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Performance correlations for characterizing the optimal off-design operation of an ORC power system

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Abstract

The goal of this work is to develop a set of simple correlations in order to characterize the optimal off-design performance of an ORC power system. To this end, a 2kWe ORC test rig is investigated as case study and a validated off-design model is used to assess the highest net power generation achievable by the system over its complete range of operating conditions. The off-design model employed is charge-sensitive (i.e. it imposes the total mass of refrigerant in the system) which permits to predict the ORC state (i.e. its pressures, temperatures, mass flow rates, subcooling, etc.) based on the system boundary conditions only. Since such modelling approach and optimization process are time-consuming, a set of simple analytical equations is developed so as to easily predict the optimal performance of the ORC systems.

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Keywords: organic Rankine cycle, off-design, correlation, performance ;

1. Introduction

A common aspect of organic Rankine cycle (ORC) power systems is the shifting nature of their operating conditions [1]. Whether for waste heat recovery [2], solar [3] or geothermal applications [4], the heat source (and sometimes the heat sink) conditions may fluctuate in time, leading the ORC system to adapt its working regime for performance (or safety) reasons. To this end, various control parameters may be adjusted, including the machines rotational speeds (e.g. of the pump, the expander or the condenser fan). For a given set of external conditions (e.g. the heat source supply conditions and the ambient temperature), these control parameters may be chosen so as to optimize one of the system outputs, like the net power generation ($\dot{W}_{net}$) or the net thermal efficiency (η_{ORC}). Such off-design performance optimization is computational-intensive and it is unlikely performed in real time when considering the ORC system for high-level studies. Therefore, it would be very useful to properly predict the effective optimal performance of a ORC system by means of simple (and easily computable) correlations.

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Nomenclature

0	reference state	$\dot{W}$	electrical power $[W]$
amb	ambient	T	temperature $[K$ or $°C]$
ev	evaporator	Δ	difference [-]
net	net	Ω	normalized electric power [-]
nom	nominal	ϕ	normalized flow rate [-]
su	supply	Ψ	normalized heat power [-]
$\dot{m}$	mass flow $[kg/s]$	Θ	normalized temperature [-]
$\dot{Q}$	heat power $[W]$		

This work aims at developing such a set of correlations. To this end, the paper is structured as follows: firstly, in section 2, the ORC system investigated as case study and the off-design model used to extrapolate its performance are presented. Then, in section 3, the charge-sensitive model is used to generate optimal performance mappings of the system over an extended range of conditions. Finally, in section 4, a set of handy correlations is developed to easily replicate the mappings characterizing the system optimal performance. The different models used to perform this study (including the charge-sensitive off-design ORC model) are developed in Matlab® and can be found in the open-source modelling library ORCmKit [5].

2. Case study and modelling method

The system investigated as study for this work is a 2kWe recuperative ORC unit developed by the University of Liège for a solar thermal application. It consists of a diaphragm pump, a scroll expander, a liquid receiver, two thermally-insulated brazed plate heat exchangers (for the evaporator and the recuperator) and a air-cooled fin coil condenser. The working fluid used to perform the closed-loop Rankine cycle is R245fa and a scheme of the unit is given in Fig. 1. Thanks to a complete set of sensors (thermocouples, flow meters, pressure sensors and power meters located at various key locations of the test rig), the system performance has been recorded over an extended range of operating conditions. Ultimately, after a dedicated post-treatment of the raw measurements, a reference database of 40 steady-state points is obtained to characterize the ORC system in off-design operations. For further details regarding the test-rig, the post-treatment process or the reference database, please refer to the authors previous work [6].

