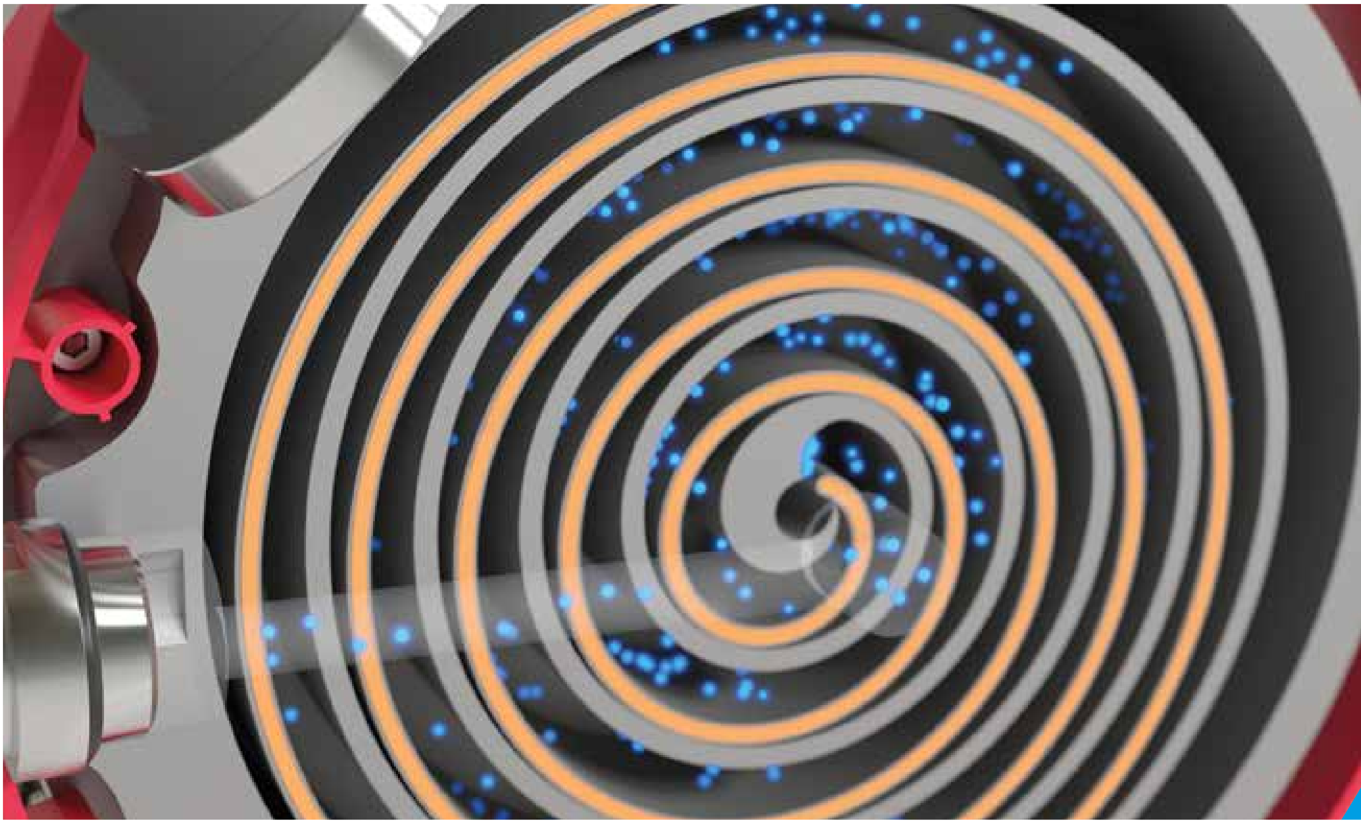
Optimization of Life Cycle Costs for Scroll Pumps

Realization of temperature management

Dry-running scroll pumps are predestined for processes that require oil-free pumping. They are an adequate replacement for the widely used rotary vane pumps, whose pumping speed is not inferior. However, the dry seal required for this is subject to progressive wear, for which the temperature conditions in the pump play a major role. By reducing operating temperatures by



15 %, maintenance intervals are extended and higher performance is achieved at higher suction pressures. At the same time, redundancy of the measured operating parameters increases operational reliability.

To optimize the temperatures, the Finite Element Method (FEM) was used to calculate the temperature field in the pump for three operating conditions and different design variants. This made it possible to identify points with the highest thermally induced wear. As a result, an intelligent fan control system was developed based on the temperature readings from a sensor in conjunction with the power consumption of the motor.

