Integration of a Rankine Waste Heat Recovery Model in Engine Modelling

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The conventional internal combustion engines of today are starting to reach their maximum possible efficiency. However the demand for highly efficient vehicles keeps increasing. There are many ways of improving the total fuel consumption of an internal combustion engine, but one of the most promising, effective and available methods is the implementation of an Organic Rankine cycle. The scope of this master thesis has been to create an Organic Rankine cycle waste heat recovery model in the Visual Studio developer environment to integrate with Volvos in-house engine performance simulation software ICES.

Rankine Waste Heat Recovery

Approximately 30 percent of the fuel energy input is rejected as heat in the exhaust gases leaving a conventional internal combustion engine. A small, vehicle mounted, Rankine WHR cycle can translate some of this exhaust heat into mechanical work via a working fluid and an expander.

The Rankine steam cycle is an old, proven and well developed method to produce power from a heat source. In fact most of the worldwide produced electricity comes from steam power plants and Organic Rankine cycles are common in areas with geothermal activity to harvest the available energy from the ground. The implementation of a small Organic Rankine waste heat recovery unit in truck engines is not something new. During the 1970s oil crisis there was research done in this area and working prototypes were built showing great fuel improvements.

The Rankine cycle has four main components; a working fluid pump, a boiler, an expander and a condenser. In Figure 1 below, the components can be seen together with the energy flow, into and out of the system.

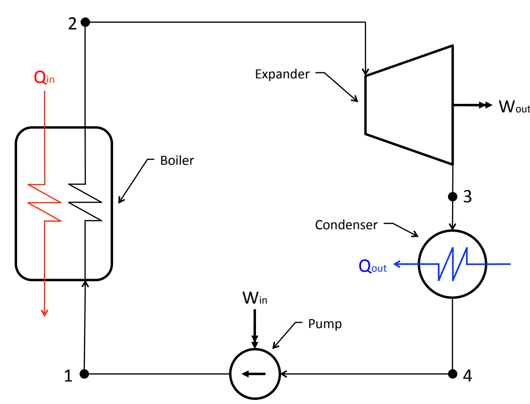

Figure 1: *Schematic description of the Rankine cycle.*

Often used to describe a Rankine cycle, is the temperature-entropy diagram (T-s diagram) in Figure 2 below. In this diagram, the corresponding point from Figure 1 is drawn to show the thermodynamic behaviour of the system.

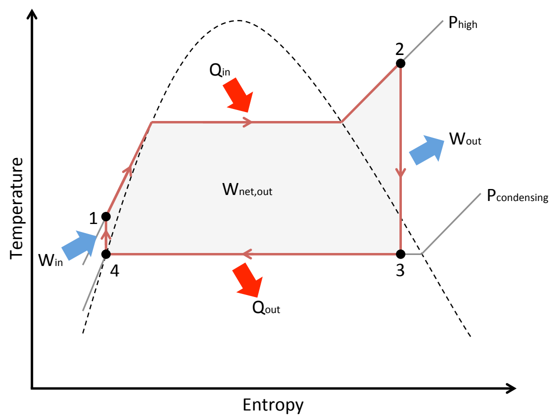

Figure 2: *T-s diagram of the ideal Rankine Cycle.*

The Organic Rankine cycle basically only differs, from the standard Rankine cycle, in the choice of working fluid. It consists of a working fluid with a higher molecular weight than water, thus has different characteristics. Organic Rankine cycles are particularly suitable for finite, low temperature, heat sources. The choice of working fluid is important and greatly depends on the working conditions.

Methodology

The main structure of this project was set early in the work process. The Rankine model work consists of five main steps (Figure 3), to achieve the final result of a functioning Organic Rankine cycle model, for waste heat recovery simulations in ICES. Due to the ease of troubleshooting and many built in tools, the first model iterations were developed in the Matlab environment.

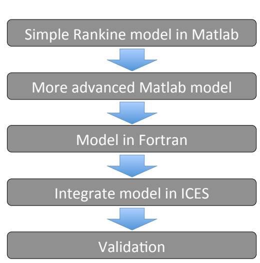

Figure 3: *Work procedure.*

The model

The final created ORC model consist of seven parts, which are illustrated in the flow chart below (Figure 4). In contrast to the schematic description in Figure 1 above, this layout consist of an expander by-pass valve, a recuperator and the heat exchanger is divided into three parts.

