Flow rate estimation in glandless circulator pumps - influence of temperature and water-glycol heat-transfer fluids

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Abstract

In this paper, the operation principle, uncertainty factors and the influence of water-glycol heat-transfer fluids at different temperature on a function that estimates the volumetric flow rate in a glandless circulator pump are investigated. The influences are examined theoretically and experimentally using a common circulator pump. Modern electronically controlled variable speed pumps determine the pump speed and power consumption. Combined with predefined characteristic maps, the pump electronics can act as a soft sensor and estimate the operating point and therefore the volumetric flow rate of the pump. To exchange this information with other systems, the LIN circulator profile, a standardized digital interface can be used. The flow rate estimation is based on characteristic maps that represent the real pump performance as accurately as possible. The extent to which deviations affect the flow rate estimation depends on the operating point of the pump. Especially at low speeds and steep head loss system curves, even small deviations lead to large uncertainties. In many thermal plants, e.g. solar thermal systems, water-glycol heat-transfer fluids are used. Here, the fluid properties deviate from clear water, which leads to a changing performance of the pump. Also, the fluid properties are highly temperature-dependent. This causes a strong effect on the flow rate estimation and leads to a wide possible error margin which is shown experimentally.

Keywords: flow rate estimation, soft sensor, circulator pump

1. Introduction

Quantifying volumetric flow rates plays an important role in the control, optimization, monitoring, and fault detection of HVAC systems. For this purpose, a wide range of sensors is available on the market. However, these sensors entail additional investment, installation, and maintenance costs. Especially in smaller systems, e.g. smaller solar thermals systems, they are a significant cost factor. But even in larger systems often not all volumetric flow rates are measured due to costs considerations.

Circulation pumps in these HVAC systems are a major energy consumer. In the European Union they were responsible for an electricity consumption of 50 TWh in 2005. To reduce this enormous demand for electricity, the EU member states decided to gradually introduce strict energy efficiency standards for circulators in Regulation (EC) 641/2009 as part of the Ecodesign Directives (ErP). Since 2013, only pumps that meet these efficiency requirements may be newly installed. Since 2020, the regulations have also applied to the replacement of existing pumps. The regulation has resulted in a technological shift, as the requirements can de facto only be met by speed-controlled circulator pumps with electronically commutated permanent magnet motors (ECM) (UBA, 2009).

One of the main efficiency advantages is based on an electronically controlled frequency converter, with which the motor speed can be reduced in part-load operation, thus lowering the power consumption of the pump. The pump electronics permanently record important operating data of the electric motor such as speed and power consumption. Based on this data and information on the pump characteristics, it is possible to estimate the flow rate delivered by the pump. Various manufacturers now offer pumps with this type of flow rate estimation. The flow rate and other values determined by the pump can, on the one hand, be used for control concepts implemented in the pump electronics. On the other hand, it can be used via communication interfaces, for instance with the new standardized Lin-Bus protocol, to exchange the acquired data with other systems. However, there is hardly any publicly available information on the quality of such a flow rate estimation or the impact of pumping media conditions that are often occurring in heating systems, such as varying temperature and propylene-glycol based heat-transfer fluids.

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2. Operating principle and relevant research

The performance characteristics of pumps can be described in the form of characteristic curves as a function of the flow rate Q. In the scope of this work the relevant parameters are the dynamic total delivery head H, the pump efficiency η and the power consumption P. The dynamic total delivery head H is a unit of energy that is often used in the in the context of pump performance. It is a measure of the specific work transferred by a pump to a fluid equivalent to the vertical rise and friction losses that occur in the system. The non-SI conform unit is meter liquid column.