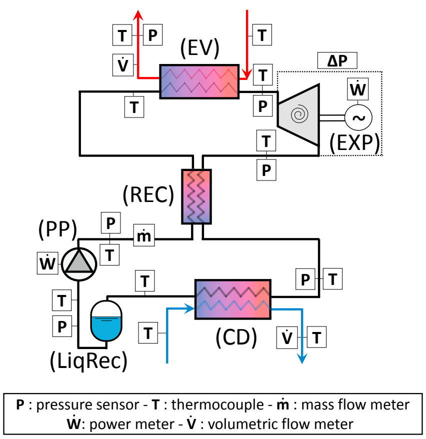


Fig. 1: Scheme of the 2kWe ORC unit investigated as case study [6]

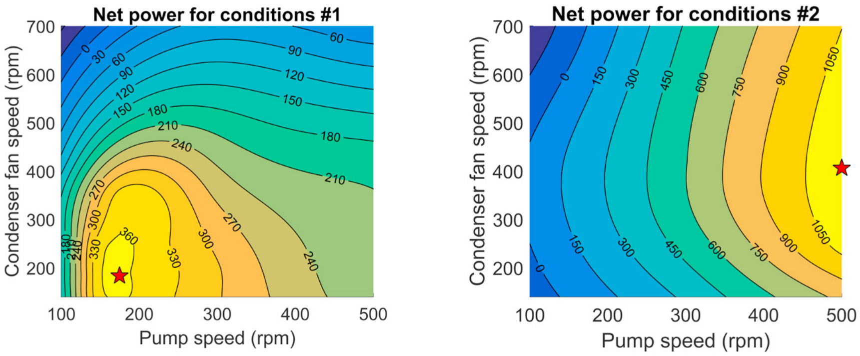


Fig. 2: Net power output (W) of the ORC system in function of the pump speed (x-axis) and the condenser fan speed (y-axis) for two different set of external boundary conditions. The highest net power generation corresponds to the red star marker. (Conditions #1: $\dot{m}_{htf,su}$ = 50 g/s - $T_{htf,su}$ = 120 °C - T_{amb} = 15 °C . Conditions #2: $\dot{m}_{htf,su}$ = 2 kg/s - $T_{htf,su}$ = 180 °C - T_{amb} = 35 °C)

In order to extrapolate the system performance in unseen conditions, a charge-sensitive model of the ORC unit is developed in Matlab®. This off-design ORC model is built so as to retrieve the system performance based on its boundary conditions only, namely the heat source and the heat sink supply conditions (mass flow rate, temperature and pressure), the pump and the expander rotational speeds, the ambient temperature, and, finally, the total mass of working fluid enclosed in the system. By accounting for the fluid mass repartition within the system, such a charge-sensitive ORC model can predict the system behaviour without making any assumptions in the fluid state along the cycle (like an imposed subcooling, superheating, condensing pressure, etc.). Such modelling approach is highly implicit and requires a proper solver framework to ensure high robustness. The ORC model is built by interconnecting semi-empirical models describing each of the system subcomponents. These semi-empirical model accounts for the components geometry and their off-design performance over wide range of conditions. For the sake of conciseness, details regarding this ORC model are not provided here but an extensive description of the model architecture and its validation can be found in [7]. As presented in the next section, this validated charge-sensitive model can be used to find the optimal off-design performance achievable by the unit over its complete range of operating conditions.

3. Optimal performance assessment

As mentioned here above, the equilibrium state and the performance of our ORC system are unequivocally defined by its boundary conditions only. These boundary conditions can be divided in two groups. On the one hand, the heat source supply conditions and the ambient temperature can be seen as external perturbations to the system operation since they cannot be influenced by the ORC itself. On the other hand, both the machines rotational speeds and the charge of refrigerant are parameters which can be used to influence the power system behaviour. In our case study, the charge of refrigerant is unchanged whatever the operating conditions (it is kept constant to 26kg) and the expander speed is set to 3000 rpm (like a grid connected two-pole generator at 50Hz). However, both the pump and the fan condenser speeds can be changed in function of the operating conditions so as to adapt the system response to the external conditions. As depicted in Fig. 2, the machines rotational speeds have an important impact on the ORC system outputs and there is an optimal combination which maximizes the performance of the test rig. Depending of the scenario, the performance criteria to maximize can either be the net power generated by the unit ($\dot{W}_{net}$, as chosen in this paper) or the system net thermal efficiency ($\eta_{ORC} = \dot{W}_{net}/\dot{Q}_{ev}$). In Fig. 2, the optimum in the net power ouput is shown for two different situations and it is worth noting that the maxima locations change in function of the conditions. If such optima are identified for the entire operating range of the ORC system, it is possible to a create a mapping of the optimal off-design performance achievable by the engine. In this work, the optimization is carried out so as to maximize the ORC net power generation ($\dot{W}_{net}$) for 192 different points covering the following range of conditions, i.e.

