} °C	Boiler power, kW	ORC power, kW
34.8	240	5141	1043
21.2	220	4115	838
12.8	199	3085	610
4.3	162	1358	204

3.2 Supply and return oil piping

Supply and return pipes allow the circulation of the diathermic oil between the ORC plant and the furnace. Each pipe is made of carbon steel with length of 50 m, internal diameter of 150 mm and thickness of 10 mm. The heat exchange model of these pipes is based on the same finite difference approach considered for the furnace, leading to a system of equations analogous to Eq.2-4 with the exception that no heat generation source is present at the right end side of Eq. 3. Main geometric and material properties data of the supply and return pipes are included in Table 1.

4. Simulations and results

Simulations are carried out to evaluate the behavior of the system shown in Figure 1, in case of a variation of the electricity load demanded by the off-grid units served by the ORC plant. The governing equations discussed in Section 3, are implemented in Aspen Custom Modeler and the resulting differential-algebraic system is integrated adopting the Runge-Kutta method. In terms of the finite differences analysis we adopt 480 intervals for the furnace piping and 100 intervals for the supply and return pipes equivalent in both cases to a spatial resolution of 0.5 m. This was proved by a sensitivity analysis on the grid resolution, to be a good compromise between accuracy of the results and computational time.

4.1 Initial conditions and load variation

The conditions of the initial steady state, considered in the first 50 seconds of the simulations are represented in Figure 2(a). The furnace operates at 30% of the rated power, producing 1542 kW_{th}, provided to the ORC through the diathermic oil. This part load condition is achieved with the rated furnace oil mass flow of 34.8 kg/s, by reducing the oil temperature variation across the boiler from 60 °C to 18 °C (i.e. 30% of the design value). A by-pass circuit at the output of the supply pipe, is employed to reduce the oil mass flow provided to the ORC to 5.0 kg/s. Under these conditions, the ORC receives a thermal power of 1542 kW_{th} (given the steady state, equivalent to that produced by the furnace), converted into 248 kW_{el}, corresponding to about 24% of the nominal value, according to part load data available from Table 3. Then, at t=50s, it is assumed that the electric power demand increases instantly, resulting in stepwise increase of the ORC to 100% of the rated power. To cope with the sudden load variation, according to Figure 2b:

- the by-pass circuit is closed in order to provide the full diathermic oil flow to the ORC
- the furnace progressively increases the production of thermal power, reaching 100% of the load through a linear power ramp with duration of 15 minutes (the ramp time depends on furnace size, kind of boiler and biomass. The relatively low value chosen here is representative of fast response systems).

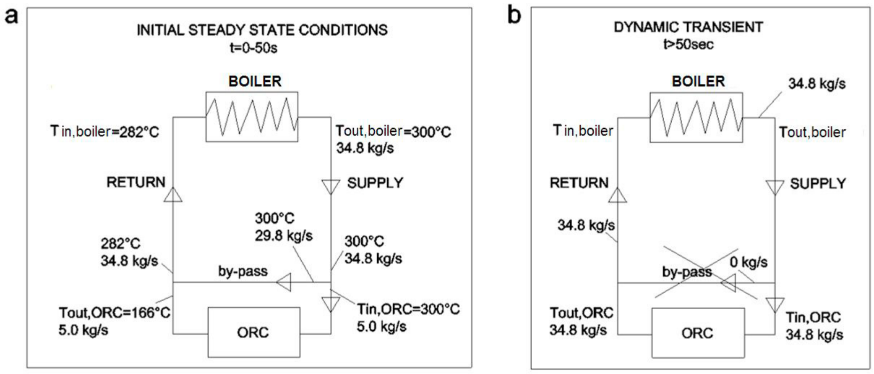

Fig. 2. (a) Steady state initial conditions of the system with the furnace operating at 30% of the rated thermal power; (b) Conditions of the dynamic transient due to a stepwise increase to 100% of the ORC power.

4.2 Results without storage

Main results of the simulations are reported in Figure 3. Figure 3(a) shows the time profiles of the four characteristic temperatures, starting from the stationary values of Figure 2(a). It can be noted that at time t=50s, it is assumed that the stepwise increase of the ORC power determines an instantaneous change of $T_{out,ORC}$ to 240 ° C, in accordance with the operating part load data of Table 2. Due to the inertia of the supply and return pipes, in the following 20-30 s, $T_{in,Furnace}$ remains close to the initial value of 282 ° C, before decreasing to about 250 °C in the subsequent 200 s. This in turn determines a reduction of $T_{out,Furnace}$ and $T_{in,ORC}$ since, by assumptions the furnace requires a 900 s to reach the rated power. The reduction of $T_{in,ORC}$ implies a reduction of $T_{out,ORC}$ and of the electric power of the ORC according to Table 2. Figure 3(b) shows, in percentage of the nominal value, the time profile of the ORC power. It is noted that the minimum power of approximately 50% of the nominal value is reached after about 350 s (in correspondence of the minimum $T_{in,ORC}$) , while the nominal power is established again at about t=1200 s, after the furnace has reached its nominal power.

