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Waste Heat Recovery Systems

ABSTRACT

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1 Introduction

1.1 Environmental concerns

According to the International Energy Agency [1], the global energy requirement has been increasing by a rate of 2 % since the beginning of this century. The actual disproportionate energy misuse will definitely lead to energy shortages if nothing is done to prevent it. Specially, in the transportation industry, the continuous growing tendency has increased more in the last decade even though we have now more efficient cars. Particularly in Europe, the energy dedicated to the transportation industry represents about 30 % of the total energy supply.

The Kyoto Protocol arose as a potential answer to the environmental concerns derived from the energy misuse. This agreement, mostly signed by developed countries responsible for the high levels of GHG (green house gases) in the atmosphere, set up restrictive environmental policies, directly affecting industry emissions. Since then, engine developers have been primarily concerned about diminishing the pollutants emitted by cars, which currently represent about 20 % of global GHG emissions.

1.2 Heat loss in internal combustion engines (ICEs)

Nowadays, a thermal efficiency of an internal combustion engine higher than 42 % is almost unachievable [2]. This basically means that a large quantity of energy is not converted into useful work and it is rejected from the engine to the surroundings as waste heat. The two main sources of waste thermal are the exhaust gases and the refrigeration system. Other sources of heat loss include the losses due to mechanical friction and the own engine radiation. On average in an internal combustion engine, depending on the type of engine: naturally aspirated or turbocharged, approximately between 20% and 40% of the combustion energy is lost through the exhaust. The heat loss through the refrigeration water and the lubrication system in an internal combustion engine usually represents a similar percentage of the total waste thermal power as the exhaust gases but depending on the engine speed and load [3].

2 Waste Heat Recovery Systems (WHRS)

As described previously, approximately 60% of the combustible energy in the engine is dissipated through the exhaust and coolant systems. The recovery of this waste energy would be tremendously beneficial as it would allow to not only increase the engine power output and reduce combustible consumption but also to further reduce harmful emissions [2]. The group of technologies which try to recover this waste heat are called waste heat recovery systems, WHRS.

2.1 Thermoelectric Generators (TEGs)

Thermoelectric generators are considered to become one of the most promising new techniques for automobile waste heat recovery. They are able to convert waste heat from a certain source into electrical energy by means of the Seebeck effect. This principle states that a voltage will be generated due to temperature difference between two different metals.

The functioning is as follows: during the normal operation of the engine, all the heat leaving the combustion chamber and passing through the exhaust manifold is taken by a heat exchanger. Then, electrical energy can be generated by means of the Seebeck effect right inside the heat exchanger [4]. Finally, energy is transferred to other engine units or stored.

Thermoelectric generators have some advantages such as they produce clean energy without any noise, and their cost of maintenance is remarkably low. In contrast, they produce small power and only when they are used at quite high temperature. Probably this is the biggest challenge of theses systems.

2.2 Turbochargers

The waste heat that is normally discharged to the environment from natural aspirated ICEs can be recovered using the turbocharging system. Turbocharging refers to a method to increase the air density by increasing its pressure before entering the engine cylinder. A compressor and a turbine are both assembled on a shaft and the stream of exhaust gases leaving the cylinder is used to drive the turbocharger turbine which, at the same time, drives the compressor which is in charge of increasing air density and pressure.

But this system also has a major drawback, what is called turbolag. When accelerating, air has to beat the turbocharging system inertia in order to satisfy the engine air flow rate demand. The time it takes to achieve this situation is called turbolag. Trying to avoid this problem, the electrical turbocharger appeared. In addition to a typical turbocharger (compressor and turbine), this turbocharger also contains a generator and a storage device. This revolutionary system compresses the air instantaneously using the energy stored. The exhaust-driven generator will fill the storage device as the engine accelerates. According to the literature [6], using this system, turbolag can be eliminated, a higher downsizing can be achieved and the fuel effiency is improved up to 25%.

