IMPLEMENTATION STUDIES OF SMALL ENERGY CONVERTERS IN WATER SUPPLY SYSTEMS

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Abstract

Small hydropower turbines have been utilized for energy recovery in water supply systems for a number of years. Commonly implemented for this purpose are centrifugal pumps in turbine operation, referred to as pumps as turbines (PAT). Due to the wide field of potential applications new requirements have arisen. The turbine has to handle both demanding and specific hydraulic conditions as well as allowing for configuration in limited space. To study the implementation of PATs in the German water sector, the German Technical and Scientific Association for Gas and Water (DVGW) has created the research project titled: “Implementation studies of small turbines in water supply systems”. The goal of the project is to improve the implementation of small turbines in transfer chambers over different pressure ranges of the water distribution systems investigated.

The Department of Hydraulic Engineering and Water Resources Management (LWW) at the University of Stuttgart is the research institution leading the investigation group in cooperation with three large regional water system operators: the Bodenseewasserversorgung (BWV), the Landeswasserversorgung (LW) and EnBW.

The effect of turbine operation on the volumetric flow measurement carried out by water flow meters when a turbine is installed upstream of the water meter is also of interest. A market analysis has produced three suitable types of energy converters: section-type pumps in turbine operation, heating circulation pumps in turbine operation, and Counter Pressure Pelton-Turbines (GDPT).

In the Hydraulic Laboratory of the LWW a turbine test bench was constructed. To cover a large range of applications, three different pipes with varying diameters from DN 50 to DN 200 are set up. For each energy converter, turbine operation characteristics under different mounting conditions are recorded. These mounting conditions reflect the real installation situation in the transfer shafts.

Introduction

Small hydropower turbines have been implemented in water supply systems for a number of years. Commonly used machine types are:

- Francis-Turbines
- Centrifugal pumps in turbine operation (PAT)

The Zweckverband Landeswasserversorgung (LWV) has applied a Francis-Turbine since 1922 in a downpipe for energy recovery, while the Zweckverband Bodensee-Wasserversorgung has only applied the use of a Francis-Turbine since 1970. Since 1984, pumps in turbine operation have been used more frequently due to their cost-effectiveness (Störzer, 2009).

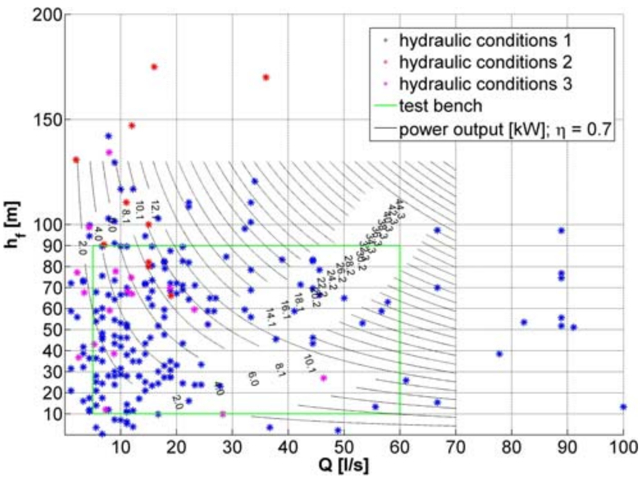

Figure 1: hydraulic conditions and potential power output in the transfer chambers.

In addition to the pumps as turbines and the Francis-Turbine, there are other energy converters available on the market within the same application range. In particular this includes the Counter Pressure Pelton-Turbine and the Axent Turbine. The idea of a Pelton runner rotation in a volume of compressed air maintained at a fixed pressure, led to the development of the Counter Pressure Pelton-Turbine, developed in 2004 by the Revita Foundation.

Figure 1 shows a brief overview of the hydraulic conditions in the transfer chambers in the German water supply sector of Baden-Württemberg. The figure indicates a widely varying field of unused potential in the area of small discharges and fall heads. There are few energy converters available on the market, especially in the field of lower output powers. For this reason, a market analysis is performed in the field of heating circulation pumps. In the following section, a short overview of the development on pumps used as turbines and the Counter Pressure Pelton-Turbine are described.

Pumps as Turbines

Pumps in turbine operation can be compared with Francis-Turbines whose circle of guide vanes is fixed in a certain position. The advantage of the pump in turbine operation is the low price due to their serial-production. However this cost advantage results in a lower degree of efficiency. Pumps in turbine operation are suitable for lower and higher fall heads and generally their range of application is restricted because they are only able to handle a constant flow rate (Chapallaz, 1995).