Illustration of an overall thermal system of a scroll pump

The new development of a scroll pump offers the possibility to use numerical simulation techniques to predict and optimize the temperature distribution within the entire pump. This also allows temperatures to be determined at inaccessible points and hotspots to be identified. In the course of product development, the Finite Element Method (FEM) is used to calculate the temperature field in the pump's components for three operating states and for different design variants.

The problem with mapping an overall thermal system is that not all physical phenomena are completely solved and thus not all boundary conditions are known. These include:

- Heat conduction in the moving fluid within the chamber volumes
- Heat conduction through the rotating bearings in which lubricant is also circulated
- Heat transfer coefficient due to forced convection at the outer surfaces of the housing, keyword impingement flow and deflection by hood

In order to determine the unknown parameters, an engineering approach is used to fit them to temperature readings from a real prototype. Figure 1 illustrates this fitting process. First, the uncertain parameters are assumed based on empirical values, the FEM model is calculated and then compared with the available measurement points. Then the parameters are adjusted and calculated again until the agreement between measurement and simulation is satisfactory. In practice, an agreement between the measured and simulated values of > 94% has proven to be satisfactory. This process is carried out for

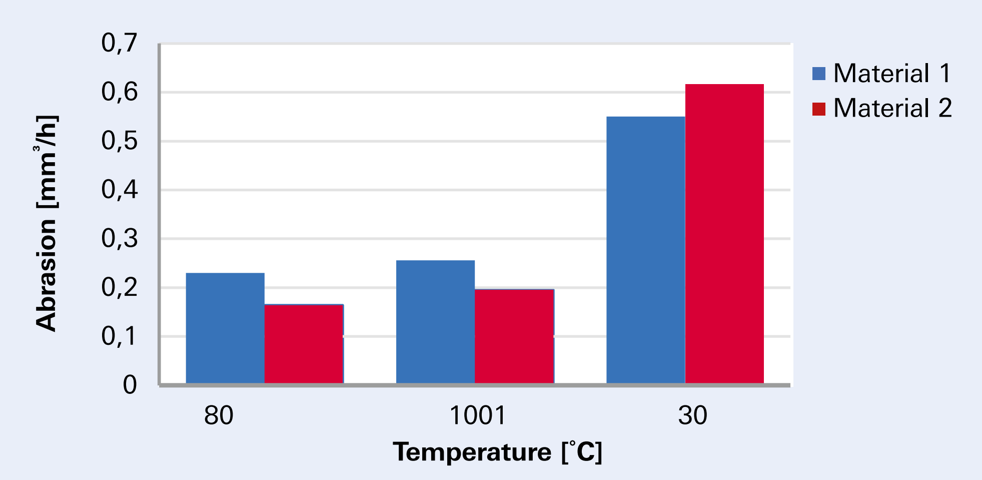


Figure 1: Mean value of abrasion of two plastics as a function of temperature, measurements by Pfeiffer Vacuum.

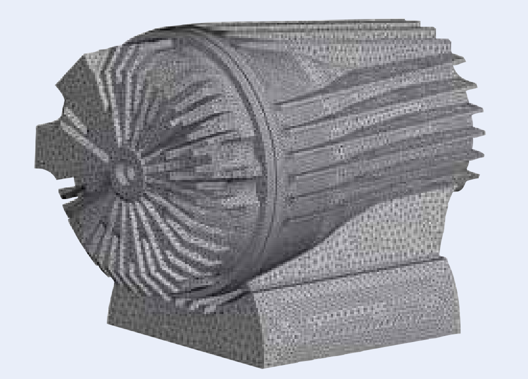


Figure 2: Calculation grid of a scroll pump.

three different operating states. Only when the deviation between measurement and calculation is small for all states, the determination of the parameters can be considered reasonable. With the numerical model and the boundary conditions found, it is then possible to compare and evaluate further design variants.

Development of a basic model for later calculation

A thermally steady state is considered and the pump is modeled as a static system. The numerical computational grid consists of 1,200,000 nodes (Figure 2). The grid resolution is sufficient for the evaluation of the temperatures, since the derivative of the temperature, the heat flux density, plays a minor role. The bearings are mapped in a simplified way and the thermal conductivity of the bearing material is adjusted to the measured values as a free parameter. In the pump volume, the gas is mapped in the innermost three chambers, since the pressure is highest here. In the outer passages, due to the low pressure, the share of heat transfer as well as the compression power is low, which is why the gas is neglected there.

