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# Modelling waste heat recovery systems applied to heavy duty vehicles

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**Abstract:** Future European regulations imposing large decrease in  $CO_2$  emissions force the manufacturers of heavy-duty vehicles to implement innovative solutions to achieve these challenging targets. In this context, waste heat recovery systems represent a suitable solution to exploit thermal energy lost to the ambient by diesel engines. To this end, waste heat recovery by means of an Organic Rankine cycle (ORC) is considered as a promising technology. This thermodynamic bottoming cycle aims to recover thermal power in order to produce electricity on-board, that can be injected into mild-hybrid drivelines.

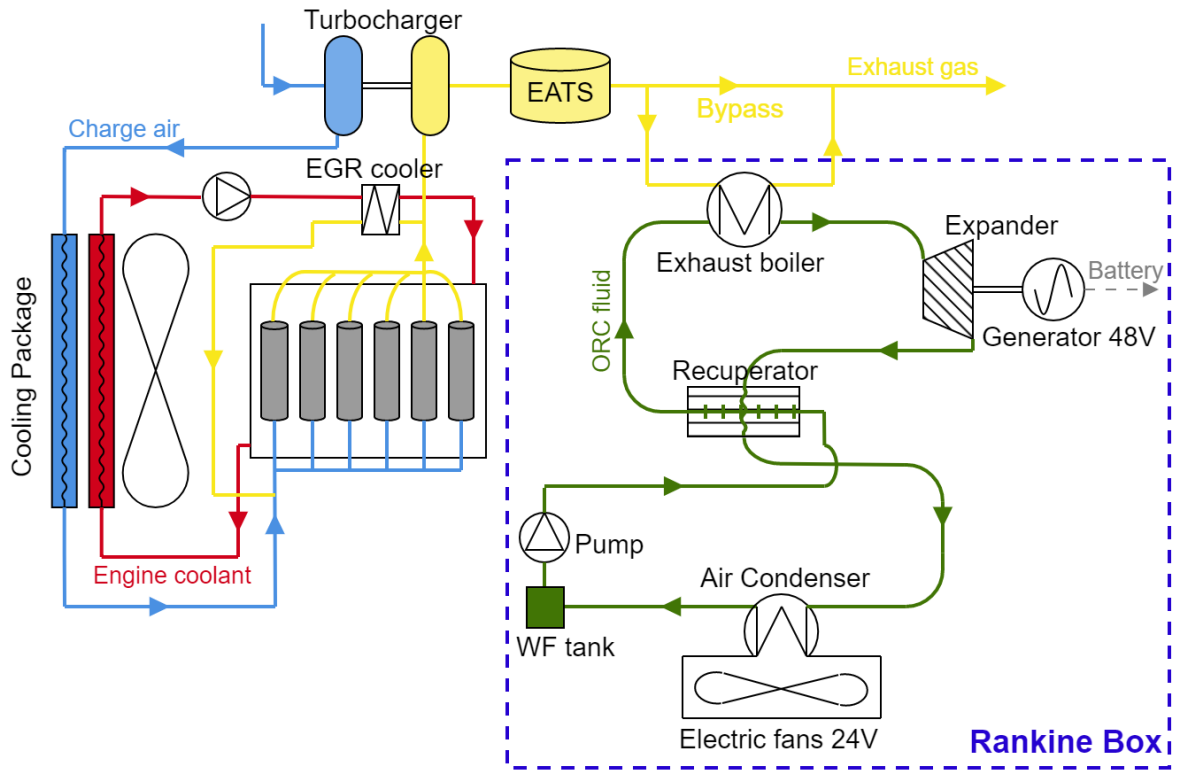
*Volvo Trucks* is studying for many years this fuel-saving technology. In the scope of their current project in which this internship takes part, exhaust gases downstream the exhaust after treatment system are exploited as heat source. The heat sink is simply the ambient air, driven towards the condenser placed behind the cab by two fans. A piston expander is used to produce mechanical power, which is in turn converted into electricity to charge a 48V battery of a mild-hybrid truck.

The modelling of an ORC is a major aspect of the system design methodology. Indeed, simulations are used in the early design phase to compare several system architectures and to select the most appropriated working fluid. At a later stage, the plant model can be exploited to design the controller of the ORC system. It is thus essential to develop a precise and efficient model integrating all the components of the Rankine cycle (heat exchangers, expander, pump, etc.) as well as an accurate procedure to compute working fluid properties. In this context, the present work aims to improve the ORC simulation tool developed by *Volvo Trucks* on *Matlab-Simulink*.

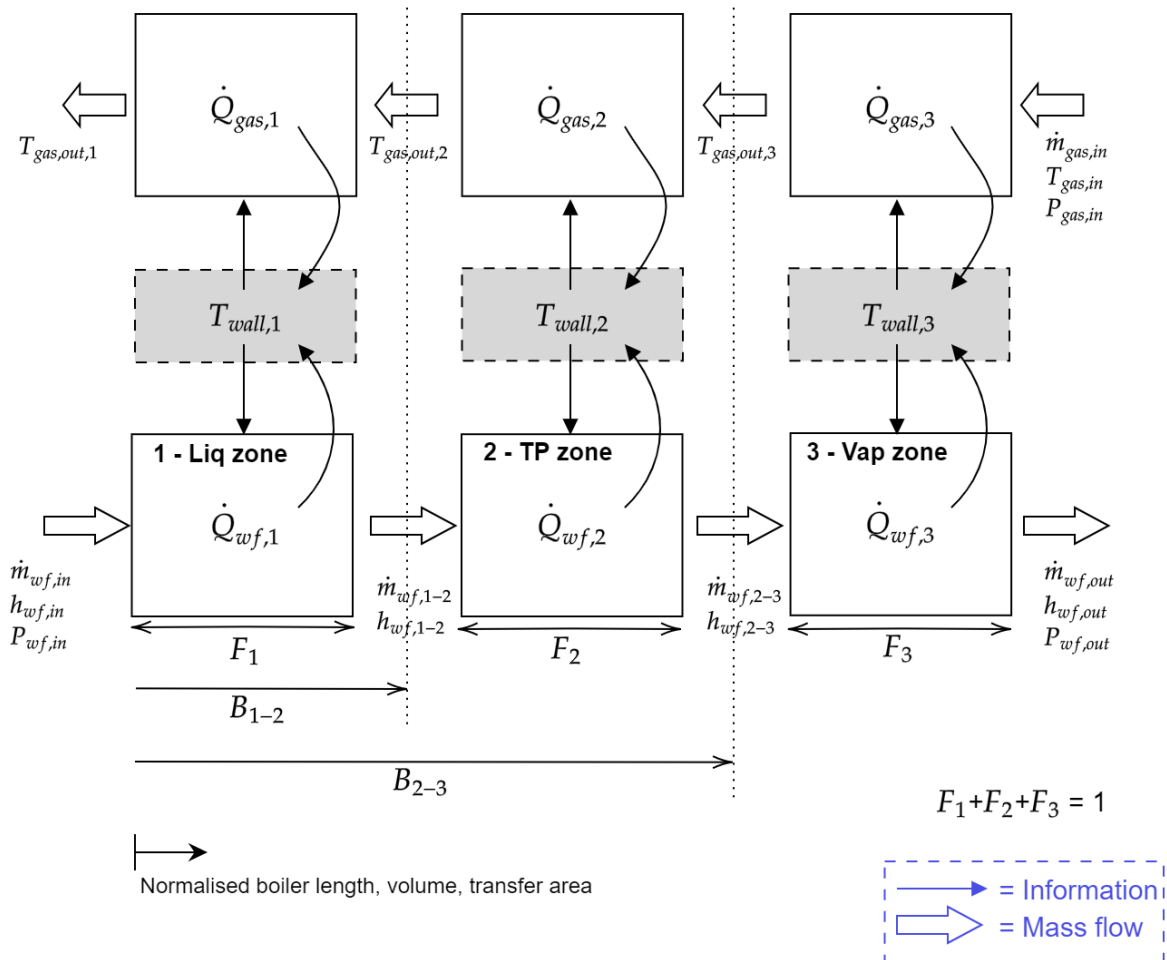
At first, a new moving boundaries (MB) model of heat exchanger is developed to replace the previous one, based on a finite volumes (FV) approach. This new model is as accurate as the FV model, but it is computationally faster. This robust model takes the form of a *Simulink* library and is exploited to model the exhaust boiler as well as the air condenser in the complete Rankine system model. It is validated regarding both steady-state and transient simulations. Thanks to this new approach of heat exchanger modelling, the computational time required to perform simulations of the ORC during a road driving cycle is drastically reduced (-72%).

Secondly, this master thesis is dedicated to the modelling of the lubricant added to the working fluid performing the Rankine cycle. This oil is needed in practice to ensure the lubrication of the piston expander, but its presence was neglected up to now in the Rankine simulation tool where pure working fluid properties are assumed. However, a brief literature review shows that it could have a significant impact on ORC performances. To this end, an empirical solubility model is exploited to compute thermodynamic properties of the mixture composed of working fluid (cyclopentane) and Polyalkylene Glycol (PAG) synthetic oil. In addition, all the components of the Rankine model are revised to take into account the presence of lubricant. This study concludes that the net ORC power is clearly impacted by the presence of lubricant. This decrease in net power depends on the exhaust conditions, the ambient air temperature and the oil circulation rate.

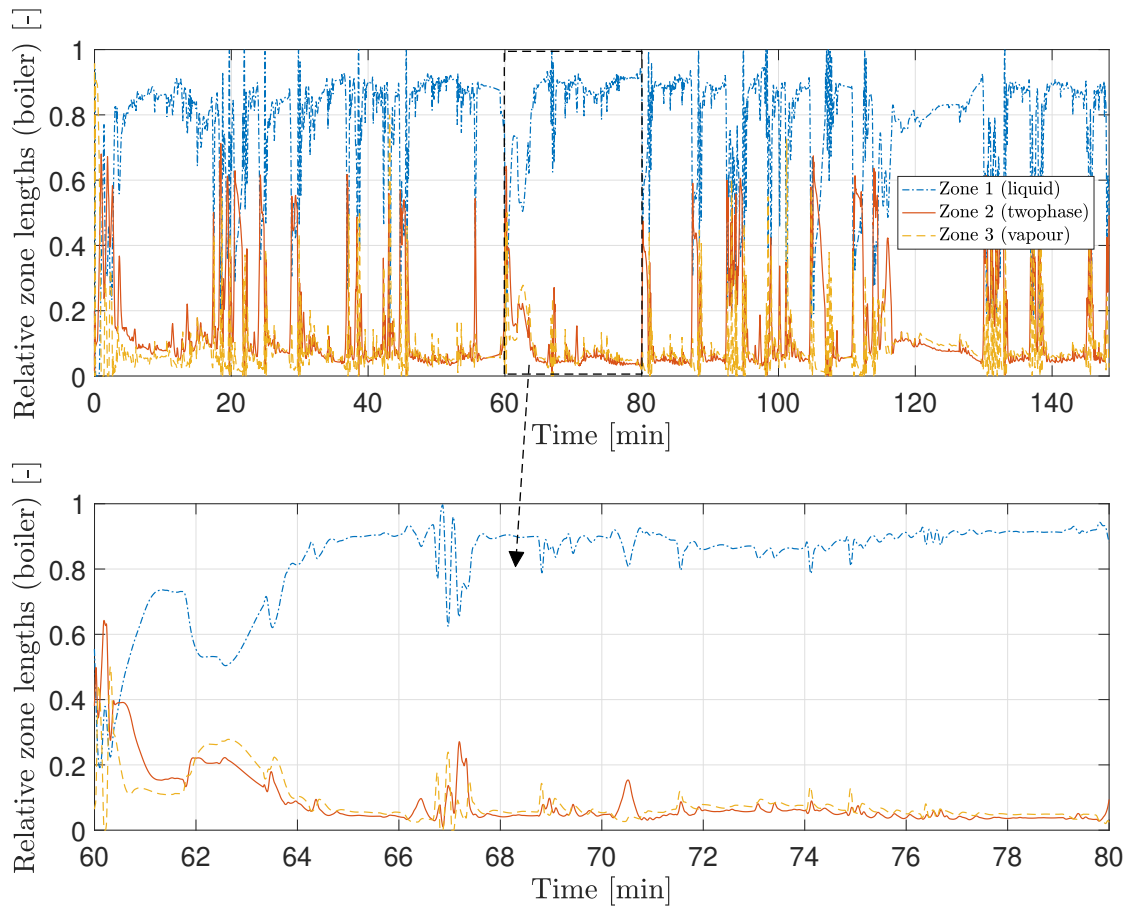
**Keywords:** waste heat recovery, organic Rankine cycle, automotive, modelling, heat exchanger, moving boundaries model, heat transfer, PID controller, lubricant, solubility model.



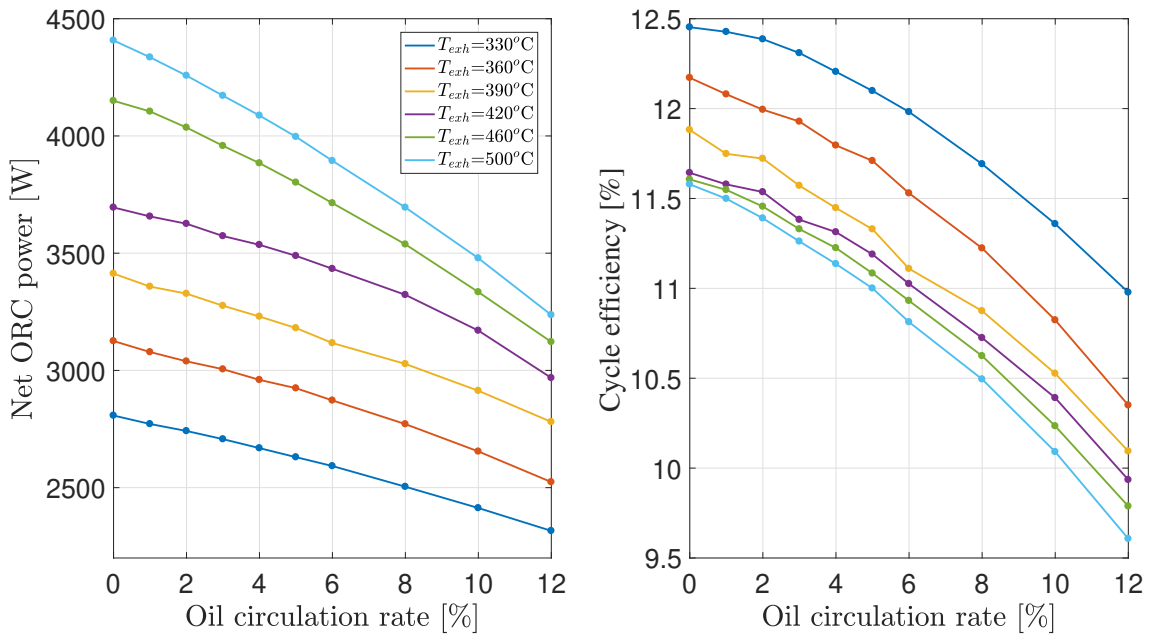
Architecture of the Rankine box developed by *Volvo Trucks*.



Block diagram of the moving boundaries exhaust boiler model.



Evolution of the relative zone lengths of the moving boundaries boiler model during the Frankfurt-Koblenz road cycle.



Evolution of the net ORC power and the cycle efficiency as a function of the oil circulation rate (mass of oil divided by the total mass of the WF/oil mixture), for different exhaust temperatures and a constant exhaust mass flow rate (0.1 kg/s), with  $T_{air} = 300\text{ K}$ .