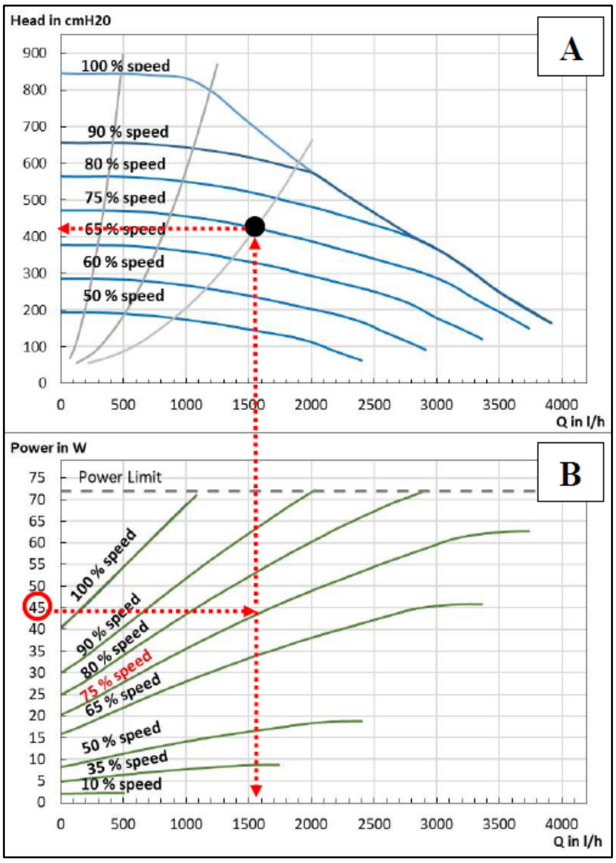

Fig. 1 A: H,Q-characteristic-curves for different pump speed levels (blue) and plant curves (grey)
B: P,Q-characteristic-curves for different pump speed levels(green). Relation between operating point, power, flow rate and speed marked red.

The head characteristic curve (H,Q-characteristic curve) describes the delivery head a pump can achieve at a specific flow rate. In Figure 1-A the exemplary characteristic of a circulator pump can be seen. The decreasing head with increasing flow rate is typical for the characteristic curve of a centrifugal pump.

The operating point is set where the head of the pump and the head-loss of the system are equal, seen as the point of intersection of the system head curve (grey) and the head characteristic curve of the pump (blue). System characteristics with high losses are called steep and the ones with low losses are called flat, according to the slope of the system head curves in the H,Q-diagram.

Various losses in the pump (fluid friction, gap flows, bearing losses, etc.) result in the mechanical energy of the pump impeller not being fully transferred to the pumped medium in the system. The efficiency of the pump describes the ratio of the mechanical power applied to the pump shaft and the hydraulic power transferred to the fluid.

The shaft power of the pump results from the required hydraulic power at the operating point and the efficiency of the pump at the operating point. The relationship of pumped flow rate and shaft power of the pump is given by the P,Q-characteristic-curve (Fig. 1-B).

For variable speed pumps these characteristic curves are not static. The head characteristic curve, the efficiency and power-flow rate relation are changing with variable speed.

This leads to a three-dimensional power-flowrate-speed-map (P,Q-characteristic-map). The power-flow curves at constant speed (P,Q-curves) are projections of this map. So, if power, speed, and the pump characteristics are known, the flow rate and head of the pump can be assigned unambiguously for most operating points.

3. Overview of relevant research

Based on this basic operating principle, various research works are dealing with the estimation of flow rate in centrifugal pumps.

Hammo and Viholainen (2005) test a method patented by ABB for a pump frequency inverter. Using laws of similarity, P,Q-characteristic curves for other speeds are calculated from a single P,Q-curve. For a centrifugal pump with 25 kW power, an estimation error between 0-28 % of the nominal flow rate is achieved.

Ahonen et al (2011) present a hybrid method. If the system curve is known, the flow rate is estimated, depending on the operating point, using the P,Q method or by estimating the delivery heads and then determining the flow rate from the intersection with the known system curve. The method was verified experimentally on one 11 kW centrifugal pump and shows lower estimation errors than the sole P,Q method.

Bakman and Vodovozov (2013) investigate the dynamic behavior of pressure and flow estimation for use in the control of centrifugal pumps.
Pöyhönen et al. (2019) show an approach that does not require pump curves given by the manufacturer or extensive measurements. With the help of four parameters: power, flow, head and speed at the nominal point and universal, dimensionless characteristics for centrifugal pumps, pump-specific characteristics are generated. Using the P,Q method, the volume flow rates are estimated from these. Applied to four pumps between 2.7 kW and 45 kW, the error is 7-15 % of the nominal flow rate.

All the considered publications deal with high power glanded pumps with a dedicated pump, motor, and inverter assemblies in cold water operation.
For the application of flow rate estimation for highly integrated glandless pumps with low power ratings (<2500 W), as often applied in small and medium sized HVAC applications, hardly any information can be found. However, various manufacturers now also implement a flow rate estimation feature in such small pumps.