- Hot source supply temperature : 80 °C → 180 °C

- Hot source supply mass flow rate : 0.05 $kg/s \rightarrow 2\ kg/s$
- Ambient temperature : 5 $°C \rightarrow 35\ °C$

To maximize the system net power generation, both the pump and the fan condenser rotational speeds are optimized within the following ranges:

- pump rotational speed N_{pp} : [100 ... 500] rpm
- fan rotational speed N_{cd} : [100 ... 700] rpm

The net power output and the heat power transferred in the evaporator in function of the external boundary conditions are depicted in Fig. 3. Only these two variables are studied because they fully characterize the ORC interactions with its environment (i.e. they can summarize the ORC performance to a black box component). A detailed explanation of all the results is beyond the scope of this paper, however the most relevant phenomena can be explained as follows. For a given heat source condition, the ambient temperature has mainly a shifting effect on the power capacity of the ORC. The higher the ambient air temperature, the higher the condensing pressure reached in the air-cooled condenser. Since the air temperature does not influence much the evaporating pressure, the increased condensing pressure leads to a reduced power generation. Regarding the heat source conditions, the supply HTF temperature has also a strong impact on the ORC power capacity. Indeed, a higher HTF temperature permits to increase the optimal evaporating pressure in the system. The evaporating pressure is raised by increasing the pump speed (growth of the fluid mass flow rate) while keeping the volumetric flow rate at the expander inlet unchanged. The combination of the increased fluid mass flow rate and the increased evaporating pressure leads to a higher power generation and heat transfer through the evaporator. Over a certain value of the heat source temperature (around 140$°C$), the pump speed reaches its maximum value and the influence of the HTF temperature becomes less perceptive. Concerning the HTF mass flow rate, low values are detrimental for the ORC performance. Indeed, a low HTF mass flow rate leads to a large glide in the HTF temperature profile. Since for such conditions the pinch in the evaporator is located at the saturated liquid state, the highest evaporating pressure reachable by the working fluid is kept low even if the heat source supply temperature is much higher. When the HTF mass flow rate rises, the heat source temperature glide is reduced and the optimal evaporating pressure of the working fluid can be increased. Over a certain HTF mass flow rate, the pump reaches its maximum rotational speed and the ORC get to the highest amount of heat power that it can absorbed from the heat source. For larger values of HTF mass flow rate, the ORC unit is undersized and cannot exploit more the heat source.

Such mappings as illustrated in Fig. 3 is very interesting because they summarize the effective optimal performance of the ORC unit while accounting for its off-design limitations. However, the creation of such mappings is time-consuming because of the computational complexity of the charge-sensitive ORC model (i.e. it requires many iterations). For instance, the simulation of one point with the charge-sensitive ORC model takes a bit less than 2 minutes to converge (simulations performed with a laptop Dell Latitude E5450, CPU Intel Core i7-5600U 2.6 GHz, 8 GB RAM). Since the optimization of the pump and fan speed requires at least 40 to 60 iterations of this model, the optimization of one point of the mapping requires up to two hours. In order to easily use these performance mappings in high-level simulations, a set of handy correlations is developed in the next section so as to quickly evaluate the ORC optimal performance.

4. Performance correlations

When developing correlations to replicate such performance mappings, a simple approach is to tune n-order multivariate polynomial regressions. However, in order to fit the mappings shape showed in Fig. 3, the order of the polynomials must be increased up to 4 which may result in poor inter/extrapolation reliability (due to Runge's phenomenon). In order to avoid this problem, it is proposed to develop a set of simple analytical equations which much better represents the optimal off-design performance of the ORC system.

