# EFFICIENCY MEASUREMENTS OF THE HYDRID MOTOR/PUMP

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## ABSTRACT

A constant displacement floating cup pump/motor has been developed as a drive unit for hydraulic hybrid (Hydrid) vehicles. The unit will be connected to the differential of a passenger car. The displacement is 24 cc per revolution. The so-called FCM24 can be operated in all 4 quadrants, with a preference for forward driving and braking. The maximum operating pressure is 500 bar and the maximum operating speed 5000 rpm, resulting in a maximum power output of almost 100 kW. This paper describes the efficiency measurements in pumping mode. From the pump data, the efficiency for motor operation is derived in 49 operating points, at two different oil temperatures. The tests have been performed at the Eindhoven University of Technology.

KEYWORDS: floating cup pump, floating cup motor, efficiency, Hydrid, hydraulic hybrid

## 1. NINETY PERCENT IS NOT ENOUGH

The efficiency of most hydrostatic pumps and motors is 90% or less. This is the peak efficiency in the best point of operation. In general, however, pumps and motors are not operated in the best point, but at far less favourable operating conditions. In these, real world operating points and cycles, the efficiency of pumps and motors often drops to values of 60% or below. This is no longer acceptable. In excavators, loaders and other mobile machinery, the fuel costs have become a substantial, if not principal part of the total cost of ownership. Moreover, a higher efficiency can help to reduce installed engine power, thereby lowering the emission demands for the vehicle.

The low efficiency of current pumps and motors is also unacceptable because there is no fundamental reason why a well-designed pump or motor should have higher losses than a well-designed electric motor, or even a gear transmission. Unlike heat engines, the energy conversion in hydrostatic machines is not limited by something like the Carnot efficiency, but is simply a matter of avoiding high leakage and excessive friction losses.

Finally, the poor efficiency of current hydrostatic machines is no longer acceptable because it strongly limits the growth of the hydraulic industry into other segments and markets. The pump/motor, which is described in this paper, is designed on behalf of the automotive industry for application in passenger cars. Hydrostatic transmissions could offer a viable alternative to current standard mechanical transmissions (which don't allow power management) and electric transmissions (which are too heavy and too expensive).

The alternative hydraulic hybrid, or 'Hydrid' transmission for passenger cars and other vehicles has already been described in previous papers [1…5]. This paper is about the floating cup pump and motor (the FCM24) that has been developed for this transmission.

## 2. THE DESIGN

The floating cup design is optimized for application in automotive drive trains. Figure 1 shows a cross section of the design, which can be used in pumping and motoring mode. The rotation is predominantly in one direction. The unit can be operated up to 500 bar at the supply side (in motor mode) as well as on the delivery side (the pump mode). The maximum operating speed is 5000 rpm. The machine can deliver almost 100 kW. Having a weight of 9 kg, the power density is more than 11 kW/kg, about 20 times better than comparable modern, automotive electric motors and generators. The outer dimensions are about 130 mm in all three directions.