4. Pump communication interface

Should the volume flow estimation be used as a soft sensor solution, a communication interface is needed to exchange data with other systems.
The Local Interconnect Network is as communication standard originally developed in the automobile industry for applications that are not time or safety critical such as the networking of seat and window controls. It is a widely used and cost-optimized digital communication standard that offers a relatively simple communication protocol and hardware requirements that are inexpensive to implement while maintaining a high reliability.
The LIN-BUS is a bidirectional, serial one-wire transmission interface. A LIN cluster is set up in a master-slave configuration. The master task makes a specific request to a LIN-slave in the form of a frame header. The associated LIN slave recognizes the header and responds with the requested information, the frame response. Header and response together form a LIN frame. The response can contain up to eight bytes of information. To detect transmission errors and to check the integrity of the data, a checksum is appended (Christmann, 2007).
In order to make the advantages of the Lin bus available for HVAC applications, a group of manufacturers has joined efforts to define a general LIN circulator profile (LCP) in VDMA Standard 24226. In the future, other plant-integrated components, such as burner fans, are also to be connected via the LIN bus (VDMA, 2020). The LCP uniformly defines an extensive number of instructions that can be sent to the pump and current operating and diagnostic data that can be retrieved from the pump. Table 3.1 shows a selection of available information.

Tab. 1: Selection of data points defined in the LIN circulator profile

Commands to the Pump	Pump operating data	Diagnostic data
• Set point • Control method (speed, head, flowrate) • Switch on/off • Additional manufacturer-specific data	• Operating status • Speed • Power output • Estimated flow rate • Estimated head • Fluid temperature (if available)	• Cumulative operating time, • Number of start-ups, • Min/max flow rate,

5. Influences on the uncertainty of the flow rate estimation

The shape of the characteristic pump map and the operating point of the pump are fundamental for the general uncertainty of the flow rate estimation. The general shape of the characteristic pump map is depending on the hydraulic design of the pump. The operating point and therefore the flowrate and head of the pump depends on the pump speed and the system head curve (cf. Fig 1 A).

The ratio of power and volume flow at a constant pump speed is described by P;Q-curves, the gradients of these P,Q-curves vary with the pump speed (cf. Fig 1 B). Here, P;Q-curves at lower speed levels have a decreases gradient, at 10 % pump speed the gradient is almost zero. It can also be seen that the gradient of a P,Q curve decreases at very high flow rates and finally also approaches zero. At this operation points a small uncertainty in power detection or a small deviation of the pump characteristics map have a very high influence on the estimated flow rate.

Fig. 5 shows the magnitude of this effect on uncertainty of the derived flow rate depending on the operating point in the H,Q-map of the investigated pump. An uncertainty in detecting the pump's power of +-0.72 W (+- 1% of the maximum pump power) is assumed. The flow rate is derived by two-dimensional linear interpolating from the existing characteristic map of pump. The uncertainty range of the derived flow rate relative to the real flow rate is shown in a colour map. For very low flow and head and also for very high flow rates no flowrate can be derived. The smallest uncertainty reached for flowrates between 1200 l/h and 3000 l/h and a delivery head between 300 cm and 859 cm, corresponding to relatively flat system head curves and moderate to high pump speeds.

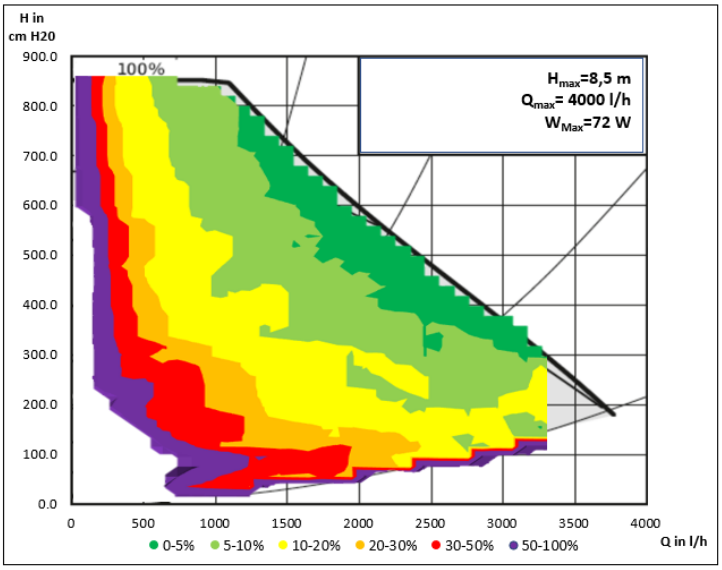

Fig. 2: Uncertainty of volume flow based on an induced power determination error of +-0.72 W

