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Analysis of hot spots in boilers of organic Rankine cycle units during transient operation

A. Benato [a,*], M.R. Kærn [b], L. Pierobon [b], A. Stoppato [a], F. Haglind [b]

[a] Department of Industrial Engineering, University of Padova, Building Ex-DIM, via Venezia 1, 35131 Padova, Italy
[b] Department of Mechanical Engineering, Technical University of Denmark, Building 403, 2800 Kongens Lyngby, Denmark

HIGHLIGHTS

- The thermal stability of cyclopentane, in an organic Rankine cycle unit, is analysed numerically.
- The case study is the Draugen offshore oil and gas platform in the Norwegian Sea.
- A transient analysis is performed to identify hot spots during load variations.
- Guidelines for safe and reliable operation of organic Rankine cycle units are suggested.

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ABSTRACT

This paper is devoted to the investigation of critical dynamic events causing thermochemical decomposition of the working fluid in organic Rankine cycle power systems. The case study is the plant of an oil and gas platform where one of the three gas turbines is combined with an organic Rankine cycle unit to increase the overall energy conversion efficiency.

The dynamic model of the plant is coupled with a one-dimensional model of the once-through boiler fed by the exhaust thermal power of the gas turbine. The heat exchanger model uses a distributed cross-flow physical topology and local correlations for single- and two-phase heat transfer coefficients.

The results indicate that severe load changes (0.4–1.0 $\mathrm{MW\,s^{-1}}$) can lead to exceedance of the temperature limit of fluid decomposition for a period of 10 min. Ramp rates lower than 0.3 $\mathrm{MW\,s^{-1}}$ are acceptable considering the stability of the electric grid and fluid decomposition. It is demonstrated that the use of a spray attemperator can mitigate the problems of local overheating of the organic compound.

As a practical consequence, this paper provides guidelines for safe and reliable operation of organic Rankine cycle power modules on offshore installations.

1. Introduction

Although investigated since the 1880s, Organic Rankine Cycles (ORC) have never been popular until today's growing interest in medium and low grade energy recovery systems where cycles using water as working fluid fail for technical and economic reasons [1,2].

Organic fluids, i.e., refrigerants and hydrocarbons [3], can mitigate the technical problems associated with the use of steam. These compounds feature higher molecular mass and lower critical temperature than water. These aspects can make small or medium scale power plants technologically and economically feasible.

Their cycle architecture is similar to that of conventional steam Rankine cycles. The high pressure liquid is first evaporated, then expanded to a lower pressure, thus producing mechanical power. The cycle is closed by condensing the low pressure vapour (coming from the turbine outlet) and pumping the liquid to the high pressure side. Hence, an ORC unit has the same devices as a conventional steam power module: an evaporator, an expander, a condenser and a pump.

An organic Rankine cycle has several advantages over steam power plants, as pointed out by Tchanche et al. [3]. The evaporation process, usually taking place at lower temperature and pressure, requires less heat. Superheating is not required, and the risk of turbine blades erosion is avoided as the expansion process ends in the vapour region. Moreover, the relatively low pressure ratio of the expander enables the use of simple single stage turbines.

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* Corresponding author. Tel.: +39 049 827 6752; fax: +39 049 827 6785.
E-mail address: alberto.benato@unipd.it (A. Benato).

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Nomenclature

A	area $[\mathrm{m^2}]$
C_o	dimensionless parameter Eq. (A.3)
D	outer tube diameter [m]
G	mass flux $[\mathrm{kg\,m^{-2}\,s^{-1}}]$
N	dimensionless parameter Eq. (A.3)
T	temperature [K]
X	operand Eq. (A.22) $[\mathrm{m^{-1}}]$
$\dot{m}$	mass flow rate $[\mathrm{kg\,s^{-1}}]$
Bo	boiling number
Fr	Froude number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
c	speed of sound $[\mathrm{m\,s^{-1}}]$
c_p	specific heat capacity $[\mathrm{J\,kg^{-1}\,K^{-1}}]$
d	inner tube diameter [m]
f_D	Darcy friction factor
g	gravity acceleration $[\mathrm{m\,s^{-2}}]$
h	heat transfer coefficient $[\mathrm{W\,m^{-2}\,K^{-1}}]$ or enthalpy $[\mathrm{J\,kg^{-1}}]$
h_{LG}	heat of evaporation $[\mathrm{J\,kg^{-1}}]$
k	thermal conductivity $[\mathrm{W\,m^{-1}\,K^{-1}}]$
p	pressure [Pa]
q	heat flow rate [W]
q''	heat flux $[\mathrm{W\,m^{-2}}]$
s	entropy $[\mathrm{J\,kg^{-1}\,K^{-1}}]$
x	vapour quality

