A PERFORMANCE PREDICTION TOOL FOR ORC APPLICATIONS BASED ON MODELICA

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ABSTRACT

Converting waste heat to electricity using organic ranking cycle (ORC) technology is an effective method to improve energy efficiency and reduce costs. However, the waste heat source is often characterized by relatively large fluctuations in load, making it a demanding task to design and operate an ORC in an efficient and economically sound manner. A reliable performance prediction in an early project phase helps to create an economically successful operation and build the business case on a firm foundation. In this paper a prototype of such a prediction tool based on existing Modelica libraries is presented. A main emphasis lays on the control strategy that allows to reproduce part load behavior including autonomous shutdown and restart events. The suggested control strategy consists of two coupled layers, a state machine and a main controller operating different actuators. The state machine enables to switch between different control schemes, which is important for example for the transition of a running state to a shutdown procedure. The compiled ORC model simulates the electrical energy generated over a time period of 30 h with a deviation less than two percent compared to measurements of the real application. The model was applied to a test run with generic boundary conditions for a time period of 30 days and showed its capabilities to autonomously and reliably shut down and restart to normal operations.

1. INTRODUCTION

Large load fluctuations are an inherent nature of many waste heat sources making the application of an ORC system a demanding task. Compounding this challenge are the relatively tight profit margins of ORC projects in general, even with the support of governmental subsidies along with the tendency to use only a rough estimation in predicting performance. These factors increase the uncertainty when trying to create an economically successful operation. To build the business case on a firm foundation, performance prediction that takes into consideration all relevant operation aspects is inevitable. Therefore, a reliable performance prediction tool for the use in an early project phase is highly desired.

Dynamic simulation is an instrument to cope with varying operation parameters of many waste heat applications. Several authors have used dynamic modeling techniques to simulate the behavior of thermal power plants mainly in conjunction with designing and testing control strategies as well as for risk and safety assessment. Snidow and Malan (1988) used the Modular Modeling System (Smith et al., 1983) to simulate the behavior of an existing fossil power plant. Open-loop step test and closed ramp test were performed for validation purposes. Colonna and van Putten (2007) implemented a modular, hierarchical and causal modeling paradigm in the MATLAB/Simulink toolbox SimECS and applied it to a small biomass-fired Rankine Cycle. Several exemplary simulations starting from on-design and off-design stable operation were performed to validate the model (van Putten and Colonna, 2007). Fiorani (2009) also developed a Simulink library and showed the transients for a fuel step in a internal combustion engine and its interaction with various ORC and control configurations. In the last decade Modelica gained considerable attention in the modeling of dynamic and multidisciplinary systems. Casella and Leva (2006) developed the open Modelica library ThermoPower, which is used to model rather complex thermal power plants. Casella and Pretolani (2006) investigated a typical combined-cycle power plant with the aim to speed up the startup time without compromising the life-time of critical components. Casella et al. (2013) also simulated the behavior of a commercially available ORC module using an open- and closed-loop approach. More recently Quoilin et al. (2014b) published the open Modelica library ThermoCycle as a framework for smaller energy systems such as heat pumps and ORC systems. Great emphasis was placed on implementing robust and computational efficient models (Quoilin et al., 2014a) using amongst others the very efficient fluid property calculation library CoolProp (Bell et al., 2014).

Waste heat applications using ORC often show significant operating hours in the part load regime with many automatic shutdown and startup cycles due to external limiting conditions such as high ambient temperatures or low heat source power. These factors should be taken into account to improve the prediction of the economic efficiency . Simulating startup and shutdown processes is a demanding task as stated by Casella and Pretolani (2006). In this reference it is noted that the direct initialisation of the plant model in the shutoff state is difficult to solve numerically due to the presence of low or zero flow rates and to the need of good starting values. As a work around the simulations in their study were initialized at the design point and then brought to idle from where the actual (warm) startup process was initiated. For a concentrated solar driven ORC plant, Ireland et al. (2014) used an alternative approach to avoid the numerical issues associated with the discontinuities in the working fluid density derivative present during rapid phase changes, e.g. while shutting down the plant. The Modelica models are based on the ThermoCycle library and consist of two submodels – an operating and an idling model, which are simulated concurrently. If shutdown conditions are met, only the idle model is brought down while the operating model keeps running at a virtual level avoiding phase changing issues in the evaporator. This approach allows the simulation of longer periods with recurring startups and shutdowns though the transient details of these processes are neglected. Erhart et al. (2013) simulated the shutdown and startup of a biomass fired ORC plant using the ThermoPower library. The simulation results match the measurements very well. No further details with respect to numerical issues are given. Felgner et al. (2011) directly coupled physical models with economical models using Modelica. The profitability of an ORC system on a typical farm biogas plant were assessed over a period of 25 years assuming boundary conditions and a shutdown of the ORC plant every second year for maintenance. Also a generic industrial waste heat application using ORC was investigated over a period of one week. This simulation included a strong variation of waste heat supply but no shutdowns. No further details on startup and shutdown procedures were given.

To study the performance of an autonomous operated ORC module including automated startup and shutdown procedures a performance prediction tool using Modelica is implemented. It is based on the ThermoCycle library (Quoilin et al., 2014b) in combination with the CoolProp software (Bell et al., 2014) necessary for calculating fluid properties and the StateGraph2 library (Otter et al., 2009) used for the higher-level control strategy. The setup and approach are described in more details in the following section.

2. SETUP AND APPROACH

A generic ORC system has been modeled inspired by an existing ORC plant of a small bio gas combined heat and power application in Klingnau (Switzerland). Figure 1 depicts the simplified layout of this plant. The heat from exhaust gases is transferred to a pressurized water circuit that is heated up to 130-150 °C before it enters the ORC module. The heat rejected by the module is discharged to a cold water circuit connected to an air cooler. The applied ORC module has a gross electrical power output of 30 kW at full load of the biogas engine, which has a rated power output of 625 kW_{el}. The ORC module contains a scroll type expander that is driven by the working fluid R245fa.

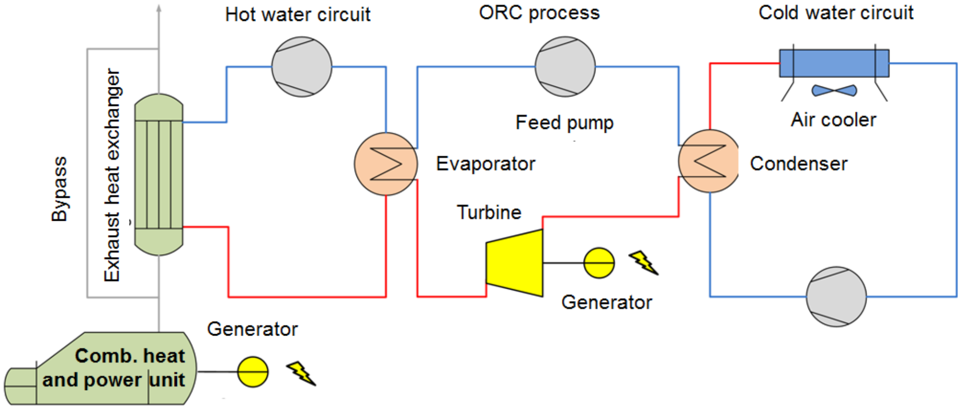

Figure 1: ORC plant of combined heat and power application. Source: Axpo Neue Energien AG

2.1 Modelica Model of the ORC Module

As only little data of the real ORC plant is currently available the topology, dimensioning as well as the control strategy are based on assumptions. To keep the model simple for testing the applicability of the derived control strategy as well as for testing the capability of performance prediction only the ORC module was taken into account within the scope of this study. Figure 2 shows parts of the overall Modelica model and the setup of the ORC module. It is a rather classical configuration. Most applied

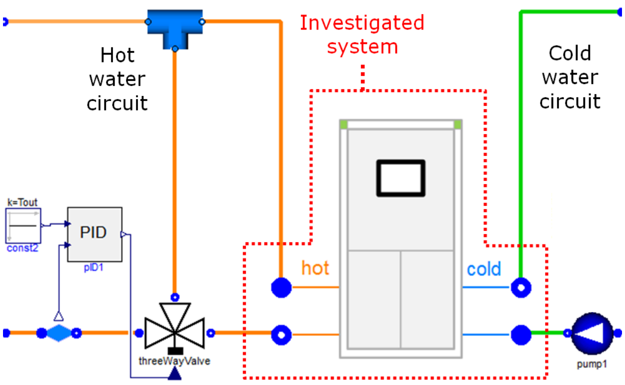

Figure 2: To keep the system simple for testing, the investigated model comprises the ORC module only.

