Optimization of a Cooling Circuit with a Parameterized Water Pump Model

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Abstract

In this work an electrically operated water pump in a cooling circuit is implemented, simulated and optimized. The presented simulation results are accomplished with *Dymola*. This simulation tool is based on the modeling language *Modelica*.
The model of the water pump is realized with time domain differential equations. The parameters of the differential equations of the water pump are defined by geometrical data. The water pump is driven by an electric machine. A generator model and a battery model are used as power sources for the electric machine driving the water pump. In the proposed application the thermal behaviour of all components of the cooling circuit (internal combustion engine, pipeline, cooler...) is implemented.
The measured and the simulated characteristics of the water pump are be compared. The efficiency improvement of the internal combustion engine when using an electrically operated waper pump in stead of a mechanically operated pump is presented.

Keywords: cooling circuit; water pump

1 Introduction

In this work a cooling circuit of an internal combustion engine (ICE) with an electrically operated water pump is presented. The results of the simulation lead to an optimized size of the water pump. All components of the cooling circuit including the water pump are modeled with the *Modelica.Thermal.FluidHeatFlow* package of the *Modelica* standard library [1]. The mechanical and rotational components as well as the ICE are modeled with *the Modelica* standard library, too. For the electrical drive operating the water pump a model of an electrical machine including converter from the *SmartElectricDrives* (SED) library is used. From the SED, an idealized battery and a model of a generator serve as electrical power sources.
The focus of this work is on the optimization of the size of the water pump for the cooling circuit. The cooling circuit model includes the following components: an ICE, a thermostat, a cooler, a fan, a pipeline and an electrically operated water pump. For the verification of the water pump model, a test bench with a mechanically operated water pump was built.

2 Water pump model

Basically, the model of the water pump is implemented by differential equations. The parameters and coefficients of the differential equations are determined by geometrical parameters of the water pump. Losses of following kind were considered in the model: flow losses including hydraulic losses of the operating fluid; hydraulic losses of the impeller wheel; impact losses of the operating fluid flowing through the distributor. Mechanical friction losses content the mechanical losses of the bearing and the seal.

2.1 Water pump design

The water pump can be seen as a fluid flow machine. The action principle of a fluid flow machine is based on the energy theorem. Using this theorem the water pump can be modelled. The driving torque of the water pump shaft is transmitted to the curved shovels of the impeller wheel which exert a pressure on the operating fluid. On account to the centrifugal effect, the operating fluid is hurled outwards in radial direction of the impeller wheel and therefore, laves the impeller wheel at the outside extent with higher speed. Beacuse of the diffuser effect in the shovel channels of the impeller wheel, the operating fluid leaves the impeller

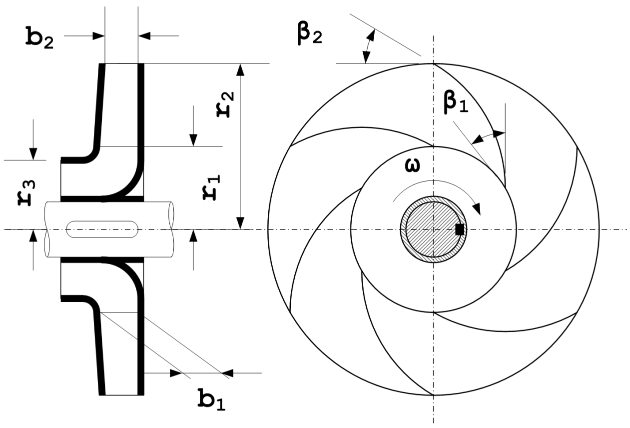

Figure 1: The impeller wheel designe and parameters

wheel with increased pressure, as well. The incoming operating fluid gets sucked because the mass movement of the operating fluid outwards causes a negative pressure at the inlet of the impeller wheel. With this energy theorem the energy transformation from the driving energy of the water pump shaft to the potential energy of the operating fluid is defined [2].

