Applied Energy 104 (2013) 758–771

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Methodology to design a bottoming Rankine cycle, as a waste energy recovering system in vehicles. Study in a HDD engine

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HIGHLIGHTS

- ▶ A study for the optimization of a bottoming cycle for recovering various waste heat sources is presented and applied in a HDD engine.
- ▶ Water and R245fa are selected as working fluid in the proposed solutions.
- ▶ The cycles with water as working fluid produces a higher power output than the solution with R245fa in almost all the operative points.
- ▶ The cycle with R245fa as working fluid is the most feasible solution from the point of view of space requirements.
- ▶ The effect of the expander machine irreversitibities is discussed.

ARTICLE INFO

Article history:
Received 20 March 2012
Received in revised form 5 September 2012
Accepted 30 November 2012

Keywords:
Organic Rankine Cycle
Diesel
Rankine cycle
Recover waste power

ABSTRACT

This article describes a methodology for the optimization of a bottoming cycle as a waste heat recovering system in vehicles. The methodology is applied to two particular cases in order to evaluate the preliminary energetic and technical feasibility of the implementation of a bottoming cycle in a heavy duty diesel (HDD) engine considering two different criteria. Initially, a study of the different waste heat sources of the engine is described. In this study, the power and exergy of each heat source is quantified, in order to evaluate which sources are suitable to be used in the bottoming cycle. The optimum working fluids to run the cycles are selected (water and R245fa). Then, the ideal Rankine cycle is optimized for the two different working fluids and different sets of heat sources (all the available heat sources and the sources with high exergy respectively) throughout the engine operating range, reaching a maximum improvement of 15% of the fuel consumption of the engine. Later, a study of the minimum temperature difference between the hot and cold flow of the heat exchangers is described. The improvements in fuel consumption and the size of the installed heat exchanger are related to this temperature difference. Finally, the non-ideal behavior of the machines (pump and expander) is analyzed, obtaining a maximum improvement of 10% in brake specific fuel consumption (*bsfc*).

1. Introduction

The interest for increasing fuel economy and efficiency has recently been growing among governments, industrial companies and engine manufactures to the extent that the quantity of waste energy produced [1], represent a driving force for development of more effective methods of waste energy recovery [2]. The carbon dioxide emissions are also gaining significant attention due to its association with global warming and the fact that about 80% of said emissions in the Organization for Economic Co-operation and Development (OECD) countries or the European Union are due to the use and production of energy, industries or manufacturing [3,4]. Nowadays, the global carbon dioxide emissions have risen steadily over the past 50 years to a concentration of approximately 380 ppm in the atmosphere as of 2006 [5].

A large number of solutions have been proposed to generate electricity from low temperature waste heat sources and are now applied to such diversified fields as solar thermal power, geothermal, biomass and industrial waste heat. Among the proposed solutions, the implementation of a bottoming cycle currently is one of the most studied options [6,7]. Among the different solutions, Rankine Cycle (RC), Organic Rankine Cycle (ORC), Stirling cycle (SC) and the Brayton Cycle (BC) can be analyzed in order to find the one generating the largest power. The RC and ORC solution is considered by Bianchi and Pascale [8] as the more profitable configuration for converting the low-grade power into the higher output power. Many

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http://dx.doi.org/10.1016/j.apenergy.2012.11.075

Nomenclature

Acronyms

BC	Bryton cycle
bsfc	brake specific fuel consumption
CFC	chrorofluorocarbon
EGR	exhaust gases recirculation
HCFC	hydrochlorofluorocarbons
HFC	hydrofluorocarbons
HDD	heavy duty diesel
HFC	hydrofluorocarbons
HP	high pressure
IC	internal combustion
LP	low pressure
OCDE	Organization for Economic Co-operation and Development
ORC	Organic Rankine Cycle
RC	Rankine cycle
SC	Stirling cycle