Power losses of a scroll pump to identify heat sources

In experiments, the total power consumption of the pump is determined at the final pressure (without gas flow), as well as at two different gas loads. Energy is converted to heat within the pump using the following loss mechanisms:

- Losses in the motor, most of which occur in the motor stator.
- Losses in the power electronics/ final stage
- Bearing friction
- Frictional power of the two tip seals
- Compression power in the gas
- Heat dissipated by gas (if gas load is present)
- Energy dissipation in the bellows

The efficiencies of the motor and converter are known. Likewise, the bearing friction can be determined as a function of the load, the lubricant viscosity as well as temperature with the help of the calculation specification of a bearing manufacturer. The compression power as well as the dissipated heat quantity of the gas can be determined with equations of thermodynamics and the pressure profile known from vacuum-technical calculations. The energy dissipation in the bellows is below one Watt and is therefore neglected. Since all losses in the final pressure are known except for the frictional power of the tip seals, this is the difference to the total power. The loss or friction power of the seal depends essentially on the contact pressure. This is determined by geometric conditions (gap ratios) as well as the pressure distribution within the pumping system. Here, a constant frictional power is initially assumed for all operating conditions.

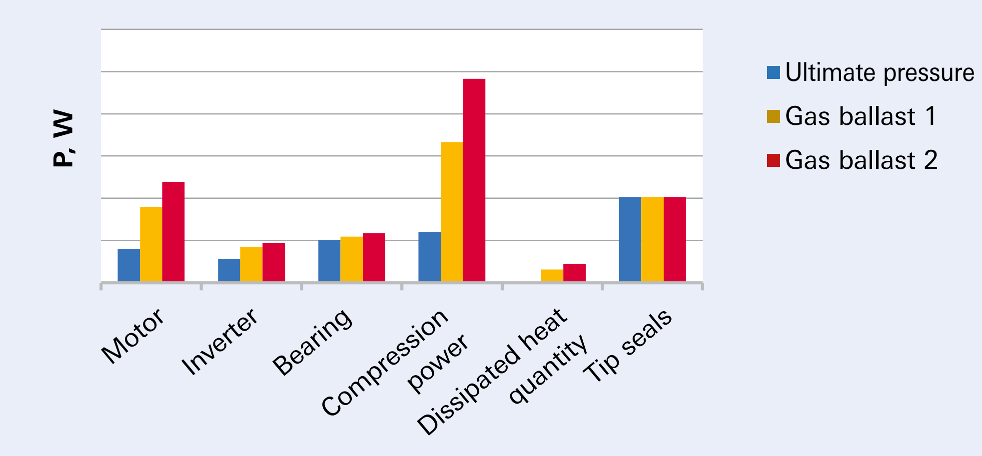


Figure 3: Calculated power losses in different operating conditions.

Figure 3 shows that in the ”final pressure“ operating condition, the friction power of the tip seal accounts for the largest share of the total losses. If gas is admitted to the pump, much of the heat is generated by the compression of the gas and thus likewise within the pumping system. These two loss mechanisms therefore have a major influence on the temperature in the moving spiral. The losses in the motor increase significantly with the amount of gas admitted. Since the motor losses mainly occur in the area of the stator due to the synchronous technology used, they can be dissipated well without placing a particularly heavy load on the temperature balance of the rotor. The losses in the bearing and in the power electronics are rather low in the operating states with gas inlet.

With regard to an optimization of the heat losses, it must be taken into account that no influence can be exerted on the compression power and the amount of heat dissipated by the gas. Likewise, the bearing losses cannot be directly influenced. The contact pressure of the tip seal influences its frictional power, and this cannot be reduced at will either, since otherwise the tightness of the system is not ensured.

Consideration of the heat transfer at the housing to analyze the cooling possibilities

Cooling of the pump is achieved by forced convection using the outside air. Cooling fins integrated into the housing in combination with a fan are used to keep the temperature level of the pump low. In order to quantify the heat transfer coefficients, the flow velocities were measured at several points on the housing. These are 2.1 m/s directly behind the air guide hood and then decrease to 1.24 m/s until the end of the pump. Between the pump and the base, air is passed through to cool the electronic components. Analytical calculations of a convectively flowed flat plate lead to heat transfer coefficients of 10–42 W/m^2/K. Since the geometry is complex and there is also an impingement flow directly behind the fan, the surface is divided into three areas and the heat transfer coefficients are adjusted to the measurement results in these areas.