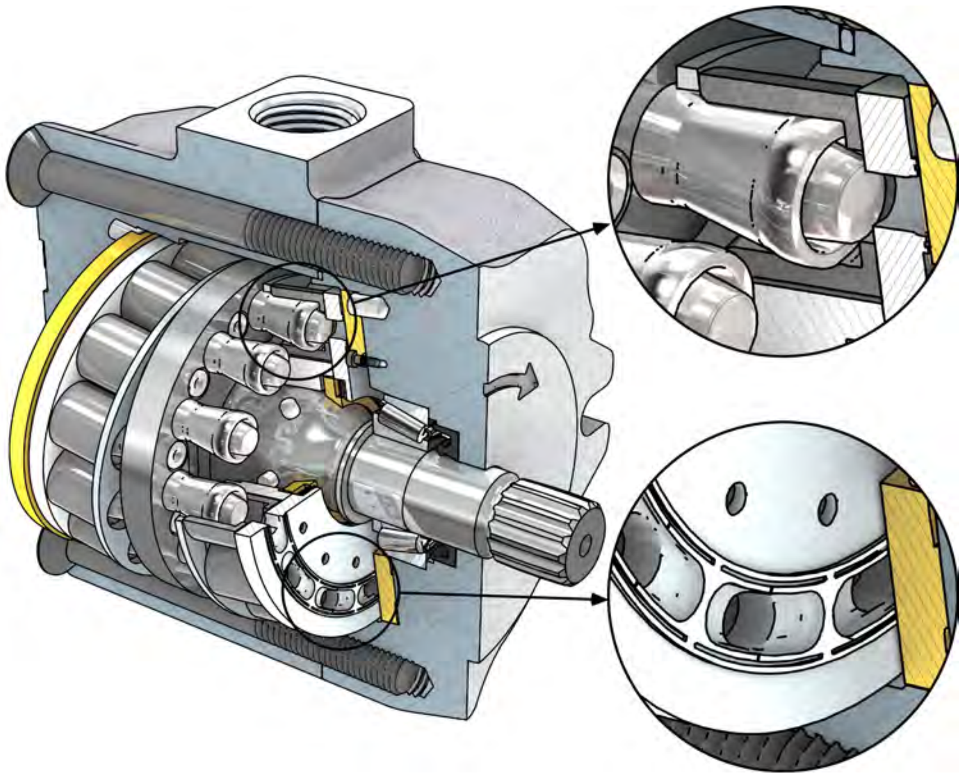

*Figure 1. Cross section of the 24 cc floating cup motor/pump. The details show the two design features that reduce the friction in the machine, the piston with the floating cup (upper detail) and the new hydrostatic bearing for the interface between the barrel and the port plate (lower detail).*

For automotive applications, low NVH (noise, vibration and harshness) is a *conditio sine qua non*. The number of pistons largely influences the NVH levels. Current piston pumps and motors have 7 or 9 pistons. The floating cup principle typically has 24 pistons, thereby reducing noise, vibration and harshness to acceptable levels for automotive applications.

The high number of pistons also reduces the strong torque variation of current hydrostatic motors, thereby increasing the available torque at start-up conditions. The breakaway torque is further increased by a strong reduction of the coulomb friction compared to other hydrostatic principles. Other tests have already proven that the torque efficiency of floating cup motors is almost 100% at start-up [6].

There is a plethora of hydraulic hybrid transmission architectures conceivable. One of the principle design decisions is how to drive the wheels. In previous papers, a direct hydrostatic wheel drive was proposed [1…5]. The automotive industry however favours a mechanical transmission. Having a 1:3 transmission ratio in the diffrential, the hydrostatic machine can be a factor of three smaller, but it will also run at three times higher operating speeds.

This puts more emphasis on increasing the efficiency at high rotational speeds, especially at relatively low loads. The floating cup principle almost eliminates the friction between the pistons and the cylinders [6]. The mirrored, multi-piston configuration also strongly reduces the bearing forces. At high operating speeds, the friction is however largely created in the sliding interface between the barrels and the port plates. Having two barrels and relatively large pitch diameters of the barrel ports, the challenge is to reduce the (viscous) friction of the interfaces between the barrels and the port plates.

A new thrust bearing annex face seal (figure 2) has been designed to reduce this friction [7].

