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Control of Organic Rankine Cycle Systems on board Heavy-Duty Vehicles: a Survey

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Abstract: Organic Rankine Cycle systems onboard heavy- duty vehicles require effective control to ensure safety and attain satisfactory performance over a broad range of operating conditions. Publications on this subject, however, are surprisingly scarce. After an overview of the different ORC architectures proposed so far, this paper presents the main features required for supervision and control and the most promising solutions in the literature.

Keywords: Waste heat recovery, Rankine cycle, heavy-duty vehicles, control design

1. INTRODUCTION

Heavy-duty vehicles (HDVs) are transport's second largest source of CO_2 emissions, accounting for about one-quarter of the total, both in Europe and the United States. Mainly because of increasing road freight traffic, HDV emissions are still rising, despite some improvements in fuel economy in recent years. To counter this trend, fuel efficiency standards for HDVs were enacted for the first time ever by Japan in 2005 (to be enforced in 2015). The United States introduced such regulations in 2011 and China in 2012. Europe should soon follow suit, as the European Commission is currently working on a comprehensive strategy to reduce CO_2 emissions from HDVs in both freight and passenger transport.

According to several studies commissioned to support these strategies (Kromer et al. (2009), to cite one), potential fuel efficiency improvement technologies for the HDV sector mostly rely on the reduction of energy losses from engine, aerodynamics and tires. Indeed, even in the most favorable conditions (that is, on highway, at near steady operation), a modern HDV diesel engine cannot convert more than 50% of fuel energy into useful work (indicated power). The remaining portion is released into the surroundings, mostly through coolants and exhaust gases. A potential to recover this wasted heat exists, especially from the heat sources with the highest temperature levels and thus the highest available energy (or *exergy*): the tailpipe exhaust gases and the EGR (exhaust gas recirculation) circuit, when present. Among the waste heat recovery (WHR) technologies being considered for fuel consumption reduction in heavy-duty vehicles, compounding the engine with a Rankine bottoming cycle has been widely considered as the most promising solution in recent years (Stanton (2013)).

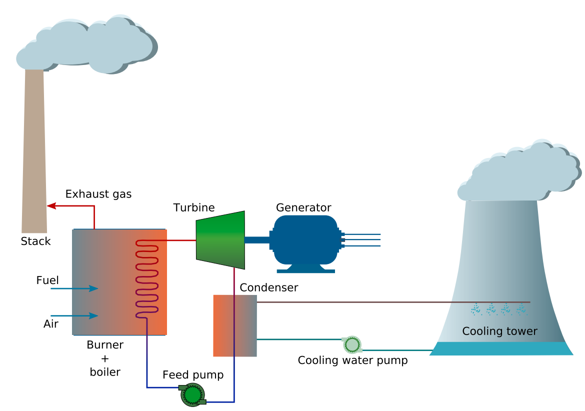

Fig. 1. Power plant.

WHR Rankine systems for automotive applications are based on the same principle used worldwide in power plants to generate electricity from heat sources (Fig. 1). A fluid at high temperature (e.g. flue gas from a furnace) supplies heat to a closed-loop circuit where a working fluid, usually water, is circulated by a feed pump. Vaporized fluid expands in a turbine, producing mechanical power and driving an alternator connected to an electrical grid. Vapor (steam) is then cooled by a condenser which transfers heat to an external cold sink, a cooling tower for instance.

For energy conversion or heat recovery from lower temperature heat sources, the steam rankine cycle (SRC) can be replaced by an organic rankine cycle (ORC) using a high molecular mass fluid with a lower boiling point than water. A positive-displacement expander (piston, scroll or screw machine) can be used instead of a turbine. The four main components of the Rankine cycle – evaporator, expander, condenser and pump – and the four corresponding thermodynamic processes – vaporization, expansion, condensation and compression – are depicted in the schematic

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of Fig. 2. There also exist variants of this basic cycle, meant to increase its thermal efficiency with features such as reheating or regeneration, obtained with additional components.

