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Iterative Approach for the Design of an Organic Rankine Cycle based on Thermodynamic Process Simulations and a Small-Scale Test Rig

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Abstract

Waste heat recovery from industrial processes may be a door opener for market penetration of Organic Rankine Cycle (ORC) systems. Within this study, an ORC for industrial waste heat recovery is designed by adopting an iterative approach. Therefore, experiments are performed in a thermal oil heated 1 kW test rig with internal recuperator and a maximum thermal efficiency of 10.6%. The results are iteratively implemented in thermodynamic process simulation. Thus, the simulation results of different stationary operating points can be compared to experimental measurements for different steps of the iterative design process. Results outline the importance of experimental results for the design of ORC systems. The simulation accuracy can be significantly improved with a single reimplementation of experimental data, which enables accurate sensitivity analysis on ORC waste heat recovery system performance. For two different representative operating points, the mean deviations between experiment and simulation decrease from 8.4% to 1.0% and 4.1% to 1.7% respectively, considering the enthalpy and pressure of all thermodynamic state points.

Keywords: Organic Rankine Cycle; waste heat recovery; scroll expander; small scale

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1. Introduction

Organic Rankine Cycle (ORC) can be used in a large field of small- to medium-size systems like biomass combined heat and power, geothermal electricity generation, solar power plants and heat recovery of industrial processes and internal combustion engines [1]. Considering industrial waste heat recovery, ORC technology offers particularly high potential, since many energy-intensive industrial processes produce waste heat with a low to medium temperature level of 100 – 500 °C. The technical potential of industrial waste heat recovery with ORC technology was estimated to be 3000 MW in the U.S. and 500 MW in Germany, while a market potential of 500 MW was assessed in Europe for the original 12 member states only [2]. A more recent study about the cement, steel and glass industry in the EU 27 estimated the potential to be 2705 MW gross power, which leads to up to 21.6 TWh of electrical energy production per year [3]. Since industrial heat source temperatures and mass flow rates differ in a large range, depending on the industrial process and the plant size, a high number of studies about ORC waste heat recovery systems exists. A review of ORC architectures for waste heat recovery with power scales of up to 7 MW is given by Lecompte et al. [4].

For the design of ORC waste heat recovery systems, appropriate design tools based on thermodynamic process simulation and experimental results are necessary. Therefore, down-scaled test rigs with a few kWs are investigated in order to get information about the actual behavior of simulated processes. The experimental results are mostly applied to validate the simulation model and to give boundaries for the accuracy of the simulation. After the validation, sensitivity analyses of component design like expanders [5–7] and heat exchangers [8], system design or of system set parameters [9] are carried out. However, the sensitivity analyses mostly take place with the original model. An approach in which the experimental results are implemented iteratively into the simulation model to improve its accuracy is not reported. Therefore, although the simulation model has been validated, the sensitivity analyses with the original simulation model might lead to inaccurate results and ORC design. Only a few publications deal with parts of this problem. Gusev et al. [10] showed that implementing empirical results into a simulation model can provide a possibility for optimum system control. Ziviani et al. [11] developed a steady state cycle model based on empirical correlations calibrated on experimental data.

This paper aims to quantify the effect of an iterative approach, which consists of alternate simulation and experimental evaluation. To do so, the simulation accuracy before and after the implementation of empirical correlations is quantified. Experiments are performed in a thermal oil heated 1 kW ORC test rig with internal recuperator, a gear pump and a scroll expander. Measurement results are iteratively implemented in the thermodynamic process simulation, which are carried out in Aspen Plus Release 8.8 [12].

2. Theory and methods

2.1. Test Rig

The test rig is a prototype of a small-scale ORC waste heat recovery unit for industrial applications. The setup is shown in Fig. 1. It is based on a basic ORC system with an additional internal recuperator. The following main components are included:

- Inverter driven scroll expander with internal generator
- Inverter driven gear pump
- Evaporator: Brazed plate heat exchanger SWEP BX8T
- Internal recuperator: Brazed plate heat exchanger SWEP B8T
- Condenser: Brazed plate heat exchanger SWEP BX8T

The applied refrigerant is R365mfc. The system is heated by a thermal oil circuit and cooled by a water cycle with temperature control unit. The temperature control unit is additionally connected to the university cooling network. Thus, water flow temperatures could be set variable from 20 °C up to 70 °C. Since it has big influence on condensing temperature and therefore pressure, water flow temperature is varied during the tests in order to emulate different