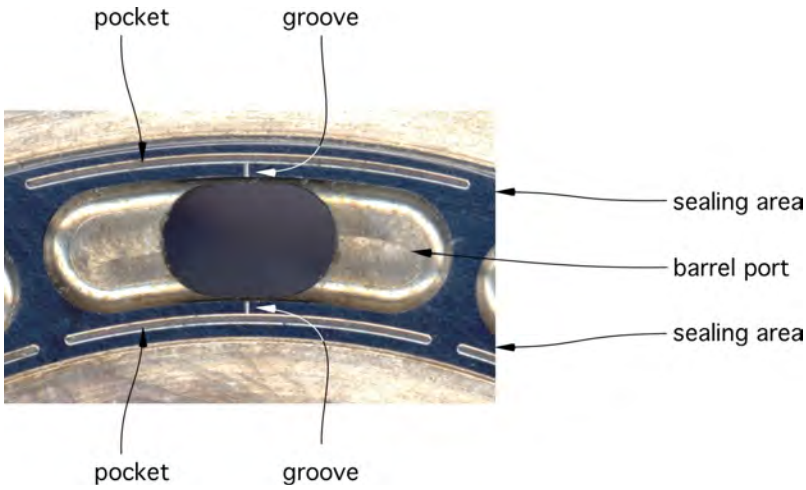


*Figure 2. The design of the sealing lands of the barrel*

The dimensions of the sealing areas and the pockets grooves are optimized for a robust bearing behaviour at all operating conditions, including variations of the oil temperature and viscosity.

## 3. EFFICIENCY MEASUREMENTS

The machine has been tested as a pump at Eindhoven University of Technology according to the test procedures described in ISO4409. The sensors have been calibrated before and after the test. Due to limitations of the test bed only a part of the total field of operation could be measured (figure 3). The pressure was limited to 350 bar, whereas the machine has been designed for rated pressures up to 500 bar. Also the rotational speed is limited to a maximum of 3000 rpm. The remaining area has been measured in a grid of 7x7 = 49 points. The tests have been performed at a supply pressure of 3 bar. Two sets of measurements have been performed at two different temperatures of the oil at the supply side of the pump, one at 40°C and one at 55°C. The oil used was Mobil DTE25 having a dynamic viscosity of 0.038 Ns/$m^2$ and 0.021 Ns/$m^2$ at an oil temperature of 55°C