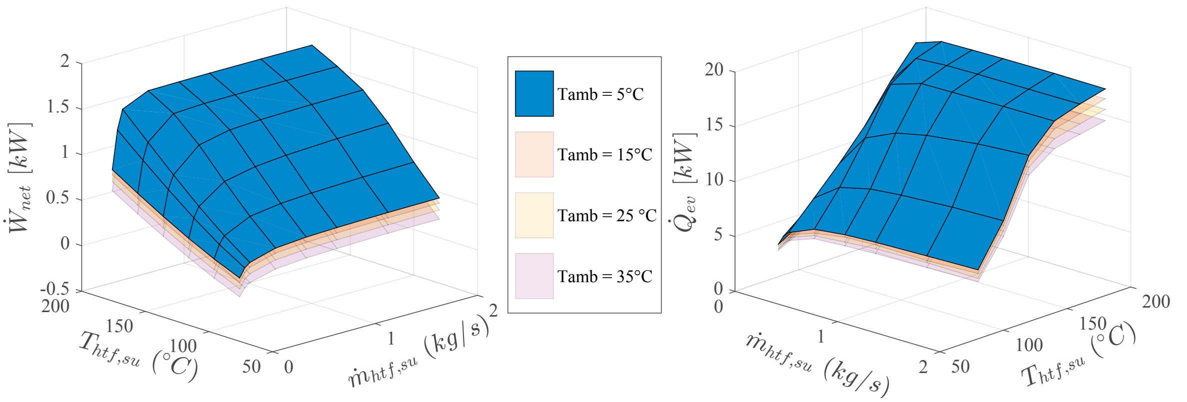


Fig. 3: Optimal performance mapping when maximizing the net power output of the ORC system. (left) Net power output in function of the external boundary conditions. (right) Heat transfer in the evaporator in function of the external boundary conditions.

4.1. Net power generation $\dot{W}_{net}$

In our case study, the ORC system has three external boundary conditions: the ambient temperature, the heat source supply temperature and the heat transfer fluid (HTF) mass flow rate. Looking at Fig. 3, it can be seen that whatever the ambient temperature, the shape of the net power generation mapping is unchanged versus to the heat source supply conditions. Considering this and by using the following normalized variables,

$$\Omega = \frac{\dot{W}_{net}}{\dot{W}_{nom}} \tag{1}$$

$$\Theta = \frac{T_{htf,su}(K)}{T_{htf,su,nom}(K)} \tag{2}$$

$$\phi = \frac{\dot{m}_{htf,su}}{\dot{m}_{htf,su,nom}} \tag{3}$$

the net power generation of the ORC system (given by Ω) can be computed in any condition as

$$\Omega = \Omega_0 + \Delta\Omega \tag{4}$$

where Ω_0 is a function of the heat source supply conditions (ϕ, Θ) which corresponds to the net power generated by the ORC system in a reference ambient temperature $T_{amb,0}$, while $\Delta\Omega$ is a correction factor accounting for the influence of the effective ambient temperature (if $T_{amb} \neq T_{amb,0}$). The nominal values used to normalize the variables are specified in Table 1. Choosing $T_{amb,0} = 5°C$, the evolution of the "reference" net power (Ω_0) in function of the HTF flow rate (ϕ) is depicted in Fig. 4a for different HTF supply temperature (Θ). Accounting for their asymptotic-like shape, the data can be fitted with a simple equation (in dashed red lines) such as