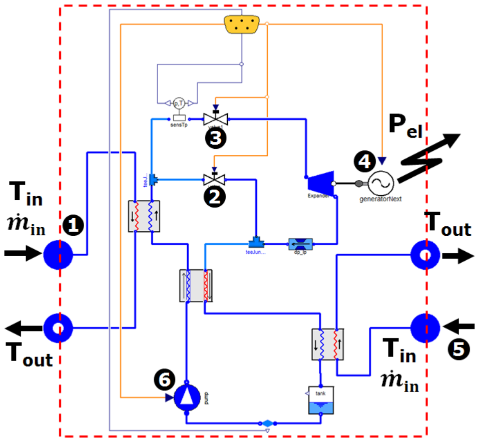

Figure 3: Assumed configuration of the ORC module. The numbered process data and actuators are altered by the controller.

models are standard or slightly modified components of the ThermoCycle library. The library comprises distributed and moving boundary heat exchanger models. Since during startup and shutdown the fluid may not be present as liquid, two-phase mixture and vapor concurrently, the distributed models seem to be more suitable as stated by Wei et al. (2008). During operation the expander bypass is closed and the expander inlet valve fully open. Both valve positions as well as the expander/generator speed may be altered by the controller during shutdown or startup phases. The expander model is extended by an additional simple leakage model. This maintains a small mass flow when the expander comes to rest, which leads to an increase of the numerical stability. The expander efficiency is correlated to the pressure ratio and the inlet pressure, see Section 2.3. The multi-stage radial pump is an own implementation inspired by Wetter (2013). It is based on the dimensionless flow and head coefficient. To enhance stability during initialization the pump characteristic is modified such that the head coefficient becomes a strictly monotonic function of the flow coefficient, see Figure 5.

2.2 Control Strategy

The real ORC plant shuts down and restarts autonomously depending on certain criteria. After reviewing the available process data, the relative power output of the internal combustion engine and the ambient temperature are assumed to trigger the shutdown and restart procedures. Additionally, the exceedance of the limits must persist for a certain time interval to prevent too frequent start/stop sequences. The model must be able to mimic these behaviors by a suitable control strategy. The suggested control strategy consists of two coupled layers, a state machine that keeps track of the current conditions and an actual controller comprising the subcontrollers of the different actuators, see Figure 4. The state machine is

