ENERGY ANALYSIS OF ORGANIC RANKINE CYCLES FOR BIOMASS APPLICATIONS

by

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The present paper aims at analysing the performances of organic Rankine cycles adopted for the exploitation of the biomass resulting from the pruning residues in a 3000 hectares district in Southern Italy. A parametric energy analysis has been carried out to define the influence of the main plant operating conditions. To this purpose, both subcritical and transcritical power plants have been examined and saturated and superheated conditions at the turbine inlet have been imposed. Moreover, the effect of the working fluid, condensation temperature, and internal regeneration on system performances has been investigated.
The results show that the organic Rankine cycle plants represent an interesting and sustainable solution for decentralised and small-scale power production. Furthermore, the analysis highlights the significant impact of the maximum temperature and the noticeable effect of internal regeneration on the performances of the biomass power plants.

Key words: *organic Rankine cycle, biomass, energy efficiency, co-generation, operating conditions, working fluids, transcritical cycle*

Introduction

The organic Rankine cycle (ORC) represents an interesting solution for power production and guarantees high efficiencies for low temperature heat sources and/or small-scale applications [1-5]. Specifically, ORC can be adopted for the exploitation of biomass and agricultural residues [6-12]. In fact, several installations demonstrated that ORC is a well established industrial technology for application in small biomass plants (lower than 1 MW_e) [6, 7] and that power production and co-generation in biomass ORC are among the most effective solutions for reliable and sustainable energy supply in small scale applications, where conventional power plants are technologically and economically unfeasible [8-11].

Biomass ORC plants present several advantages compared with conventional installations due to minimum costs and maintenance requirements, good partial load performances, reliable operations and fast start-up and stop procedures. Furthermore, the use of an appropriate dry organic fluid assures no erosion problem of the turbine blades, higher turbine efficiency (up to 85-90%) and life, and lower mechanical stress of the turbine in comparison with water-steam turbine of the same size [11, 12].

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The proper choice of the organic working fluid is crucial in order to maximise the system performances and guarantee reliable operations. Specifically, the maximum temperature in biomass power generation systems is high with respect to other ORC applications. The maximum operating temperature for organic fluids is 400 °C, provided that the fluid stability temperature is significantly higher [13]. On the other hand, the flame temperature during the combustion process is usually larger than 900 °C and a thermal oil circuit is necessary to avoid local overheating and to prevent organic fluids from becoming chemically unstable [11]. Moreover, for combined heat and power (CHP) production, the condensation temperature usually is relatively high (80-120 °C) to permit co-generation. As a consequence, most fluids for low temperature source cannot be adopted, due to the high vapour pressure at these condensation temperatures [11, 12]. Octamethyltrisiloxane (OMTS) has been adopted in most biomass applications [6, 11, 14, 15], even though the thermal and the global efficiency of the system is comparatively low [11]. Consequently, more suitable working fluids should be adopted, taking into account the high temperature heat source availability.

The definition of the most appropriate plant configurations is essential to optimise the energy efficiency of ORC systems. The researchers focused the attention on saturated ORC cycles. Conversely, the adoption of both superheated and transcritical conditions with internal regeneration are of great interest, because these configurations may lead to higher system efficiencies and, as a consequence, lower operating costs [16-20]. However, few studies are present in literature on this topic.

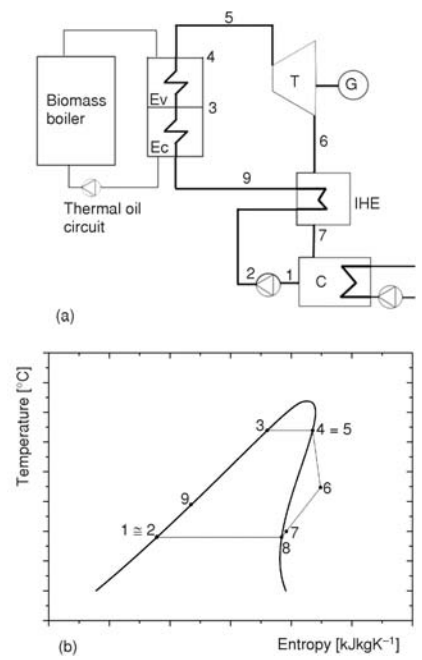

Figure 1. Typical plant layout (a) and *T-s* diagram (b) for an ORC with internal heat exchange; Subcritical cycle: C – condenser, Ec – economyser, Ev – evaporator, T – turbine, G – Electrical generator, IHE – internal heat exchanger