Also, the pump characteristic maps are typically created for standardized fluid conditions, (normally water at 20 °C). Fluid properties that deviate from these conditions can significantly influence the pump characteristics and therefore the accuracy of the flow rate estimation. The most important fluid characteristics in HVAC systems are the viscosity and the density of the fluid. Both properties have a significant temperature dependence. A higher fluid density causes an approximately direct proportional increase in power requirement. The influence of the viscosity is more complex. With increasing viscosity, the various friction losses in the guide vanes and especially the disc friction loss between fluid and pump impeller increases. This leads to a decreased overall pump efficiency and therefore an increased P,Q-ratio. The impact of decreased pump efficiency is also dependent on the speed, and to a lesser extent on the flow rate, and therefore on the operating point of the pump. The head characteristic curve is also influenced by the viscosity. Here, with increasing viscosity, the hydraulic performance of the pump changes, which leads to a reduction in the head characteristic curve. However, for the viscosity of water glycol-mixtures at typical operation temperature (ν<10 mm²/s), this effect is very small and can usually be neglected (Gülich, 2014). Fig. 3 shows the effects of increased density and viscosity on the pump characteristics schematically.

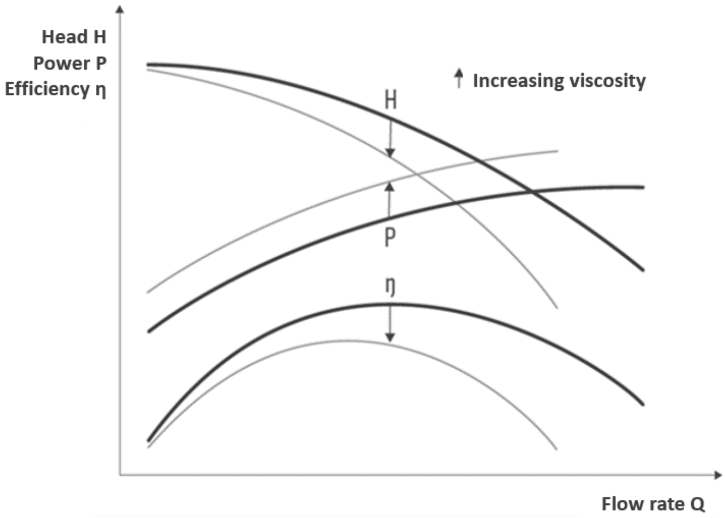

Fig. 3: Schematic representation of the viscosity influence on head, power and efficiency curves based on (EDUR, 2018).

6. Experimental investigation of the flow rate estimation

The tests are carried out on a closed loop test rig, see Fig. 4. With the aid of a restrictor valve, the pressure loss coefficient and thus the system characteristic can be adjusted. To compensate for the dissipating pump energy and guarantee a constant fluid temperature, excess heat can be removed with a heat exchanger. With a controlled flow heater, the fluid can be also heated up to 85 °C. A small storage tank reduces thermal and hydraulic oscillations in the system. The pressure difference between the suction and discharge side of the pump is measured by a differential pressure sensor. As a reference value for the flow rate estimation, the flow rate is measured by a calibrated electromagnetic flowmeter.

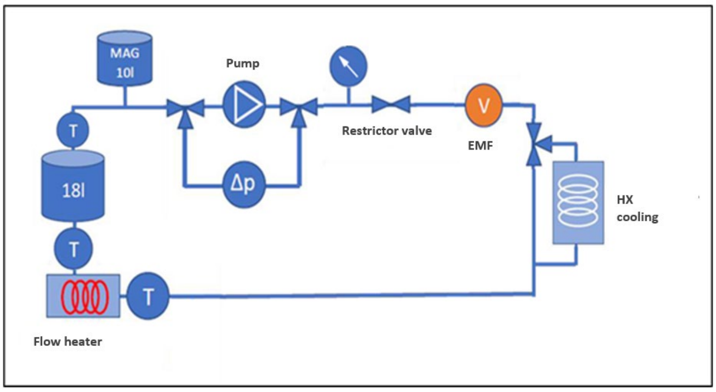

Fig. 4: Layout of the flow rate test rig

For control and communication with the pump, a LIN cluster is set up, consisting of only two nodes. An ATmega2560 microprocessor acts as master. All frame responses defined in the LCP can be retrieved from the pump and corresponding control signals, in this case the speed input, can be sent to the pump. The speed is defined according to LCP as integer per mil value of the maximum speed.

