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Generic superstructure synthesis of organic Rankine cycles for waste heat recovery in industrial processes

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HIGHLIGHTS

- Superstructure optimization methodology for organic Rankine cycle integration.
- Superheating, reheating, turbine-bleeding and transcritical cycles are addressed.
- A dynamic linearization technique for thermal streams is proposed.
- Some issues with previous studies that were revealed by benchmarking are addressed.
- Results showed combinations of architectures yield thermo-economic benefits.

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ABSTRACT

Waste heat accounts for up to 70% of input energy in industrial processes which enunciates the importance of energy recovery measures to improve efficiency and reduce excessive energy consumption. A portion of the energy can be recovered within the process, while the rest is rejected to the environment as *unavoidable* [1] waste; therefore, providing a large opportunity for organic Rankine cycle (ORC)s which are capable of producing electricity from heat at medium-low temperatures. These cycles are often regarded as one of the best waste heat recovery measures but industrial applications are still limited due to the lack of comprehensive methodologies for their integration with processes. As such, this work proposes a novel and comprehensive superstructure optimization methodology for ORC integration including architectural features such as turbine-bleeding, reheating, and transcritical cycles. Additional developments include a novel dynamic linearization technique for supercritical and near-critical streams and calculation of heat transfer coefficients. The optimization problem is solved using a bi-level approach including fluid selection, operating condition determination and equipment sizing and is applied to a literature case study. The results exhibit that interactions between these elements are complex and therefore underline the necessity of such methods to explore the optimal integration of ORCs with industrial processes.

1. Introduction

Industrial processes often generate large amounts of waste heat which is evacuated by various media such as air or cooling water. This evacuation of heat can reach 70% of the input energy in some industries [2], encouraging industries to evaluate heat recovery and process integration to mitigate associated cost and emissions [3]. Several researchers have focused on defining waste heat and developing methodologies to estimate the recovery potential from processes [1] and the combination of processes and excess heat of utility systems [4]. Guidance in this process commences with the definition and quantification of waste heat, followed by exploration of options for greater efficiency and system integration with a final step to identify appropriate technologies for waste heat recovery (WHR) technology. Bendig et al. [1] clearly dichotomized *avoidable* and *unavoidable* waste heat according to thermodynamic principles. The former can be avoided through better system design by improving energy efficiency, energy integration, and process integration; therefore, must not be used in WHR applications since this would create a dependency on inefficient processing. The latter is defined as the total exergy destruction after implementing all possible efficiency, integration and recovery measures. There are many technologies available for waste heat recovery and the choice is typically influenced by the temperature level of the waste heat. They include different types of heat exchangers for internal heat recovery, heat

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Nomenclature

Abbreviations

GA	Genetic Algorithm
GCC	Grand Composite Curve
GWP	Global Warming Potential
HEN	Heat Exchanger Network
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
NLP	Non-Linear Programming
ORC	Organic Rankine Cycle
SIC	Specific Investment Cost
TAC	Total Annualized Cost
WHR	Waste Heat Recovery

Sets

$\mathbf{P}^H$	Set of all the hot process streams
$\mathbf{P}^C$	Set of all the cold process streams
$\mathbf{U}^H$	Set of all the available hot utility streams
$\mathbf{U}^C$	Set of all the available cold utility streams
$\mathbf{T}_i^{liq}$	Set of all the temperatures in the liquid layer at pressure stage i
$\mathbf{T}_i^{vap}$	Set of all the temperatures in the vapor layer at pressure stage i
$\mathbf{U}^{all}$	Set of all the units, i.e. turbines, pumps, evaporators, and condensers
TI	Set of temperature intervals

