



Analysis and comparison of dynamic behavior of heat exchangers for direct evaporation in ORC waste heat recovery applications from fluctuating sources

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HIGHLIGHTS

- Dynamic behavior of two types of ORC evaporators for direct heat exchange is studied.
- The dependence of response time on geometric dimensions and materials is highlighted.
- Implications in pressure drops, volume and weight of heat exchangers are included.
- Fin and tube evaporators with large diameters are preferred for slow responses.
- Slow-response ORC evaporators can dampen source fluctuations in WHR applications.

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ABSTRACT

Organic Rankine Cycle (ORC) is one of the most prominent technologies for power generation from waste heat sources. Due to their nature, as residual energy from an upstream process, waste heat sources typically present a fluctuating behavior that makes the recovery of the waste heat a challenging task.

Direct evaporation from the waste heat carrier has gained substantial interest, especially on volume and weight sensitive applications where the introduction of an additional intermediary thermal oil heat exchanger can hinder the feasibility of the system. Because of the highly dynamic operation of direct evaporators under fluctuating waste heat sources, it is important to consider the thermal response time of the evaporator already at the design stage.

In this paper, a systematic analysis and comparison of the dynamic response of two types of ORC evaporators for direct heat transfer between an exhaust gas and the organic working fluid is performed. Based on detailed dynamic models and simulations, maps are built to highlight in a generalized, compact and systematic way the dependence of the thermal response time of the evaporators on the geometric design and boundary conditions and its implications on the weight, volume and pressure drops. The analysis and application of the methodology to diesel engines long haul duty trucks, shows that fin and tube evaporators with large tube diameters and small cross-sectional areas of the exhaust side are the preferred option for high thermal inertia design, while louver fin multi-port flat tubes evaporators with large port diameters are better for fast response, despite the high pressure drops.

1. Introduction

Waste heat recovery is an effective method to reduce emissions and consumption of energy resources [1]. Indeed, there is a huge energetic and economic potential on the utilization of waste heat. For instance, in the case of Southeast Asia, the economic and technical potential of

waste heat to power from industrial sources have been estimated to be 1188 MW and 1788 MW, respectively [2]. In internal combustion engines, about 60–70% of the primary energy is lost as waste heat, approximately 33% in the exhaust gases [3]. Amongst the available waste heat recovery solutions, Organic Rankine Cycle (ORC) is a well-established technology for power generation from low-grade heat sources

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Nomenclature

M	mass, kg
V	volume, m ³
t	time, s
ρ	density, kg/m ³
h	specific enthalpy, J/kg
p	pressure, Pa
$\dot{m}$	mass flow rate, kg/s
$\dot{Q}$	Heat transfer rate, W
T	temperature, K
c	specific heat capacity, J/(kg K)
R	thermal resistance, K/W
A	heat transfer area, m ²
θ	film heat transfer coefficient, W/(m ² K)
U	overall heat transfer coefficient, W/(m ² K)
Δp	pressure drop, Pa
f_D	friction factor, -
L	tube length, m
D	diameter, m
v	velocity, m/s
Re	Reynolds number, -
ϵ	tube roughness, m
τ_{ev}	evaporator response time, s

τ_w	wall conduction time constant, s
th	thickness, m
α	thermal diffusivity, m ² /s
k	thermal conductivity, W/(m K)
Γ	dynamic regime number, -
T_{step}	source step time, s
$f_{sinusoidal}$	frequency, sinusoidal source, Hz

Subscripts

w	metal wall (heat exchanger)
wf	working fluid
exh	exhaust
in	inlet condition
out	outlet condition
int	internal side
ext	external side
SH	super-heating

Acronyms

ORC	Organic Rankine Cycle
WHR	waste heat recovery
ICE	internal combustion engine

including waste heat [4]. Due to higher availability and higher temperatures, some of the most relevant waste heat sources for power generation with ORCs include waste heat from energy-intensive industries [5–8] and from internal combustion engines [9–13].

1.1. Fluctuating sources and ORC evaporator options

Due to their nature as residual energy from an upstream process, in waste heat recovery applications the heat source profile often fluctuates over time according to the main process to which it is subordinated. As it is very often the case, ORCs and its components are optimized for a certain fixed design point, usually that corresponding to the upper boundary of the fluctuations [14]; this leads to poor off-design performance for much of the operation due to the variation of the heat input.

Measures to dampen the fluctuations of the heat source include the introduction of an intermediary thermal energy storage device in order to decouple the waste heat source from the ORC [15,16], or the dampening of the fluctuations with the integration of a thermal fluid loop between the waste heat source and the ORC [17]. By doing so, it is possible to increase the amount of energy recovered as well as protect the organic working fluid from chemical decomposition at high temperatures. However, these options have important drawbacks. First, the inclusion of an intermediary component decreases the efficiency potential of the power cycle due to the exergy loss in two heat transfer processes instead of one. Second, an extra piece of equipment increases capital costs and reduces the feasibility in volume and/or weight restricted applications as it is the case of waste heat recovery in road-transport applications [18]. For these reasons, direct evaporation of the working fluid from waste heat sources can be the preferred or required arrangement [19].

However, direct evaporation is a challenging task especially when highly dynamic conditions of the heat source are present. This is because the design and control of the system needs to ensure the integrity of the working fluid with the absence of any type of external buffer that can reduce the variability of the source.

1.2. Previous research on ORC evaporators

There has been a lot of research regarding heat exchanger options

for ORC evaporators. Shell and tube is the most common type of heat exchanger and its optimized design as ORC evaporator has been the subject of several studies [20–22]. However they are usually more suitable for large scale ORC systems, such as geothermal applications, in which the hot fluid is a liquid and flows through the tubes (e.g. the kettle boiler configuration [23]). In small scale applications, compact heat exchangers as evaporators are a preferred option [24]. The most widely researched option for compact ORC evaporators are brazed plate heat exchangers [25–27]. Brazed plate evaporators, however, are better suited when the hot fluid is a liquid [28] and thus has limited application in direct evaporation from gaseous streams. For direct evaporation from gaseous fluids, compact options include the fin and tube heat exchanger [29] and louver fin and flat tubes [30] geometries. Studies considering fin and tube heat exchangers as an evaporator option from gaseous fluids, mostly aim at the optimization of the geometry at design point [31,32]. Comparisons of the performance of different types of heat exchangers as ORC evaporators, including shell and tube and compact geometries, have also been undertaken based on system optimization [33] or on cost-effectiveness and return of investment [34].

However, all the studies mentioned earlier, only focus on design point optimization and do not take into account the dynamic response of the heat exchanger.

In the case of the dynamic behavior of heat exchangers for ORC applications, most of the attention is focused on dynamic modelling mostly for control purposes [23,35–37]. Approaches for the dynamic modeling of ORC heat exchangers usually include the finite volume and moving boundary models [38,39]. Recently, a study on the influence and selection of the working fluid in the dynamic response of the ORC has been presented [40], with an emphasis on control design. However, to the best of the authors' knowledge, there is still no systematic methodology to the influence of component design parameters and boundary conditions in the dynamic response times of ORC evaporators.

1.3. Motivation and objective of current study

In direct evaporation there is no buffer (i.e. thermal storage or intermediary fluid) between the heat source and the working fluid,

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