The flowrate estimation is examined systematically at different operating points of the pump.
The operating point and thus the real flow rate of the pump is determined by the system characteristic curve and the speed of the pump. The loss coefficient of the system curve can be adjusted via the regulator valve. The pump speed is given as the setpoint value. At each constant system characteristic curve 15 operating points are considered by varying the pump speed. The 15 speed levels are evenly distributed between 4800 rpm (100%) and the minimum

speed 499 rpm (10.3%). For each operating point the flow rate estimated by the pump Q_{pump} is compared with the flow rate measured by electromagnetic flowmeter Q_{meas} under steady state conditions. To evaluate the accuracy the relative estimation error f_Q is used (eq. 1) is used

$$f_Q = \frac{Q_{pump} - Q_{meas}}{Q_{meas}} * 100\% \qquad \text{(eq. 1)}$$

The approach with constant system curve and variable pump speed reflects the operating conditions as they are found, for example, in a solar circuit with variable flow rate (matched flow system).
In order to reproduce typical fluid conditions in such thermal plants, in addition to cold water, the operation with a 42%-propylene-glycol antifreeze mixture at temperatures between 20°C and 80°C was investigated.

7. Estimation uncertainty in operation with cold water

To examine the accuracy of the volume flow estimation in operation with clean water at 20°C water, Fig. 5 shows the relative estimation errors f_Q for three different system curves (A B C). The error for the 15 operating points is plotted versus the flow rate under constant system curve conditions.
For better comparability of different system curves, the flow rate at operating point is shown as fraction of the maximum flow rate Q_{max} that can be achieved with maximum pump speed for the respective system curve. With a constant system characteristic curve, the volume flow increases in direct proportion with the pump speed. This means that 50 % of the maximum flow rate of the system characteristic curve is also achieved at approximately 50 % of the maximum pump speed.
In Fig. 5 A (Top) the estimation error for a system characteristic curve with a maximum flow rate Q_{max} = 1250 l/h and a maximum head loss of H_{max} = 8.7 m at maximum pump speed can be seen. In part B (bottom left) the error for a much steeper curve with Q_{max} = 500 l/h and a head loss of H_{max} = 8.9 m is shown. A relatively flat system characteristic curve with an almost completely open restrictor valve, Q_{max} = 2000 l/h and H_{max} = 6.6 m is shown in part C (bottom right).

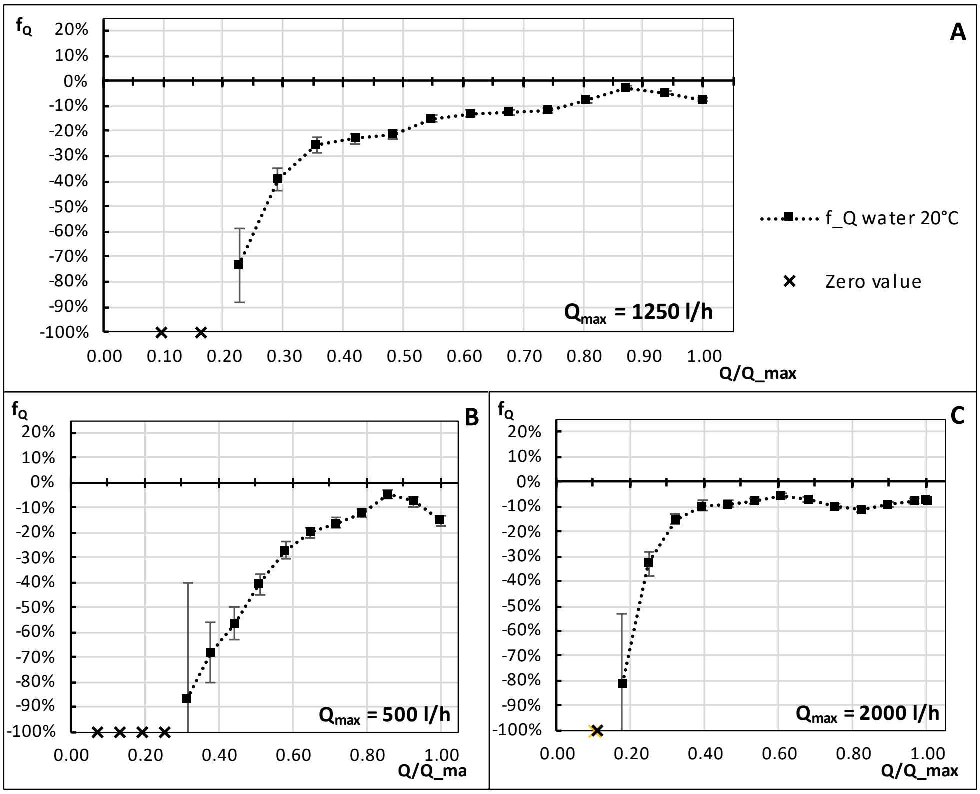

Fig. 5: Relative error of flow rate estimation over real dimensionless flow rate for different system characteristics with 500 l/h (B), 1250 l/h (A) and 2000 l/h (C) maximum flow rate