There is a hotspot directly at the discharge area of the pump system with temperatures up to 122 °C.

Figure 5 shows in which areas the highest temperatures of a scroll pump can be expected. There is a hot spot directly at the outlet area of the pump system with temperatures up to 122 °C. This is due to the high compression performance of the inner chambers. Despite the increased convection at the outer surface of the spiral stator, heat can be poorly dissipated there due to the wall thickness of the spirals. It is to be expected that the thermally induced wear of the seals is greatest in this area, which can be confirmed by tests. Otherwise, the temperature distribution is relatively homogeneous or low temperature gradients are present, which can be attributed to a sufficiently dimensioned wall thickness.

With the model parameters found, the following optimization variants, among others, are investigated:

- Substructure thermally decoupled so that heat losses in the electronics are not dissipated via the pump.
- Flange bearing decoupled from the moving spiral part so that the bearing friction losses are not dissipated into the moving spiral part.
- Shaft made of aluminum instead of steel, as the coefficient of thermal conductivity is significantly higher
- Effect of lower friction of the tip seals
- Increased heat conduction in the bearings, due to changed lubricant
- Additional fan on the motor side of the housing

Through the calculations, the influence on the thermal behavior in the different operating conditions can be shown. Due to minor changes in the temperature profile, some variants can be excluded, thus minimizing the effort required for tests. In principle, it can be concluded that a reduction in the temperatures in the area of the seals can only be achieved by reducing the overall temperature level. This, in turn, can be achieved with increased convection on the outer surfaces, which inevitably leads to increased airflow as a result of improved fan performance.

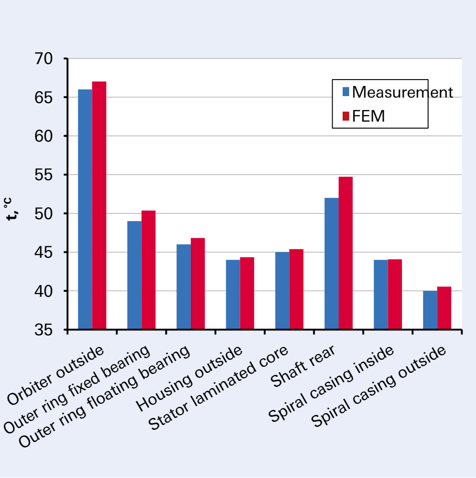


Figure 4: Comparison of temperature measurement with simulation at ultimate pressure.

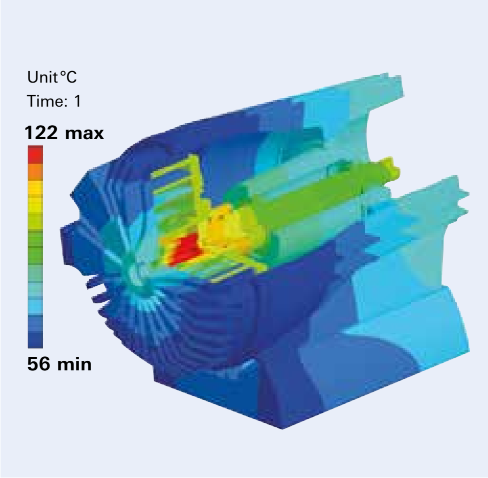


Figure 5: Temperature field inside the scroll pump for the operating condition ″Gas ballast stage 2“ at higher ambient temperature.

Implementation of an intelligent control system to manage temperatures using appropriate sensors

The temperature measurements carried out on real pumps have shown that it is not possible to reduce individual component temperatures independently, taking into account moderate design changes. Furthermore, it was found that at different load conditions, the temperature level of the individual pump components behaves approximately simultaneously. Therefore, it is not absolutely necessary to install sensors to detect the temperatures at the critical components, such as the moving spiral component.

During product development, the position of temperature sensors can be defined within the newly developed scroll pump. Using these temperature sensors, a control loop can be implemented to provide meaningful temperature management. Extensive experiments are carried out to determine the control parameters. For different applications and outside temperatures, this ensures that the pump is operated in the optimal temperature range. With the help of integrated temperature sensors, the speed control of the motor and the fan is used to keep the pump temperature as low as possible under all operating conditions and to prevent critical operating states.

