Energy Conversion and Management 66 (2013) 304–311

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

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

Using the analytic network process (ANP) to determine method of waste energy recovery from engine

Xingyu Liang [a,*], Xiuxiu Sun [a], Gequn Shu [a], Kang Sun [a], Xu Wang [b], Xinlei Wang [c]

[a] State Key Laboratory of Engines, Tianjin University, Tianjin 300072, PR China
[b] School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Australia
[c] Agricultural & Biological Engineering Department, University of Illinois at Urbana-Champaign, USA

ARTICLE INFO

Article history:
Received 3 January 2012
Received in revised form 26 July 2012
Accepted 3 August 2012
Available online 8 December 2012

Keywords:
Analytic network process
Waste energy recovery
Engines
Automobile

ABSTRACT

There are many ways to recover engine waste energy. But which way is the most suitable or feasible ways in future? This is belongs to a multi-criteria decision-making (MCDM) process. Existing methods for project selection does not reflect interdependencies of criteria and candidate methods. Consideration of criteria interdependencies enables valuable cost savings and great benefits to engine and environment. When these problems are evaluated, it is necessary to collect group opinion because the interdependence relationship among criteria is known and it is very important to consider the criteria for the problem solving and decision-making. In order to collect group opinions for interdependent project problems, expert interviews are conducted. Analytic network process (ANP) is applied for measurement of the dependency among the strategic factors, which can help engineer determine their decisions. (1) It is found that thermoelectricity technology is the most suitable method to recovery waste energy in future and the ANP technique is useful as a decision judgment tool.

1. Introduction

In the total heat energy generated by fuel burning of internal combustion engine (ICE), only 30–45% (diesel) or 20–30% (gasoline engine) can be converted into effective take-off power [1]. Except for less than 10% was used for overcoming friction and for other power losses, the rest of energy was discharged into the atmosphere in forms of heat energy through cooling and thermal discharge of the cooling medium (20–30%) and exhaust system (30–40%). Under normal circumstances, the temperature of the thermal discharge of the cooling medium (water) is about 90 °C, while the temperature of exhaust heat varies between 200 °C and 900 °C and the pressure of exhaust heat energy flow varies between 0.1 and 0.5 MPa as the operating conditions of the internal combustion engine change, and the temperature and pressure also vary with the fluctuation of rotating speed in each work cycle [2]. Therefore, the waste heat energy of the internal combustion engine has the cascade characteristics from low-grade energy to high-grade energy, and the temperature and pressure of exhaust heat energy flow have transient pulse characteristics varying with the work cycles and operating conditions of the internal combustion engine.

In recent years, due to increasingly stringent emission regulations, electronic control technology, supercharging technology, exhaust after-treatment technology and so on have been generally adopted in internal combustion engine. The manufacturing costs of internal combustion engine rise increasingly which provides possibility for the waste heat energy conversion using a variety of technical means and measures [3,4]. At present, innovative ideas and methods used for waste heat energy conversion of the internal combustion engine are plenty, and mainly reflected in the following aspects.

1.1. Energy recovery and conversion utilization of exhaust heat energy

In 1915, Swiss Engineer Alfred Buchi converted the mechanical-driven supercharger into the internal combustion engine's exhaust turbine-driven turbo-supercharger, which used the internal combustion engine's exhaust heat energy for the first time to improve the performance of the internal combustion engine. Since Alfred Buchi's invention, the exhaust energy recovery and utilization efforts for the internal combustion engine from academic research and engineering development have never stopped. However, the increased exhaust backpressure led to the increase of pumping loss and even produced negative work under low-load operating condition. Massive consistent efforts have been made in recent years.

In 2002, Volvo Corporation first developed the compound turbine mechanical-driven energy recovery prototype, namely transforming the surplus pressure energy of the exhaust gas into the shaft work of the engine through turbine [5], which can recover

* Corresponding author. Fax: +86 22 27891285.
E-mail address: lxy@tju.edu.cn (X. Liang).

0196-8904/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2012.08.005

20% of exhaust heat energy, save 5% of fuel at most and improve 10% of maximum output torque. However, the fuel saving potential only occurred on the large-scale engine with high-efficient turbo-supercharger at high-load condition (high exhaust gas temperature).

To overcome the shortcomings of the compound turbine mechanical-driven energy recovery system, research of the compound turbine power generation system has gained attention. The compound turbine mechanical-driven energy recovery system directly couples the internal combustion engine's shaft power output via transmission while the compound turbine power generation system is via turbine-driven generator. Therefore, the output work and rotating speed control of the compound turbine system are independent of the load and rotating speed of the internal combustion engine, and its converted electricity can be directly supplied for auxiliary systems or improving transient acceleration performance through battery storage and driven hybrid system [7].

The research at the University of Southampton, UK suggests that the application of the compound turbine power generation system has more advantages than that of the compound turbine mechanical-driven energy recovery system and predicts that 7–10% fuel saving effect can be achieved at the full range operating conditions [8]. The research of Volvo Corporation shows that the compound turbine power generation system coupled with hybrid power device to reduce idling operation has obtained 10% fuel saving effect [6]. The compound turbine power generation system developed by the U.S. John Deere Corporation for high-power agricultural diesel engine under steady-state and high-load condition improved 7% of overall energy conversion efficiency [9].