2.2 Main equation of the fluid flow machine

An ideal model of the water pump is consided as a fluid flow machine with an infinite number of shovels. In this case the energy balance between the converted energy in the impeller wheel of the water pump and the kinetic energy of the operating fluid is fulfilled. Therefore, the main equation of the ideal fluid flow machine and the ideal water pump represent the relationship between mechanical energy of the input shaft with respect to the impeller wheel and the spezific energy of the operating fluid [3]. The main equation of the ideal fluid flow machine and the ideal water pump [2, 4] is represented in (1):

$$\dot{m} \cdot \omega = 2 \cdot \pi \cdot b_2 \cdot \rho \cdot \tanh(\beta_2) \cdot \left(r_2^2 \cdot \omega^2 - Y_\infty\right) \quad (1)$$

In this equation r_2 is the outer radius of the impeller wheel of the water pump, b_2 is the outer width of the impeller wheel, ρ is the density of the operating fluid and β_2 is the outlet angle of the shovels of the impeller wheel. The mass flow of the operating fluid in the water pump is $\dot{m}$ and the spezific energy of the impeller wheel for an infinite number of impeller shovels with Y_∞ respectively. The basis impeller wheel design of a water pump [5] is represented in the Figure 1.

2.3 Decrease of the specific energy

A rate of the mechanical rotational energy of the impeller wheel gets reduced by the decreasing twist in the outlet area of the impeller wheel. This reduction of the energy is equal to the diffrence between the release energy of the impeller wheel and the absorbtion energy of the operating fluid. This energy reduction, Y_k, of the water pump can be calculated with a loss factor k. The energy reduction of the water pump [2] is represented by (2). With an empirical number, know as *Pfleiders* number, p, the loss factor, k, can be found using (3). For the calculation of *Pfleiders* number in practice there exist two equations: one equation for single curved and one equation for double curved impeller shovels [2]. In this paper a water pump for cooling circuit of the ICE is modeled. This type of the water pump is designed with single curved impeller shovels [3]. For calculating *Pfleiders* number (4) is used.

$$Y_k = (1-k) \cdot Y_\infty \quad (2)$$

$$k = \frac{1}{1+p} \quad (3)$$

$$p = \frac{a}{z} \cdot \left(1 + \frac{3 \cdot \beta_2}{\pi}\right) \cdot \frac{r_2^2}{r_2^2 - r_1^2} \quad (4)$$

In these equations z is the number of the impeller shovels of the water pump, r_1 is the radius of the inlet area of the impeller wheel, and the constant parameter, a, is an experimental coefficient, with a value between 1.2 and 2.0, depending on the design of the impeller wheel and the diffuser [3].

2.4 Hydraulic losses in shovel channels

A particular part of the energy stored in the operating fluid between the shovels of the impeller wheel is reduced by flow resistances outside of the shovel channels. These losses, known as hydraulic losses of operating fluid, are determined by hydraulic friction, changes of the operating fluid flow direction, and changes of the flow cross sectional area in the shovel channels. The calculation of the hydraulic losses is not trivial. A simplifield calculation of the hydraulic losses of the operating fluid in the shovel channels is represented by (5), where Y_h determines the hydraulic losses and c is the average velocity of the operating fluid in the shovel channels. The parameter ξ is the friction factor of the hydraulic losses and can be calculated using the flow equation, taking the geometry of the impeller wheel and the shovels into account. In this case the friction factor, ξ, is considered as a constant parameter [3].

$$Y_h = \xi \cdot \left(\frac{c^2}{2}\right) \tag{5}$$

2.5 Impact losses

In an arbitrary operating state deviating from the nominal operating state, impact losses occur. In such an arbitrary operating state the fluid flow direction is not tagential with respect to the shoveled channels of the impeller wheel and the control device. The impact losses occour if the impeller wheel is overloaded or underloaded. The proportion of the impact losses is depending on speed and load of the impeller wheel. For calculating the impact losses (6, 7) are used [2, 4]. In the (6), Y_i represents the impact losses, a_i is an experimental value according to (7), r_3 is the radius of diffuser and $\dot{m}_A$ is the fluid mass flow at the nominal operating point of the water pump.