2.3 Organic Rankine Cycle (ORCs)

The Organic Rankine cycle is based on the same principle as the steam/water Rankine cycle used to transform thermal power into mechanical power in common energy plants. The difference between both cycles arises when considering the working fluids since ORCs use organic working fluids. The main feature of organic fluids compared to water is that they have lower boiling points at same working pressure. Moreover, organic fluids show a lower specific volume in the vaporization process and this allows the equipment size to be smaller and therefore, cheaper. On the contrary, compared to water, organic fluids can be inflammable, harmful to the environment and more expensive.

2.3.1 Energy analysis in ORCs

Organic Rankine cycles are the most studied waste heat recovery systems. Essentially, they comprise four elemental components: pump, evaporator, turbine and condenser. Figure 2.1 shows a general view of an ORC. As we can see, a basic ideal Rankine cycle has four main thermal processes.

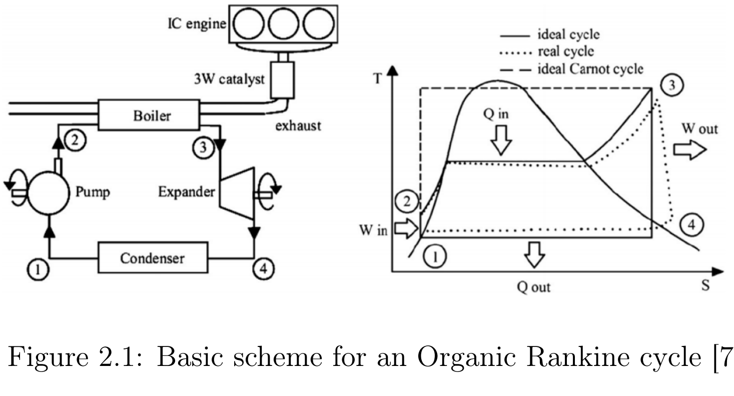

Figure 2.1: Basic scheme for an Organic Rankine cycle [7]

- **Process 1 - 2 : compression in a pump**: the organic fluid gets compressed and eventually pumped to the evaporator. Ideally, the compression process is isentropic. A general energy analysis can be applied in order to compute the working fluid change of energy. The energy balance equation reads,

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{system}}{dt} \;\Rightarrow\; \dot{E}_{in} = \dot{E}_{out} \tag{2.1}$$

since we can assume an steady-flow process as the pump will operate for long periods of time under the same conditions. Expanding this expression, the energy balance for a control volume containing the pump can be rewritten as

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}\left(h + \frac{v^2}{2} + gz\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}\left(h + \frac{v^2}{2} + gz\right) \tag{2.2}$$

where $\dot{Q}$ stands for the thermal power, $\dot{W}$ represents the mechanical power, $\dot{m}$ the organic fluid mass flow rate, v the flow velocity, h stands for the fluid enthalpy, g is the gravity and z is the height from the reference level. Since the pump could be assumed to be completely insulated from its surroundings, no heat is lost or gained by this component. In addition, a pump does not produce any work and we may neglect both kinetic and potential energy terms as they are really small compared to work and heat transfer terms. Thus, it gives

$$\dot{W}_{pump,in} = \dot{m}\left(h_{out} - h_{in}\right) = \dot{m}\left(h_2 - h_1\right) \tag{2.3}$$

- **Process 2 - 3 : heat addition in an evaporator**: the compressed liquid goes through the evaporator and leaves it as superheated vapor. The evaporator is a heat exchanger where the waste heat is transferred to the organic fluid at constant pressure. Performing the same analysis as done for the pump and knowing that an evaporator does not deal with any work, we get

$$\dot{Q}_{evap,in} = \dot{m}_{organicfluid}\left(h_3 - h_2\right) \tag{2.4}$$

- **Process 3 - 4 : expansion in a turbine**: After leaving the vapor generator, the fluid goes to the turbine where it is expanded producing useful work. The energy balance for a control volume within the turbine leads to,

$$\dot{W}_{turbine,out} = \dot{m}_{organicfluid}\left(h_3 - h_4\right) \tag{2.5}$$