The flow rate in this operating condition is underestimated for all three system curves, i.e., it has a negative measurement error. With increasing flow rate (increasing pump speed), the relative measurement error tends to decrease. The error bars show the relative standard deviation of the estimated flow rate value received from the pump. Here for smaller volume flows/speeds, the flow rate value received from the pump fluctuates considerably.
For even lower speed points the pump only returns a zero value for the flow rate, the real flow rate is here outside the detection limit and the error is consequently -100 %. This is marked with a cross in the diagram.
Looking at a moderate system head curve (Fig. 5-A), the operating point at which a flow rate value is returned by the pump is at a relative volume flow of 23 % or 280 l/h. However, only a flow rate of 75 l/h is detected here and thus the flow rate is underestimated by 73 %. The smallest estimation error (-2.7 %) is reached at a relative volume flow of 87 %.
For the steep system characteristic curve with a maximum flow rate of 500 l/h in Fig. 5 B (bottom left), the lower detection limit shifts to higher relative flow rates. Also, the decrease of the measurement error with increasing flow rate is much less pronounced compared with the flatter system curves. An estimation error of less than 20 % can only be achieved at relative flowrates of 60% and more.
For very flat system curves as in Fig. 5 C (bottom right), the measurement error for small relative flows/speeds is also very large, but this quickly decreases with increasing flow and reaches a plateau with an estimation error ≤ 10 % at about 50 %of pump speed.

In order to further investigate the consistent underestimation of the volume flow, it useful to plot the measurement data as P,Q-characteristic curve (cf. Section 1 – Operating Principle).
Fig. 6 therefore shows the P,Q-curves based on real measured flow rate (black) and the P,Q-curve that results from the estimated flow rate (orange) of the pump. In this representation, the pumps speed levels are constant in P,Q-curves. It can be seen that all real performance P,Q-curves in comparison to the estimation P,Q-curves are shifted to the right, to a higher volume flow. That means, for a specific power determined by the pump, a larger volume flow than defined in the characteristic map that used for the estimation is delivered. The volume flow is consequently underestimated by the pump.

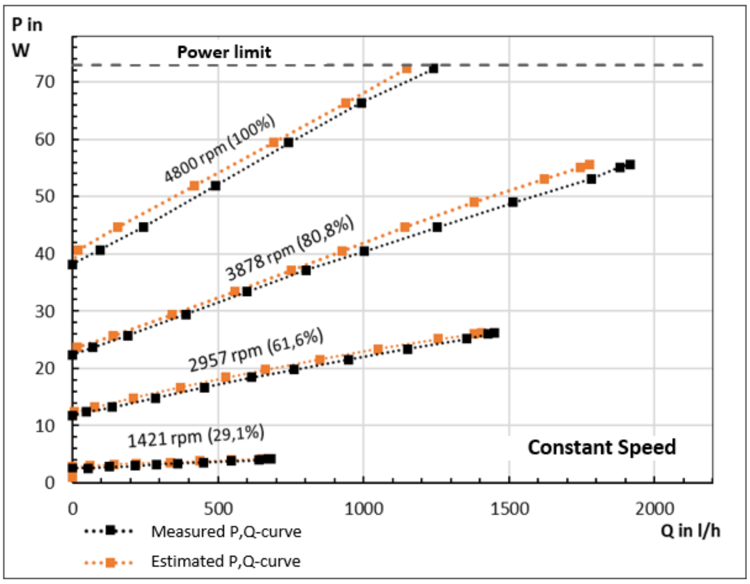

Fig. 6: P,Q-characteristic curve at constant speed levels for measured flow rate and pump estimated flow rate

It is shown that the error of the volumetric flow estimation varies very strongly with the operation point of the pump. For the regarded pump a reasonable quantification is only possible if the system characteristics are not too steep, and the pump speeds are relatively high.
These results are in line with the theoretical considerations in section 4. As the pump speed decreases, the uncertainty of the flow rate estimation increases. This effect is also much more noticeable with steep system curves and therefore lower flow rates. However, the root cause of the consistent estimation error is a significant deviation between the characteristic pump map that is used for the flow rate estimation and the real performance of the pump.
There are several possible reasons for the deviation between the real and the stored pump map. One potential cause are production-related variations of the pump performance.