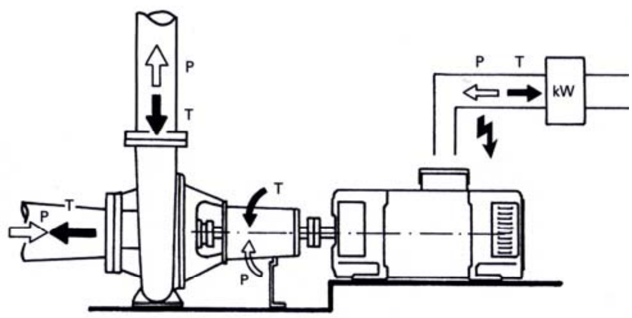

Figure 2: pump in turbine operation (Chapallaz, 1995).

The research on using pumps as turbines began around 1930. The first experiments were conducted by Kittredge and Thoma (1931). Kittredge and Thoma found that pumps work very efficient in turbine operation. The turbine operation became an interesting task for many pump manufacturers. Due to the high costs of test rigs further investigations focussed on prediction methods for the turbine performance of centrifugal pumps (Kittredge, 1933; Stepanoff, 1957) were carried out. Additional investigations on the prediction of turbine characteristics were conducted by Schmiedl (1998) in the nineties by Williams (1992) and Cohrs (1997). These prediction methods contained uncertainties, but can be seen as the starting point for the technological expansion.

Recently research has focussed on the improvement of the degree of performance of the pumps in turbine operation. The aim of the project "pumps as turbines with a variable guide vane system" is to transform a pump used as turbine into a turbine equipped with variable guide vanes, similar to a Francis-Turbine. This can be realised by taking away the existing spiral casing of a standard pump and replacing it using a guide vane system with a new spiral casing (Chapallaz, 2007).

Currently there are no scientific findings on the implementation of energy converters in pipes of small diameters as they are found in the transfer chambers in a water supply system. In fact the topic "necessary pipe diameters of water supply installations used for energy recovery" is referred to as the main research in the "energy research program hydropower for the years 2008-2011" by the Swiss Federal Office of Energy (Jorde, 2011).

Counter Pressure Pelton -Turbine

In 2004, a study financed by Swiss Federal Office of Energy and other private investors demonstrated the possibility of a Pelton-Turbine operated under backpressure conditions. The target was to develop a universally applicable turbine for water supply systems which can be operated under normal pressure and backpressure conditions, instead of using pressure reducing valves. The Pelton-Turbine has a high efficiency, damps water hammer in the distribution network, and allows flow and pressure control (Schindelholz, 2009).

The functional principle of the Counter Pressure Pelton-Turbine (GDPT) corresponds with a conventional Pelton-Turbine. The difference is the insertion of an air cushion, which is generated with an air jet pump or a compressor. The air cushion keeps the Pelton wheel free of water and dampens pressure bumps in the network. The required backpressure can be provided by the air cushion which needs to be maintained. Therefore the pressure casing and especially the wave seal must be airtight (Schindelholz, 2009).

Air entrainment in water supply systems is to be avoided due to water hammer and water quality aspects. In the case of the Counter Pressure Pelton-Turbine, the volume of detrained air is equally important and therefore a series of tests, regarding the aspects of air detrainment, will be conducted with a model turbine. Figure 3 shows the functional principle of the Counter Pressure Pelton-Turbine.

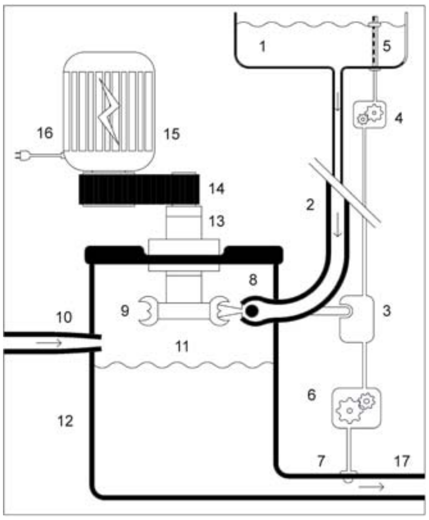

Figure 3: functional principle of the Counter Pressure Pelton-Turbine (Revita, 2010).

1: reservoir; 2: inflow; 3: nozzle needle control; 4: water level control; 5: water level sensor; 6: pressure control; 7: pressure transmitter; 8: nozzle; 9: Pelton wheel; 10: air jet pump; 11: compressed air cushion; 12: pressure casing; 13: shaft sealing; 14: belt transmission; 15: generator; 16: network-supply; 17: outflow

Turbine test bench

The experimental investigations on the different turbine types are conducted at the hydraulics laboratory of the Institute for Modelling Hydraulic and Environmental Systems, University of Stuttgart. The test bench (see figure 4) is connected to the intern water circulation of the hydraulics laboratory. To provide the hydraulic conditions, a pressure booster pump is installed. Table 1 summarizes the diverse measurement equipment utilized in the test bench.