- **Process 4 - 1 : heat rejection in a condenser**: This is the process which closes the cycle. After being expanded, the fluid goes through the condenser. At this point, the fluid is usually a saturated liquid-vapor mixture with high quality. In the condenser, the organic fluid rejects heat to the atmosphere or any other cooling medium. We want this rejection of heat to be the least possible in order to get the maximum efficiency. As no work is related to the condenser, the equation to compute the fluid energy change is

$$\dot{Q}_{cond,out} = \dot{m}_{organicfluid}\left(h_4 - h_1\right) \tag{2.6}$$

2.4 Organic working fluids

The efficiency of the ORC strongly depends on the thermodynamic properties of the working fluid. Thus, and optimal selection of the fluid is essential. In their article, Wang *et al* [2] classify the organic working fluids within three categories depending on their slope in T-s diagram: dry, wet and isentropic fluids. Table 2.1 shows the mathematical relationship between temperature and entropy (slope) for these fluids. According to Chen *et al* [8], the thermophysical properties of the fluid should be the basis of the selection since they affect the efficiency and final cost of the equipment. Some of the preferred features are: low specific volume (it allows to reduce pipe size and cost), low vapor pressure (high pressure can derive

Organic fluid		
Dry	Wet	Isentropic
$dT/ds > 0$	$dT/ds < 0$	$dT/ds = \infty$

Table 2.1: Slope comparison between the different types of organic fluids.

into risk of explosion), low viscosity (less friction losses) and high thermal conductivity (heat transfer will be higher). Moreover, the working fluid should be the least harmful to the environment. Due to the wide range of fluids available in the market, the selection of the working fluid is based on an analysis of advantages/disadvantages for a certain application. Generally, both dry and isentropic fluids are commonly selected. They show better efficiency result as they do not condense during expansion process inside the turbine, fact that is detrimental for energy generation purposes [2].

3 Applications

3.1 Cargo ships

A relevant application of WHRS can be found in container ships, which nowadays carry around the 90% of the worldwide non-bulk cargo. Due to the fact that the ships frequently sail in environmentally sensitive areas, they require engines powered with efficient propulsion systems which must be compliant with current emission legislations. In order to establish these legislations, the emission of air pollutants from ships is measured by the so-called Energy Efficiency Design Index (EEDI).

Adding a WHRS to a container ship has shown fuel consumption reductions of between 4-11% and will save per year up to: 11.000 tons of CO_2 emissions, 300 tons of NO_x emissions, 200 tons of SO_x emissions and 30 tons of particulates. In addition, these fuel and emission savings are responsible for a 9.2% reduction in the ships' EDDI, lowering the index from 13.144 $gram\ CO_2/dwt$ to 12.009 $gram\ CO_2/dwt$ [9].

Therefore, the technology behind WHRS plays an essential role in the reduction of fuel consumption, emissions and EEDI; making ships cleaner and helping them meet the required energy-efficiency regulations.

3.2 F1 cars

The Formula 1 competition has always been seen as the maximum expression of car development in the technological point of view. Ten years ago, F1 engines started to use the concept of energy recovery with the so-called KERS (Kinetic Energy Recovery System) which transformed the kinetic energy generated under braking into electrical energy.

Today's F1 car engine is comprised of two main parts, the typical combustion engine and the energy recovery system (ERS) which comprises two motor generator units (MGU-K and MGU-H), plus an Energy Store (ES) which accumulates the recovered energy. The MGU-K (K stands for kinetic) is nothing but and updated version of the KERS. On the other hand, the MGU-H (H stands for heat) is waste heat recovery system which converts the waste energy from the exhaust gases into electrical energy.

When the KERS was first introduced in 2009, a maximum of 30% of the wasted energy could be recovered. In the current season (2016), the improvements developed in the KERS itself and the addition of the MGU-H allows a total recovery of 95% (10% improvement with respect to last season) of the wasted energy (from braking and exhaust gases). In other words, up to 4 MJ per lap could be recovered and returned to the MGU-K. This means that an additional 150 hp per lap are available in the power train [10].

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