The work aims at investigating the energetic performances of biomass ORC for the exploitation of the biomass resulting from agricultural residues in a farmer cooperative area of about 3,000 hectares. To this purpose the influence of the working fluid and operating conditions on system performances has been investigated. Specifically, cyclohexane, decane, and toluene have been used as working fluids. Saturated and superheated conditions at the turbine inlet have been imposed and both subcritical and transcritical configurations have been analysed. Moreover, the influence of the internal regeneration and condensation temperature on the plant performances has been evaluated.

Methodology

Organic Rankine cycle

The ORC cycle consists primarily of a pump system, an evaporator, a turbine group, and a condenser fig. 1(a). The pump supplies the organic fluid to the evaporator (1-2 process), where the fluid is preheated (2-3) and vaporized (3-4). The vapour flows into the turbine where it is expanded to the condensing pressure (5-6) and, finally, it is condensed to saturated liquid (6-7-8-1). Sometimes, an internal heat exchanger (IHE) can be used to recover the thermal energy at the turbine outlet (6-7). Point 8 refers to saturated vapour. Figure 1(b) shows the corresponding cycle in the *T-s* diagram for a typical dry organic fluid with saturated conditions at the turbine inlet. It is worthy to notice that the deaerator is not necessary. In fact, the air infiltrations are low (ORC plants are often sealed in industrial practise) and a small vacuum pump in the condenser can be used to remove the excess air [21, 22].

Figures 2(a) and (b) illustrate the ORC cycle with the adoption of superheated conditions at the entrance of the turbine and transcritical cycle respectively. In particular, the low critical pressure of organic fluids makes supercritical cycles feasible without running into extreme operating conditions [18, 19, 23-25].

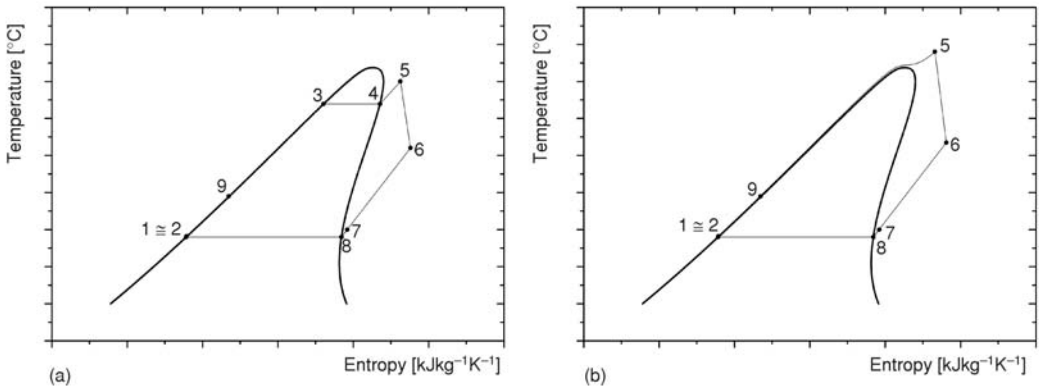

Figure 2. Typical *T-s* diagrams for superheated (a) and transcritical (b) ORC

Thermodynamic model

A thermodynamic model has been developed to characterise the performances of biomass ORC. To this purpose, the REFPROP database [26] has been integrated with the energy model to define the thermodynamic properties of the organic fluids. For the analysis, a steady state condition has been assumed, while pressure drops and heat losses in the plant components have been neglected. The system performances have been expressed in terms of electrical power and efficiency, energy utilisation factor, and co-generation efficiency.

The ORC net electrical power P is evaluated as follows:

$$P = \eta_{\mathrm{em}} P_{\mathrm{u}} \tag{1}$$

where P_{u} is the net power output and η_{em} takes into account the mechanical and electrical losses.