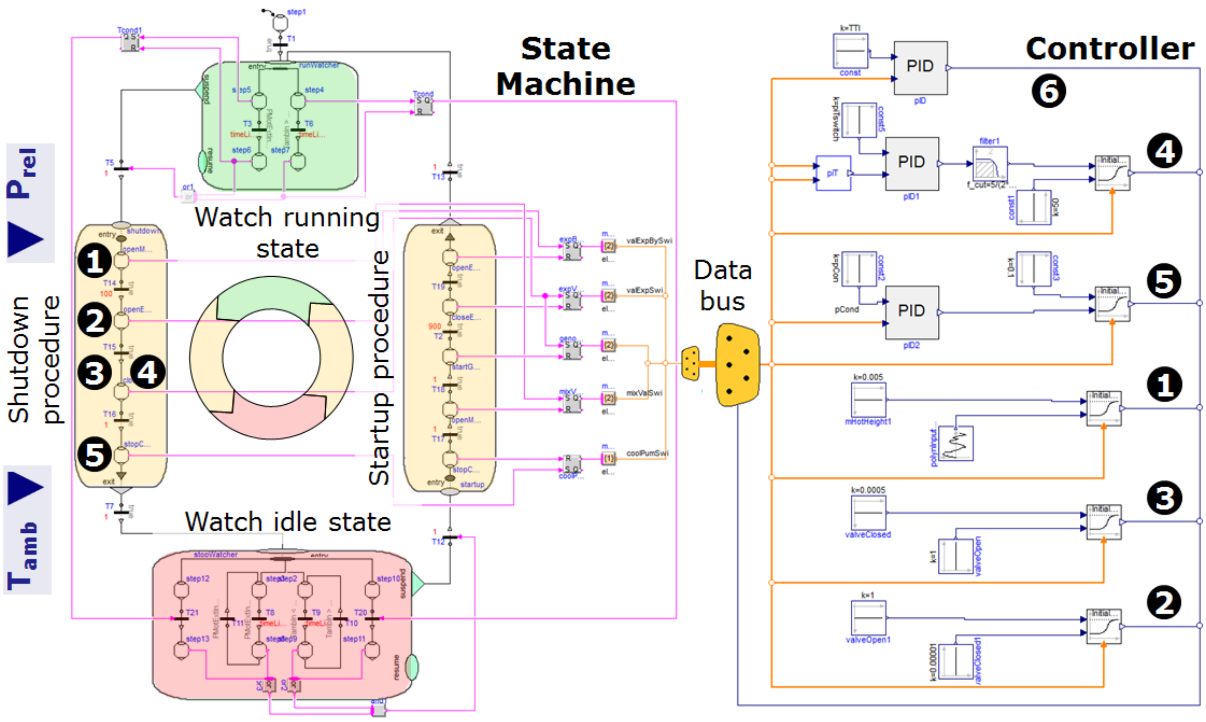

Figure 4: The control strategy consists of a state machine coupled with a controller. The numbers in the state machine and controller section correspond to the process data and actuators depicted in Figure 3.

implemented using the Modelica library StateGraph2 (Otter et al., 2009). The state machine is divided into four subparts, a running and idle state watcher as well as a shutdown and restart procedure. Due to numerical reasons the module is initially in the running mode as proposed by Casella and Pretolani (2006). As soon as the power or ambient temperature criteria is infringed for the time interval defined the running state is suspended and the shutdown procedure is initiated. The shutdown procedure consists of a sequence of steps to be performed. Each step triggers a switch that in turn alters the behavior of the controller (the numbers corresponds to the black numbers in Figure 2 and 4):

1. The hot water input to the module is decreased by fully opening a mixture valve, see Figure 2 left. Since this process is not modeled yet the mass flow into the module is prescribed as a mass flow source (open-loop control). By extending the model with a mixture valve, a corresponding closed-loop controller can easily be dropped in at the position of the current mass flow source.
2. With some time lag the expander bypass valve opens.
3. Simultaneously the expander inlet valve closes.
4. Concurrently also the generator stops. During the transition a closed-loop controller is applied to stabilize the simulation. By shutting down the generator too late the expander may create a very low (even negative) pressure at the expander inlet causing the fluid property calculation to crash. A sudden stop of the generator creates strong gradients, which in turn impact also the stability.

5. Finally, the cold water mass flow is shut down by switching from a closed-loop to an open-loop control and setting a near zero mass flow.
6. The feed pump control scheme is not changed. The feed pump controls the expander inlet temperature. As the heat input ceases the pump speed goes down trying to maintain the prescribed expander inlet temperature. It virtually shuts down itself. However, a small pump speed is maintained due to numerical reasons.

After processing all the shutdown steps the idle watch state becomes active. The ORC module remains in this state as long as the engine power and ambient temperature startup criteria are not fulfilled. As soon as the criteria are met the state proceeds to the startup procedure, where the reverse steps are performed. Finally, the running state is reached and maintained as long as no shutdown criteria arises.

The switch between different control schemes and signals is executed by a smooth transition function triggered by the state machine via a data bus. This increases the numerical stability significantly.

2.3 Model Calibration

Since no internal process data were available the heat exchanger areas were pragmatically calibrated based on few thermodynamic data received from the plant operator. These were the inlet and outlet temperature of the ORC module both for the hot and cold water circuit as well as the hot water inlet mass flow. The cold water mass flow rate is adjusted to keep the condenser pressure within limits, see Figure 3.