1.2. Recycling waste heat energy via thermodynamic cycle

After oil crisis of the 1970s, Doyle and Patel et al. from the U.S. Mack Trucks Corporation designed the device by using Rankine cycle to absorb exhaust heat energy on a 288Hp trunk engine and achieved 12.5% fuel saving effect through a 450 km test run [10]. In recent years, with the development of expansion machine and new working medium, utilization of Organic Rankine Cycle (ORC) to transform the low-grade energy to electricity has attracted more and more attention [11].

At present, utilization of ORC technology in internal combustion engine is rare for waste heat recovery from the internal combustion engine's cooling circuit but is most used for exhaust heat recovery of internal combustion engine. Therefore, the transient fluctuation characteristics of exhaust heat source became the key problem of system control [12]. Japan Honda Corporation proposed a control strategy, that is, the water flow rate entered the evaporator is controlled by the pump rotating speed and thus working medium temperature as well as the pressure entered the expander are controlled by the rotating speed; besides, 2.5 kW (100 km/h) recovery work has been obtained on a 19.2 kW engine, which means that the thermal efficiency of the engine was raised from 28.9% to 32.7% [13]. Cummins Inc. utilized ORC of waste heat of exhaust gas in its Series 8 truck engines to enhance 5.4% of thermal efficiency [14]. Italy Pamar University obtained 12% of overall efficiency improvement compared with the engine without bottom cycle. This can be achieved by selecting the best working medium to match thermodynamic cycle and by comprehensively optimizing the thermodynamic cycle parameters in a combined energy system [15].

1.3. Thermoelectricity conversion by use of thermoelectric material with temperature difference

The thermoelectric material is the semiconductor function material which transports solid internal charge carrier and phonon and utilizes their interactions to realize the conversion between heat energy and electric energy, with the advantages of without mechanical moving parts, quiet operation, small and lightweight, and without pollution to the environment, and has important value and broad prospect in application fields of temperature difference power generation and refrigeration.

Since the material's thermoelectric phenomenon (Seebeck Effect) was found by Seebeck in 1821, the scientists' research on thermoelectric material has been continuing. In 2008, the U.S. Ohio State University and Japan Osaka University published an article in *Science* and demonstrated that a kind of new thermoelectric conversion material was developed with the conversion efficiency equal to twice of the general thermoelectric material [16]. The thermoelectric conversion efficiency of this kind of new material reached more than 10% at around 500 °C while the efficiency of the general thermoelectric conversion material was only 7–8%.

The thermoelectric conversion performance of the thermoelectric device depends on the thermoelectric material, the device structure, and preparation technology. Although the research of thermoelectric conversion device began in the 1820s, the development has been slow since then. In the 1950s, the research of thermoelectric conversion device was speeded up due to the requirements of space program and refrigeration field and was applied in aviation, spaceflight and navigation fields.

As the thermoelectric material technology develops and internal combustion engine's manufacturing costs increase, application of thermoelectric conversion material to recover the internal combustion engine's waste heat energy has become a new and hot research topic. Thus, the U.S. Department of Energy has set up and supported the project of utilization of thermoelectric material to convert internal combustion engine's waste heat energy, has organized a team composed of GM Corporation, Michigan State University, United Technologies Corporation, BSST Corporation and etc. to carry out relevant research. The project established two objectives: the first is to commercialize the laboratory research outcomes and the second is to improve 10% of the internal combustion engine's fuel economy [17]. The U.S. and Japanese scientists have obtained the same conclusion that the current utilization of thermoelectric material can recover 7% of exhaust energy to electric energy [18,19]. Furukawa Machinery & Metal Corporation of Japan developed a square thermoelectric conversion device with 5 cm side length, 8 mm thickness, and weighed about 140 g, which can maintain 33 W generated power under 720–50 °C temperature difference. It is estimated that using 20 pieces of the aforesaid new materials can save 2% of fuel consumption [19]. The U.S. Ford Corporation designed a lightweight thermoelectric conversion device with low backpressure and fast transient response and provided its recovered electric power for the use of hybrid power automobile, which effectively improved the fuel economy [20].

1.4. Research and application of refrigeration

The passenger car air-conditioning generally consumes 8–12% of the engine power, among which the compressor accounts for 80–85% and the fan accounts for 15–20% [21]. The air-conditioning consumed engine power not only increases fuel consumption, increases exhaust emission, exacerbates air pollution, but also easily leads to overheating of water tank and affects the passenger car dynamic property. In the same time, the greenhouse effect may be aggravated as the working medium of refrigeration used for compression air-conditioning system is Freon compound. The bus refrigeration compressor is equipped with a dedicated engine auxiliary and the air-conditioning performance is not affected by the driving cycle. However, such the complex structure may increase the vehicle weight and lead to layout difficulty. It may increase vehicle fuel consumption and exhaust emission, and make the