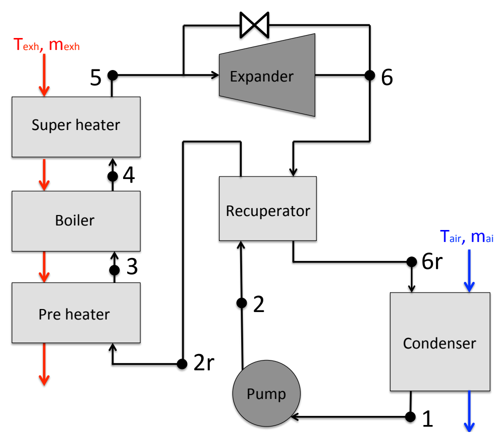

Figure 4: *Component chart of the ORC model.*

The model itself is a steady state Rankine cycle model, written in Fortran code and integrated in the ICES software. It enables users to quickly evaluate different possible powertrain configurations, before more thorough design studies are performed. It collects engine speed, exhaust mass flow and exhaust temperature every engine cycle to perform the simulations. The calculated torque is then fed back into the engine torque control and consequently, the fuel injection is adjusted. The user also has the choice to feed back exhaust temperature after the heat exchanger and air temperature after the condenser to the engine model.

The interaction between engine model and Organic Rankine cycle model is visualised in Figure 5 below.

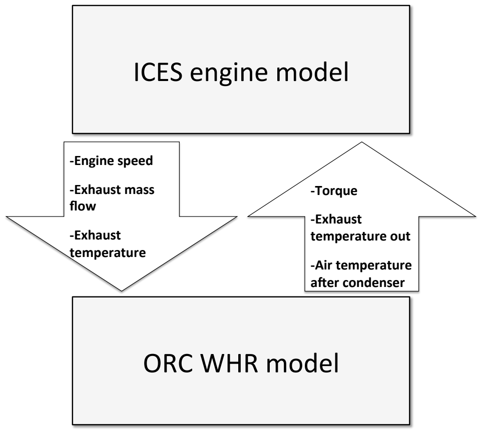

Figure 5: *Interaction between ICES and ORC model.*

Validation

When the ORC[1] model is created in Matlab a sensitivity analysis is performed to investigate the impact of possible fluid state data errors and faulty user inputs. A complete sensitivity study is also made to investigate if the fluid data tables can be replaced by faster and more simple polynomial functions, without any introduction of large output errors.

The finishing phase is the model validation. To validate the output results the model is compared to an existing Simulink ORC[1] WHR[2] model within Volvo. Two comparisons are made; the first with EGR[3] flow and the second with exhaust flow. Both comparisons are made with engine speeds, mass flows and temperatures from an engine optimization with a Volvo in-house engine drive cycle.

The validation shows the drawbacks of a steady state model with a static pinch point as heat exchanger approximation. A comparison is seen in Figure 6 below and clearly shows how the static model slightly overpredicts the power output at high exhaust mass flows and temperatures (points 8, 10 and 11).

[1]Organic Rankine Cycle
[2]Waste Heat Recovery
[3]Exhaust Gas Recirculation

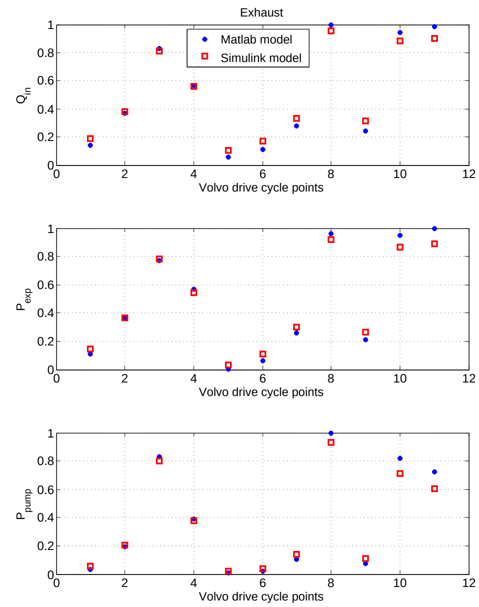

Figure 6: *Q_{in}, expander power and pumping power validation. Compared to a dynamic in-house Simulink model.*

Summary

The goal of this master thesis project was to create a fast and simplified Organic Rankine cycle waste heat recovery model for integration into the Volvo in-house engine performance software ICES. The main purpose of the model was to be able to perform steady state simulations and complete engine system optimizations with an ORC[1] WHR[2] installed. This goal has been achieved through a steady state thermodynamic model with real expander dimensions and the model is validated against an advanced dynamic Simulink model.

Furthermore, the implemented model in ICES works together with Volvo validation and optimization software without any observed ORC[1]-specific crashes or slowdowns.