$$Y_i = \frac{a_i}{2} \cdot \left[r_2^2 \cdot \omega^2 + \left(\frac{r_2 \cdot \omega}{1+p}\right)^2 \cdot \left(\frac{r_2}{r_3}\right)^2 \right] \cdot \left(\frac{\dot{m} - \dot{m}_A}{\dot{m}_A}\right)^2 \tag{6}$$

$$a_i = (0.3...0.6) \cdot \frac{2 \cdot \beta_2}{\pi} \tag{7}$$

2.6 Friction losses of the impeller wheel

Between the faces of the impeller wheel and the housing of the water pump a fluid film exists. This fluid film is responsible for the friction losses, known as friction losses of the impeller wheel, P_r. These losses can be determined using (8) according to [2]. The variable ν is the kinetic viscosity of the operating fluid which equals the viscosity of coolant in this case.

$$P_r = 8 \cdot 10^{-4} \cdot \left(\frac{10^6}{\omega \cdot r_2 / \nu}\right)^{1/6} \cdot \rho \cdot \omega_2 \cdot r_2^5 \tag{8}$$

3 Configuration of the test bench

The test bench of the mechanical water pump is needed for the determination of variables that cannot be measured if the water pump is embedded in the vehicle. For measuring the family of characteristics like pressure difference and flow, as well as power consumption and hydraulically efficiency, sensors are used that cannot be applied in the tight ICE compartment. The more important reason, of course, for using a test bench is that the measurements are not restricted to just one characteristic curve due to the cooling circuit of the vehicle.

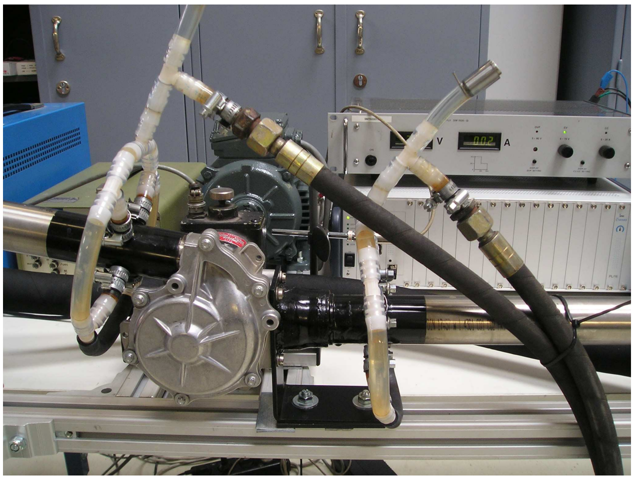

Figure 2: Test bench of the water pump

For the test bench, a low resistance water circuit with 5/4 inch diameter tubes and controllable valve was built, as shown as in Figure 2. To minimize measurement errors of the differential pressure and volume several rules of measuring hydrodynamics values have to be considered. The diameter of the inlet and outlet pipe have to be the same size as well as changes in diameter must not lead to angles larger than 8 deg. At the existing water pump a rectangular inlet and an circular outlet with different cross section surfaces require changeover solutions to standardized pipes. The measurement of pressure and volume need defined inlet and outlet pathes for repeatable results. The water pump delivery is measured with a magnetic inductive flow meter for electrically conductive fluids. This kind of flow meter for coolants causes the smallest backlash to the system and works accurate enough in an effective range from zero to 300 lit/min.

A pressure vessel is installed to operate the water pump with constant pressure, similar to the conditions in the vehicle, and to prevent operating fluid cavitation and degasifying of the media. If negative pressure occurs at the suction side of the water pump the media starts degasifying. Therefore a pressure of about two bar absolute was held in the system. This is equivalent to a coolant temperature of approximately 120 °C in the coolant circuit of the ICE, a typical water temperature in a modern ICE. The pressure vessel acts as expansion tank too.

During building the test bench attention had to been drawn to the possibility of bleeding the system entirely. The torque was detected with a regular rotating torque sensor located between the water pump and the electric machine. The appropriate drive for the test bench was not to find as easy as a torque sensor. Without using a transmission, what would have brought an additional effort, a drive with an rotational speed spread from 84 rad/s to 733 rad/s had to be used. A controlled, converter fed asynchronous motor drive is operating the pump. All measurements are made in the described arrangement and beside little adjustments due to leakage the test bench worked properly during the whole measurement procedures.

The measurement results obtained from the test bench deduce accurate statements about the behavior of the water pump and the energy saving potential with an optimized electrically operated water pump.