Parameters

T_{in},T_{out}	Inlet and outlet temperature of thermal stream (utility or process) [°C]
$\dot{Q}$	Heat load of process stream [kW]
$\dot{q}$	Specific heat load of utility stream [kJ/kg]
N_p	Number of pressure stages
$F^{u,min}$	Minimum size of unit u [variable unit]
$F^{u,max}$	Maximum size of unit u [variable unit]
η	Isentropic efficiency of an equipment [–]
C^{hu}	Cost of hot utility hu [USD/kWh]
C^{cu}	Cost of cold utility cu [USD/kWh]
C^{el}	Cost of electricity el [USD/kWh]
$Cf^{t\,(trh)}$	Fixed linearized cost of a main (reheat) turbine [USD]
$Cp^{t\,(trh)}$	Proportional linearized cost of a main (reheat) turbine [USD/kW]
$Cf_{i,j}^{p}$	Fixed linearized cost of a pump between pressure stages i and j [USD]
$Cp_{i,j}^{p}$	Proportional linearized cost of a pump between pressure stages i and j [USD/kW]
Cf^{HEN}	Fixed cost of a heat exchanger [USD]
Cp^{HEN}	Proportional cost of a heat exchanger [USD/m^2]
α	Heat transfer coefficient [kW/(m^2 K)]
irr	Interest rate [–]
t	Operating time [hr/y]
n_{year}	Lifetime [y]
ΔT_{min}	Minimum approach temperature in heat recovery [°C]
ΔT_{LM}^{k}	Logarithmic mean temperature difference in interval k
T^{tol}	Maximum temperature difference defined for linearization [°C]
T_{boil}	Boiling temperature of working fluid (at 1 bar) [°C]
M_{molar}	Molar mass of working fluid [g/mol]

Independent variables (outer GA)

$\varkappa$	Variable in the range [0,1] for calculation of weighted TAC [–]
ζ_i	Variable in the range [0,1] for pressure calculation at stage i ($i < N_p$) [–]
P_{N_p}	Pressure at the lowest stage [bar]
ΔT_i^{sup}	Superheating temperature difference at stage i ($i < N_p$) [°C]
ΔT_i^{rh}	Reheating temperature difference at stage i ($2 < i < N_p$) [°C]
WF	Discrete set of working fluids

Dependent variables (outer GA)

P_i	Pressure at the stage i ($i < N_p$) [bar]
$\dot{\omega}$	Specific electricity production (turbine) or consumption (pump) [kJ/kg]
	Saturation temperature at stage i [°C]
$T^{u,in}$	Inlet temperature of unit u [°C] ($u \in \{t,p,trh\}$)
$T^{u,out}$	Outlet temperature of unit u [°C] ($u \in \{t,p,trh\}$)
$h^{u,in}$	Inlet specific enthalpy of unit u [kJ/kg] ($u \in \{t,p,trh\}$)
$h^{u,out}$	Outlet specific enthalpy of unit u [kJ/kg] ($u \in \{t,p,trh\}$)
$s^{u,in}$	Inlet specific entropy of unit u [kJ/kg.K] ($u \in \{t,p,trh\}$)
$s^{u,out}$	Outlet specific entropy of unit u [kJ/kg.K] ($u \in \{t,p,trh\}$)
$\dot{\omega}$	Specific electricity production/consumption [kW/kg]
W_{net}	Net power output [kW]

Variables (inner MILP)

$\mathbf{y}$	Binary variables denoting the existence of a unit
$\mathbf{m}$	Continuous variables denoting the size of a unit

Superscripts

cap	Capital cost
cond	Condenser
cu	Cold utility
el	Electricity
evap	Evaporator
hu	Hot utility
inv	Investment
k	Temperature interval
liq	Liquid state
op	Operating
p	Pump
rh	Reheat state
sat	Saturated state
sup	Superheated state
t	Main turbine
tol	Tolerance
trh	Reheat turbine
vap	Vapor state
u	Unit

Subscripts

i,j,k	Pressure stages
p	Pressure
wf	Working fluid
cr	Critical state
pinch	Indicator of pinch temperature
bleed	Indicator of bleeding state