For the fine calibration a modified controller adjusted the expander efficiency to match the measured power output for different operating points. The calculated efficiencies are correlated to the expander pressure ratio and inlet pressure using a variant of the Pacejka formula as proposed by Declaye et al. (2013). Due to the small number of data points the adjusting of the fitting parameter is done manually. Figure 6 shows the calculated and reconstructed efficiencies. Most of the reconstructed efficiencies deviate by less than ±5 % from the input values, see Figure 7. The derived correlation is finally implemented as a characteristic in the expander model.

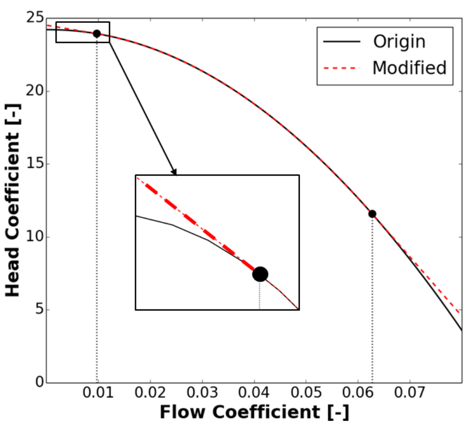

Figure 5: Dimensionless pump characteristic as a strictly monotonic function

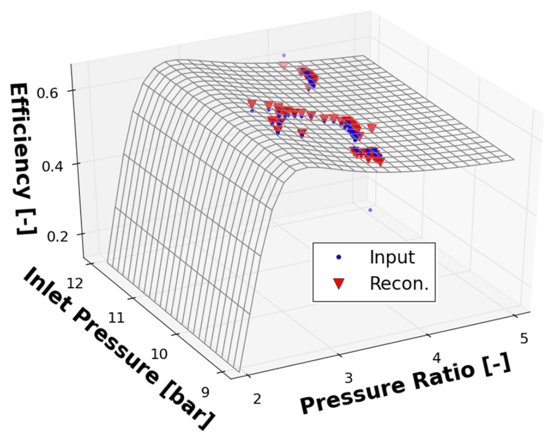

Figure 6: Deduced expander characteristic

3. RESULTS

To validate the model and the control concept a period of 30 hours is simulated and compared to measurements. There are two shutdown events within this period, one triggered by a low engine power output and the other by a too high ambient temperature. To avoid highly inefficient events during the simulation the input data are prepared as smooth piecewise polynomials as proposed by Quoilin et al. (2013). Figure 9 shows exemplarily the normalized measured and smoothed water inlet temperatures of