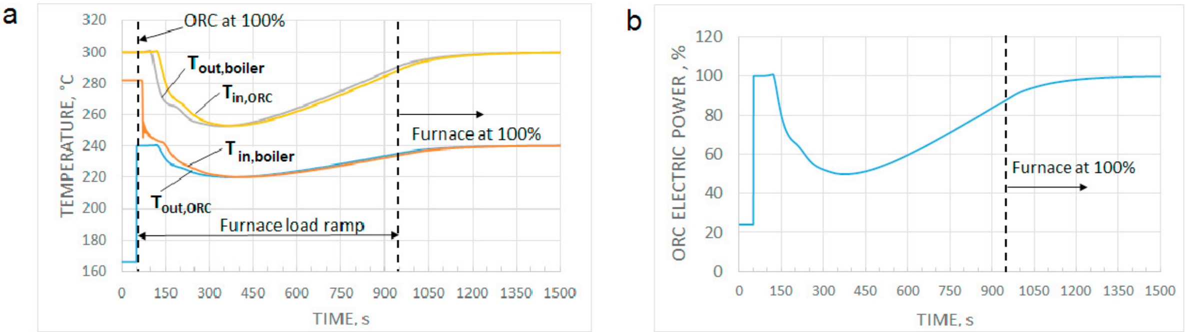

Fig. 3. (a) Time profile of the characteristic temperatures of the system shown in Figure 1, in case of a step change to 100% of the ORC power (at t=50s); (b) ORC electric power time profile.

4.3 Thermal storage

To limit the electric power undershoot shown in Figure 3(b), the possibility of employing a thermal storage, with characteristics similar to that described in [13] was considered. It consists of one block of storage material crossed by 36 carbon steel pipes with length of 50 m where the thermal oil flows. Thus, the thermal energy is stored in the form of sensible heat in the mass of the storage material and can be exchanged with the oil through contact with the pipe walls. The number of pipes is determined by imposing, in nominal conditions, the same velocity of 2.3 m/s in the supply and return pipes (Table 1). A sketch of the storage system with the relevant geometrical data is shown in Figure 4.

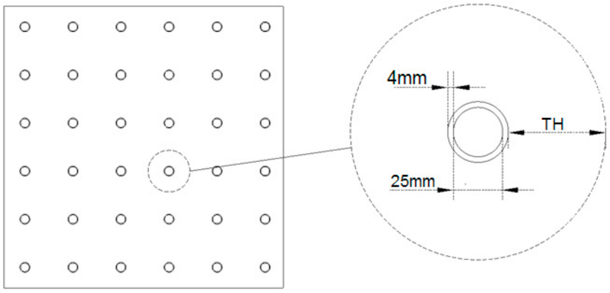

Fig. 4. Axial section of the storage system consisting of block of storage material crossed by 36 carbon steel pipes with length of 50 m.

For simplicity, we model a single pipe, considered representative of the average conditions within the storage. The overall dimension and weight of the storage is therefore defined by the thickness of the storage material TH (Figure 4) that will be optimized in the following analysis. Two different storage materials are considered, namely concrete and cast iron whose physical properties are reported in Table 4. We consider the thermal storage to be positioned either before or after the boiler i.e. replacing the return and supply pipe. From the point of view of the mathematical model, we adopt a two dimensional finite difference with cylindrical coordinates [14] in order to monitor the temperature distribution in both radial and axial direction of the storage. In order to increase thermal storage it becomes advantageous increasing the oil temperature above the nominal operating temperature of the ORC. In the following, a maximum temperature of 370°C has been considered. The adoption of this temperature would require the use special types of thermal oil as well as different solutions for the boiler realization, yielding to more expensive system. Notably, in cases with maximum oil temperature of 370°C, in order to keep the temperature of the oil at 300 °C at the ORC inlet, we consider the possibility to recirculate part of the oil mass flow at the ORC outlet. The following six cases are defined in terms of: storage material/ diathermic oil maximum temperature/position in the layout of Figure 1: (a) Concrete / 300 °C / after the boiler; (b) Cast iron / 300 °C / after the boiler; (c) Concrete / 370 °C / after the boiler; (d) Cast iron / 370 °C / after the boiler; (e) Concrete / 370 °C / before the boiler; (f) Cast iron / 370 °C / before the boiler. Clearly, the operation at 370 °C implies the use of a thermal oil of higher quality and cost. Simulation are carried out in the same conditions defined in Section 4.1, starting with the storage fully charged with a uniform temperature distribution.