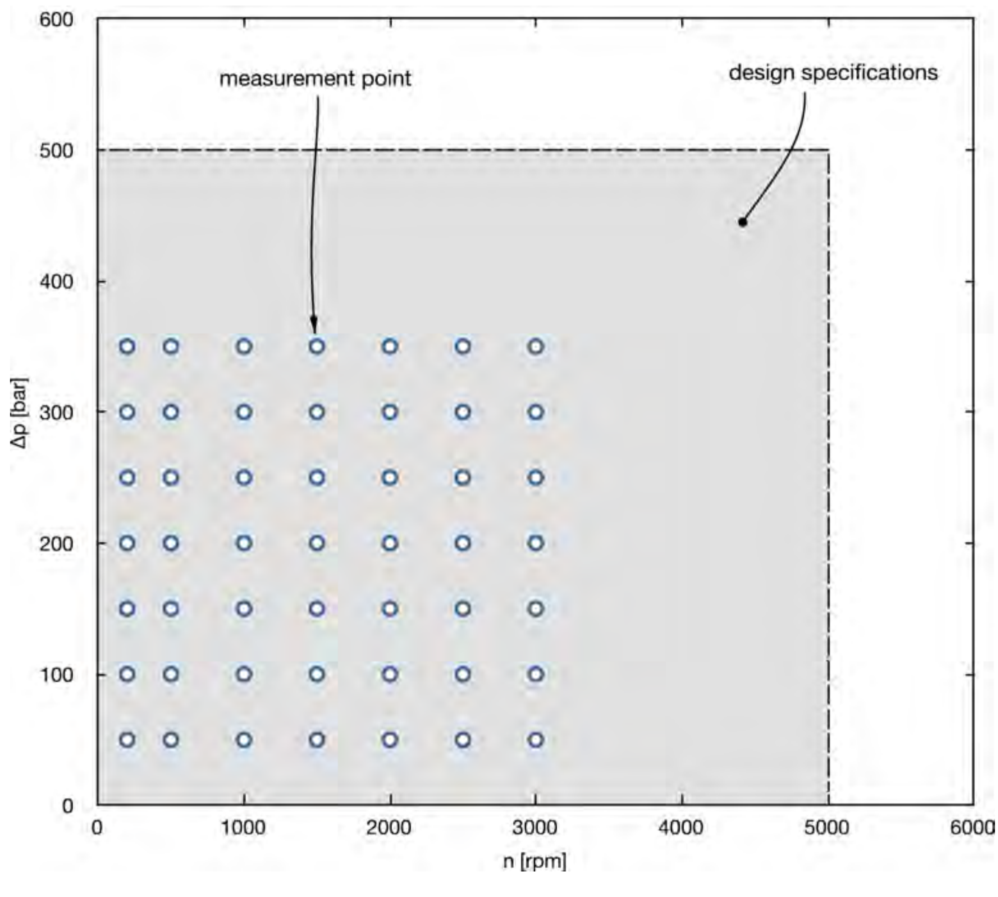


*Figure 3. Design specifications and limited test area*

Although the test points only cover about 42% of the specified design area, the measurements do cover the area that is most important for the vehicle operation in terms of energy consumption and $CO_2$-emission.

The contour plots of figure 4 show the results of the efficiency measurements for pump operation only. There are two plots, one for an oil temperature at the supply side of 40°C and one at 55°C, having an oil viscosity which is about half the value at 40°C. For both measurements the peak efficiency is 96 to 97%. The average efficiency for all test points is 93.5%. The temperature influence is as expected: a lower oil temperature reduces the volumetric losses, but increases the viscous friction. Consequently, a low oil temperature results in a higher efficiency at low operating speeds in combination with high loads. At higher oil temperatures, the reduction of the viscous losses is especially apparent at high operating speeds in combination with relatively low loads.

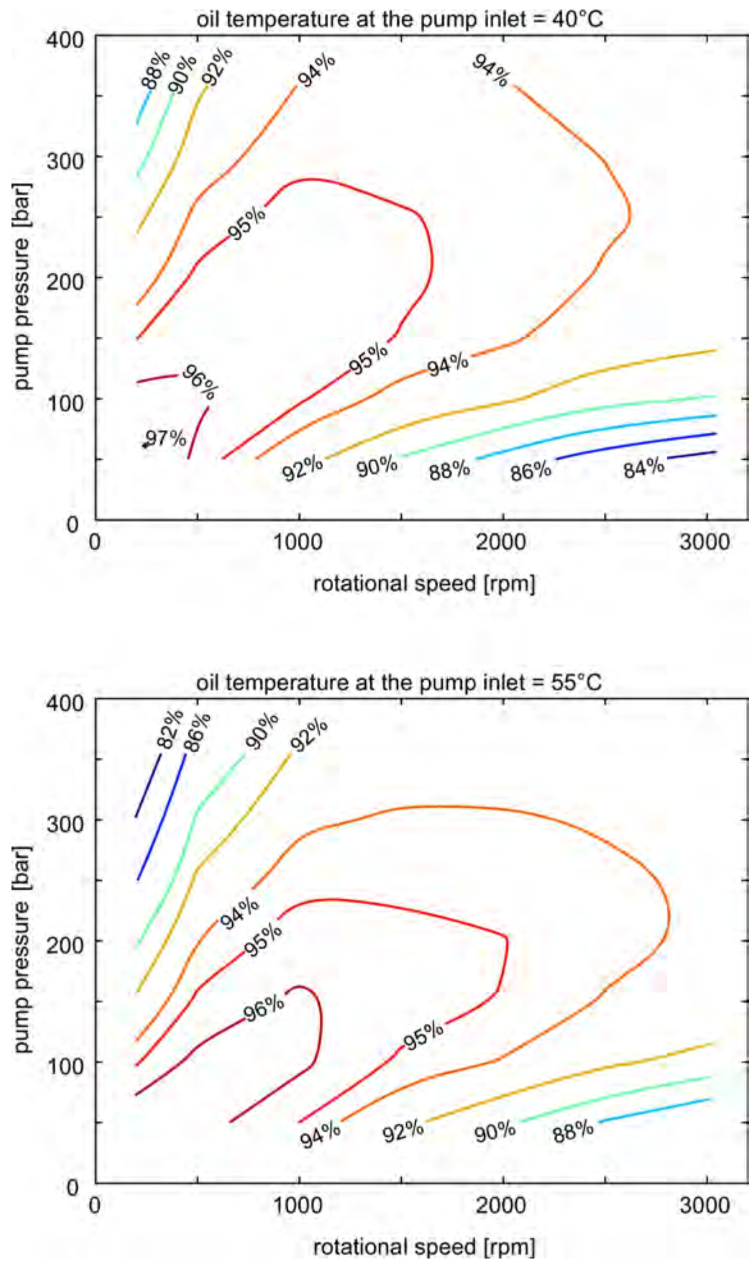


*Figure 4. Total efficiency of the FCM24 in pump operation at two different oil intake temperatures (according to ISO4409)*