In particular, the net power output represents the difference between the turbine power P_{t} and the power requested by the pump P_{p}:

$$P_{\mathrm{u}} = P_{\mathrm{t}} - P_{\mathrm{p}} \tag{2}$$

The turbine and pump power are calculated according to eqs. (3) and (4), respectively:

$$P_{\mathrm{t}} = \eta_{\mathrm{t}} \dot{m} l_{\mathrm{is,\,t}} = \dot{m} l_{\mathrm{t}} = \dot{m}(h_5 - h_6) \tag{3}$$

$$P_{\mathrm{p}} = \dot{m} \frac{l_{\mathrm{is,\,p}}}{\eta_{\mathrm{is,\,p}}} = \dot{m} l_{\mathrm{p}} = \dot{m}(h_2 - h_1) \tag{4}$$

where $\dot{m}$ is the organic fluid mass flow rate, η_{t} – the isentropic efficiency of the turbine, η_{p} – the isentropic efficiency of the pump, $l_{\mathrm{is,t}}$ – the isentropic specific work of the turbine, $l_{\mathrm{is,p}}$ – the isentropic specific work of the pump, l_t – the specific work of the turbine, l_p – the specific work of the pump, and h_i – the specific enthalpy of the generic state point i.

The electrical plant efficiency is defined as:

$$\eta_e = \frac{P}{Q_t} \tag{5}$$

where the biomass thermal power $\dot{Q}_t$ is:

$$\dot{Q}_t = \dot{m}_b H_i \tag{6}$$

where $\dot{m}_b$ and H_i are the biomass flow rate and the lower heating value, respectively.

The thermal power transferred to the working fluid is:

$$\dot{Q}_i = \eta_{bt} \dot{Q}_t = \dot{m}_{qi} \tag{7}$$

where η_{bt} takes into account the biomass boiler efficiency and the effectiveness of the heat exchange process between organic fluid and thermal oil and q_i is the heat transmitted to the organic fluid:

$$q_i = h_5 - h_2 \tag{8}$$

if the internal heat exchanger is absent, while:

$$q_i = h_5 - h_9 \tag{9}$$

when the internal regenerator is used. According to the literature [2, 11], the efficiency of the internal heat exchanger is given by:

$$\eta_{IHE} = \frac{h_9 - h_2}{h_6 - h_7} \tag{10}$$

where the temperature at the exit of the internal regenerator T_7 is higher than the condensation temperature T_{cond} as follows:

$$T_7 = T_{cond} + \Delta T \tag{11}$$

Finally, as co-generation merit parameter, the energy utilization factor EUF and the co-generation efficiency η_{cog} have been evaluated as follows [27-30]:

$$EUF = \frac{P + \dot{Q}_{cog}}{\dot{Q}_t} \tag{12}$$

$$\eta_{cog} = \frac{P}{\dot{Q}_t - \dfrac{\dot{Q}_{cog}}{\eta_{sb}}} \tag{13}$$

where $\dot{Q}_{cog}$ is the thermal power from the condensation process used for co-generation and η_{sb} – the efficiency of a second boiler that should be used to produce $\dot{Q}_{cog}$ separately.

Operating conditions

Cyclohexane, decane, and toluene have been chosen for the energetic analysis. In fact, literature review highlights that the three organic fluids guarantee chemical stability at the high operating temperatures, consistent with the requirements of biomass plants, and present very interesting performances when high temperature heat sources are available [11, 31-36].

The investigations have been carried out considering saturated and superheated conditions at the turbine inlet. Furthermore, subcritical and transcritical cycles have been examined.

For transcritical conditions, only decane has been adopted owing to its lower critical pressure (21.03 bar).

Table 1 shows the critical temperature and pressure of the selected organic fluids, and the operative conditions assumed in the work. In particular, according to the literature [6, 11, 13], the condensation temperature has been set to 100 °C for CHP applications, in order to satisfy the needs of heating networks or other low heat applications (*i. e.*, heat demand of the farmer cooperative, wood drying and cooling through absorption chillers).

Table 1. Operative conditions for working fluids and ORC power plants

		Cyclohexane	Decane	Toluene
Critical conditions				
Critical temperature	[°C]	280.49	344.55	318.6
Critical pressure	[bar]	40.75	21.03	41.26
Saturated cycle conditions				
Condensation temperature	[°C]	20; 100	85; 100	35; 100
Condensation pressure	[bar]	0.10; 1.75	0..05; 0.10	0.06; 0.74
Evaporation temperature	[°C]	200-269	200-337	200-300
Evaporation pressure	[bar]	13.44-35.30	1.87-18.96	7.51-32.76
Superheated cycle conditions				
Condensation temperature	[°C]	20; 100	85; 100	35; 100
Condensation pressure	[bar]	0.10; 1.75	0.05; 0.10	0.06; 0.74
Evaporation temperature	[°C]	250	250	250
Evaporation pressure	[bar]	27.63	5.04	16.72
Maximum temperature	[°C]	260-400	260-400	260-400
Transcritical cycle conditions				
Condensation temperature	[°C]		85; 100	
Condensation pressure	[bar]		0.05; 0.10	
Maximum pressure*	[bar]		21.66; 30.00	
Maximum temperature	[°C]		340-400	