Table 1: Measurement equipment of the test bench

Name	Device	Measurand
MID1	E+H Promag 50 W	Q: flow rate
MID2	E+H Promag 50 W	Q: flow rate
WZ	Water flow meter	Q: flow rate
M	KTR Dataflex	M: torque
P1	Keller PA-21Y	P: pressure
P2	Keller PA-21Y	P: pressure
n	KTR Dataflex	n: rpm
p	Isolated operation	p: power

To implement all three types of turbines, the test bench is modified during the temporal course of the project. The water is led from a high level tank to the bench with an upstream pressure of about 1 bar. The overall flow rate is regulated with a gate and is measured with an inductive flow meter. The pressure is then raised to 10 bars with the booster pump. A water flow meter and the test turbine, equipped with a torque shaft are located in the main pipe. To adjust the backpressure another gate valve is located downstream. Additionally, a bypass is installed to achieve the necessary hydraulic conditions. Both the main pipe and the bypass end in the low-level tank of the hydraulics laboratory.

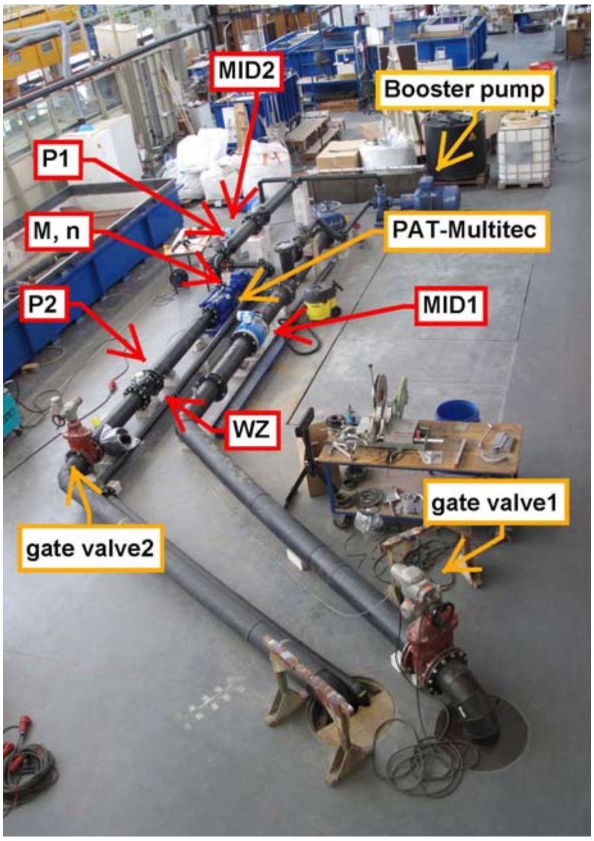

Figure 4: Turbine test bench at the hydraulics laboratory

Test schemes

To select the hydraulic machinery, the hydraulic conditions, or rather standard operational conditions are defined (compare figure 1). To cover a wide range of transfer shafts, three different turbine types scaled 1:1 are investigated:

- Pump as Turbine; type: PAT-multitec,
- Heating circulation pump; type: Rio-Eco,
- Counter Pressure Pelton-Turbine.

Different mounting conditions are required for the reverse running centrifugal pump (PAT-multitec) and the heating circulation pump (Rio-Eco). The first mounting condition represents an undisturbed inflow. This undisturbed pipe flow is achieved through the length of the straight upstream pipe. The second mounting condition represents a real situation in a transfer chamber. The straight piece of pipe, where the turbine is connected, is located downstream of a bend and therefore the flow is heavily turbulent. In the test bench, these conditions are achieved by changing the arrangement of the pipes. The loss of power can be quantified by comparing with the reference condition.

To illustrate the characteristic curve and the efficiency curve, the turbines are operated under varying speeds with different hydraulic heads and discharges. The mechanical and electrical power output is measured with a torque shaft respectively with an electrical power meter. The heating circulation pump is a wet rotor pump with a can, only the electrical output is detected. The electrical losses of the generator are relatively independent of the applied load and are known. Therefore conclusions regarding the mechanical power output of the heating circulation pump can be drawn. The characteristic curves of the Counter Pressure Pelton-Turbine are recorded in one mounting condition and the detrainment of air is quantified under different operating conditions. Both investigations on the Counter Pressure Pelton-Turbine and the heating circulation pump are currently being conducted and therefore no results of these measurements can be published yet.

Test results

The PAT-multitec is a 5 stage centrifugal pump with a rotor disc diameter of 193 mm. The turbine and the electric motor are installed on a ground plate. At the pressure side connection the main pipe (DN 200) is reduced to a diameter of 65 mm. On the axial suction side, the pipe is expanded from 125 mm to the diameter of the main pipe. The electric motor has 2 terminal pairs and is operated as a generator. The generator is an asynchronous machine and needs reactive power to be excited. In the test bench, this reactive power is provided by a condensator connection.