Abbreviations

CC	combustion chamber
GEN	electric generator
GT A, GT B, GT C	gas turbine A, B and C
HPC	high pressure compressor
HPT	high pressure turbine
HRSG	heat recovery steam generator
LPC	low pressure compressor
LPT	low pressure turbine
ORC	organic Rankine cycle
OTB	once-through boiler
PT	power turbine
TUR	organic Rankine cycle expander

Greek letters

δ	fin thickness [m]
η	fin efficiency
μ	viscosity $[\mathrm{kg\,m^{-1}\,s^{-1}}]$
ρ	density $[\mathrm{kg\,m^{-3}}]$
φ	operand Eq. (A.22)

Subscripts

c	cold fluid
f	fin
G	gas
h	hot fluid
in	inlet
L	liquid
o	overall
S	static
T	total
$t0$	bare tube surface
th	throat
wi	inner wall
wo	outer wall
cb	convective boiling
nb	nucleate boiling

The ORC technology is suitable for recovering heat from solar radiation [4–12], ocean warm layers [13–17], hydro-thermal and engineered geothermal systems [18–21], abandoned oil fields [22–24], biomass [25–29], and industrial processes [1,30,31].

The choice of the working fluid tightly relates to the characteristics of the heat reservoir, as it determines the configuration, performance and economics of the plant [32]. These aspects justify the abundant literature dedicated to the fluid selection (see for example [33,34]) and plant configurations [35].

As pointed out by Pasetti et al. [36], another key parameter is the thermal stability of the organic fluid. It is defined as the maximum temperature at which the fluid can be used in power plants without risk of decomposition. Fluid overheating or hot spot and the consequent fluid decomposition is more likely to occur in the vapour film in contact with the tube metal walls of the terminal part of the primary heat exchanger. As the system performance strongly relates to transport and physical properties of the working fluid, hot spots can severely reduce the net power output, the fluid stability and the components' integrity [37].

Fluid thermochemical decomposition depends on the breakage of chemical bonds between the molecules and the formation of smaller compounds. These species can then react to create other hydrocarbons. Although studies on the thermal stability of organic compounds date back to the early 60s [36], the data available in literature are scarce and often contradictory [2,37–39]. These research efforts paid attention to the development of testing techniques to quantify the maximum operating temperatures of the organic fluid.

The hot spot phenomenon is in some way analogous to that observed in the materials of boiler tubes, core of nuclear reactors and heat exchangers. Tanzer [40] described the effect of long-term material overheating on the lifetime of steam boilers. The overheating of the tube metal wall induces a reaction between the steam and the tube material itself. The result is an adhesive oxide layer. This additional resistance induces the deterioration of the metal walls as the temperature raises to the maximum tolerable limit. As surveyed by French [41], hot spot corrosion on the steam side of operating boiler tubes of fossil fuel-fired power plants is imputable to the departure from nucleate boiling. This phenomenon leads to acid or caustic attack, and deteriorates the protective magnetite film of the tube walls.

Occurrence of hot spots is a well-known problem in the core of nuclear reactors. This chemical process occurs if the ratio between the power density insisting on the fuel and its average value at design conditions exceeds the prescribed threshold. Statistical analysis and probabilistic evaluations were performed by Amendola [42] and Zhang et al. [43], respectively. Measurement techniques for hot spot identification in nuclear reactors were proposed by Gandini [44]. As regarding the hot spot formation in heat transfer devices, Francis [45] analysed the conditions inducing corrosion in copper alloys of condenser tubes. Prasher et al. [46] conducted similar investigations for micro heat exchangers utilized in electronic devices.

To the authors' knowledge, the fluid overheating (hot spot) and consequent decomposition during the transient operation of ORC power systems have not been analysed before. As underlined by