* Supercritical pressure

Furthermore, when only the electrical demand is present, the condensation temperature has been lowered to 20 °C or at a temperature that corresponds to a condensation pressure higher than 0.05 bar, the lowest pressure accepted for the condenser as suggested in literature [11, 13].

Table 2 summarises main assumptions used for the parametric energy analysis. Specifically, the turbine and pump efficiencies have been imposed equal to 0.85 and 0.75, respectively, the internal heat exchanger efficiency has been set to 0.95 and the global efficiency of the heating process (from biomass to organic fluid through the thermal oil circuit) is 0.85, according to the literature [11, 32]. Furthermore, the temperature at the exit of the internal heat exchange (T_7) has been imposed 10 °C higher than the condensation temperature [11].

Table 2. Main assumptions for the energetic analysis

Turbine isentropic efficiency, η_t	[%]	85
Pump isentropic efficiency, η_p	[%]	75
Internal heat exchanger efficiency, η_{IHE}	[%]	95
Internal heat exchange temperature difference, ΔT	[°C]	10
Boiler and thermal oil circuit efficiency, η_{bt}	[%]	85
Electro-mechanical efficiency, η_{em}	[%]	90
Biomass humidity, φ	[%]	40
Biomass lower heating value (dry basis), H_i	[MJkg^{-1}]	18.5
Power plant working hours per year, Δt	[hour per year]	7,200

Results

The possible exploitation of the biomass resulting from agricultural residues in ORC plants has been evaluated. The analysis has been carried out considering a farmer co-operative area of about 3,000 hectares in the Sibari district (Southern Italy).

A previous work analysed the mechanised harvesting, transportation, and logistics of the biomass resulting from pruning residues of peach trees in the region [34]. Specifically, a GIS-based model was developed to evaluate the biomass amount distribution as well as the times and costs associated with the harvesting and transportation operations and the optimal location of the conversion plant. The analysis demonstrated that an interesting biomass potential exists in the investigated area and that the agricultural residues could be economically and competitively used for small-scale power production [37, 38]. Table 3 presents the biomass amount from 2011 to 2020, taking into account the trees' age and the consequent annual yield variation in the pruning residues. The mean biomass amount for the investigated period is 7,500 tons per year, that corresponds to a thermal power input for the power plant equal to 2.93 MW_t. To this purpose, a biomass lower heating value on dry basis H_i = 18.5 MJ/kg and 7,200 working hours per year have been considered (tab. 2).

Table 3. Available biomass in the Sibari district; year 2011-2020

Year	Biomass [t]
2011	8583
2012	8958
2013	8800
2014	8370
2015	7438
2016	6525
2017	6622
2018	6317
2019	6579
2020	6658

Saturated plant configurations

A parametric energy analysis has been performed to evaluate the proper operating conditions and the suitable organic fluids for "high temperature" ORC biomass applications. The analysis has been carried out adopting cyclohexane, decane, and toluene as working fluids and saturated conditions at the turbine inlet.

Figure 3 shows the influence of the evaporation temperature on the electrical power and efficiency of saturated ORC. Minimum evaporation temperature has been set to 200 °C while the maximum value has been chosen to avoid the presence of liquid during the expansion phase and it depends on the slope of the saturated vapour curve in the *T-s* diagram [31]. The plot highlights a progressive increase in performances with the evaporation temperature according to the literature [20, 39-41]. At 200 °C the electrical power is 274.8 kW_e for decane, 296.3 kW_e for cyclohexane and 316.1 kW_e for toluene. The corresponding electrical efficiencies are 9.4%, 10.1%, and 10.8%, respectively. At the maximum evaporation temperatures, electrical efficiencies are always larger than 12.1% while power values higher than 350 kW_e are found.

