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Research Paper

Performance investigation of reciprocating pump running with organic fluid for organic Rankine cycle

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HIGHLIGHTS

- Experimental investigation of reciprocating pump with organic fluid.
- Pump power chain analysis and modelling.
- Pump cavitation analysis and impact on ORC performance evaluation.

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ABSTRACT

Organic Rankine cycles (ORC) are used to convert lowgrade heat sources into power. Current research and development investigate small scale and variable heat sources application such as waste heat recovery. Many experimental data on ORC are available. Feed-pump performances achieved are lower than expected and some authors reported cavitation issue. Pump performance has a non-negligible impact over the ORC performance, especially for transcritical cycles. Operations of diaphragm pumps in three different test benches with different fluid and pump size are analyzed. A semi-empirical model of the pump power chain is proposed and validated. Energetic analysis show highlevel of losses in the variable speed drive and electric motor, mainly due to design oversizing. Then a model and analysis of reciprocating pump volumetric efficiency is proposed, taking into account fluid properties. Finally, cavitation limits in different conditions are calculated. Required Net Positive Suction Head (NPSHr) calculated for R134a are found to be in accordance with manufacturer limits for water. Pump vibration sensor could be used for cavitation monitoring. This work gives information for ORC feed-pump simulation, design and operation.

1. Introduction

The organic Rankine cycle (ORC) is a heat to power conversion technology suitable for heat sources between 80 °C and 300 °C [1]. Current commercial ORC units ranges from 10 kWe to 10 MWe and are used for various applications such as geothermal energy, biomass (usually for combined heat and power), thermal solar plants and waste heat recovery [2]. The Rankine cycle is a thermodynamic cycle using the power gain between liquid compression and vapor expansion. The ratio between pump consumption and expander output power is called back work ratio (BWR) [3]. In steam Rankine cycle, the BWR is very low and therefore feed-pump performance has a negligible impact over the engine thermal efficiency. In ORC, this assumption is no longer appropriate as BWR is respectively about 2 and 4 times higher for R245fa and R134a compared to water. BWR is increasing as the heat source temperature and fluid critical temperature is low [3,4]. Operating above the critical point strongly increase the BWR (Fig. 1). Therefore, pump efficiency has a strong impact on transcritical ORC thermal efficiency [5]. In numerical study or engine design, pump efficiency is taken between 65 and 85% [4]. Few ORC experimental studies provides pump real data or analysis. Fig. 2 shows an overview of ORC feed-pump performance reported in the literature. For an ORC of a kW scale, pump mean efficiency is

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Nomenclature

m	mass flow rate (kg/s)
P	pressure (bar)
Q	heat transfer (W_{th})
T	temperature (°C)
V	volume flow rate (m^3/h)
v	volume (m^3)
W	power (W)
β_T	isothermal compressibility coef. (Pa^{-1})
Δ or δ	difference
η	efficiency (–)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
Φ	irreversible dissipation (W)
Ω	rotational speed (rpm)

Subscript

comp	compressed
dead	dead (volume)
dis	discharge
disp	displaced
el	electric (power)
esti	estimated (model)
flu	fluid
hyd	hydraulic (power)
is	isentropic
in	inlet
leak	leakage
los	losses
meas	measured
me	mechanical (power)
mot	motor
n	nominal
0	reference
out	outlet
pp	pump
sat	saturation
suc	suction
t	transferred
vol	volumetric
vsd	variable speed drive

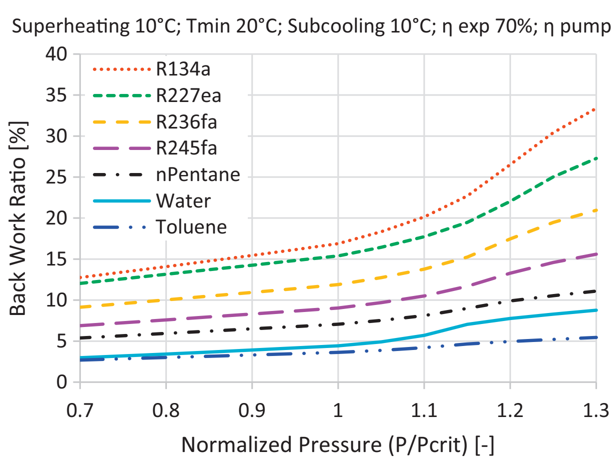

Fig. 1. Back work ratio function of evaporative pressure.

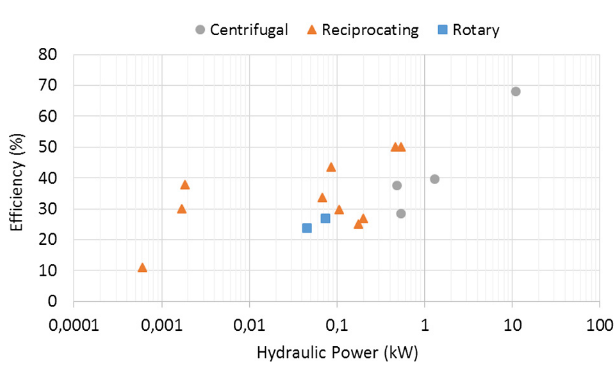

Fig. 2. Reported pump maximum efficiency and hydraulic power.

35% and maximum efficiency is about 50% which is lower than typical design values. Performances are low, especially for small-scale units. Yamada et al. [6] even reported a negative net power (i.e. BWR above 100%) for its micro-ORC prototype and proposed a pumpless system as an alternative.

Another issue of pump operation in ORC is the cavitation. Cavitation occurs when fluid at the pump inlet get close to saturation, it leads to flow rate reduction and pump damages. Cavitation is believed to be more serious with organic fluid since compared to water, they have lower latent heat of vaporization and evaporation temperature [7]. Pump manufacturer use the Net Positive Suction Head (NPSH) for cavitation analysis and prevention. NPSH is the difference between the measured pump inlet pressure and the fluid vapor pressure for the pump inlet temperature. In ORC literature, the subcooling is often used instead of the NPSH. The subcooling is the difference between the fluid vapor temperature for the pump inlet pressure and the measured pump inlet temperature. Both express the gap to saturation condition, either in pressure or temperature units. Yang et al. [7] reported cavitation in piston pump for subcooling under 20 °C. Dumont et al. [8] and Chang et al. [9] plunger pumps requested respectively 10 °C and 11 °C subcooling to avoid cavitation. Leontaritis et al. [10] diaphragm pump required 0.5 bar of NPSH whether a 2 °C subcooling for smooth operation. Decrease the minimum subcooling is essential for ORC, especially at low temperature. Fig. 3 shows evolution of BWR and ORC thermal efficiency function of the subcooling at

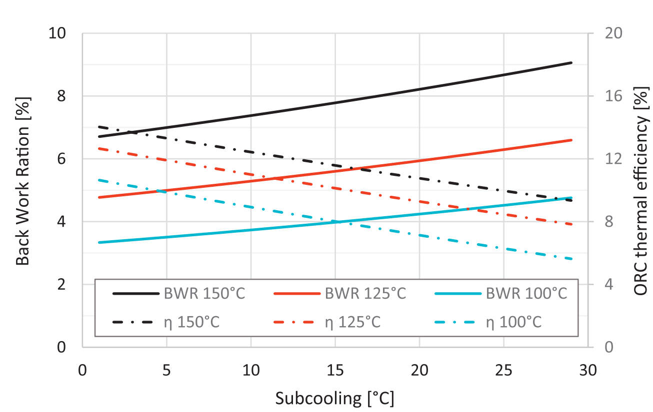

Fig. 3. ORC performance function of subcooling.