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**Simulation Model for a low grade waste  
heat recovery organic Rankine cycle**

**DISSERTAÇÃO DE MESTRADO**

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Dissertation presented to the Programa de Pós-Graduação em Engenharia Mecânica of the Departamento de Engenharia Mecânica, PUC-Rio as partial fulfillment of the requirements for the degree of Mestre em Engenharia Mecânica.

Advisor: Jose Alberto dos Reis Parise  
Co-Advisor: Samuel Fortunato Yana Mota

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## Resumo

Rodriguez Mejía, Oscar Juan Pablo; dos Reis Parise, Jose Alberto. **Modelagem de um ciclo orgânico Rankine com recuperação de calor de rejeito a baixa temperatura**. Rio de Janeiro, 2012. 75p. Dissertação de Mestrado - Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

A presente dissertação trata do estudo de sistemas de potência baseados em ciclos Rankine orgânicos (ORC – Organic Rankine Cycle) acionados por energia térmica de rejeito. O objetivo é descrever mediante a simulação numérica um ciclo Rankine orgânico, dimensionar os trocadores de calor para o ciclo proposto e aplicar o conceito para sistemas de trigerção. Um modelo termodinâmico simples é apresentado, relacionando as características termodinâmicas do ciclo Rankine orgânico àquelas da corrente com rejeito térmico (como, por exemplo, vazão mássica, capacidade térmica e temperaturas de operação). A seguir, o método de multi-zonas, ou de fronteira móvel, é aplicado aos trocadores de calor do ciclo, condensador e caldeira, para dimensioná-los às condições do efluente de rejeito térmico. Na escolha do tipo de trocador de calor para a caldeira, é feita a distinção quanto à natureza do efluente, se gasoso ou líquido. No primeiro caso empregam-se trocadores de tubo e aleta e, no segundo, trocadores de placas. A solução numérica do sistema de equações algebraicas é obtida através de um programa computacional escrito em FORTRAN. São também estudados novos fluidos de trabalho de menor impacto ambiental e os resultados apresentados fazem uma comparação com fluidos de uso tradicional. As propriedades termodinâmicas e de transporte dos fluidos considerados foram obtidas usando o programa REFPROP 9.0 do NIST. Finalmente, o conceito do ciclo Rankine orgânico é aplicado a sistemas de trigerção, caracterizados pela produção simultânea de eletricidade, aquecimento e refrigeração.

## Palavras-chave

Ciclo orgânico Rankine; calor de rejeito; cogeração; modelagem.

## Abstract

Rodriguez Mejía, Oscar Juan Pablo; dos Reis Parise, Jose Alberto.

**Simulation Model for a low grade waste heat recovery organic Rankine cycle.** Rio de Janeiro, 2012. 75p. MSc. Dissertation - Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

The present dissertation addresses the study of power generation systems based on organic Rankine cycles (ORC) driven by waste thermal energy (heat). A simple thermodynamic model is presented, relating the thermodynamic characteristics of the organic Rankine cycle to those of the waste heat flow (for instance: mass flow, thermal capacity and operation temperatures). Furthermore, the multi-zone, or movable boundary method is applied to the heat exchangers of the cycle, boiler and condenser, in order to size them for the waste heat flow conditions. In choosing the type of heat exchanger for the boiler, the distinction is made on the nature of the waste heat, either gaseous or liquid. New working fluids for the cycle, of less environmental impact, are studied. For the first case, tube and fin heat exchangers are considered, and in the second, plate heat exchangers. Finally, the concept of the organic Rankine cycle is applied to trigeneration systems, characterized by the simultaneous production of electricity, heating and cooling.

## Keywords

Organic Rankine cycle; low grade waste heat; cogeneration; simulation.



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## NOMENCLATURE

$A$	Total heat transfer area	[m <sup>2</sup> ]
$\alpha$	Area of exchangers using new organic substances divided by the area obtained using R134a	[-]
$b$	Mean channel spacing	[m]
$Bo$	Boiling number	[-]
$COP$	Coefficient of performance	[-]
$c_p$	Constant pressure specific heat	[kJ/kg·K]
$D_h$	Hydraulic diameter	[m]
$d_i$	Tube inside diameter	[m]
$d_o$	Tube outside diameter	[m]
$\dot{E}_{to}$	Electricity power load	[kW]
$ECR_{cv}$	Energy conversion ratio of a conventional system	[-]
$ECR_{tg}$	Energy conversion ratio of a trigeneration system	[-]
$F$	Logarithmic mean temperature difference correction factor	[-]
$Ge$	Non-dimensional geometric parameter	[-]
$G_f$	Fluid mass flux	[kg/s·m <sup>2</sup> ]
$\dot{H}$	Energy rate equivalent of fuel consumption	[W]
$h$	Specific enthalpy	[kJ/kg]
$k$	Thermal conductivity	[kW/m·K]

$\dot{m}$	Mass flow rate	[kg/s]
$Nu$	Nusselt number	[-]
$Pr$	Prandtl number	[-]
$\dot{Q}$	Total heat transfer rate	[kW]
$q''$	Heat flux	[kW/m <sup>2</sup> ]
$R_{EC}$	Electricity-to-cooling load ratio	[-]
$R_{HC}$	Heating-to-cooling load ratio	[-]
$R_{HE}$	Heating-to-electric load ratio	[-]
$Re$	Reynolds number	[-]
$U$	Overall heat-transfer coefficient	[kW/m <sup>2</sup> ·K]
$\dot{W}$	Power output	[kW]

### Greek Letters

$\alpha$	Heat transfer coefficient	[kW/m <sup>2</sup> ·K]
$\alpha_{ec}$	Fraction of energy rate equivalent of fuel consumption that goes to engine coolant	[-]
$\alpha_{es}$	Fraction of energy rate equivalent of fuel consumption that goes to engine shaft power	[-]
$\alpha_{ex}$	Fraction of energy rate equivalent of fuel consumption that goes to engine exhaust	[-]
$\beta$	Chevron angle	[radian]
$\gamma$	Void fraction of tube cross sectional area	[-]
$\delta$	Liquid film thickness	[m]
$\eta$	Efficiency	[-]

$\varepsilon_{ec}$	Heat recovery efficiency of heat engine	[-]
$\theta$	Dry angle	[radian]
$\mu$	Dynamic viscosity	[Pa·s]
$\rho$	Density	[kg/m <sup>3</sup> ]
$\sigma_L$	Liquid surface tension	[N/m]
$\Phi_{ECR}$	ECR ratio between trigeneration and conventional systems	[-]
$\varphi$	Ratio of the developed length to the projected length	[-]

### Subscripts

$cb$	Convective boiling
$cd$	Condenser
$cv$	Conventional
$ec$	Economizer
$ev$	Evaporator
$f$	Fluid
$fb$	Boiler fuel consumption
$fe$	Engine fuel consumption
$fu$	Total fuel consumption
$g$	Gaseous
$h$	Heating
$in$	Input
$l$	Liquid
$lo$	Power load
$nb$	Nucleate boiling



<i>out</i>	Output
<i>pb</i>	Peak boiler
<i>r</i>	Refrigeration
<i>sh</i>	Superheater
<i>strat</i>	Stratified
<i>tg</i>	Trigeneration
<i>v</i>	Vapor
<i>wf</i>	Working Fluid

### **Acronyms**

BPHE	Brazed plate heat exchanger
CCHP	Combined cooling, heat and power
ECON	Economizer
EVAP	Evaporator
ORC	Organic Rankine cycle
SUP	Superheater