In addition to the aforementioned sensor technology, the pump uses a synchronous IPM motor instead of an asynchronous motor, which initially results in higher efficiency. It also allows speed control over a wide speed range. Furthermore, with this motor technology, most of the power losses are generated in the stator, which has a positive effect on the temperature development in the rotor.

Increasing convection cooling to regulate the temperature

As a first approach to reduce the temperature, an increase of the forced convection cooling can be done by increasing the fan speed or choosing an alternative fan with higher throughput.

It should be noted that both options will increase noise emissions. Scroll pumps in the small to medium pumping speed range are frequently used in laboratory applications. Here, the noise level plays a very important role. Figure 6 shows the emission sound pressure level of a test pump as a function of the fan speed of two fans. It can be seen that the noise level of the pump increases almost proportionally with increasing fan speed (and thus higher air flow). It is therefore necessary to find a sensible compromise between the noise and temperature levels of the pump.

> **It can be seen that as the fan speed increases, the noise level of the pump increases almost proportionally.**

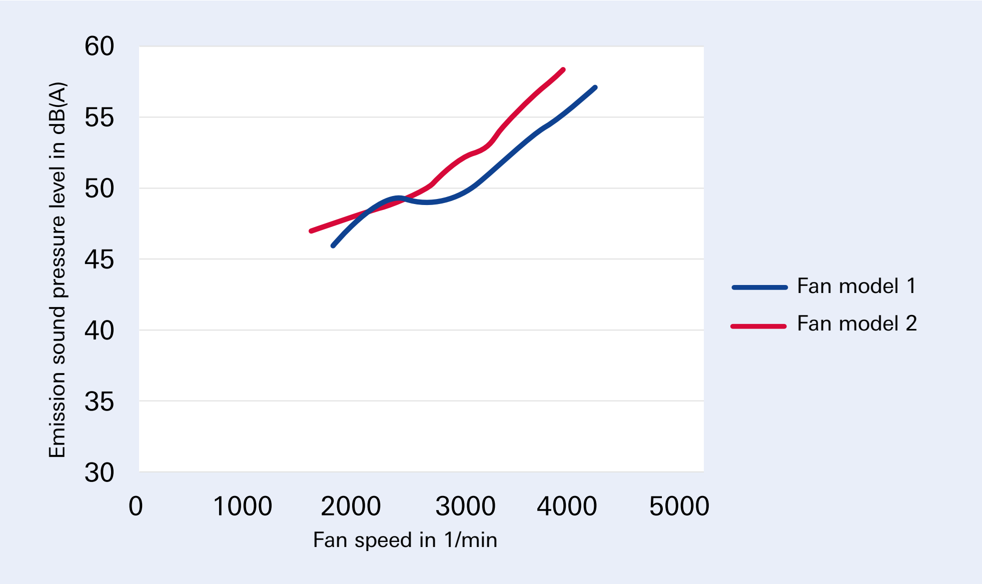


Figure 6: Measured emission sound pressure level of a test pump as a function of the respective fan speed and fan model.

In the case of a low load on the pump, for example operation of the pump at ultimate pressure at low ambient temperatures, convection cooling and thus the noise level can be kept low. Even a short operation of the pump under load (evacuation of a small container) will make little difference to the temperature level due to the massive component design and associated inertia. However, if the pump is operated for evacuation of larger containers, in higher ambient temperatures, permanently at higher intake pressures (> 100 mbar) or with larger gas ballast quantities, a significant increase in pump temperatures and thus wear is to be expected. In these cases, an increase in convection cooling over the period of the load increase is the target.

In order to meet all requirements, it is therefore advisable to control the convection cooling according to the pump temperatures, but also according to the pump load. Furthermore, in some situations (for example, an unintentional overload of the pump) it may be necessary to reduce the performance data of the pump in order to prevent long-term damage to the pump.

If, for example, the pump is subjected to a further load even though it has already reached its thermal load capacity, the pump speed or the maximum available drive power will be reduced until the pump stops. This ensures the intrinsic safety of the pump. Thermal loads can be reached by higher ambient temperatures or by higher pressure ratios.

Modern vacuum pumps have drive electronics that can be used to control the pump motor, integrate electrical accessories or provide electrical interfaces for communication. The drive electronics can also be used to implement temperature management in the form of situational control of convection cooling and temperature-based reduction of performance data.