Table 4. Properties of the materials employed for the storage system ([11],[13]).

Storage material	Specific heat J/kgK	Density kg/m^3	Thermal conductivity W/mK
Concrete	1120	2400	2.2
Cast iron	500	7500	50

4.4 Results in case of storage

Results of the simulations are summarized in Figure 5, where the minimum power reached by the ORC during the transient analysis is plotted as function of the storage thickness TH (Figure 4). The following comments can be made:

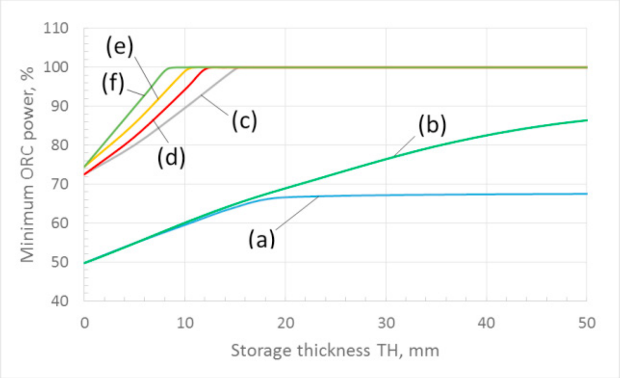

Fig. 5. Results of the simulations in case of storage, with furnace ramp time of 15 min. The following six cases are defined in terms of: storage material/diathermic oil maximum temperature/position. (a) Concrete/300 °C/after the boiler; (b) Cast iron/300 °C/after the boiler; (c) Concrete/370 °C/after the boiler; (d) Cast iron/370 °C/after the boiler; (e) Concrete/370 °C/before the boiler; (f) Cast iron/370 °C/ before the boiler.

- the cases without storage (TH=0) show a poor capacity of the system to comply with load variations as the ORC power reduces to about 50% and 70% in case of maximum oil temperature of 300 ° C and 370 ° C respectively
- in case of maximum oil temperature of 300 °C the storage system cannot fulfill the 100% load demand required during the considered transient. The minimum power reached by the ORC is about 68% for concrete with TH=20 mm (case *a*) and about 85% for cast iron with TH=50 mm (case *b*). On the contrary, in case of maximum oil temperature of 370 °C it is possible with a reasonable size of the storage to maintain the ORC at rated power (case *c,d,e,f*)
- cast iron generally shows better performance than concrete as storage material, thanks in particular to the higher thermal conductivity (50 vs. 2.2 W/mK). This results in a more uniform temperature distribution in radial direction which determines a better exploitation of the of overall storage mass. This fact becomes evident when the load ramp of the furnace is increased: for instance, it can be shown that by increasing the furnace ramp time

from 15 to 45 minutes, the use of concrete determines a reduction of the ORC power of at least 10% of the nominal value. However as a consequence of the higher density (Table 4) the solution with cast iron is penalized by the overall weight: in the case with oil at 370 °C the resulting overall optimized mass of storage are respectively about 11 tons (case *e)* and 19 tons (case *f*).

- it is more effective to position the storage before the furnace inlet (cases *e* and *f* vs. cases *c* and *d*). This fact can be explained considering the comparatively lower temperature of the oil in this portion of the system. This implies a potentially higher heat flux from the storage and a consequent better exploitation of the heat stored therein.

5. Conclusions

A dynamic model for the simulation of an off-grid system based on 1 MW_{el} Turboden biomass ORC plant was developed and implemented in Aspen Custom Modeler to study various storage solutions for the real time matching of the power demand. In particular, we considered a thermal storage composed by a bunch of pipes employing either concrete or cast iron as coating materials. To this purpose, we simulated the transient occurring in case of a stepwise increase of the power demand in correspondence to a 15 minutes furnace power ramp from 30 % to 100 %. It comes out that while the system without storage shows a poor capacity to comply with load variations, it is possible, adopting a diathermic oil with maximum temperature of 370 °C, to maintain the ORC at the rated power, resorting to a storage with overall mass of 11 and 19 tons, in case of concrete and cast iron respectively. Moreover, despite the greater weight of the cast iron, this solution in general provides better performances than concrete - particularly in case of slower furnace power ramp - thanks to the higher thermal conductivity (50 vs. 2.2 W/mK), resulting in a more uniform temperature distribution in the radial direction. Finally, further applications of the model may include the analysis of various existing boiler technologies, characterized by different oil mass and thermal inertia, as well as considering different simulation conditions in terms of both ORC load change and furnace ramp time.

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