As a pump, the unit will be used to convert the engine power to hydraulic power, thereby pumping oil to the high pressure accumulator of the car. Since the internal combustion engine has a minimum rotational speed of 1000 rpm, the pump will not be operated below 1000 rpm. For performing the New European Driving Cycle or NEDC, all of the pump operation will be between 1000 and 2000 rpm. The limited pressure range of the accumulators furthermore forces the pump to be operated between 200 and 420 bar only.

On the secondary side, at the differential, the FCM24 is also used as a pump while braking, thereby regenerating the kinetic energy of the vehicle. Here, the most dominant mode is however motor operation for creating propulsion at the wheels.

## 4. MOTOR EFFICIENCY

The FCM24 has not been tested as a motor. Instead, the data acquired during pump testing have been used to calculate the efficiency of the FCM24 used as a motor. The main difference is that, according to the definition of ISO4409, the compression energy of the high pressure flow leaving (pump mode) or entering (motor mode) the machine, is regarded as an energy loss for the pump efficiency and as an energy gain for the motor efficiency.

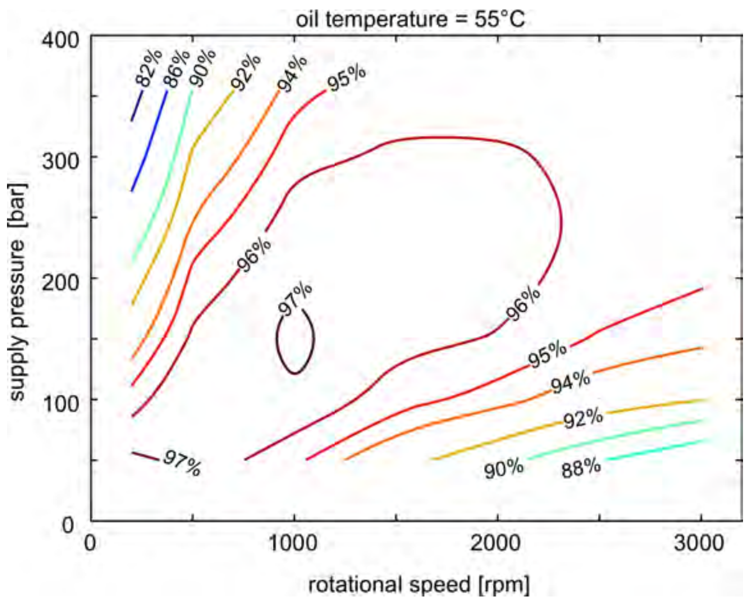


*Figure 5. Efficiency of the FCM24 for motor operation*

The efficiency differences between motor and pump mode are small, but nevertheless important. The hydraulic transmission can compete with the mechanical transmission because of energy recuperation. As a consequence, the hydraulic regenerative transmission performs well when having frequent braking operation. But while cruising at more or less constant speed, there is no regeneration. Even then, the Hydrid drive train often has a lower fuel consumption, because the engine will only be operated at or around the best point of efficiency. But this efficiency benefit can easily become offset by the losses in the hydrostatic transmission. In these modes it is of great importance to reduce the losses in the hydrostatic components as much as possible.

## 5. ALLOCATION OF LOSSES

In order to investigate whether a further improvement of the efficiency is possible, an analysis of all the losses has been made, largely based measurement data. Aside from the total loss, the friction of the piston-cup-interface, the bearing losses, the friction of the shaft seal, the churning losses and the flow losses of the house channels, have all been measured. The commutation losses have been calculated by means of an AmeSIM-model of the FCM24. The most difficult loss to determine is the friction between the barrels and the port plates. This loss has been determined by subtracting all other individual losses from the total loss measured.

