Applied Thermal Engineering 142 (2018) 502–510

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Towards working fluid properties and selection of Rankine cycle based waste heat recovery (WHR) systems for internal combustion engines – A fundamental analysis

Xingyuan Su[a,*], Timothy A. Shedd[a,b]

[a] Department of Mechanical Engineering, University of Wisconsin-Madison, Madison, WI 53706, United States
[b] Department of Mechanical Engineering, Florida Polytechnic University, Lakeland, FL 33805, United States

HIGHLIGHTS

- A new theoretical thermal efficiency formula was derived and validated.
- Fluid properties effects were analyzed from system thermal performance perspective.
- A fluid with smaller Jakob number is preferable for system thermal efficiency.
- A fluid with smaller Jakob number achieves higher effective evaporation temperature.
- A fluid with a smaller Jakob number runs closer to the Carnot cycle.

ARTICLE INFO

Keywords:
Working fluid properties
Working fluid selection
Waste heat recovery
Internal combustion engines
Rankine cycle
System thermal efficiency

ABSTRACT

Working fluid selection is one of the most important procedures in the design of Rankine cycle based waste heat recovery systems for internal combustion engines. The system's performance, cost, and environmental impacts can be greatly influenced by the properties of its working fluid. In this work, we present an original formulation of a theoretical thermal efficiency model to fundamentally understand how the working fluid properties affect the thermal performance of the Rankine cycle based waste heat recovery systems for internal combustion engines. The derived theoretical thermal efficiency formula is validated under several different operating conditions. Overall very good agreements are achieved between the actual and theoretical approximated solutions. The results show that when the evaporation and condensation temperatures of the waste heat recovery system are fixed, the system's thermal efficiency is simply governed by a non-dimensionalized parameter Jakob number. A working fluid with a smaller Jakob number is preferable in terms of system thermal efficiency. The observation is also further understood from a more fundamental physical perspective. Finally, a preliminary working fluid selection approach with a solid physics is proposed to screen the fluid candidates from the perspective of system performance.

1. Introduction

Internal combustion (IC) engines are the primary power source for ground transportation in the United States and are responsible for about 80% of the fossil fuel consumption in recent years [1]. However, the overall fuel economy of current IC engines is still quite low and a major part of the fuel energy is not harnessed. For current gasoline vehicles, up to 70% of the fuel energy is lost as waste heat in the exhaust gases and to engine coolant; for diesel engine powered vehicles, approximately 64 percent of the fuel energy can be released to the environment [2–5]. However, it is well known that IC engine waste heat sources can be converted into mechanical or electrical power. One of the most promising approaches to harness IC engine waste heat is the Rankine cycle (RC) process [7–24].

The Rankine cycle is a well-established technology for converting heat into work. It has been widely used in thermal power plants, combined heat and power (CHP) generation, solar power plants, and industrial waste heat recovery [6]. The investigations of RC based IC engine WHR applications began in the 1970s [7]. Recently, considerable interest has been reignited thanks to the improved system

---

[*] Corresponding author.
E-mail addresses: xsu8@wisc.edu, xingyuan.su6@gmail.com (X. Su).

https://doi.org/10.1016/j.applthermaleng.2018.07.036
Received 5 April 2018; Received in revised form 17 June 2018; Accepted 7 July 2018

Nomenclature

h	specific enthalpy [J/kg]
s	specific entropy [J/kg-K]
P	pressure [Pa]
T	temperature [K]
L	specific latent heat of vaporization [J/kg]
q	heat transfer per unit mass [J/kg]
w	specific work [J/kg]
u	specific internal energy [J/kg]
v	specific volume [m^3/kg]
R	specific gas constant [J/kg-K]
C	specific heat capacity [J/kg-K]
$\dot{m}$	mass flow rate [kg/s]
$\dot{Q}$	heat rate [W]
$\dot{W}$	power [W]

Subscripts

in	input
out	output
exp	expander
pump	pump
sat	saturated
g	gas
f	fluid
1 ~ 4	state points

Greek symbols

η	thermal efficiency

Abbreviations

IC	internal combustion
RC	Rankine cycle
CHP	combined heat and power
OEM	original equipment manufacturer
WHR	waste heat recovery
ODP	ozone depletion potential
GWP	global warming potential
Ja	Jakob number

components and broader options of working fluids. Engine and truck OEMs, such as Cummins [8], Daimler [9], Volvo [10], Navistar [11], and Caterpillar [12], have devoted significant efforts to recovering diesel engine waste heat using RC based technologies. Meanwhile, similar interests were also generated among passenger vehicle OEMs, such as Honda [13,14], BMW [15,16], and Ford [17], to achieve fuel economy.