Further development of the thermal concept
Expansion of the analyses to define limitting values as well as further optimizations

In the course of product development, the pump was equipped with temperature sensors and a fan model was selected which, in addition to a high life expectancy, also has the property of speed control over a wide range by means of pulse width modulation (PWM). Temperature sensors on spiral components were not used due to the limited practicability of the cable connections, especially since the simulation results show that the temperatures of the components behave analogously to each other in steady-state operating conditions.

In most cases, electronic components (e.g. the power stage of the drive) have temperature sensors. In addition, a temperature sensor is provided within the motor winding.

In extensive temperature tests, including those with changed ambient temperatures, temperature management options and limit values were defined. With the series of tests, conclusions can be drawn about the temperatures on other components based on the measured values of the existing temperature sensors.

The tests showed that a pure control of convection cooling based on the data of a temperature sensor is not effective due to the multitude of possible operating conditions. A fan control based on the temperature readings of a sensor in conjunction with the power consumption (available parameter in the drive electronics) was defined. If a specified limit is exceeded, the fan speed is continuously adjusted to match the power consumption. Furthermore, limitting values have been defined for all temperature sensors. If these threshold values are exceeded, the fan speed is also increased to the maximum independently of the power consumption, since it can be assumed that a critical operating state is imminent. If a second threshold value of the individual temperature sensors is exceeded, the pump power is gradually reduced on the drive side, thus preventing damage to the pump or drive components.

This empirically developed temperature management based on power consumption and temperature measurement has the advantage over purely temperature sensor-based convection cooling that it can react dynamically to load changes. It also ensures that a minimum noise level is achieved under all operating conditions. For example, immediately after the end of an evacuation process, the fan speed and thus the noise level are reduced as the power consumption decays. At the same time, a significantly higher cooling capacity is achieved during the evacuation process, in contrast to the operation of a fan at a fixed speed. The situational fan control also allows a significantly higher load on the pump–for example, higher performance can be achieved at higher intake pressures. In particular, a short-term overload capability (boost mode) is made possible. A low fan speed at final pressure or after the pump is switched on ensures rapid heating and thus operational readiness.

> **At the same time, a significantly higher cooling capacity is achieved during the evacuation process.**

Since several temperature measurement variables as well as the power are included in the temperature management, redundancy is achieved and thus operational reliability is increased. In the event of a simple fault (e.g. defective fan, inadmissible intake or discharge pressures), the reduction in performance data prevents the destruction of individual pump components or the entire pump.

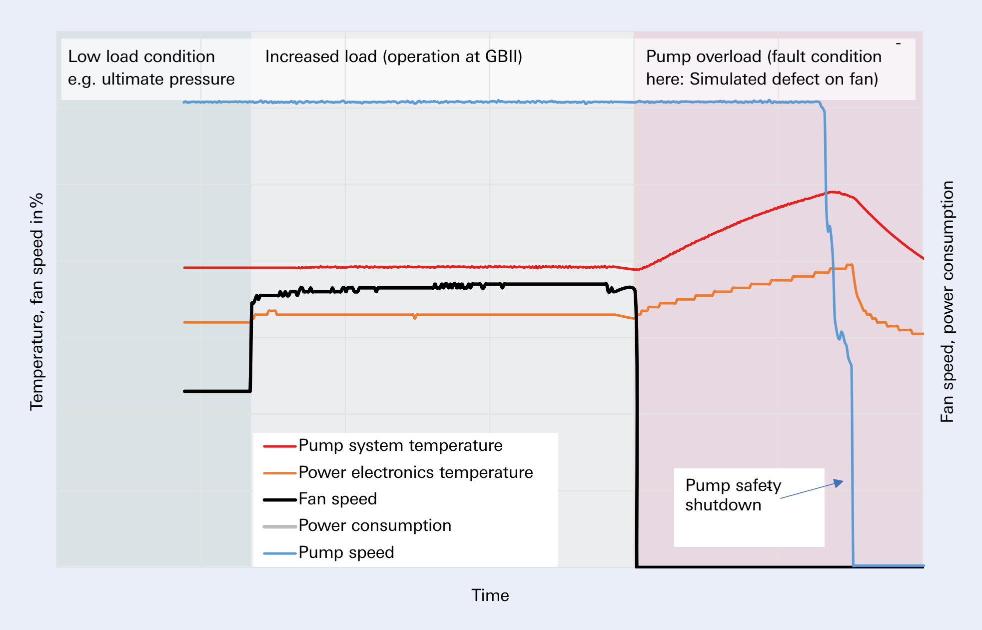


Figure 7: Functionality of the temperature management described using the example of a scroll pump under various load conditions.