4 Evaluation of the water pump model

For the evaluation of the water pump a simple circuit is modeled. The circuit model is implementet according to the test bench. The main components of circuit model are: the water pump, the pipeline systems and an electric drive. The following geometrical parameters of the water pump are measured and applied to the simulation:

$r_1 = 42/2\,\mathrm{mm}$

$r_2 = 62/2\,\mathrm{mm}$

$r_3 = 51/2\,\mathrm{mm}$

$b_1 = 9\,\mathrm{mm}$

$b_2 = 6.6\,\mathrm{mm}$

$\beta_1 = 15\,\mathrm{deg}$

$\beta_2 = 50\,\mathrm{deg}$

$\dot{m}_A = 3.5\,\mathrm{kg/s}$

Figure 3 shows the circuit of the test bench modeled in *Modelica*. The `valve` creates the friction losses in the circulation. While the `water pump` is driven at constant speed, the friction losses are adjusted by the `valve`. The specific speed of the `water pump` equals the specific speed measured at the test bench. The circuit is investigated for five different valve settings.

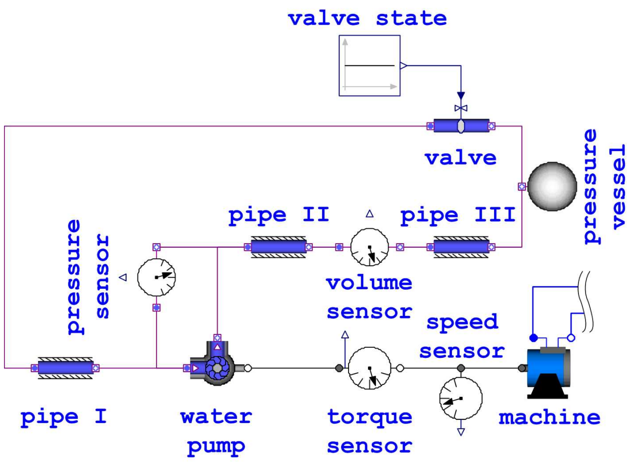

Figure 3: *Modelica* model of test bench

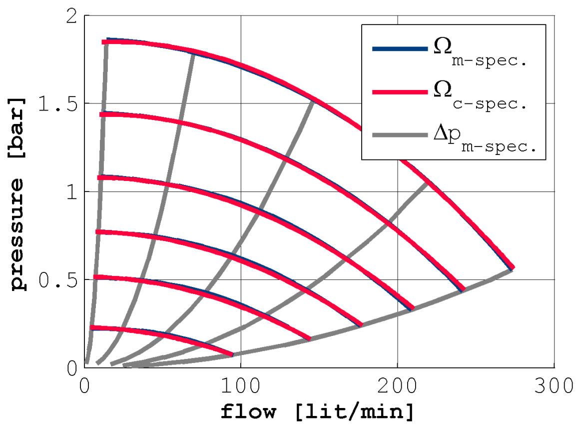

Figure 4: The measured and simulated caracteristic curves of the water pump

Figure 4 represents the characteristic flow and pressure diagram of the water pump. Quantity $\Omega_{m-spec.}$ represents the specific speed of the water pump, which is measured at the test bench, $\Omega_{c-spec.}$ is the specific speeds of the water pump, which is simulated with the *Modelica* model. The $\Delta p_{m-spec.}$ is the specific flow resistances of the circuit, which is defined with the setting of the valve.

A comparison between the test bench and the simulation shows good coherence. It can be seen that the measured and calculated caracteristic curves of the water pump look alike with differences in a band of merely a few percent. The difference between the two caracteristic curves is very low. Figure 4 confirmens therefore the good implementation of the water pump model. Furthermore, the *Modelica* model of the water pump can be used as a verified *Modelica* model for further implementations and designs of the ICE cool-