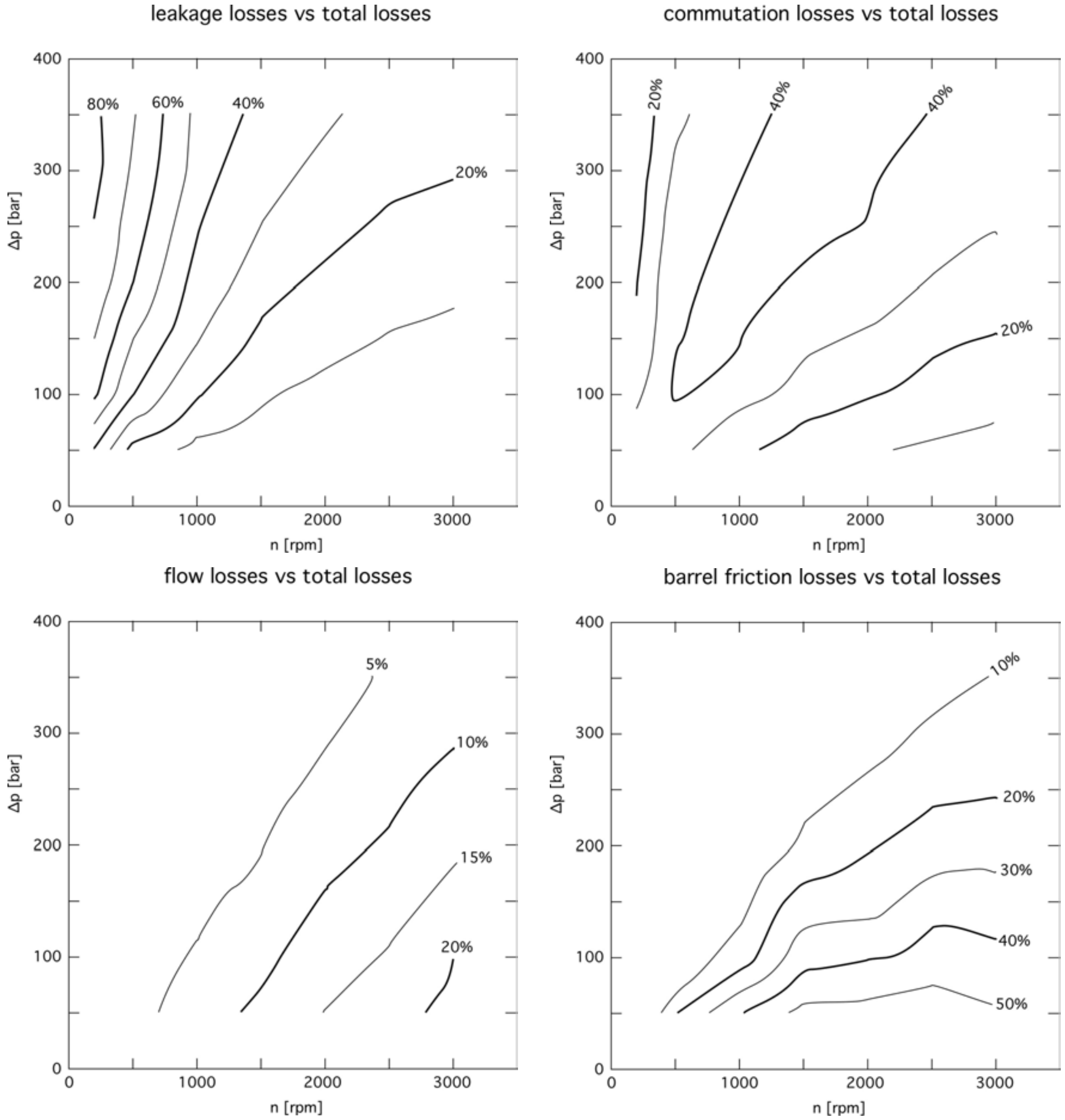


*Figure 6. Most important power losses of the FTM24 relative to the total loss*

Figure 6 shows the most important losses of the FTM24. At low operating speed in combination with high loads, the efficiency is dominated by the leakage. This area is not used frequently in the passenger car application.

