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Control variables and strategies for the optimization of a WHR ORC system

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Abstract

In this paper, the dynamic behavior of a WHR (Waste heat Recovery) ORC system with positive displacement rotary expander has been analyzed and an optimal control strategy was defined to increase the system efficiency and flexibility. Input heat flow was varied in time by varying the heat source mass flow and inlet temperature, according to two different load cycles. Three different control strategy were implemented and compared. The first strategy was sliding pressure, where expander speed was kept constant and system power output was controlled by evaporator pressure variations. The second control strategy was sliding velocity, where expander speed was varied to keep the evaporating temperature to a constant set point value. The third control strategy was a combination of sliding-pressure and sliding velocity: the set point of evaporating pressure varied according to a suitable function of easily measurable variables, with the objective of maximizing system efficiency. A function of the heat source admission temperature and of the product of the volume flow rate by the admission pressure was used to define the evaporating temperature set point. This function was evaluated in steady-state conditions from the model of the plant. Results showed that the last control strategy, maximized system efficiency and flexibility, and that the control parameter chosen were suitable to drive the set point variation.

Keywords: WHR ORC, Control Strategies, Control Variables, Volumetric Expander.

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Nomenclature		**Subscript**	
U	Internal Energy [J]	ad	Expander admission
u	Specific Internal Energy [J/kg]	is	Isentropic
V	Volume [m^3]	p	Pump
$\dot{m}$	Mass Flow Rate [kg/s]	0	Ambient conditions
h	Specific Enthalpy [J/kg/K]	$exch$	Exchanged
Q	Heat [J]	av	Available
A	Area [m^2]		
T	Temperature [K]	**Greeks**	
$\dot{W}$	Mechanical power [W]		
$\dot{V}$	Volume flow rate [m^3/s]	ρ	Density [kg/m^3]
P	Pressure [Pa]	λ	Heat exchange coefficient [W/m^2/K]
C_p	Constant Pressure Specific Heat [J/kg/K]	η	Efficiency
C_v	Constant Volume Specific Heat [J/kg/K]	η_{cycle}	Cycle efficiency
m	Mass [kg]	ε	Recovery Efficeincy

1. Introduction

The integration of Organic Rankine Cycles (ORCs) with other systems to recover waste heat can bring many benefits, such as better economic management of energy, higher efficiency and CO_2 emissions reduction. Several publications in the literature studied the behavior of WHR (Waste Heat Recovery) ORC in steady-state conditions, analyzing various working parameters to optimize system design [1-6], highlighting the influence of the evaporation temperature on the efficiency. Due to the variations in temperature and mass flow rate, flexibility is one of the most important characteristics of WHR. In small-scale applications, flexibility may be increased by employing positive displacement expanders [7-9]. Differently from turbines, they do not need any extra device, such as Variable Inlet Guide Vanes (IGV), when operating at off-design point [10].

Currently, few studies have analyzed the effects of the control strategies on the behavior of following WHR (FWHR) systems: Hu et al. in [10] defined three different control strategies in steady-state conditions (sliding velocity, sliding pressure and a combination of them both), to drive an ORC for geothermal or WHR applications with a variable IGV radial turbine. Wei et al. in [11] compared moving boundary and discretization model techniques in a dynamic modeling of heat exchangers for an ORC/WHR plant, showing the equivalence of the two approaches respect to experimental data. Quoilin et al. in [12] compared two control strategies for a WHR ORC system with scroll expanders: sliding-velocity and a combination of sliding-pressure and sliding-velocity. In this last case, the authors employed an optimal function of the HTF temperature, working fluid mass flow rate and condensing temperature. Zhang et al. in [13], created a dynamic simulation of a Following Electric Load (FEL) WHR ORC, and demonstrated the ability of the control system of tracking the set point values and their disturbance response. They developed in a further paper [14] a predictive controller for a Following Waste Heat (FWH) WHR ORC demonstrated the better efficiency of FWH systems over FEL systems.

In this work, a dynamic model of the FWH WHR ORC system was created in AMESim and sliding-pressure, sliding-velocity and a combination of both strategies were compared. The set point was defined through an optimal function extrapolated in steady-state condition from the dynamic model of the plant. This function depended on the heat source temperature, and on the product of the volume flow rate to the admission pressure of the expander. These three variables are easily measurable and this control strategy can be easily implemented.

2. Methodology

The WHR system described (Fig. 1) includes a heat source (generic stream of hot air at relatively low temperature, less than 200°C), an evaporator, a condenser, a pump and a rotary volumetric expander derived from a Wankel engine. The working fluid was composed of R-600a, which gave the best results in the temperature range 100-200°C amongst