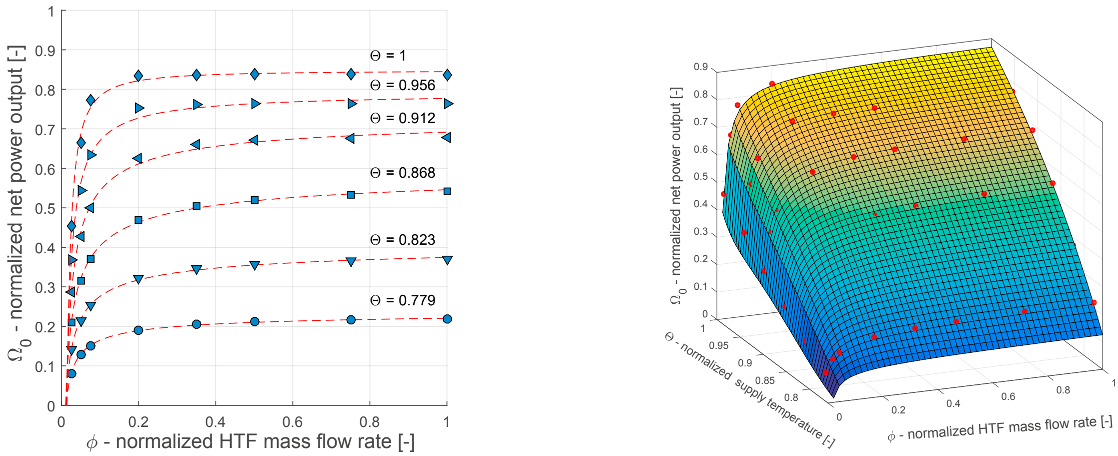
$$\Omega_0 = K_1 \left(1 + \frac{K_2}{\phi^{K_3}}\right) \tag{5}$$

where the parameters K_i can be correlated to the HTF supply temperature by means of another equations i.e.

$$K_i = a_i \cdot \Theta^{b_i} + c_i \tag{6}$$

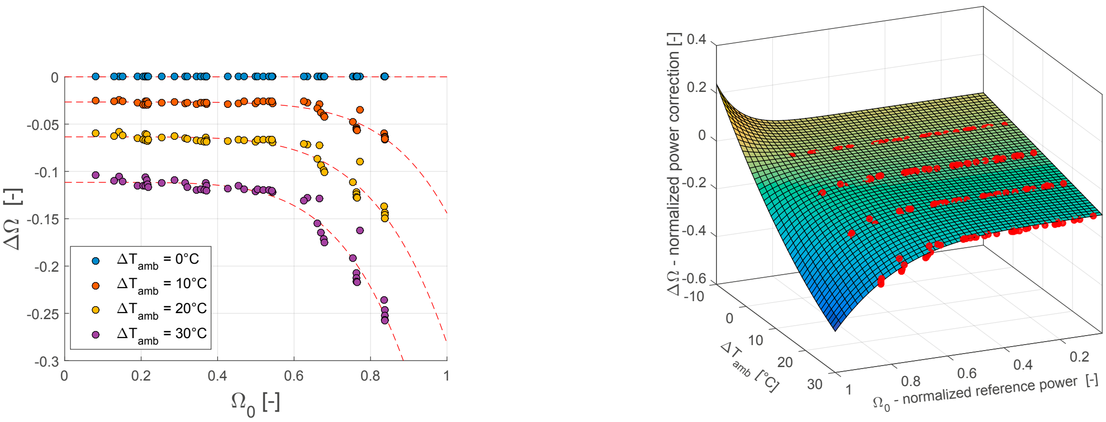
Coupling the Eqs. 5 and 6, a very smooth surface characterizing Ω_0 can be created as shown in Fig. 4b. As mentioned before, Ω_0 corresponds to the net power generated by the ORC system for a given reference ambient temperature. In practice, however, the ambient temperature may differ from $T_{amb,0}$ and its effect on the power generation of the ORC is taken into account by means of a correction factor $\Delta\Omega$ as shown in Eq. 4. If we define ΔT_{amb} i.e.

$$\Delta T_{amb} = T_{amb} - T_{amb,0} \tag{7}$$



(a) (b)

Fig. 4: (a) Evolution of the optimal net power (Ω_0) in function of the HTF supply conditions (flow rate ϕ and temperature Θ) with $T_{amb,0} = 5°C$ - (b) Correlations used to predict Ω_0 in function of the HTF supply conditions (the red markers correspond to the initial optimal points for $T_{amb,0} = 5°C$). Note: some red markers of the initial mapping are hidden behind the surface.