Figure 7 shows measured temperatures, fan speed, pump speed and internal power consumption under different load conditions of a scroll pump with software-based temperature management. Due to the increased fan speed, which is analogous to the power consumption, the pump system temperature and the temperature of the power electronics are kept almost constant. Furthermore, the diagram illustrates the function of the safety shutdown, for example due to a defect in the fan. After a limit temperature has been exceeded, the power of the pump is gradually reduced until it is switched off completely, thus preventing irreversible damage to the pump components. Furthermore, it is clear that the elimination of forced convection results in a significant increase in temperatures.

Figure 8 shows measured temperature curves under the influence of a fixed fan speed compared with an intelligent fan control defined according to the above description for a pump operating point. It is evident that there is a significant difference in heating over the operating time. In this example, a temperature reduction of 7-9 °C is achieved using the fan control. At the same time, low noise emission is ensured at low load.

The temperature reduction achieved not only has a positive effect on the service life of the seals, but also on the durability of other components such as the bearings and power electronics.

The temperature reduction achieved has a positive effect on the service life of the seals

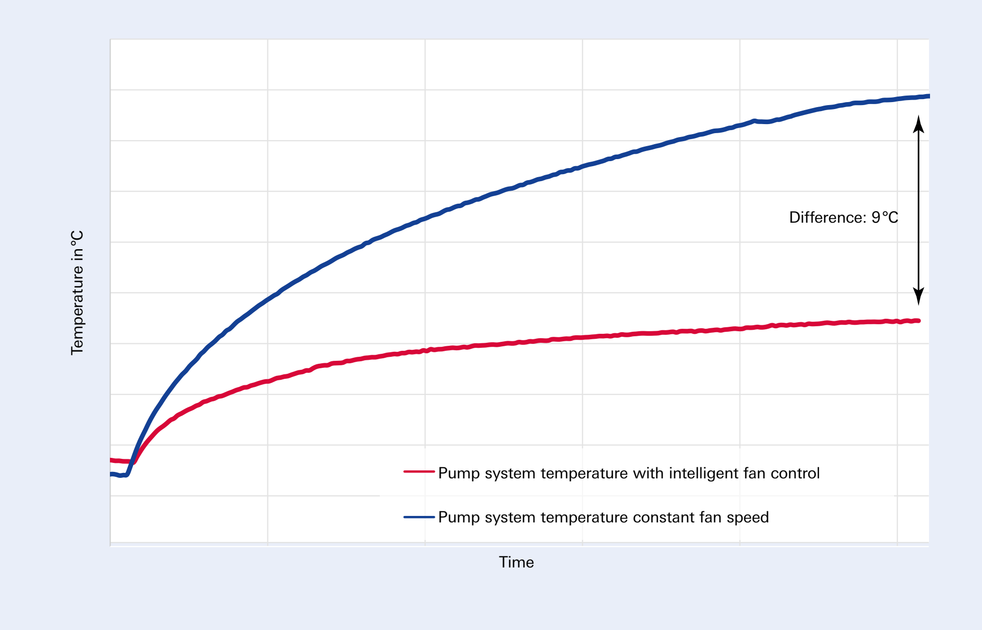


Figure 8: Measured exemplary temperature curves of an average load condition of a scroll pump (comparison of constant fan speed with intelligent fan control).

Summary

In summary, it can be said that using intelligent drive technologies, high-quality fans and modern calculation methods, the temperature balance of scroll pumps and thus the service life of essential components can be optimized. Simulations allow critical components to be defined at an early stage, optimization variants to be identified and different approaches to be compared. In addition, simulation enables conclusions to be drawn about temperatures at critical components that cannot be determined empirically using a reasonable amount of effort.

Extensive test series are used to control the fan and pump speed by means of existing sensor technology, thus defining a software-based intelligent temperature management. Consequently, a higher performance of the pump is realized. This is achieved without compromising the service life of the components, especially the tip seals. Compared with conventional design principles, temperatures can be reduced by up to 15%, which extends maintenance intervals.

The temperature management in the scroll pump to be developed is being implemented with the aim of optimizing the service life of the individual components at a low noise level, especially at higher loads, and thus meeting today's requirements in terms of sustainability and CO_2 footprint.

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