Also, different design decisions can influence the estimation pump map. For example, the manufacturer may prioritize reliable detection of a required minimum flow rate over the lowest possible estimation error. This 'flow switch' function could be, for example used for fault and functions checks in a thermal system where otherwise there is no information on the flow rate at all.

8. Estimation uncertainty in operation with water-glycol heat-transfer fluids

The flow rate estimation in operation with a 42%-propylene-glycol water mixture is examined at temperatures of 20°C, 50°C and 80°C. Figure Fig. 7 shows the relative estimation errors f_Q for the three different system curves (A B C). For the glycol-mixture at 20°C (blue), the volume flow rate is significantly overestimated. This is true for all investigated system head curves and for most relative flow rates. For steep system curves (Fig. 7-B), the flow rate is overestimated by up to 65%. Only at very low pump speed the flow rate is underestimated here as well.

Compared to water, the lower detection limit shifts clearly to smaller flow rates. It is also noteworthy that a flow rate is indicated for the glycol-mixture at 20°C even with the restrictor valve fully closed. In contrast, in operation with water these zero flow rates can be detected reliably. At 50°C, the relative measurement error becomes smaller than in operation with cold water. Especially with large flow rates and flatter system-curves, the estimated flow rate value gets very small. (Fig. 7 C). But in contrast to the operation with pure water, the volume flow rate is both underestimated and overestimated here, depending on the speed and system characteristic curve. An interpretation as a guaranteed minimum flow is not possible.

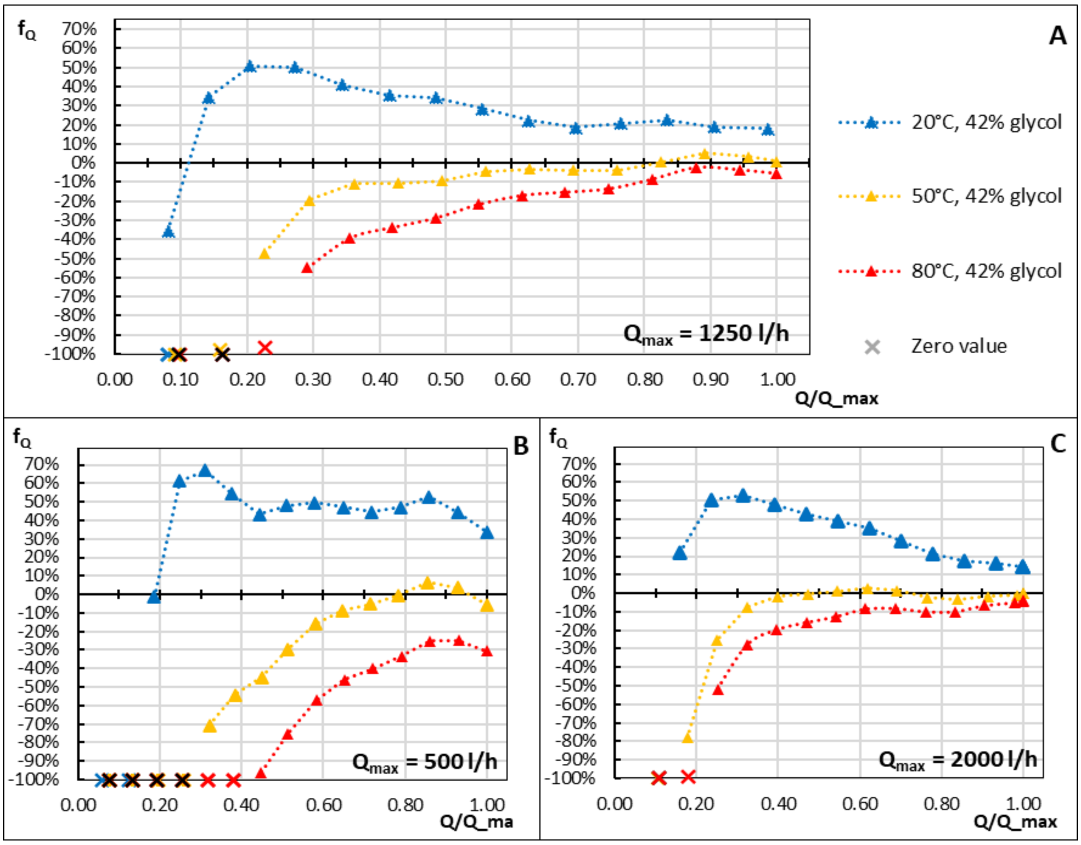

Fig. 7: Relative error of flow rate estimation over real dimensionless flow rate for different system characteristics with 500 l/h (B), 1250 l/h (A) and 2000 l/h (C) maximum flow rate in operation with 42%-glycol-water mixture at 20 °C (blue) 50 °C (yellow) and 80 °C (red)

In operation with glycol mixture at 80 °C (red) the flow rate is underestimated strongly at low speeds, the error decreases with increasing flow for all system curves. For steep system curves (Fig. 7 B) the estimation error is still at least 25% even at high speeds.