(a) (b)

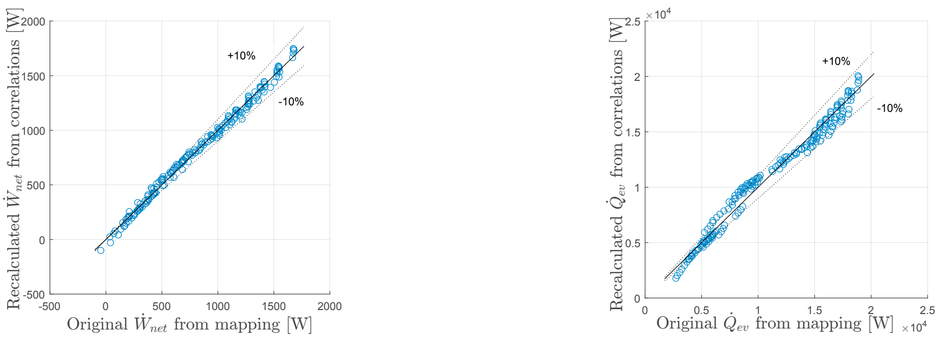
Fig. 5: (a) Shift of the power generation ($\Delta\Omega$) in function of the difference of ambient temperature ΔT_{amb} and the load of the ORC (Ω_0) - (b) Predictions of $\Delta\Omega$ in function of Ω_0 and ΔT_{amb} (the red markers correspond to the initial database)

and if we look at Fig. 5a, it is very interesting to see that $\Delta\Omega$ is not only function of ΔT_{amb} but it is also proportional to the load of the unit (given by Ω_0). In other words, the influence of the ambient temperature is more important when the load of the ORC is high. In a similar manner as before, the term $\Delta\Omega$ can be evaluated as a simple power function of Ω_0 i.e.

$$\Delta\Omega = L_1 \left(1 + \frac{L_2}{\Omega_0^{L_3}}\right) \tag{8}$$

where the parameters L_j are correlated to ΔT_{amb} by means of another equation i.e.

$$L_j = a_j \cdot \Delta T_{amb}^{b_j} + c_j \tag{9}$$



(a) Net power generation

(b) Evaporator heat transfer

Fig. 6: Parity plot between the original mappings and the correlations predictions

Here again, by coupling the Eqs. 8 and 9, a smooth surface characterizing $\Delta\Omega$ can be generated as illustrated in Fig. 5b. The combination of these different equations (from Eq. 4 to Eq.9) permits to properly predict the optimal net power generated by the ORC system based on its boundary conditions only. As shown with a parity plot in Fig. 6a, this set of equations permit to fit the initial mapping (depicted in Fig. 3) with a mean relative error of 6.64% and a coefficient R2 of 99.37%. The various correlations coefficients (a_{ij}, b_{ij}, c_{ij}) calibrated for our case study are summarized in Table 1. Despite of the smooth surface areas characterizing the Eqs. 5 and 8, the true validity of these correlations outside of the initial mapping conditions (i.e. in extrapolation) is not guaranteed. Therefore, it is highly advised to first build an optimal performance mapping over the *complete* range of conditions in which the system may operate (with the off-design model), and then fit the correlations on this mapping to permit fast results interpolations.

4.2. Heat transfer in the evaporator $\dot{Q}_{ev}$

When considering an ORC engine, the power generation is generally not the only output desired to characterize the system. The heat power transferred in the evaporator ($\dot{Q}_{ev}$) is also very important to know. Following the very same methodology as presented here above and by introducing the normalized heat power $\Psi = \dot{Q}_{ev}/\dot{Q}_{ev,nom}$, the evaporator heat transfer corresponding to the optimal off-design performance of the ORC system can be characterized by the following set of equations:

$$\Psi = \Psi_0 + \Delta\Psi \tag{10}$$

$$\Psi_0 = M_1 \left(1 + \frac{M_2}{\phi^{M_3}}\right) \tag{11}$$

$$M_k = a_k \cdot \Theta^{b_k} + c_k \tag{12}$$

$$\Delta\Psi = N_1 \left(1 + \frac{N_2}{\Omega_0^{N_3}}\right) \tag{13}$$

$$N_l = a_l \cdot \Delta T_{amb}^{b_l} + c_l \tag{14}$$

(15)

Here again, this set of equations permits to properly fit the mapping showed in Fig 3. A comparative parity plot between the original mapping and the correlations predictions is given in Fig 6. Ultimately, the equations proposed here above permits to estimate the evaporator heat transfer in optimal off-design conditions with a mean relative error of 6.3% and a R2-factor of 97.9%. The different coefficients fitted for our case study are also summarized in Table 1.