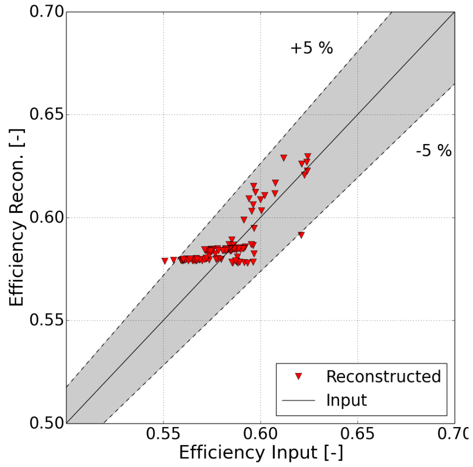

Figure 7: Reconstructed efficiencies using Pacejka formula

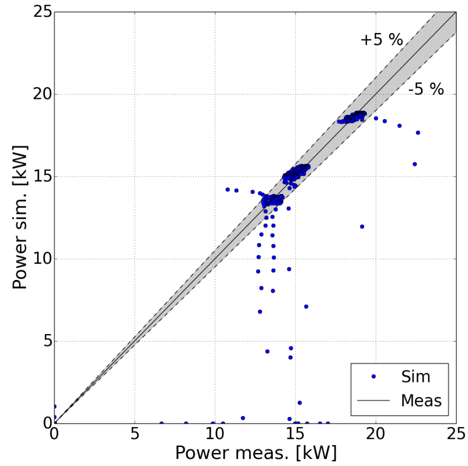

Figure 8: Simulated versus measured power for different points in time

the hot and cold side of the module. Additionally, a comparison between measurement and simulation is given for the outlet temperature on the hot side as well as the power output of the module. In operation the simulated outlet temperatures match the measurement well. During the shutdown period the outlet temperature cools down too fast. Raising the thermal inertia by increasing the thermal capacity of the heat exchanger and/or the fluid quantity did not improve the situation. As mentioned before a small mass flow rate is maintained within the module due to numerical reasons. Further investigations revealed that the temporal profile of the temperature during the shutdown period is very sensitive to this remaining mass flow rate. However, as this temperature discrepancy has a negligible effect on the performance prediction the deviation is acceptable. The simulated power output is well reproduced – of course also due to calibration, which is based on the measured power output. The deviation between the measured and simulated power is shown in more detail for different points in time in Figure 8. Most of the data points lie within a ±5 % deviation range. The larger deviations originate from the transitions at shutdown and restart where the measurements show some peak values. These peak values are not covered due to the smoothed boundary conditions, see Figure 9. The simulated electrical energy generated over the period of 30 h is slightly lower than the energy derived from measurements. However, the deviation is less than two percent.

To further test the applicability of the model, generic boundary conditions are produced for a time period of 30 days. The input data consist of ambient temperature and engine power production. A mean ambient temperature of 19 °C is assumed which corresponds to the long-term average value at Klingnau in July. A diurnal temperature variation of 16 °C as well as some lower frequency variations to mimic changing meteorological conditions is superimposed sinusoidally to this average temperature. The engine is assumed to operate at a rather low power output with small sinusoidal variations in the vicinity of the 45 % load. However, the data are chosen in a way that several shutdowns and restarts are triggered either by the ambient temperature and/or engine power criteria. Figure 10 shows the process data that triggers the shutdown and restart as well as the simulated electrical power of the ORC module. Within the first three days the module is shutdown three times due to high ambient temperatures. At day six the engine power output goes slightly below the shutdown limit. However, the lower limit is not infringed long enough to trigger the shutdown. Between day 13 and 16 as well as between day 21 and 22 frequent shutdowns are produced due to the minimum power and/or ambient temperature criteria.

4. DISCUSSION

The question may arise why there are automatic shutdown/restart sequences at all. Besides emergency stops and shutdowns for maintenance reasons there are performance issues. When the heat input to the

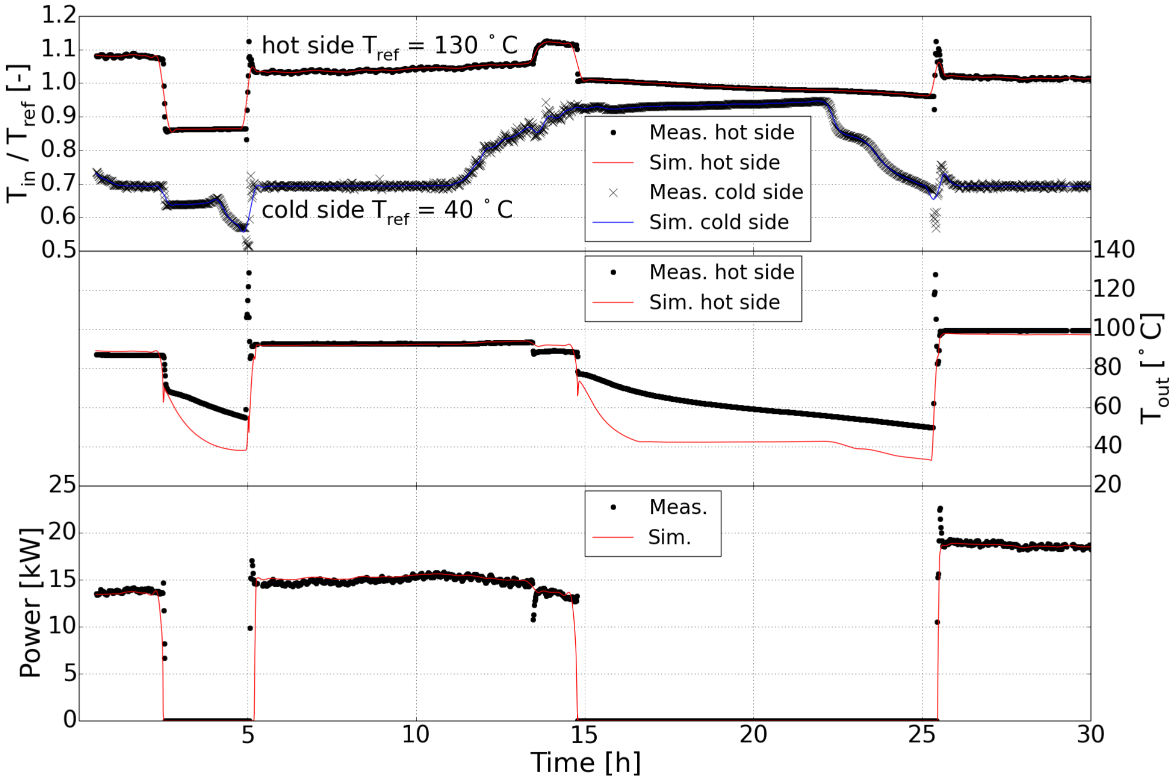

Figure 9: Top: Normalized water temperatures at the evaporator and condenser inlet. Middle: Measured and simulated water temperatures at the evaporator outlet. Bottom: Measured and simulated gross electrical power of the ORC module.

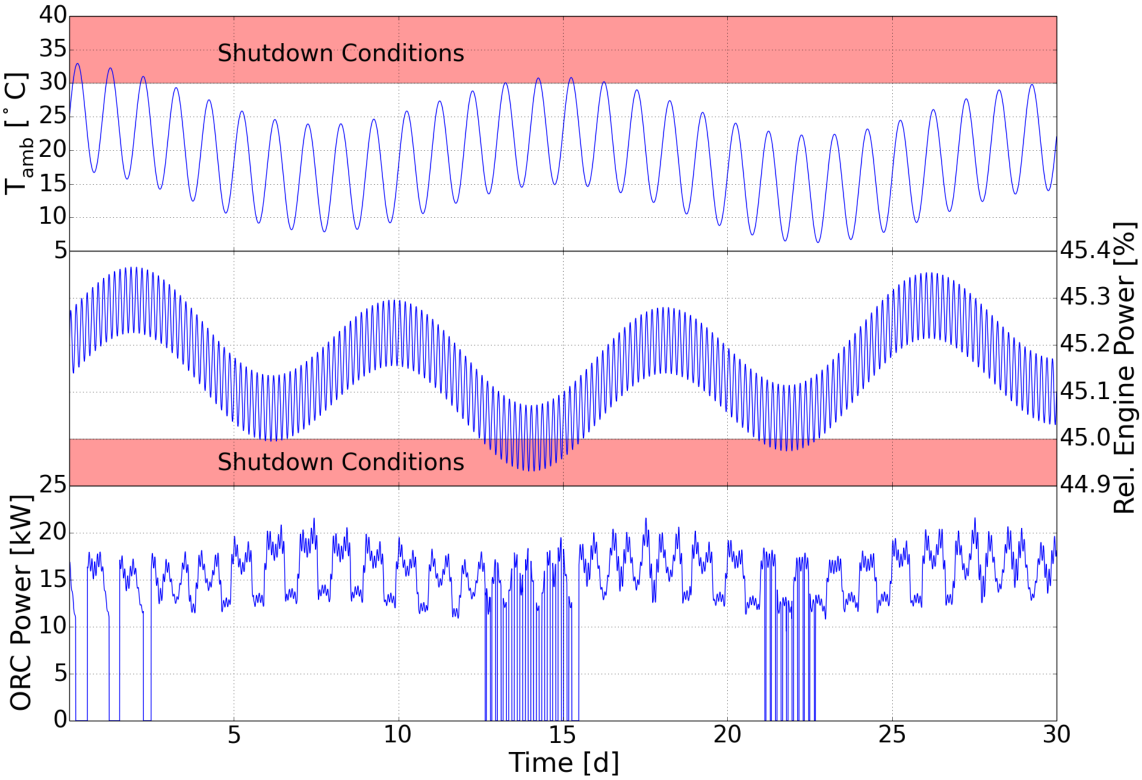

Figure 10: Top: Generically produced ambient temperatures. Middle: Generically produced relative engine power. Bottom: Simulated gross electrical power of the ORC module.