Comparing the estimation error in operation at 20°C (blue) and 80°C (red), the range between the error declines with increasing speed and flow rate. But even with the flattest considered system characteristic (Fig. 7 C), the temperature induced error range is still at least 18% percentage point. In the worst case, steep system characteristic and low speed, the error range is over 165%.

In order to further investigate the large temperature-dependent variations in the flow rate estimation, the efficiency of the pump in the different operating conditions is considered in more detail. Figure 5.10 therefore shows the efficiency for constant speed levels for water at 20 °C and the antifreeze-mixture with 42 % glycol content at 20 °C The efficiency of the pump can be determined from the ratio of the hydraulic power measured on the test rig and the power consumption of the pump. Since this efficiency is determined based on the electric power consumption detected by the pump electronics, it includes both the efficiency of the electric motor and the hydraulic efficiency of the pump, losses in the power electronics are not included. For a better visualization a characteristic curve is interpolated between the measuring points. It can be seen that the pump efficiency with the cold glycol-mixture is indeed significantly lower than with water. The effect is also depending on the speed of the pump. At lower speed levels the relative decrease in efficiency, and therefore the negative influence on the P;Q-Characteristic curve is higher.

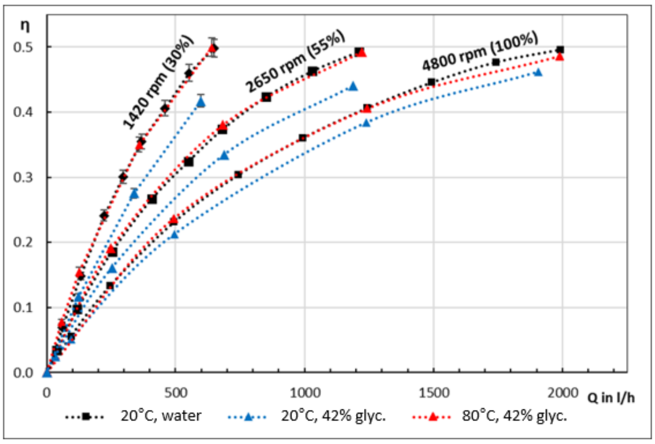

Fig. 1: Efficiency curves of the pump for water and a water-glyocle mixture at 20°C for different constant pump speeds.

The strong deviations can be explained based on the fluid properties of the 42%-glycol-mixture. The glycol-mixture at 20°C has a slightly higher density ρ=1039 kg/m^3 and much higher viscosity ν=5,12 mm^2/s than cold water (ρ=998 kg/m^3 ν=1,004 mm^2/s). Also, the fluid properties of glycol are highly temperature-dependent (e.g., at 80°C the viscosity decreases significantly to ν=1,1 mm^2/s). As described in section 4, a higher viscosity has a strong influence on pump efficiency and therefore on the P,Q-characteristic curve.

9. Summary and conclusion

Both the theoretical and the experimental investigation have shown that the flow rate estimation requires characteristic pump maps that match real pump performance as closely as possible. Even small deviations can lead to large estimation errors, especially at low speeds and for steep system curves.

For the investigated pump a reasonable estimation of the flow rate is only possible for some areas of the operational spectrum. In most operational conditions, the flow rate estimation could at least be used as a ‘flow switch’ to detect if a minimum required flow rate exist. But especially with glycol-mixtures, this is not possible in every operating point. Overall, the composition and the temperature of the pumped medium can have a strong influence on the efficiency of the pump and therefore on the flow rate estimation, while the intensity of the impact can differ depending on the operational point. For a reasonable quantification of glycol-water mixtures at varying temperatures, corrective measures must be taken. This could be done, for example, by a subsequent correction of the estimated flow rate via specific correction schemes that are provided by the pump manufacturer or with fluid property-based adjustments of the characteristic pump map.

10. Acknowledgement

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