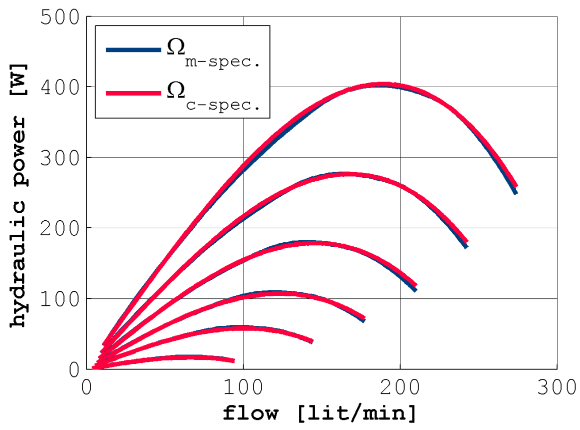

Figure 5: The measured and simulated caracteristic curves of the water pump

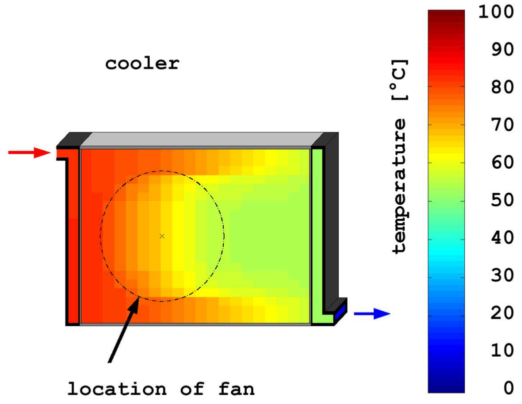

Figure 6: Temperature distribution of the cooler

ing circuit.
Figure 5 represents the hydraulic power of the water pump versus flow. In this figure $\Omega_{m-spec.}$ is the measured specific speed and $\Omega_{c-spec.}$ is the simulated specific speeds of the water pump in the flow and hydraulic power diagram. The very low difference between the measured and simualted hydraulic power of the water pump approve the good implementation of the *Modelica* water pump model.

5 Cooling circuit

All components of the cooling circuit are implemented in *Modelica*. Each of the implemented models of the cooling circuit considers flow equation. The mass flow balance of the operating fluid from the fluid inlet and the fluid outlet is defined in the equations stated in [6]. The friction losses of the pipe components and the valves are implemented with caracteristic curves and the models are extened from *Modelica.Thermal.FluidHeatFlow* library. All another components of the cooling circuit are implemented as physical models.
The cooler of the cooling citcuit is modeled by means of discrete volume elements [7, 8]. In the cooler model the coefficients of convection for the coolant, the air and the steel tubes of the cooler are determined by calculation. The effect of the cooler fan was determined by calculation of the coefficients of convection. The discrete volumes, which flow through the cooling fan area of the cooler have a higher coefficient of convection. In Figure 6 the temperature distribution of the discrete cooler volumes is shown. One significant results is that the discrete volumes in the cooling fan area have a higher temperature decrease.

5.1 Electrically operated water pump

Figure 7 shows the cooling circuit with the electrically operated water pump and cooling fan. The electric power source of the cooling circuit is an idealzed battery model. The `battery` feds the `pump motor`, which is controlled by a pump speed controller (`PSC`) model. The `PSC` calculates the reference speed of the `pump motor` for the actual temperature of the `ICE`. The `pump` is driven by this `pump motor`. The pipeline configuration is design according to a conventional `ICE` cooling circuit. The cooler fan, marked as `fan`, is driven by a `fan motor` fed by the same electric sources than the water pump. A generator, marked as `gen.`, is used as electrical energy source, mechanically coupled with the `ICE` and electrically coupled with the `battery`. The generator torque controller (`GTC`) model calculates the torque state of the generator depending of the state of the charge (SOC) of the `battery`. The `ICE` thermal model is implemented with the caracteristic curves of the `ICE`. With this concept of the cooling circuit it is possible to control the speed of the water pump independent from the speed of the `ICE`. The speed of the cooling fan is constant in this model of the cooling circuit. All electric machines are taken from the SED library using the quasi stationary permanent magnet synchronus machine models.
The efficiency of electric machines at the nominal operating point is 0.95, and the efficiency of battery is 0.87. The efficiency of generator belt drive is taken as the efficiency from a flat belt drive and accounts for 0.96 [9].

