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Response time characterization of Organic Rankine Cycle evaporators for dynamic regime analysis with fluctuating load

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Abstract

The Organic Rankine Cycle (ORC) is one of the main technologies for recovery of low grade heat. However, many of the applications, especially waste heat recovery, present the challenge of thermal power fluctuations of the heat carrier. These fluctuations result in sub-optimal component selection and poor cycle performance at off-design conditions.
This study aims to characterize the dynamic behavior of an ORC evaporator under fluctuating load as a method for dynamic behavior optimization at the design stage. This is done by constructing response-time charts that highlight the dependence of the thermal inertia of the evaporator in three main design variables: heat exchanger geometry, heat exchanger wall material and working fluid thermal properties. The characterization can then be used at a particular application to choose the proper design parameters that can reduce some of the variability of the heat input. This is illustrated with a case study from an ORC evaporator recuperating waste heat from a billet reheating furnace.

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Keywords: ORC, WHR, dynamic modelling, transient analysis, time constant, thermal power fluctuations

1. Introduction

Low grade heat is present in numerous renewable and low carbon energy sources such as geothermal, solar thermal and waste heat recovery (WHR). In particular, waste heat recovery has the enormous potential to increase the overall

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energy efficiency of various energy-intensive sectors, and in this way mitigate carbon emissions, exploit new economic opportunities and reduce energy resources waste [1]. One of the most established and well suited technologies to recover low grade heat is the Organic Rankine Cycle (ORC) due to the lower evaporation temperatures of the organic fluids and its economic advantage at low power [2].

Some of the most promising sectors for WHR such as the heavy industry (i.e. steel manufacturing) and the transport sector (i.e. excess heat from vehicle engines) typically show fluctuations over time of both the thermal power content and temperature of the heat carriers. These fluctuations are intrinsic due to the batch or pulsating nature of some of the processes as well as irregularities of production or driving conditions. Although of a slower nature, other low-grade energy sources such as geothermal and solar-thermal also show daily or seasonal fluctuations.

Fluctuations of load present many challenges. The ORC will operate most of the time at off-design condition and will require a suitable control design in order to operate within safe and acceptable ranges and reduce the deviations from design point. Off-design operation due to the fluctuation has a detrimental effect on the overall efficiency of the system and can lead to increased pay-back periods or economical unfeasibility. On the other hand, particularly in automotive applications, direct evaporation (direct heat exchange without an intermediary thermal oil loop between hot source and working fluid) is an attractive option due to constraints of space and mass of the equipment, but the high fluctuations of the load have hindered its application.

When working under fluctuating input, ORCs will respond to the changes in load in a certain amount of time according to their thermal inertia. As transients are significantly slower in heat exchangers than the other ORC components [3,4], the system thermal inertia can be well represented by the evaporator response times. Consequently, one way to simplify the analysis of the ORC dynamic behavior is to isolate the evaporator. To some extent, the evaporator will act as a buffer between the thermal load and the downstream components, specifically the expander.

Because of the afore-mentioned challenges, it is important to understand and characterize the dynamic behavior of the system in a systematic and simple way in order to design the system and control from not just the steady-state thermodynamic optimization perspective but also from an operational optimization point of view. For instance, it may be preferred to design an evaporator that can effectively filter out some of the large amplitude fluctuations in order to have a more robust system to the variability of the load.

One way to characterize the dynamic behavior of the system under a particular load is to compare the response time of the ORC evaporator to the rate of change of the fluctuations and identify different dynamic regimes of response: behavior close to a quasi-steady state, response transient dominated or fluctuations effectively filtered out.

The present work aims to characterize the dynamic behavior of ORC evaporators under fluctuating load in a systematic way, by examination of the evaporator response times as a function of the fluid properties and heat exchanger design parameters and compare it to the frequencies of load fluctuation. This can help as a tool for the design of evaporator heat exchanger for optimized dynamic operation.

Nomenclature

Γ	Dynamic regime number, -	Subscripts	
τ_{ev}	Evaporator response time, s	w	Metal wall (heat exchanger)
T_{load}	Characteristic period of load fluctuation, s	f	Working fluid
D	Diameter, m	avg	Average value
L	Length, m	sat	Saturation state
$CapR$	Capacity ratio, dimensionless parameter, -	l	Sub-cooled liquid state
Ja_{lv}	Jakob number, dimensionless parameter, -	v	Super-heated vapor state
ρ	Density, kg/m^3		
C	Specific heat capacity, solid, J/(kg·K)	Acronyms	
T	Temperature, K	WHR	Waste heat recovery
ΔH_{vap}	Spec. enthalpy of vaporization, J/kg	ORC	Organic Rankine Cycle
C_p	Specific heat capacity, working fluid, J/(kg·K)		