At high power, i.e. high speeds and loads, switching from one kidney to the other (the commutation losses) causes about half of the losses. The barrel friction and the leakage together cause about 35% of the losses.

The third area is at high rotational speeds and low loads. In this lower right corner of the field of operation, the barrel friction becomes a substantial part of the total losses. Also the flow restriction in the barrel ports, the port plates and the channels is an important loss factor at these operating conditions.

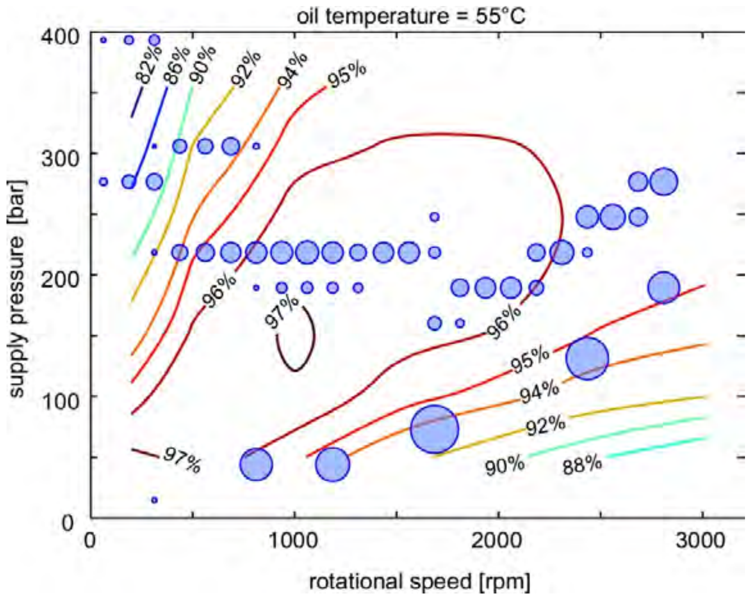


*Figure 7. Points of operation of the motor, applied in a mid-sized passenger car, while performing the NEDC. The size of each circle indicates the amount of energy spend in that operating point.*

The operation of the motor in the passenger car is visualized in figure 7. The blue circles indicate the amount of energy spend in various operating points, while the vehicle performs the NEDC duty cycle. Only the motor operation is shown, not the pump operation during braking. For most operating points, the total efficiency of the motor is 94% or higher. The average efficiency is close to 96%.

A further improvement of the average cycle efficiency is still possible. There is one general remark to make, before considering the means to improve the design: the oil temperature in the vehicle will probably be higher than 55°C. As a result, the flow losses and the viscous friction of the barrels will be further reduced. Otherwise, the leakage will be increased and will become an important loss factor. A further design optimization is therefore needed to reduce the leakage. Furthermore, the commutation losses have become a substantial part of the loss. For most of the operating points in the NEDC the commutation losses already account for up to 40% of the total loss. It will be difficult to reduce these losses, without deteriorating the noise and vibration levels of the motor.

## 6. CONCLUSIONS AND FURTHER OUTLOOK

From a manufacturing point of view, hydraulic transmissions are like gear transmissions, having a housing, some bearings and shafts. Also the loads, tolerances and materials are quite similar. Unlike gear transmissions, hydrostatic transmissions offer much better opportunities for power management, allowing for energy recuperation and improved engine operation. This can result in a strong reduction of the fuel consumption and the $CO_2$-emission, provided that the hydrostatic components have a high efficiency.

A 24 cc constant displacement floating cup motor/pump has been designed specifically for this purpose. The efficiency is higher than 95% in a large area of the operating field. While performing the NEDC in a passenger car application the average motor efficiency is close to 96%. In order to further improve the efficiency a reduction of the volumetric losses has to be realized.

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