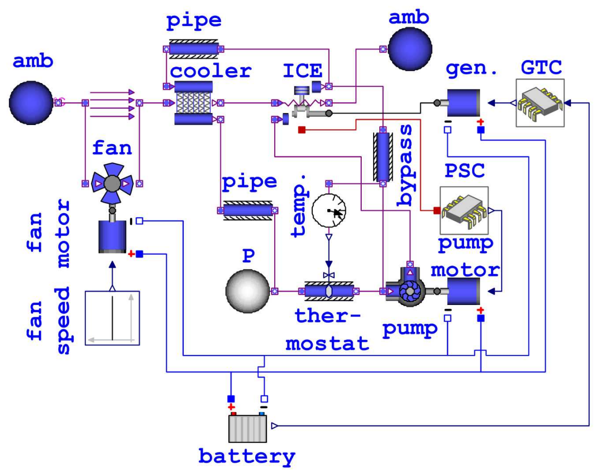

Figure 7: *Modelica* model of cooling circuit with electrically operated water pump and cooling fan

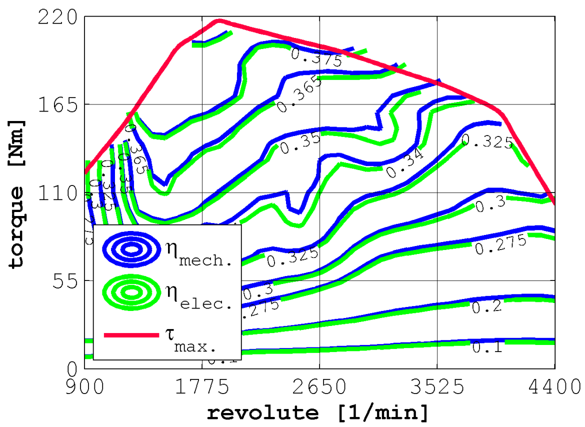

Figure 8: Efficiency comparison of the ICE with electrically and mechanically operated water pump

5.2 Mechanically operated water pump

The mechanical model of the cooling circuit contains the mechanically operated water pump. The major difference to the model of Figure 7 is the mechanically operated water pump. The water pump is driven with a belt drive from the ICE shaft. The efficiency of the belt drive is approximately 0.96 [9].

6 Cooling circuit optimization

For optimizing the cooling circuit the different concepts are simulated und compared. First, the cooling circuit with the mechanically operated water pump is simulated and then the ellectrically operated water pump is considered. The ICE is driven with specific speed and torque. The speed band is used from idle speed to upper speed limit of the ICE and the torque is used from zero to maximal torque at according to the actual speed of the ICE. Therewith the ICE is driven in the entire speed and torque range of the caracteristic map. In the simulation the maximal acceptable temperature of the ICE is used. The speed of the cooling fan for both concepts is the maximal speed of the fan.

Figure 8 shows the different efficiency maps of the ICE. Quantity $\eta_{mech.}$ is the efficiency of the ICE with the mechanically operated water pump, the $\eta_{elec.}$ is the efficiency of the ICE with the electrically operated water pump and the $\tau_{max.}$ the maximal torque of the ICE which is depending on the ICE speed.

In Figure 8 the difference between the ICE efficiency maps can be determinated. The increase of ICE efficiency in case of a cooling circuit with electrically operated water pump can be identified clearly. There is an improvement of efficiency with respect to almost the complete map of the ICE. The efficiency increase is higher in upper speed and torque regions of the ICE. This increase can be expected, because the nominal operating point of the mechanically driven water pump is designed for lower speeds of the ICE.

7 Conclusions

The performed simulation of cooling circuits allows the determination of the fuel consumption as well as a declaration of the economic saving potential of an electrically operated water pump. The fuel and energy consumption of an ICE can be reduced by means of an electrically operated water pump.

The efficiency increase of the ICE was demonstrated for stationary operation. For dynamic operation, however, a similar improvement can be expected. Using the concept of an electrically operated water pump a thermal shock of the ICE and the cooling circuit can be avoided. The concept of an electrically operated water pump increases the efficiency of a conventionally cooled ICE and makes energy saving potentials possible this way.

The experimental verification of the water pump model is presented. The presented model of the water pump can therefor also be applied to other thermal management models like battery cooling, fuel cell cooling or cooling of electric machines.

8 Abbreviations

ICE	internal combustion engine
SED	*SmartElectricDrives*
PSC	pump speed controller
GTC	generator torque controller
SOC	state of charge

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