Table 1: Coefficients of the correlations for the case study accounting for that $\dot{W}_{net,nom} = 2000W$, $\dot{Q}_{ev,nom} = 20000W$, $\dot{m}_{htf,su,nom} = 2kg/s$ and $T_{htf,su,nom} = 453.15K$

Parameters	a_i	b_i	c_i
$K1$	-0.6632	-2.739	1.543
$K2$	0.2951	1	-0.3074
$K3$	0.3961	10.47	0.5897
L_1	-0.003562	1	0.002565
L_2	-0.05421	1	4.726
L_3	-0.1957	1	10.37
M_1	-0.1825	-6.326	1.212
M_2	0.2793	1	-0.3036
M_3	1.466	0.8189	-0.6667
N_1	-0.004898	1	-0.003119
N_2	-0.1089	1	8.735
N_3	-0.001427	1	0.0007907

5. Conclusion

This paper presents a set of correlations developed to characterize the optimal off-design performance of a 2kWe ORC system. In a first step, the optimal performance of the unit is assessed over a wide range of conditions by using a validated charge-sensitive off-design model. More specifically, the net power generation of the system is maximized for 192 different operating conditions by optimizing the pump and the condenser fan speeds. The results are presented in the form of performance mappings which are then fitted by a set of simple analytical equations. These correlations are using normalized variables in order to be ultimately generalized to other ORC systems. Prospective works include to perform a similar analysis for ORC systems of different typologies so as to verify the general validity of the current equations.

References

[1] E. Macchi, M. Astolfi (Eds.), Organic Rankine Cycle (ORC) Power Systems - Technologies and Applications, elsevier Edition, Woodhead Publishing Series in Energy, 2016.

[2] S. Lecompte, M. V. D. Broek, M. D. Paepe, Optimal part-load operation of an 11 kWe organic Rankine cycle for waste heat recovery, in: Proceedings of ECOS 2016, 2016.

[3] J. Wang, Z. Yan, P. Zhao, Y. Dai, Off-design performance analysis of a solar-powered organic Rankine cycle, Energy Conversion and Management 80 (2014) 150–157. doi:10.1016/j.enconman.2014.01.032.
URL http://dx.doi.org/10.1016/j.enconman.2014.01.032

[4] D. Hu, Y. Zheng, Y. Wu, S. Li, Y. Dai, Off-design performance comparison of an organic Rankine cycle under different control strategies, Applied Energy 156 (2015) 268–279. doi:10.1016/j.apenergy.2015.07.029.
URL http://www.sciencedirect.com/science/article/pii/S0306261915008582

[5] R. Dickes, D. Ziviani, M. de Paepe, M. van den Broek, S. Quoilin, V. Lemort, ORCmKit : an open-source library for organic Rankine cycle modelling and analysis, in: Proceedings of ECOS 2016, Portoroz (Solvenia), 2016.
URL http://hdl.handle.net/2268/198722

[6] R. Dickes, O. Dumont, R. Daccord, S. Quoilin, V. Lemort, Modelling of organic Rankine cycle power systems in off-design conditions: an experimentally-validated comparative study, Energy 123 (2017) 710–727. doi:10.1016/j.energy.2017.01.130.
URL http://hdl.handle.net/2268/207441

[7] R. Dickes, O. Dumont, S. Quoilin, V. Lemort, Charge-sensitive modelling of organic Rankine cycle power systems for off-design performance simulation, under review in the journal Applied Energy, not published yet - publication expected in July 2017.