Though most Rankine technologies in industry have a high degree of maturity, their transposition to automotive applications is far from being trivial. First of all, significant efforts are required to design compact and lightweight components in a cost-effective way and to integrate them into a vehicle. Then, the peculiarities of the hot source and cold sink on-board make the operation of an automotive Rankine system very different. On the one hand, heat supplied by exhaust gas depends on driving conditions and can be very transient, which is a major difference with power plants where the amount of heat supplied the external source can be controlled, to a certain extent (for instance, by burning more or less fuel). In this respect, automotive Rankine systems bear more resemblance to Rankine systems used in heat-driven combined heat and power (CHP) generation plants, whose operation must be adapted to a variable hot source (though this is most often done via an intermediate thermal-oil circuit). On the other hand, the cooling capacity on-board is very limited and also depends on the driving conditions. Furhermore, interactions with the engine and the rest of the vehicle have to be taken into account, regarding both thermal management and energy management, or even drivability. Last but not least, automotive applications impose stringent requirements in terms of operational safety and environmental protection. These requirements must be addressed at the design stage (e.g. by choosing an appropriate working fluid) and handled at the operational stage, by keeping key system variables within acceptable limits.

From these considerations, it appears evident that WHR systems for automotive application require effective control systems to ensure safety and attain satisfactory performance over a broad range of (transient) operating conditions. After an overview of the different architectures proposed so far, this paper presents the main features a supervision and control system for ORC onboard a heavy-duty vehicle must have and the most promising solutions in the literature.

2. ORC SYSTEMS FOR HEAVY-DUTY VEHICLES

The idea of compounding a vehicle engine with a Rankine system is not new. It was indeed one of the principal perspective solutions to reduce fuel consumption studied in the United States in response to the oil shock of the seventies. A Diesel engine – ORC compound system for a Mack Trucks long-haul vehicle, developed in the framework of a program initiated by the U.S. Environmental Protection Agency (EPA) and continued by the U.S. Department of Energy (DOE), was described as early as in 1976 (Patel and Doyle (1976)), with a reported fuel economy by 15% over a typical long-haul truck duty cycle. The system used a mixture of trifluoroethanol as working fluid and featured:

- a turbine geared to the engine output shaft, to supply additional mechanical power;
- a vapor generator (evaporator) with an exhaust-gas diverting valve and pipe, allowing the exhaust gas to by pass the evaporator core;

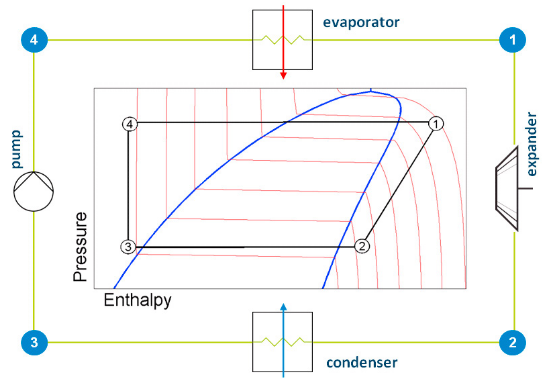

Fig. 2. Rankine cycle schematic and p–h diagram for a "dry" fluid (4 → 1: vaporization; 1 → 2: expansion; 2 → 3: condensation; 3 → 4: compression).

- a unit integrating a water-cooled condenser and a regenerator;
- a variable-displacement feed pump driven by the engine;
- a compound radiator used to satisfy cooling requirements for both the Diesel engine and the Rankine system;
- a radiator fan driven by the engine through a viscous drive, which varied the fan speed as a function of the engine coolant temperature;
- a control system for the Rankine system.

Several years later, DiBella et al. (1983) underlined the primary importance of a well-designed control system for a successfully implementation of this diesel-ORC compound in the trucking industry and reported several problems in the early stages of its development.

Referring to the schematic view of the ORC system shown in Fig. 3, the adopted solution consisted in controlling the conditions at evaporator outlet (turbine inlet) by adjusting pump volumetric flow rate $\dot{V}_{pump}$ according to the ratio between compressor discharge pressure p_{CD} and engine speed N_{eng}, with a proportional-derivative feedback correction on the evaporator outlet temperature T_{evap}.

It is not clear why, after so many years of development and despite promising fuel consumption reduction results, the diesel-ORC compound had been abandoned. One reason may be that, at the time, there still was considerable room for improvement of engine efficiency (according to Stanton

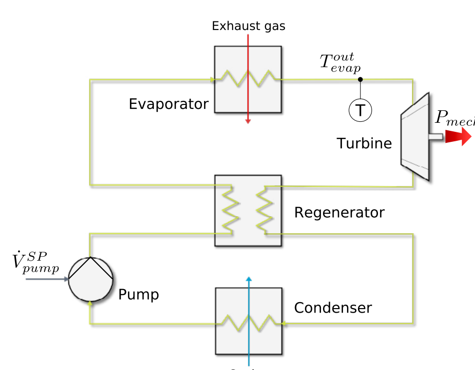

Fig. 3. Mack Trucks ORC with control.