A key design factor of an RC based IC engine WHR system is the working fluid selection. A literature review shows that selecting an appropriate working fluid for a waste heat recovery application is not a straightforward task. This is because (1) there are numerous fluids that can be potentially used as a working fluid; (2) a system's performance, component design, cost, environmental and safety impacts are greatly influenced by the properties of its working fluid and trade-offs may be necessary; (3) different performance evaluation criteria may dictate a different working fluid; (4) no single fluid is optimal for all WHR applications.

From an environmental and safety perspective, the main fluid properties considered are ozone depletion potential (ODP), global warming potential (GWP), flammability, toxicity, corrosion and stability [25]. From the system performance and component design perspective, the major fluid properties screened are the saturation curve, boiling temperature, critical temperature, molecular weight and latent heat of vaporization [26–32]. Based on the slope of the vapor saturation curve in its T-S diagram, a working fluid is classified as a wet, dry and isentropic fluid if the slope is negative, positive and zero, respectively. As its name indicates, a wet fluid may fall in the two-phase region during expansion process causing turbine blade erosion. However, volumetric expanders, like screw and scroll expanders, have a higher tolerance of liquid formation [26,27]. Boiling temperature affects the heat exchanger performance and design, and critical temperature affects the system's operating temperature range [28,29]. High molecular weight generally indicates higher vapor density, which is good for momentum transfer in expansion machines and thus results in greater cycle efficiencies with less complex and less costly single stage expanders [30–32].

Researchers have mixed views on the property of latent heat of vaporization. Chen et al. [33] claimed that fluids with higher latent heat could generate higher unit work output when the temperatures and other parameters were defined. They argued that fluids with higher latent heat were expected to occupy a larger area in the T-S diagram, indicating larger work output. Hung et al. [34] indicated that a working fluid with a high latent heat should be used in order to raise the efficiency of heat recovery. Bao et al. [35] suggested that for waste heat or geothermal binary plants, suitable but not large vaporization latent heat would result in a better overall performance of ORC plants. On the other hand, Wang et al. [36] and Yamamoto et al. [37] argued that fluids with lower latent heat values were preferable since they were easier to gasify and more saturated vapors could be generated under an identical heat addition quantity condition.

Clearly, a different understanding of working fluid properties could lead to different working fluid selection. However, very few studies can be found in the literature that performed deep fundamental analyses on how the working fluid properties affect the performance of RC based WHR system. Kuo et al. [38] suggested a non-dimensionalized figure of merit (FoM) to screen working fluids, where FoM = $Ja^{0.1}(T_{evap}/T_{cond})^{0.8}$, and the Jacob number was defined as the ratio of the sensible heat transfer and the latent heat of evaporation. However, they did not provide detailed fundamental analyses on how their screening criterion was derived. Mikielewicz et al. [39] proposed thermodynamic criteria for working fluid selection of low temperature subcritical and supercritical organic Rankine cycles, from the thermal efficiency point of view. For the subcritical cycle case, they considered the ratios of $\Delta H(T_2)/h_{lv}(T_1)$ and $C_p T_1/h_{lv}(T_1)$ and claimed that the smaller the value of the ratio of these two terms, the higher the efficiency obtained by the working fluid in the cycle. Nevertheless, the physical fundamentals behind this screening method were not explained in detail and it appears that the criterion involving two terms is still not convenient to use. He et al. [40] developed a theoretical formulation of net power output to find the optimal evaporation temperature for a simplified subcritical Rankine WHR system based on its T-S diagram. However, the authors did not provide any conclusions or indications on how the working fluid properties affect the performance. Zhu et al. [41] conducted a theoretical study on the thermodynamic processes of a bottoming Rankine cycle for engine waste heat recovery. A theoretical formula of the global recovery efficiency was developed to investigate the influences of primary operating parameters on the Rankine cycle performance for the engine WHR. They concluded that the influences of the evaporating pressure and the super-heating temperature on the global recovery efficiency were complicated and mainly depended on the working fluid properties according to the formulation.

In this paper, we present an original formulation of a theoretical