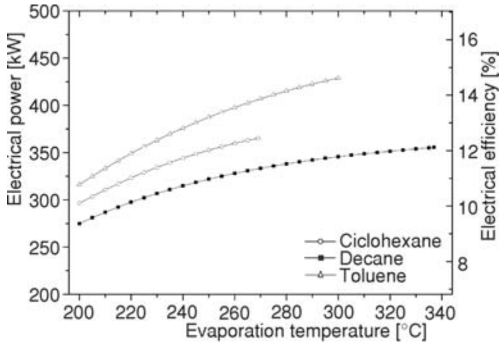

Figure 3. Influence of evaporation temperature on ORC electrical power and efficiency

The analysis put in evidence that toluene guarantees better performances while decane presents the lower electrical power and efficiency, even though this fluid is characterised by higher evaporation temperature. Furthermore, it is evident that the difference between the fluids upsurges with the evaporation temperature.

Figure 4 illustrates the influence of the internal heat exchange (IHE) on ORC energetic performances. A significant increase in the electrical power is achieved when the regenerator is used and the effect is amplified with the evaporation temperature. In this condition, the largest power plant (589 kW_e) is registered with decane at 337 °C. The corresponding value without internal regeneration is lower than 360 kW_e. The considerable upsurge in plant performances is due to the increase in thermal cycle efficiency and to the higher organic mass flow rate when internal regeneration is adopted.

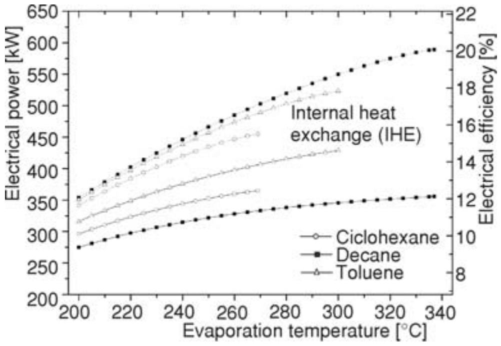

Figure 4. Influence of evaporation temperature and internal regeneration (IHE) on ORC electrical power and efficiency; saturated configuration

Specifically, fig. 5 shows the raise in organic flow rate for the three working fluids, taking into account that the biomass thermal input for the power plant is fixed (2.93 MW_t) and the heat requested by the organic fluid decreases with the internal regeneration technique, according to eqs. 5-7.

Obviously, the higher the evaporation temperature and the electrical power, the lower the mass flow rate and the thermal output for co-generation purposes. In particular, the maximum heat power for co-generation is registered at the evaporation temperature equal to 200 °C for decane (2.19 MW_t) and toluene (2.10 MW_t) in simple and IHE configuration respectively. It is useful to notice that, when the thermal regeneration is adopted, a lower thermal power for co-generation is available.

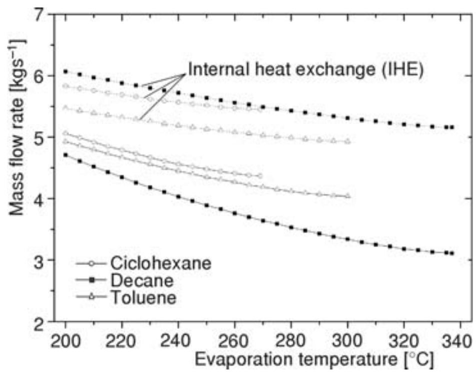

Figure 5. Influence of evaporation temperature and internal regeneration (IHE) on mass flow rate; saturated configuration

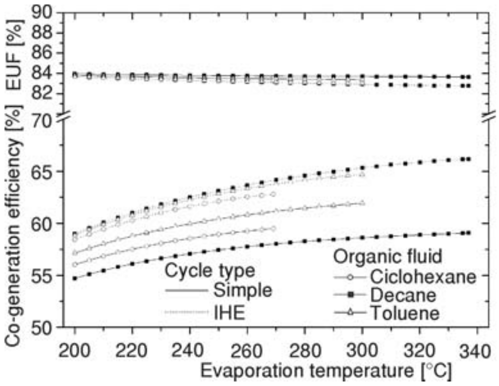

Figure 6. Influence of evaporation temperature and internal regeneration (IHE) on co-generation efficiency and energy utilization factor (EUF); saturated configuration

As co-generation merit parameter, the energy utilization factor EUF and the co-generation efficiency η_{cog} have been used. Figure 6 highlights that the energy utilization factor presents similar values for the different configurations (82.8%-84.0%). Specifically, the highest performances are found without internal regeneration owing to the larger co-generation contribute.

