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ScienceDirect

Energy Procedia 107 (2017) 390 – 397

Energy Procedia

3rd International Conference on Energy and Environment Research, ICEER 2016, 7-11 September 2016, Barcelona, Spain

Selecting and Optimizing a Heat Exchanger for Automotive Vehicle Rankine Cycle Waste Heat Recovery Systems

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Abstract

This paper contributes for the selection and optimization of an adequate compact heat exchanger (HEX) for an automotive vehicle Rankine cycle Waste Heat Recovery Systems (RC-WHRS). Both tube type and plate type HEX were considered. Among the different HEX designs available, a robust cross-flow tube heat exchanger (CFT-HEX), with the working fluid circulating inside the tubes was selected. The selected HEX accomplishes with the specific pressure drops limits on both exhaust gas and working fluid side. The compactness of the CFT-HEX strongly depends on the optimization of the HEX pre-heater section, which mainly depends on the augmentation of the working fluid heat transfer coefficient. The present study data reveals that a transitional flow regime with a working fluid Reynolds number, Re > 3200, allows a significant increase of the Nusselt number (Nu > 20) as compared to laminar flow regime.

Peer-review under responsibility of the scientific committee of the 3rd International Conference on Energy and Environment Research.

Keywords: Waste heat recovery, Rankine cycle; heat exchanger; heat transfer performance.

1. Introduction

Escalating fuel prices and future carbon dioxide emission limits are creating a renewed interest in methods to increase the thermal efficiency of vehicles equipped with internal combustion engines (ICE). Over the time ICE

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Peer-review under responsibility of the scientific committee of the 3rd International Conference on Energy and Environment Research.
doi:10.1016/j.egypro.2016.12.181

manufacturers have developed and implemented techniques to increase thermal efficiency. However, around 60-70% of the fuel energy is still lost through the coolant or the exhaust as wasted heat [1,2]. To increase the ICE thermal efficiency and to reduce CO_2 emissions, different waste heat recovery (WHR) techniques were recently proposed [1-5]. Among the existing WHR techniques, the most relevant are the electrical turbo-compounding (ETC), the mechanical turbo-compounding (MTC), the thermo-electric generator (TEG) and the Rankine cycle (RC) or organic Rankine cycle (ORC) [1-3].

At the present, Rankine cycle Waste Heat Recovery Systems (RC-WHRS) seem to be the best solution for heavy-duty Diesel engine (HDDE) vehicle applications. The RC-WHRS is based on the steam generation in a secondary circuit that represents an indirect method of WHR. For HDDE, recent studies [4,5] have shown that RC-WHRS allows reducing fuel consumption by up to 6 %. In a RC-WHRS, the waste energy is transferred to the working fluid by a pre-heater plus an evaporator plus a super-heater. Such heat exchanger (HEX) is also known as the evaporator (or boiler), where the working fluid at high pressure changes from liquid to superheated vapor. Subsequently, the working fluid, which has a high enthalpy is expanded in an expander, and output power is generated.

The key components of a RC-WHRS are the heat exchanger (HEX) and the expander, which have a dominant impact on the RC-WHRS efficiency. A RC-WHRS for HDDE vehicle applications requires long life and high performance compact heat exchangers. Although several simulations and theoretical studies about RC-WHRS in ICE have been reported in the literature [1-5], few studies have been developed with regard to the HEX design.

The major outcome of the present work is to contribute for the HEX development. To this end, one starts with the selection of the HEX design suitable for such an application, specifically, reviewing and discussing the heat transfer, pressure drop and technical challenges of both tube and plate type heat exchangers. Next, the fundamental fluid flow and heat transfer phenomena within the channels of the pre-heater section of the HEX are investigated. The obtained experimental data allows to better understand the fundamental transport phenomena involved, so that new guidelines for the HEX optimization will be drawn.

Nomenclature

Gr	Grashof number [-]
Nu	Nusselt number [-]
Pr	Prandtl number [-]
Re	Reynolds number [-]

2. Heat exchanger design

The heat exchanger suitable for a heavy-duty Diesel engine (HDDE) vehicle RC-WHRS should be capable of operating at elevated temperatures of up to 600 ºC, elevated pressures on the working fluid side of up to 40 bar, with long life and in a harsh environment. The thermal hydraulic characteristics of high effectiveness and low pressure drop (to minimize the exhaust back pressure) are required. In addition, light weight and high compactness are required.

Regarding to the selection of the HEX design, it can be divided into two main categories: tubes and plates. The former group includes all the heat exchangers types and configurations that use tubes to conduct and separate the working fluid from the exhaust gas (hot source). The second group includes all the plate heat exchangers, which are based on configured "sheets", creating several levels of intermittent cold and hot source passages.

The HEX design and configuration requires taking into account the thermal source (exhaust gases) and working fluid (liquid, two-phase and vapor) operating conditions, temperature difference, mass flow rate and flow direction. The main difficulty would be the specification of a single HEX for constantly changing working conditions on both exhaust and working fluid side. For this, a compromise must be found between performance (effectiveness/pressure drop) and heat exchanger volume for the most relevant engine conditions.