ORC system is low compared to the design point the total efficiency will significantly drop. When the electrical power consumption of the pumps and cooler fans exceed the generated electricity a shutdown may be more beneficial. Wearing concerns may be an other reason, e.g. due to insufficient lubrication of critical parts caused by unfavorable mass flows and pressure ratio at lower part load. Of course, in reality a proper dimensioning of the ORC plant will avoid excessive shutdown/restart cycles. However, operational caused fluctuations of the waste heat supply and/or altered process data due to modifications or a redesign of the main process are very common. Anticipation of such situations during the planning phase of an ORC plant are therefore highly recommended. A corresponding simulation tool helps to assess an expected operation behavior and power output of a future ORC plant by investigating different alternatives. Prior to building the plant the selected system can be tested on a virtual test bed revealing, for example, that a high portion of the operation hours lie within the part load regime with bad efficiency and possibly with many shutdown cycles. This would indicate a suboptimal sizing of the plant and corrective actions can be conducted in the planning rather than the commissioning phase.

The models developed within the scope of this work are a starting point for such a virtual test bed. So far, the investigated system comprises the ORC module only. The models need some further improvements and enhancements before applying them to a real world project. First of all, the ORC module should be expanded to an overall system model including at least peripherals such as exhaust heat exchangers, hot and cold intermediate circuits and air coolers. This allows to assess the overall performance taking into account auxiliary power consumption and the opportunity to derive and test alternative shutdown criteria, e.g. based on the overall performance. The implemented control system is fairly simple and probably not complete. Though the model is not crash-proofed, the simulations work fairly stable. However, more sophisticated control strategy may even improve stability and hopefully improve performance.

For the generic test run presented above the module shut down 30 times. It took about 33 minutes to perform the simulation task with Dymola 2015 FD01 having parallel execution capabilities on multiple cores. The simulations were conducted on a virtual machine assigned four Intel Core i7 processors. The calculation time is acceptable taking into account the many shutdowns, which significantly increase the CPU time. An analogous case was calculated where the ambient temperature and engine power was slightly shifted to avoid any shutdown. The CPU time reduced to about five minutes. The calculation time of an overall system simulation will definitely increase. This will be assessed in a future task.

Overall models may also be used for monitoring purposes. Simulations can be performed online with boundary conditions derived from measurements. Comparing the simulated power output with the measured power may show deviations. Corrective tasks such as cleaning heat exchangers or readjusting control parameters can then be initiated.

5. CONCLUSIONS

The Modelica library ThermoCycle together with the fluid property calculation package CoolProp provide robust and computationally efficient physically based models to simulate ORC systems. These were used to build up a simulation model of the Klingnau ORC plant. This simulation model reproduced the measured electrical power output within a ±5 % deviation compared to the measured power. The simulated and measured electrical energy generated over the period considered deviated by less than two percent. A simple control strategy allowing for automatic shutdown and restart events was implemented and successfully tested with generic boundary conditions. The control strategy consists of two layers, a state machine and an actual controller comprising several subcontrollers. The state machine keeps track of the current conditions and switches between different control schemes, e.g. for the transition of a running state to a shutdown procedure. Using the Modelica library StateGraph2 proved to be a convenient way to model a corresponding state machine. In particular its graphical representation of the state flow is a valuable feature to test and track online the behavior of the controller and its interaction with the plant.

Finally, enhancing the model to an overall system will make it a viable tool to predict plant behavior and performance in the planning phase. This ensures a suitable sizing and choice of optimal components. It will also be possible to use the models for optimizing and testing different control strategies as well as for monitoring and assessing the performance of existent plants. In the future, use of such simulation models will reduce the uncertainty when trying to create an economically successful operation and help build the business case on a firm foundation.

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