On the other hand, the co-generation efficiency is more sensitive to the plant configuration and working fluid. The behaviour of the dimensionless parameter with the evaporation temperature reflects the trend of the electrical production with a lower increasing rate. If the simple cycle is considered, the better results are found for toluene at 300 °C (η_{cog} = 61.9%), while decane guarantees the higher efficiency (η_{cog} = 66.2%) when the internal heat exchange is employed.

Superheating and transcritical plant configurations

The influence of the superheating process on main cycle performances has been analysed. Results refer to the same condensation (100 °C) and evaporation temperatures (250 °C).

A twofold behaviour in electrical power and efficiency is found depending on the presence of internal heat exchange (fig. 7). A decrease from the saturation condition is observed without internal regeneration, in line with the literature [2, 11, 39]. The plant efficiency reduction ranges from 1.4 (toluene) to 2.1 (decane) percentage points, moving from saturated conditions (250 °C) to 400 °C.

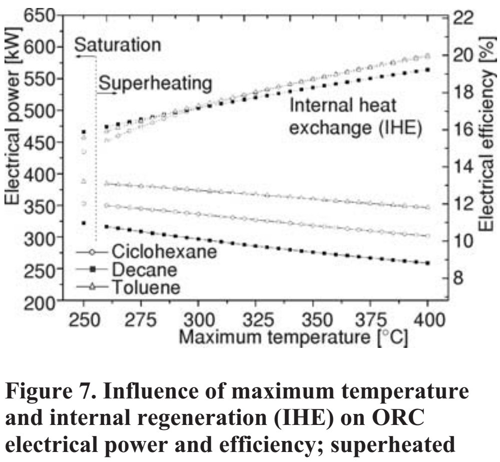

Figure 7. Influence of maximum temperature and internal regeneration (IHE) on ORC electrical power and efficiency; superheated configuration

Conversely, an increase in electrical power and efficiency with the maximum temperature is observed adopting the internal recuperator, due to the higher fluid energy at the turbine exit.

The plot highlights that the superheating practise guarantees similar performances between the three fluids. At 400 °C electrical power and efficiency are always higher than 564 kW_e and 19.2%.

The comparison with the maximum performances of the saturated cycle put in evidence a 4.5% and 2.1% increase for cyclohexane and toluene, respectively, while a slight decrease (0.9%) is registered for decane.

As already observed, the internal regeneration practise determines higher organic mass flow rates when the plant thermal input is fixed (fig. 8). This increase is significantly higher for the superheated cycles with respect to the saturated case already discussed in fig. 5.

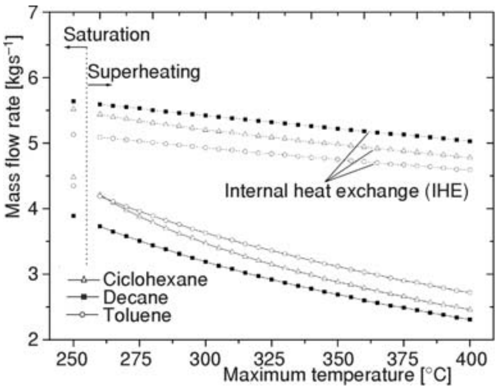

Figure 8. Influence of maximum temperature and internal regeneration (IHE) on mass flow rate; superheated configuration

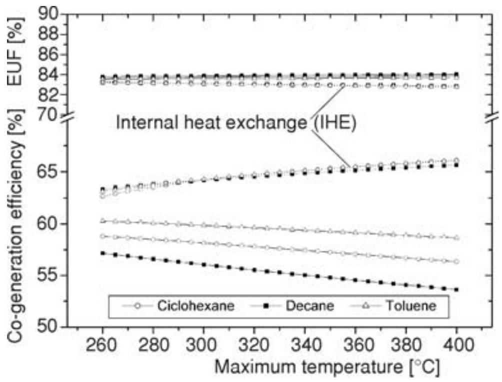

Figure 9. Influence of maximum temperature and internal regeneration (IHE) on co-generation efficiency and energy utilization factor (EUF); superheated configuration

Similar energy utilization factor values are also registered for the different superheated configurations (fig. 9). Particularly, EUF values around 83% are found, in line with saturated cycles. The twofold behaviour in the electrical power and efficiency is reflected on the co-generation efficiency (fig. 9). Negligible differences between the three organic fluids are visible if the internal regeneration is considered, with a 3.5% rise moving from 260 °C to 400 °C. For the same temperature range a mean decrease by 1.6% is found for the simple cycle, with a significant influence of the organic fluids.

