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Experimental Investigation with Steady-State Detection in a Micro-ORC Test Bench

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Abstract

The exploitation of low grade thermal sources is recognized as a feasible strategy in order to pursue the primary energy saving target worldwide. This concept, adaptable to a number of different applications, is aimed at exploiting low-value heat fluxes that would be wasted otherwise; additional useful electric power can be produced locally, with ORC energy systems; this is one of the most promising heat recovery solutions.
In particular, the paper refers to the test bench developed in the laboratories of the University of Bologna; a prototypal micro-ORC energy system is here investigated. The micro-ORC system presents a reciprocating three-piston expander operated with refrigerant fluid. Heat is provided to the ORC from via hot water at low temperature, in order to simulate a constant low-enthalpy heat recovery process. The system rejects unused heat via a water-cooled condenser, dependent on the external ambient conditions.
The test bench layout and the real-time data acquisition system, developed in the LabVIEW environment, are here described. In particular, the paper focus is on the system steady-state detection methodology. Starting from an experimental campaign, steady-state operational points are identified through an appropriate literature approach. The measured quantities and calculated performance have been post-processed in order to evaluate the influence on steady state detection, of different hot source temperature set points. Moreover, the selected steady-state detection method is suitable for real-time implementation, due to its simple formulation and the low number of variables required to be stored at time step of acquisition.

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Keywords: ORC; test bench; thermodynamic measurements; system efficiency; steady state detection

1. Introduction

The Organic Rankine Cycle (ORC) is an advanced power generation technology commonly used to convert low grade heat into electricity, for a wide range of power values (scales from a fraction of kW_e to several MW_e). ORC technology results now mature and advantageous in many ways and it has shown a renewed interest over the last

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decades thanks to its flexibility and easy maintenance. At low temperatures, organic working fluids lead to higher cycle efficiency than water and these kinds of fluids are preferable, leading to high turbine efficiency in both full and partial load conditions. Almost all the units available on the market are in the medium to-high power range, while micro-small size are still in demonstration phase, but their application could save primary energy and reduce pollutant emissions [1]. Small and micro size ORCs are interesting for several applications, such as electric generation in remote area, domestic cogenerative units or trigeneration applications, etc. Recently, there have been many experimental investigations on small scale ORC, focusing on design optimization, fluid selection, expander technologies, operating conditions, components performance or complete cycle, dynamic control and the experimental analysis are useful for model validation and data-feeding [2]. In particular, process data employed for benchmark analysis should be collected when steady-state conditions have been achieved, in order to get realistic and meaningful results from experimental test. Data accuracy is of great importance for power plant on-line performance monitoring and it is fundamental to implement efficient methods for online steady-state detection. Moreover, power plants steady state is not *a priori* defined and a tolerable constancy of the mean values of measurements, over a given period of time, depends on the nature of the system under investigation.

The issue of steady-state detection has been discussed by a number of researchers in the literature. For instance, an available method is proposed by Kim & al. [3]. This technique is based on standard deviation calculated over a time moving window. Steady-state is declared when the moving deviation lies under an established threshold over a predefined time period. This approach requires storing past measurements over the whole moving window, which is critical for real-time applications. Furthermore, using a normal average, instead of a weighted one, creates a delay in the characterization of process measurement. This delay can cause detection problems in periods where the signal varies in a short time period.

Another method, called *R-test*, has been proposed by Cao & Rhinehart [4], based on a ratio of variances evaluation: when this ratio is lower than an arbitrary value, the process reaches the steady-state condition. The method does not need to store past measures and it is computationally inexpensive compared to Kim's method [3].

Nomenclature

Subscripts

Cold	Cold Source
el	Electric
EVAP	Evaporator
EXP	Expander
f	Filtered Value
i	Instant
iso	Isentropic
rrc	Reversible recuperation cycle

Roman symbols

FS	Full Scale
h	Enthalpy [kJ/kg K]
Hot	Hot Source
$\dot{m}$	Mass flow rate [kg/s]
Max	Maximum
min	Minimum
ORC	Organic Rankine Cycle
P	Electric Power [kW]
p	Pressure [bar]
PCB	Printed Circuit Board
Q	Thermal Power [kW]
RV	Reading Value
R	Ratio of Variances [-]
s	Estimated Variance [-]
SP	Set-Point hot source temp. [°C]
T	Temperature [°C]
v	Measured Variance [-]
$\dot{v}$	Volumetric flow rate [l/s]
x	Acquired Value

Greek letters

Δ	Variation
ρ	Density [kg/m^3]
λ	Filter Factor [-]
δ	Mean Squared Difference [-]
η	Efficiency [%]

A third method available in literature has been suggested by Jiang & al. [5]. Using wavelet-based multi-scale data processing, the process trends are first extracted from raw measurements by eliminating random noise and abnormalities. The process status at each time point is then analyzed according to the wavelet transform of the extracted process trends. This method appears to be reliable for detecting rate of change in variables and estimating the measurement status at a point in time; in this case, if measures are affected by nonrandom errors, the detection