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Research paper

Energy integration study on a hybrid electric vehicle energy system, using process integration techniques

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HIGHLIGHTS

- The vehicle is an energy system with excess of heat.
- For the energy integration a cold utility is required.
- For the highest operating point, the energy requirement is between 33 and 36 kW.
- The organic Rankine cycle gains 9% of efficiency for hybrid electric vehicles.

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ABSTRACT

The needs of efficiency improvement of the vehicle energy systems require to find innovative solutions during the design process, integrating all vehicle services and energy requirement on a vehicle system level.

In this article the boundary of the energy system are extended to the powertrain and the cabin and the requirements for mobility and comfort are integrated.

The energy balance of the internal combustion engine is done and discussed, according to its operating points. The energy requirement for comfort in the cabin is also determined, according to the seasonal requirement for heating or cooling. In this article an energy integration methodology, using process integration techniques is discussed and applied on the extended vehicle energy system. The minimal energy requirement is determined for different mobility and comfort situations. The energy recovery potential of an organic Rankine cycle, with sensitivity of different working fluids, is assessed.

The energy integration methodology is applied on a hybrid electric vehicle energy system, and is studied for adapted dynamic profile, represented by characteristic clustered operating points.

Multi-objective optimization is applied to define the optimal design of a hybrid electric powertrain and the optimal ICE size, from efficiency and cost point of view.

1. Introduction

The target of the present work is to illustrate the methodological transfer of the energy integration from the process engineering to the vehicle energy systems design and so to assess the theoretical potential for efficiency improvement and fuel consumption reduction through heat recovery, using working cycles as utilities.

The novelty and the purpose of this paper are to apply the single energy optimization and process integration on an autonomous and dynamic energy system – the vehicle. The energy system boundaries are extended. The vehicle powertrain and the cabin are defined as unitary processes, with heat exchange that has to be integrated, in function of the ambient temperature. In order to do so, an energy integration model based on mixed integer linear programming (MILP) has been developed. A hybrid electric vehicle dynamic model gives the thermal and the mechanical flows of the vehicle. The engine thermal model is calibrated with a real engine map measurement. This study zooms especially on the energy integration structure. This structure is used as a slave structure linked by the state variables with the dynamic and the thermal models (Fig. 4). The problem statement and the energy recovery potential of the ORC are developed in the part “Results”.

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Nomenclature

NEDC	New European Drive Cycle
SI	engine Spark ignition engine
ICE	internal combustion engine
EM	electric machine
Car shell	equipped car without the powertrain
SC	super capacitor
HVBT	high voltage battery
q_{bat}	battery capacity
LHV	low Heating Value in [kJ/kg]
P_{eff}	effective power in [kW]
m_{fuel}	fuel flow rate [kg/s]
$\eta_{powertrain}$	powertrain efficiency [−]
P_{hybrid}	hybrid power in [kW]
$Q_{heating/cooling}$	thermal energy for heating or cooling in [kJ]
el. machine	electric machine
ORC	organic Rankine cycle
Q_e^+	heat transferred to the ORC loop in [kJ]
Q_a^+	heat evacuated from the ORC loop in [kJ]
$\dot{E}_p$	pump power in [kW]
E^-	electric power in [kW]
DT	delta T [°C]
GWP	global warming potential in [kg CO_2equivalent]
SES36	working fluid
R1234yf	working fluid
PI	process integration
MER	minimum energy requirement in [kW]
MILP	mixed integer linear programming
MINLP	mixed integer non-linear programming
P_{meca_out}	engine output mechanical power in [kW]
P_{fuel}	power in the fuel in [kW]
BSFC	brakespecific fuel consumption [g/kWh]
BMEP	brakemain effective pressure [bar]
RPM	rotation per minute
EGR	exhaust gas recirculation
OSMOSE	optimization structure for multi-objective system Engineering
EI	energy integration
MOO	multi-objective optimization
$\dot{E}_{pump}$	pump power in [kW]
$\dot{E}_{turbine}$	power on the turbine shaft in [kW]
$\dot{E}_{shaft}$	power on the engine shaft in [kW]
η_{orc_cycle}	efficiency of the cycle in [%]
$\dot{E}_{net}$	ORC net power in [kW]
$\dot{Q}_{in}$	heat power delivered to the cycle in [kW]
ζ	ORC exergetic efficiency in [%]
$\dot{E}_{cooling\_water}$	exergy of the cooling water in [kW]
$\dot{E}_{exhaust\_gas}$	exergy of the exhaust gas in [kW]
$X_{decision\_variables}$	domain of decision variables
P_{wheel}	power demand of the wheels in [kW]
P_{fuel}	power in the fuel in [kW]
P_{elec}	power delivered by the electric machine in [kW]
P_{ICE}	power of the ICE in kW [kW]
P_{SC}	power of super capacitors in [kW]
$C_{vehicle}$	vehicle cost in [€]
C_{car_shell}	cost of the car shell in [€]
C_{ICE}	cost of the ICE in [€]
C_{EM}	cost of the EM in [€]
C_{HVBT}	cost of the high voltage battery in [€]
C_{SC}	super capacitor cost in [€]

1.1. Mobility and energy balance

Passenger cars are evaluated in standardized test cycles. In Europe, the New European Driving Cycle (NEDC) is used, in which only the energy needed for the propulsion is considered. Fig. 1 displays a real measured efficiency map for a thermal engine.

The characteristics and the efficiency order of magnitude for internal combustion engines are reviewed in Ref. [1].

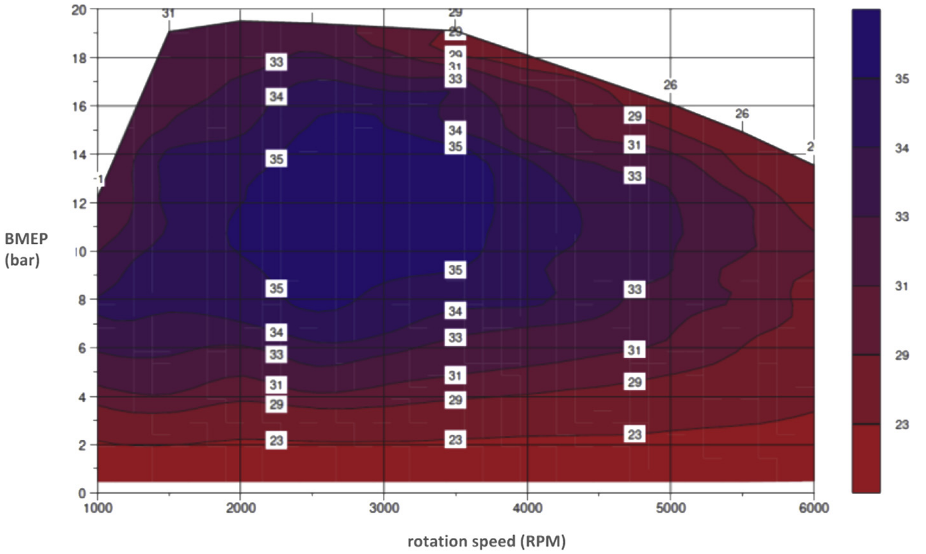

Fig. 1. Efficiency map of turbocharged homogenous combustion gasoline engine.