Vehicle model for transient simulation of a waste-heat-utilisation-unit containing extended PowerTrain and Fluid library components

Max Eschenbach Jörg Ungethüm Dr. Peter Treffinger
German Aerospace Center; Institute of Vehicle Concepts
Postfach 800320, 70503 Stuttgart
max.eschenbach@dlr.de joerg.ungethuem@dlr.de peter.treffinger@dlr.de

Abstract

DLR Institute of Vehicle Concepts uses MODELICA for vehicle simulation. One major application is the power train analysis with regard to fuel consumption, emission and performance. The multi-domain approach of MODELICA has already been a benefit when describing alternative vehicle concepts like fuel cell vehicles and hybrid vehicles.

This paper describes the first approach modelling another concept of low-emission vehicles, i.e. a vehicle powered by an internal combustion engine (ICE), where a waste-heat-utilisation–unit in the exhaust system is applied. The recovery and conversion of waste heat in the exhaust system of ICE-powered vehicles is very attractive, because as a rule of thumb about one third of the fuel energy is emitted with the exhaust to the ambient. There are several approaches to convert exhaust energy into useful energy, e. g. applying a thermal engine, which is powered by the exhaust. Another possibility are thermoelectric devices, which convert heat into electricity. However, in almost all concepts for waste heat utilisation a heat exchanger in the exhaust system has to be integrated and additionally a heat sink has to be provided to run the complete process.

As an example for a waste-heat-utilisation-unit a thermoelectric device is considered in this paper. To predict the performance of such a thermoelectric device in vehicle operation the PowerTrain library [1] has been extended with elements of the Fluid library for representation of the exhaust system. Most important a special heat exchanger model has been developed which describes the thermoelectric device.

The paper gives an overview over the modelling approach of the complete system and the component models respectively. Finally, first results of simulation runs are given.

Keywords: model, dynamic simulation, waste heat recovery, thermal management

1 Modelling approach

The vehicle model has been based on components of the PowerTrain library. Figure 1 shows the object diagram of the vehicle model.

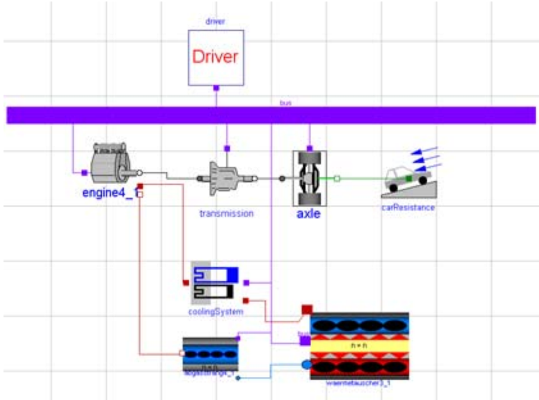

Figure 1: Object diagram of the PowerTrain vehicle model

It consists of the following main parts:

1. the vehicle model, including driver, engine, drivetrain, axle, and vehicle resistance as known from the PowerTrain examples.
2. the engine HeatModel, which determines the heat flow to the exhaust system and the cooling system (see heat flow connection to the respective sub systems). It also provides mass flow rate of the exhaust.
3. the cooling system, with its connection to the cooling system as a thermal heat flux.
4. the exhaust system, whereby actually no direct fluid connection to the engine has been realized. Instead the exhaust flow is generated in an exhaust gas generator as a first component of the exhaust line by using the heat flow, air and fuel mass flow provided by the engine.

Several signals from the bus are used as well in the physical models, e.g. the vehicle speed is taken into account when calculating heat transfer from the exhaust pipes to the ambient.

1.1 Engine Model

As already indicated above the engine model must provide the heat flow to the exhaust system and the cooling system. Having in mind that the waste-heat-utilisation–unit is installed in the exhaust stream also the flow dynamics of the exhaust stream could be of interest. However, at the current stage of the development it was decided to concentrate on the thermal aspects. Precise determination of the heat flows in internal combustion engines by simulation requires CFD-Modelling of the coolant flow through the engine when the boundary conditions of the combustion are known to determine local velocities and heat transfer coefficients. This is mainly done during engine development and out of the scope of this work.

To obtain thermal engine models for thermo-management issues still semi-empirical approaches are used. These are based on simplified distributed mass models of the engine.

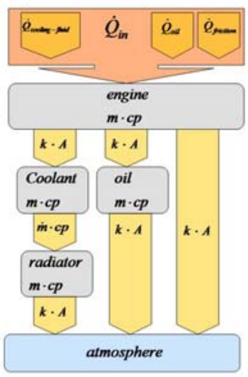

Figure 2: Thermal engine model with 4 masses

Figure 2 shows as an example the scheme of a thermal engine model with 4 masses. Road and roller dynamometer testing are used to determine the different thermal mass allocations by dynamic testing. Measurements on engine test benches can be used to quantify specific heat sources, e.g. by a successive component strip down, to identify the component friction as a heat source into the oil. As a result the energy transferred in cooling system and engine oil can be described depending on engine rotational speed and load. The engine-speed depending HeatModel included in the PowerTrain library has been extended to consider these dependencies. Thereby it turned out that the quadratic approximation of the total heat release into the cooling system, which was already implemented, did not fulfil the special requirements of this application. The HeatModel was therefore refined regarding the distribution of the different thermal flows.

For instance the engine temperature is now considered when determining the heat flow into the engine coolant. A simplified engine heat up is thereby considered in the heat model. In [2] it is stated that a temperature rise of the cylinder wall temperature from room temperature up to 150°C reduces the heat flux through the walls by approximately a third.

Convective heat flux over the engine surface has been neglacted so far. This holds, when low power cycles, e.g. the New European Drive Cycle (NEDC) are investigated. The new approach ensures that the fuel energy is either converted into mechanical energy, a heat flux into the coolant system (by friction or conduction) or released as sensible heat with the exhaust gas.

1.2 Exhaust system model

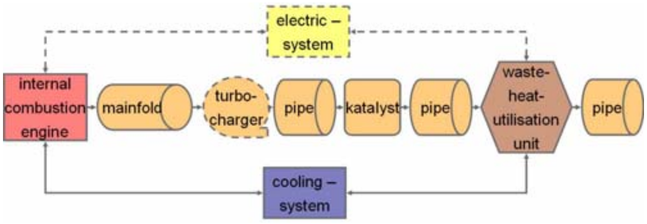

Figure 3: Scheme of exhaust system

Figure 3 shows a schematic representation of an exhaust system with a waste-heat-utilization-unit integrated. First element is the exhaust flow from the internal combustion engine into the manifold. The behavior of the exhaust system regarding thermal and flow characteristic is accounted for by combining components like pipes and catalysts. The position of the waste-heat-utilization-unit within the exhaust line is important, because the temperature of the exhaust decreases along the exhaust line due to heat release to the ambient.

Due to the requirement to reach the operation temperature of the catalyst quickly, such a device will be most likely placed behind the catalyst. The heat transfer from the exhaust line to the ambient depends on the geometry of the exhaust line, the geometry of the air ducts around the exhaust line, the ambient temperature, the velocity of the vehicle and many more parameters. It was out of the scope of this study to implement a complex model, which takes all these effects in account.

A correlation derived from experiments [3], which gives the heat release of exhaust line components to the ambient as function of the vehicle velocity has been applied to the components of the fluid library (e.g. pipe).

1.3 Waste-heat-utilization-unit

Figure 4 shows a scheme of the waste-heat-utilisation-unit. It is basically a heat exchanger, where heat is transferred from the hot exhaust gas to the engine coolant, whereby a temperature difference over the thermoelectric material accurs, which is placed between the walls of the exhaust gas channel and the cooling channel.

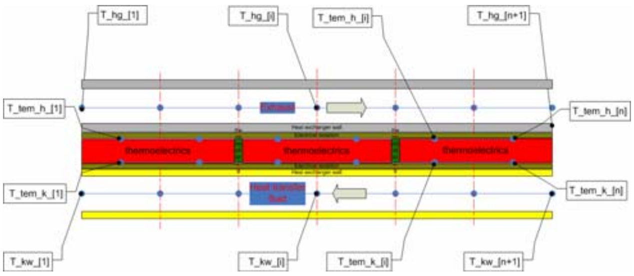

Figure 4: Scheme of the waste-heat-utilization-unit.

Depending on the Seebeck-coefficient and the temperature difference a voltage is generated.

$U_{th} \approx (\alpha_n + \alpha_p) \cdot (T_h - T_c)$ with

α_n/α_p abs. of neg./pos. Seebeck-coefficient, V/K

T_h/T_c hot/cold side temperature of thermoelectric material, K

Peltier-Effect and the heat release caused by electric resistances in the thermoelectric material are taken into account as proposed in [4]. Basics about thermoelectrics can be found e.g. in [5]. Traditional thermoelectric materials are PbTe, Bi_2Te_3, SiGe, BiSb or $FeSi_2$. Thermoelectric devices based on these materials allow efficiencies – i.e. electrical power divided by the heat flow dragged through the thermoelectric material - of around 5 %, whereby temperature differences around 200 K are required. Due to recent innovations in thermoelectric materials, which promise higher efficiencies – higher than 10 % - their application for waste heat conversion is gaining more interest [6].

As indicated in figure 4 the waste-heat-utilisation-unit is modelled as a distributed exhaust heat exchanger, which contains thermal masses and considers heat conduction between the different layers and along the layers as well. Due to the varying engine loads during the cycle a wide range of flow velocities on the hot side were observed. However, the basic “DistributedPipe_thermal”-model of the Fluid library considers only a constant heat transfer coefficient. Therefore a heat transfer correlation was implemented, which gives the heat transfer coefficient as function of Reynolds- and Prandtl-number, namely the Gnielinski-correlation [7].

2 Simulation results

The complete simulation model has been tested applying the NEDC, which is equipped with an 80 kW-Gasoline engine. The parameters of the vehicle model have been estimated mainly from experimental investigations, which are taken from the literature [8]. The parameters of the waste-heat-utilisation-unit have been estimated by analyzing similar devices, which have been built for automotive application [9].

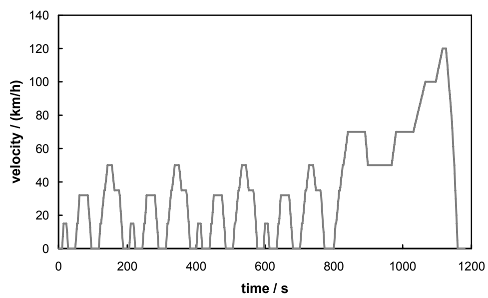

Figure 5: New European Drive Cycle (NEDC).

Figure 5 shows the velocity profile of the NEDC, which is a relative low power cycle. This leads to a slow warm up phase.

Most simulations or testing procedures of waste-heat-applications are performed under steady state conditions at higher engine loads and vehicle speeds, defining the optimum operation point. This simulation is focused on the dynamic power output under disadvantageous conditions for waste-heat-applications regarding the lower thermal energy supply to the exhaust system. Under these driving conditions noticeably gradients in cooling and exhaust temperature lead to a dynamic power output of the device.

As can be seen in figure 6, which shows the development of the hot (red) and cold side temperature (blue) over the NEDC, starting from ambient temperature the heat up of the waste heat utilization unit takes considerable time. A temperature difference near 100 K is only reached after around 1100s, where the highest load of the cycle occurs.

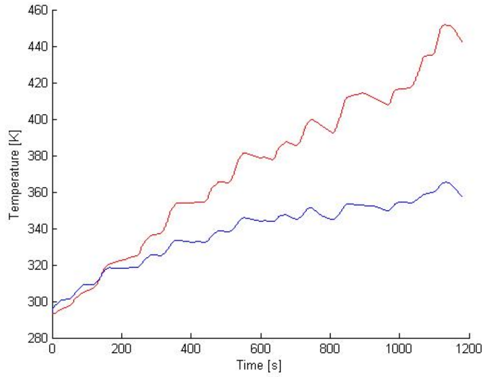

Figure 6: Hot and cold side temperature of the thermoelectric device over the NEDC.

The hot side temperature increases almost steadily over the cycle. The cold side temperature seems to approach a maximum, which means that the cooling system comes near to its operation temperature. As indicated above a temperature difference of around 200 K would be necessary to achieve a good performance of the thermoelectric device, which has been assumed in this work. The thermoelectric device delivers therefore only a fraction of its specified electrical power output under nominal conditions. Figure 7 shows the efficiency of the conversion of the thermal energy into electricity by the thermoelectric device over the NEDC, i.e. when the temperature difference shown in figure 6 is applied.

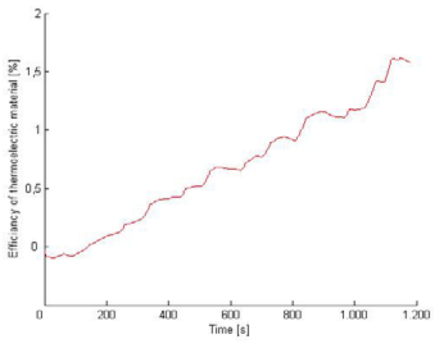

Figure 7: Efficiency of thermoelectric material over the NEDC (see also figure 6).

The efficiency is negative in the beginning, caused by a reverse heat flow through the heat exchanger. It reaches 1,6 % at the maximum, when the highest temperature differences of that cycle are present. However, the temperature difference should be even higher to approach the nominal value of the design point for this type of device. As we have seen in figure 6, the hot side temperature is almost steadily increasing over the NEDC. Therefore reducing the mass of the waste-heat-utilisation-unit should not only improve the response time, but also yield to higher temperature differences.

The effect of a 50 % mass reduction of the waste-heat-utilization-unit on the temperature difference over the NEDC is shown in figure 8 (top). The smaller response time is indicated by sharper temperature drops in the periods, when no load is applied in the NEDC. However, also the temperature difference is considerable higher compared to the reference waste-heat-utilization-unit with 100 % mass. Consequently the electrical power output during the complete cycle is higher for the device with 50 % mass (see figure 8, bottom).

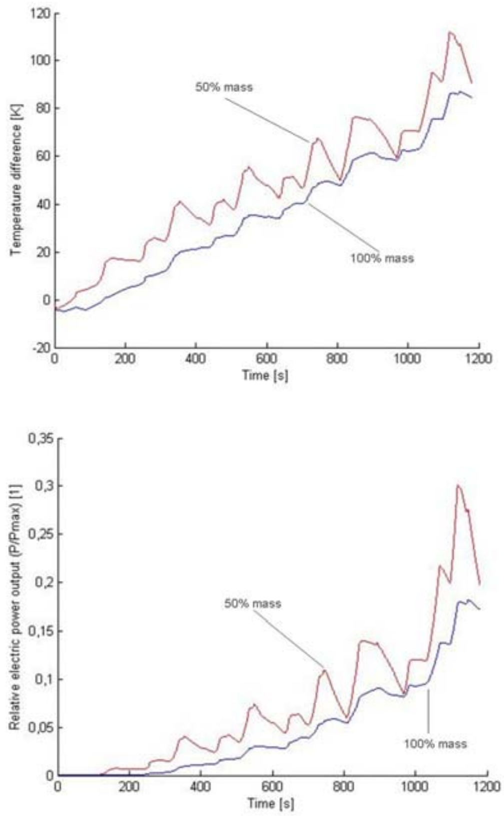

Figure 8: Top: Temperature difference between hot and cold side of the thermoelectric device with 50% (red) and 100% (blue) mass over the NEDC;
bottom: Relative electrical power output of the thermoelectric device with 50% mass (red) and 100% mass (blue) over the NEDC.

The electrical output of the waste-heat-utilization-unit is reduced by the auxiliary power required to drive the coolant pump and possibly the cooling fan. An experimental investigation of a vehicle on a roller dynamometer equipped with a prototype waste-heat-utilization-unit showed even negative net power at low loads, i.e. low vehicle velocities [10].

The reason is the power demand of the cooling pump, which has been operated continuously over all load conditions. This coolant mass flow is covered for an optimal power output at high temperatures.

Considering the following constraints:

1. Maximum temperature of the thermoelectric modules
2. Boiling temperature of the coolant fluid

a flow controller and an electrical cooling pump were implemented in the cooling system model. This allows decreasing the flow rate of the cooling fluid to a minimum value at low engine loads to avoid unintentional heat flux into the cooling system at operation points with negative net power.

Figure 9 shows a comparison of the electrical power output of the 100 % mass waste-heat- utilization-unit w/o and with a flow controller. After approx. 750 s the controller switches from a minimum flow rate to the maximum flow rate due to rising coolant temperatures.

The electrical power output of the configuration with controller is behind the configuration w/o controller for the first 750 s. After applying the optimum flow rate the electrical power output rises quickly and reaches even higher values than the configuration w/o controller, which is due to the conversion of thermal energy stored in the unit.

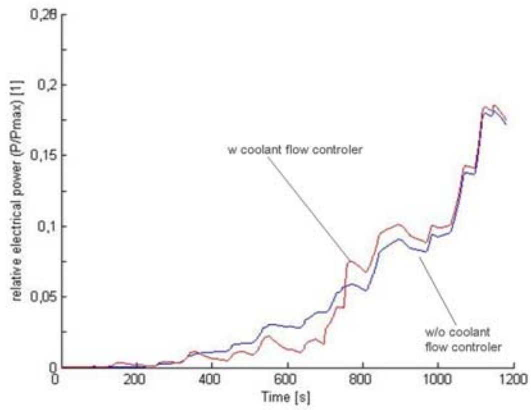

Figure 9: Relative electric power of the 100% mass waste-heat-utilization-unit: a) w/o flow controller (blue line), b) w flow controller (red line).

Over the complete NEDC the electrical output of the unit with flow controller is 2% than the one of the configuration w/o flow controller. However, this is overcompensated by the reduction of the power consumption of the cooling pump and yields to a higher net efficiency.

3 Conclusions

A model of a vehicle with a waste-heat-utilization-device in the exhaust system has been built based on the PowerTrain library. Therefore some components of the PowerTrain library have been extended with respect to the modelling of their thermal behaviour. Components of the Fluid library have been taken and improved to describe the exhaust system. Thereby it was possible to set up a simplified vehicle model. However, looking on the capabilities of specialised automotive tools for the simulation e.g. of the exhaust system or the cooling system, the additional effort to realize more detailed models becomes apparent. Nevertheless the multi-domain approach of MODELICA allows simulation with one environment and avoids co-simulation.

The usage of the model has been underlined by some simulation results, whereby the investigation of control strategies with respect to optimised net power output has been indicated. From the given examples it can be seen, that a suitable control strategy and optimized design supports the electric power output .

As already mentioned above the model should be refined, especially the representations of the exhaust system and the cooling system are expandable. Having in mind the unsteady electrical power output of the waste-heat-utilization-unit also the electrical system of the vehicle should be added in order to investigate, whether the power supply fits to the power demand.

References

[1] Otter, M., Dempsey, M., Schlegel, C.; Package PowerTrain. A Modelica Library for Modeling and Simulation of Vehicle Power Trains. Proceedings of the 1st Modelica Workshop, Lund, Sweden, October 2000, Modelica Association, pp. 23–32.

[2] Guzzella, L., Onder, C.; Introduction to Modelling and Control of Internal Combustion Engine Systems. Springer-Verlag Berlin Heidelberg, 2004.

[3] Kandylas, I., Stamatelos, A.; Berechnung des Wärmeübergangs in Motorabgassystemen. Motortechnische Zeitschrift (MTZ), Ausgabe 1998-08.

[4] Müller, E.; Thermoelectric materials for waste heat recovery, linerized thermal sensors and Peltier cooling. German Aerospace Center (DLR), Institute of Materials Research, at Steinfurter Keramiktage, Dezember 2002.

[5] Nolas, G.S., Sharp, J., Goldsmid, J.; Thermoelectrics: basic principles and new material developments. Springer-Verlag Berlin Heidelberg, 2001.

[6] Venkatasubramanian, R., Sivola, E., Colpitts, T.; Thin-film thermoelectric devices with high room-temperature figures of merit., Nature Magazin, 2001 Volume 413, pp. 596-602.

[7] VDI-Wärmeatlas, 7.Auflage, 1994, Abschnitt Gb

[8] Poruba, C., Seider, G., Kröner, M.; Energiebilanierung im Entwicklungsprozess von Motoren. Wärmemanagement des Kraftfahrzeuges V, Haus der Technik Fachbuch, Düsseldorf 2006, pp. 54-80.

[9] Vázquez, J., Sanz-Bobi, M.A., Palacios, R., Arenas; A.: State of the Art of Thermoelectric Generators Based on Heat Recovered from the Exhaust Gases of Automobiles. Universidad Pontificia Comillas Escuela Técnica Superior de Ingeniería. Instituto de Investigación Tecnológica, Madrid, Spain.

[10] Thacher, E.F., Helenbrook, B.T., Karri, M.A., Richter, C.J.; Testing an automobile exhaust thermoelectric generator in a light truck. Clarkson University, Potsdam, New York, USA, Department of Mechanical and Aeronautical Engineering, Delphi Corporation, Lockport, New York, USA, 2005.