Moreover, the effect of the transcritical conditions on the plant performances has been analysed. To this purpose, only decane has been adopted in the investigation owing to its lower critical pressure (21.03 bar). Figure 10 illustrates the comparison adopting two supercritical and two subcritical pressures. Specifically, 30.0 bar and 21.7 bar (corresponding to $p = 1.03\ p_{crit}$ as suggested in literature [18]) have been used for transcritical cycles, while 19.0 bar (related to the maximum saturation level) and 5.0 bar (corresponding to 250 °C of fig. 7) have been imposed for subcritical conditions.

When the internal heat exchange is absent, a progressive decrease in system performances with the maximum temperature is found. The plot highlights that the higher the saturation pressure, the higher the electrical power and efficiency, with a significant performance increase moving from 5.0 to 19.0 bar. A lower influence is evident for pressures larger than 19.0 bar. Furthermore, the results depict that the internal regenerator produces a significant efficiency rise. Similar values are registered when the evaporation pressure is larger than 19.0 bar and the maximum temperature is larger than 385 °C. In these conditions, the biomass plant electrical efficiency and power are higher than 22.1% and 648 kW. It is noteworthy that the tri-

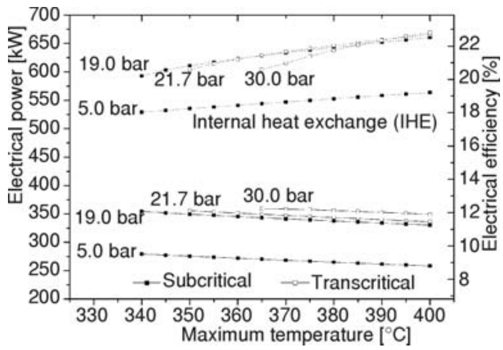

Figure 10. Influence of maximum temperature and internal regeneration (IHE) on ORC electrical power and efficiency; transcritical configuration

angular shape of the supercritical cycle generates a more efficient heat exchange between the organic fluid and the thermal oil and a decrease in the irreversibility and energy destruction due to the heat transfer and losses [18, 23, 42]. However, these aspects are beyond the scope of the present work.

Effect of the condensation temperature

The plant configurations and the corresponding working fluids that showed the better performances in the previous analysis are summarised in fig. 11. These data refer to a 100 °C condensation temperature adopted for co-generation purposes. Furthermore, the plot highlights the main performances when the heat demand is absent and the condensation temperature is reduced to 20 °C or to a value that corresponds to a pressure higher than 0.05 bar, the lowest pressure accepted for the condenser [11, 13]. Specifically, 20 °C, 35 °C, and 85 °C have been imposed for cyclohexane, toluene, and decane, respectively.

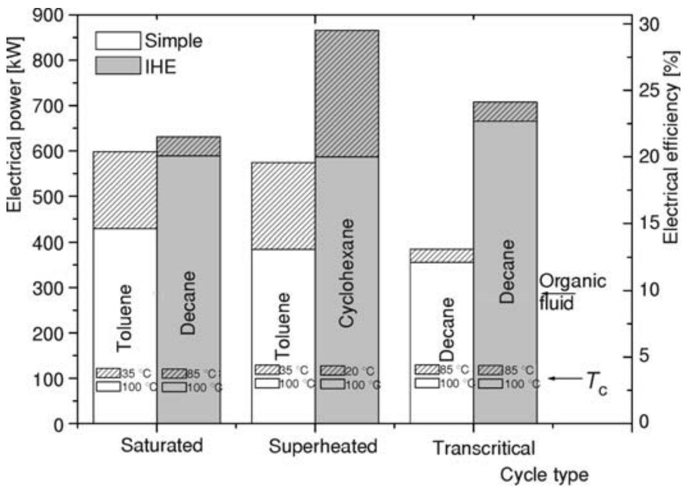

Figure 11. Influence of condensation temperature and plant configuration on ORC electrical power and efficiency

The comparison highlights that, when the condensation temperature is 100 °C, the transcritical arrangement with internal regeneration assures the highest electrical performances. A 6.4% improvement in electrical efficiency and power is obtained when the condensation temperature is lowered to 85 °C. It is worth noting that, when transcritical configurations are adopted, a special attention should be paid on the more stringent safety problems that occur due to the higher maximum operating pressure.