Latin

C_p	heat capacity at constant pressure (kJ/kg K)
C^*	heat capacity rate ratio
D	heat exchanger diameter (m)
dT	minimum temperature difference in the heat exchanger (°C)
E	energy (kW)
Ex	exergy (kW)
F	log mean temperature difference correction factor
G	mass flow velocity
h	specific enthalpy (kJ/kg)
j	ideal Coulburn heat transfer factor for the shell side
J	correction factors of the heat transfer coefficient in the shell-side
L	heat exchanger length (m)
Lx	heat exchanger length in *x* direction (m)
Ly	heat exchanger length in *y* direction (m)
Lz	heat exchanger length in *z* direction (m)
m	mass flow (kg/s)
NTU	number of transfer unit
Pr	Prandtl number
T	temperature (°C)
rpm	revolution per minute
s	specific entropy (kJ/kg K)

Greek letters

$\triangle$	increment
μ	viscosity

Subscripts

flow	waste sources mass flow
s	shell side
w	wall conditions
0	environmental condition
1	inlet condition
2	outlet condition

theoretical investigations have been performed in order to design the optimum cycle (working fluid, evaporator and condenser pressure, superheating temperature, choise of the expander, etc.) taking into account the heat source characteristics [9–15].

One of the largest sources of waste energy is the internal combustion (IC) engine used in different vehicles (naval ship, railway, automotive, etc.) as shown in the Eurostat publication in 2011 [16]. The IC engine converts approximately one third of the combustion power into mechanical power. The remaining power is distributed to different heat exchangers or is directly released to the ambient (exhaust gases). As a result, an IC presents various waste heat sources with a wide range of temperature and exergy levels [17–19]. Additionally, the waste heat sources vary considerably depending on the engine operating point [20]. Therefore, the preliminary design of the optimal solution is usually not an easy task [21,22]. Therefore, the published articles on this topic focus on different factors about this complex problem. In this paper, the problem of designing a bottoming cycle to recover the energy of waste heat sources in an IC engine is addressed generally. Consequently, this work considers all these partial issues studied in other articles as parts, integrating them in a general methodology and considering the influence of these partial topics in the obtained final result.

The methodology discussed in this paper is a comprehensive theoretical study for simplifying the complex problem of the waste heat source recovery system in vehicles. This methodology implies the evaluation of all the heat sources at each operating points and selection of the waste heat sources. It then applies an iterative-parametric optimization procedure in order to calculate the optimum working fluid and cycle conditions based on the maximum power output cycle for each operating points taking into account various restrictions as space requirements limitations, maximum expansion ratio etc,. The methodology is also applied to a bottoming cycle for a heavy duty diesel (HDD) engine with a two-stage turbocharging system, from which experimental data are available. The resulting power balance was used to propose an optimal configuration for the most frequent combinations of speed and load engine conditions (operating engine points) [23]. The goal of this paper is to develop a general theoretical methodology in order to evaluate the maximum power and sizing of the system (energetic and technical feasibility) of the different configurations and show valuable results for the remaining problem of the waste heat power recovery in IC engines.

2. Methodology

The design of the implementation of a heat power recovery system in a vehicle is complex due to numerous restrictions (maximum pressure ratio in the expander, condensation temperature, minimum temperature difference between hot and cold source, etc.) or goals (reduction of fuel consumption, maximum output power, space limitations, etc.) that must be considered. Sometimes the selection of the waste heat sources in a bottoming cycle for a vehicle constitutes the key part of the design process. Two important criteria are associated with this selection: the power output and the space requirements of the cycle. The more wasted heat to recover, the higher the power output and heat exchanger volume. Once the waste heat sources are selected, the design calculations are essentially a series of iterative calculations made on the preliminary design until a satisfactory solution is achieved. In these calculations, different working fluids, the effect of the different irreversibilities and other additional restrictions are considered in order to define a preliminary design of the heat recovery system.

In this section, a methodology is proposed in order to simplify the process of the selection of the best configuration of a bottoming cycle by taking into account different initial limitations and goals. The proposed methodology consists of the following steps, also shown in Fig. 1: