Energy Conversion and Management 157 (2018) 169–175

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A new understanding on thermal efficiency of organic Rankine cycle: Cycle separation based on working fluids properties

Yongzhen Wang[a], Jun Zhao[a], Guibing Chen[a], Shuai Deng[a], Qingsong An[a,*], Chao Luo[a,b], Junaid Alvi[a]

[a] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy (Tianjin University), MOE, Tianjin 300350, China
[b] Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou 510640, China

ARTICLE INFO

Keywords:
Organic Rankine cycle
Cycle separating
Working fluids selection
Molecular complexity
Performance prediction
Superheat degree

ABSTRACT

The pivotal of organic Rankine cycle (ORC) promotion and optimization is revealing the thermodynamic relationship between cycle configuration, condition and its working fluid properties. Different from the traditional numerical calculation method (TNCM) of ORC, a new thermodynamic cycle separating method (TCSM) is introduced in this paper. Then, efficiency of ORC is conducted expediently by TCSM where Triangle cycle (η_{TC}), Carnot cycle (η_{CC}) and Brayton cycle (η_{BC}) efficiencies are regarded as variables, that is, $\eta_{SORC} = f(\eta_{TC},\eta_{CC},\eta_{BC})$. When comparing with TNCM, TCSM not only has the acceptable precision for all the investigated 21 working fluids, but also the influence of critical temperature, molecular complexity of the working fluid and superheat degree as well as the reduced operating conditions of ORC can be revealed qualitatively and quantitatively. Finally, three conclusions are revealed: (1) Relationship between ORC limited efficiency (the reduced evaporating temperature of 0.9) and critical temperature of working fluid is revealed; (2) When superheat degree increases, ORC efficiency of dry fluid decreases and wet fluid increases linearly, while the variation of isotropic working fluid remains constant; (3) If the reduced temperatures of two different working fluids are equal, the corresponding efficiencies are equal too. The proposed thermodynamic cycle separating method provides an approach for working fluids selection and performance prediction of ORC.

1. Introduction

Organic Rankine cycle (ORC) is one of the most promising technologies for recovery of the low-medium grade waste heat and utilization of the renewable energy [1–8]. Excellent thermodynamic performance and low cost of ORC have always been attempted to be obtained as much as possible. In the view of thermodynamics, ORC is named for its use of an organic, low boiling temperature working fluid based on Rankine cycle (RC). Therefore, working fluids thermodynamic property is the premise to realize the critical process of ORC, and the four principal thermodynamic processes and specific working fluid consists of architecture of ORC. Furthermore, thermodynamic performance of ORC depends on the matching relationship between heat source/sink and the architecture of ORC. Therefore, the existing multivariable and nonlinear coupling relationship between cycle performance and its working fluid thermodynamic properties [9,10] as well as cycle operating conditions [11,12] imposes restrictions on the analysis of ORC, impeding the high investment of ORC. Obviously, revealing the coupling relationship is the pivotal and intrinsic issue to design and optimize ORC [13].

Correspondingly, two kinds of methods have been conducted to deal with this issue: on the one hand, majority of ORC design and optimization are based on numerical calculation for decades, [14–17], called thermodynamic numerical calculation method (TNCM) in this paper. TNCM even relies on intelligent algorithms (such as genetic algorithm, ant colony algorithm [18–21]) to solve the strong nonlinear coupling problem between cycle indicators and working fluid properties, because of the inherent barrier of the complete properties or equations of state of working fluids. Although the optimal cycle performances, working fluids or conditions as well as configurations can be obtained accurately by TNCM under different cooling and hot sources, such as Lakew [22], Qiu [23], Vijayaraghavan [24] and Papadopoulos [25], TNCM is difficult to form a unified guidance and often needs plentiful repetitive calculations. In other words, TNCM has feasible or precise results but insufficient or poor explanations for extremely depending upon the cumbersome calculations.

On the other hand, some approximate thermodynamic analysis methods on ORC performance prediction and working fluids selection have been carried out recently. Although, comparing with TNCM, thermodynamic analysis methods do not always have the higher

* Corresponding author.
E-mail address: anqingsong@tju.edu.cn (Q. An).

https://doi.org/10.1016/j.enconman.2017.11.079
Received 29 July 2017; Received in revised form 25 October 2017; Accepted 24 November 2017

Energy Conversion and Management 157 (2018) 169–175

Nomenclature

Abbreviation

BC	Brayton cycle
CC	Carnot cycle
ORC	saturated organic Rankine cycle
RC	Rankine cycle
SORC	superheated organic Rankine cycle
TC	Triangle cycle
TCSM	thermodynamic process decoupling model
TNCM	thermodynamic numerical decoupling method

Subscript

c, con	condensation
cri	critical statet
e, eva	evaporation
H	high
Hot	heat source
in	inlet
pre	preheating
L	low
pp	heat exchange pinch point
sup	superheating

Symbols

Cp^l	specific heat at constant pressure (kJ/kg K)
h	specific enthalpy (kJ/kg)
Ja	Jacob number
m	mass flow (kg/s)
P	pressure (kPa)
Q	heat flux (kW)
r	latent heat (kJ/kg)
s	specific entropy (kJ/kg K)
T	temperature (K)
W	work (kW)
w	acentric factor of the working fluid
η	efficiency (%)
R	universal gas constant, 8.1345 J/(mol K)

precision than that of TNCM, they are not only easier to guide ORC optimization, but also simpler to analyze the coupling relationship between ORC and its components. For example, Mikielewicz [26], Zhao [27], Javanshir [28] recommended a thermodynamic performance prediction model of ORC by dimensionless parameter *Jacob*, and expressed thermal efficiency as a function of Figure of Merit (a dimensionless parameter) for a saturated subcritical ORC. Moreover, Li [29] developed by a second-law analysis of analytical expressions for ORC efficiency and indicated influence of the dimensionless variable C_pT_{eva}/r_e (T_{eva} is evaporating temperature, r_e is latent heat of evaporation at T_{eva}, and C_p is average heat capacity of the saturated liquid) on cycle performance. In addition, Yang [30] defined two dimensionless integration temperature differences in ORC, to evaluate the effect of the heat exchanger on the thermal to power conversion system. As a consequence, some rules can be observed for the performance prediction and working fluids selection of ORC by the defined dimensionless variables when using the deduced thermodynamic process.

It is noted that, researches on aforementioned thermodynamic analysis methods play an inspirational role on separating ORC to the basic cycles for this paper, such as Carnot cycle (CC). It is well known that CC provides an upper limit on the efficiency that any classical thermodynamic engine attempts to achieve during the conversion of heat into work. Similar with the expansibility of thermodynamic process in the aforementioned thermodynamic analysis methods, therefore, ORC is able to be separated or modified through the basic thermal cycle process according to the thermodynamic cycle evolution mechanism on Temperature-Entropy coordinates (TS map), called thermodynamic cycle separating method (TCSM) in this paper. To some extent, compared with TNCM of ORC, TCSM is able to clearly reveal ORC thermodynamic performance and perfection by decoupling the relationship between ORC and its architecture as well as working fluid. TCSM will be easier to be understood than thermodynamic analysis methods, because it not only depends on dimensionless parameters, but also regards the basic cycles as variables (details will be introduced in Section 2).

The objectives of this paper are: tries to establish a TCSM for the thermal efficiency calculation of ORC; tries to reveal some relationships between ORC performance and its working fluids properties as well as operating conditions. Fortunately, an efficiency calculation model of ORC is established, which makes Triangle cycle (TC), CC and Brayton cycle (BC) efficiencies as variables. Logically, the influence of the key physical properties of working fluid (such as: molecular complexity, critical temperature) and as well as cycle superheat degree and reduced temperature on the cycle performance are analyzed by TCSM.

This paper is carried out in accordance with the following steps: The decoupling methodology and thermodynamic deduce process of ORC are put forward in the first part; Then, validation of TCSM is conducted in the second part; Last but not least, applications of TCSM on ORC are displayed as shown in Fig. 1.

2. Methodology of TCSM on ORC

2.1. ORC TCSM on T-S map

The most common representative subcritical ORC is regarded as the objective of this paper, and it should have the following characteristics:

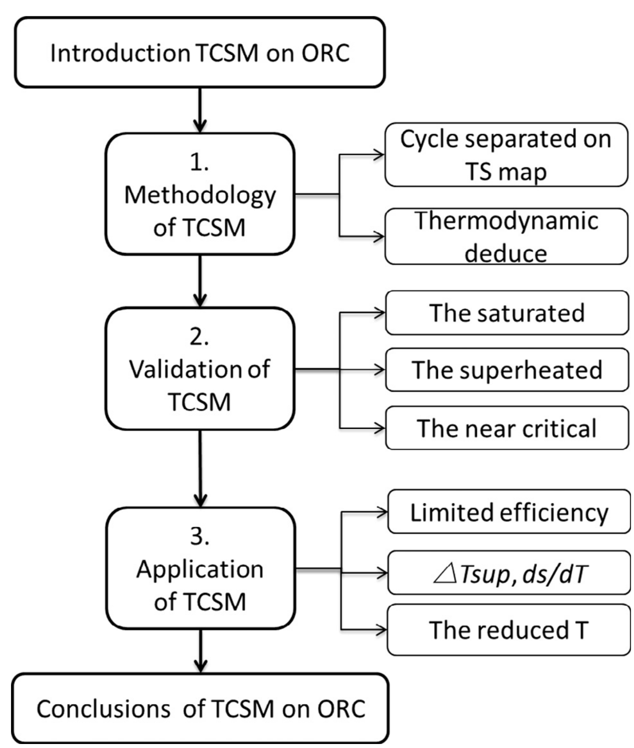

Fig. 1. Methodology of TCSM in this paper.