When the internal regeneration is absent the comparison between the biomass power plants with a condensation temperature T_c = 100 °C, put in evidence that the better electrical performances are reached with saturated configuration and toluene as working fluid. An increase in power and efficiency is obtained by decreasing the condensation temperature to 35 °C (598.3 kW$_e$ and 20.4%).

If the heat demand is missing, the condensation temperature can be reduced to the minimum value in order to maximise the electrical production. Specifically, superheated cycle adopting cyclohexane with IHE guarantees the highest performances (865.8 kW$_e$ and 29.5%).

Conclusions

The energetic performances of biomass ORC have been analysed. The work focused on the exploitation of agricultural residues in the Sibari district. The mean biomass amount for the investigated period (2011-2020) is 7,500 tons per year that corresponds to a thermal power input equal to 2.93 MW$_t$.

Saturated and superheated conditions at the turbine inlet and subcritical and transcritical configurations have been considered. Furthermore, the influence of the internal regeneration and working fluid on system performances have been investigated. To this purpose, three dry organic fluids have been analysed: cyclohexane, decane, and toluene.

The investigation shows that the net electrical power output is in the range of 0.27-0.87 MW_e, depending on the selected organic fluid and the relative operating conditions.

The relevant influence of the evaporation temperature on ORC electrical power and efficiency has been illustrated: the higher the thermal level, the higher the system performances. Furthermore, a significant increase in the electrical efficiency is obtained when the internal heat exchange is adopted and the effect is amplified with the evaporation temperature.

Specifically, for saturated conditions, the largest plant efficiency is found when toluene is used (14.6%) while decane assures a significant increase in performances with the adoption of the internal heat exchange (20.1%). The corresponding electrical power and co-generation efficiency values for simple configuration are 429 kW_e and 61.9% (with toluene) while the values for IHE design reach 589 kW_e and 66.2% (with decane).

When superheating technique is adopted, a twofold trend in the system behaviour is observed. Specifically, a progressive decrease with the maximum temperature is found without internal regeneration, whereas a positive effect is registered when the internal heat exchange is used. In these conditions, the cyclohexane guarantees the optimal results (η_e = 20.0%, η_{cog} = = 66.1% and P_e = 586 kW_e).

Furthermore, decane has been adopted for the analysis of transcritical plants owing to the lower critical pressure that makes supercritical cycles feasible without running into extreme operating conditions. The analysis highlights that the adoption of supercritical conditions and internal heat exchange produces a further improvement in the system performances (η_e = = 21.7%, η_{cog} = 67.1% and P_{el} = 636 kW_e).

The comparison between the different plant configurations shows that the energy utilization factor presents similar values for all the ORC configurations, with values slightly larger than 82.5%.

When the heat demand is absent, the condensation temperature can be reduced in order to maximise the electrical production. In particular, the condensation temperature has been lowered to 20 °C or at a temperature that corresponds to a condensation pressure higher than 0.05 bar. The highest performances are assured with IHE superheated cycle adopting cyclohexane as working fluid (865.8 kW_e and 29.5% with T_c = 20 °C).

Nomenclature

- EUF – energy utilization factor, [%]
- H_i – biomass lower heating value, [$MJkg^{-1}$]
- h_i – specific enthalpy of the generic state point i, [$kJkg^{-1}$]
- l – specific work, [$kJkg^{-1}$]
- $\dot{m}$ – organic fluid mass flow rate, [kgs^{-1}]
- P – power output, [W]
- $\dot{Q}_t$ – biomass thermal power, [W]
- $\dot{Q}_i$ – thermal power transferred to the working fluid [W]
- t – power plant working hours, [hours per year]

Greek symbols

- η – efficiency, [%]
- φ – biomass humidity, [%]

Subscripts

- b – biomass
- bt – boiler and thermal oil circuit
- cog – co-generation
- cond – condensation
- el – electrical
- em – electro-mechanical
- IHE – internal heat exchanger

is	– isentropic	t	– turbine
p	– pump	t	– thermal
sb	– second boiler	u	– net output

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