Characteristic curves in different mounting conditions

As mentioned above, the PAT-multitec is tested in two different mounting conditions. Mounting condition 1 (E1) represents the undisturbed inflow, the straight pipe to the pressure side has a length of 1.6 m and the velocity profile is almost fully developed. This length corresponds to 25 times the pipe diameter. In the second mounting condition, a 90° bend is installed directly upstream the turbine, the inflow is disturbed. Figure 4 and 5 are showing the turbine characteristics and the efficiency curves for both mounting conditions.

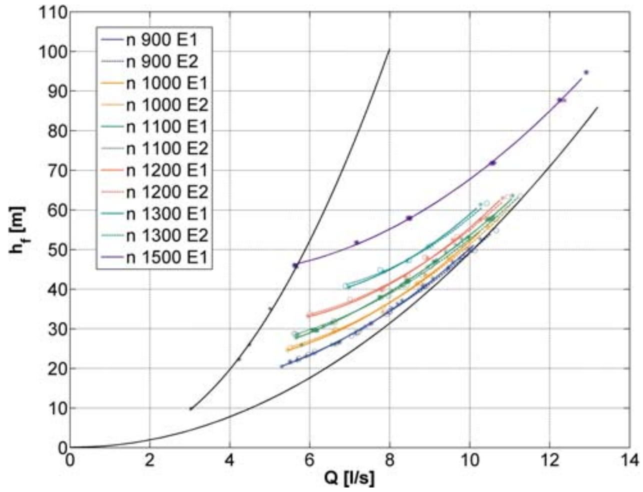

Figure 5: characteristic curves of the PAT-multitec with undisturbed (E1) and disturbed (E2) inflow.

It can be seen that the course of the characteristic and the efficiency curves in both mounting conditions are nearly identical. Only in the case of speed n=1000 and n=1200 minor changes in the efficiency under low discharges are noticeable. However these changes are in the range of typical measuring inaccuracy of the implemented measurement devices. The maximal efficiency of 0.7 is achieved in both mounting conditions and all speeds (besides n=900; eta_{max} = 0.69). A conclusion can be drawn that the bend upstream of the turbine has no significant effect on the operating behavior of the PAT-multitec.

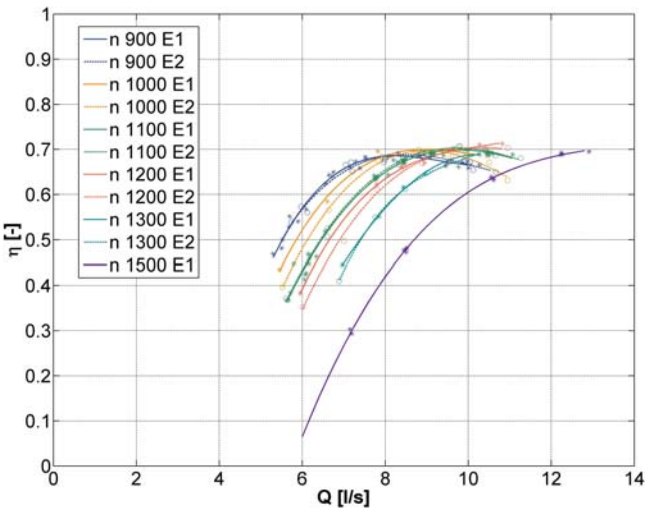

Figure 6: efficiency curve of the PAT-multitec with undisturbed (E1) and disturbed (E2) inflow.

Different operation conditions in installations can be realized with throttle-, bypass-, or speed control. In general, speed control is advantageous, if the volume flow and the fall head vary in a range, where the turbine can be operated under different speeds near the optimum operation point. This is situational and depends both on the turbine characteristics and on the particular water demand. In the case of speed control, also the investment costs and electrical losses of a frequency converter have to be considered, particularly in the range of low power outputs.

Behavior of the turbine under abnormal conditions

To describe the behavior of the turbine under abnormal conditions, the run-through and braking characteristics are recorded. They are shown in figure 4.

Reverse running pumps have radial rotor disks. In case of a load rejection, the flow rate is reduced and a water hammer upstream of the turbine may be induced. An exemplary drop load and runaway of the turbine is shown in figure 6. A reduction of the flow rate from 8.5 l/s to 5.7 l/s in within a few seconds can be recognized. At the same time, the speed ascends from 1100 rpm to runaway-speed.

In the subfigure 6a the pressure pattern upstream and downstream the turbine is recorded. A water hammer occurs to a low degree, while the pressure level before and after the throttling is nearly constant.

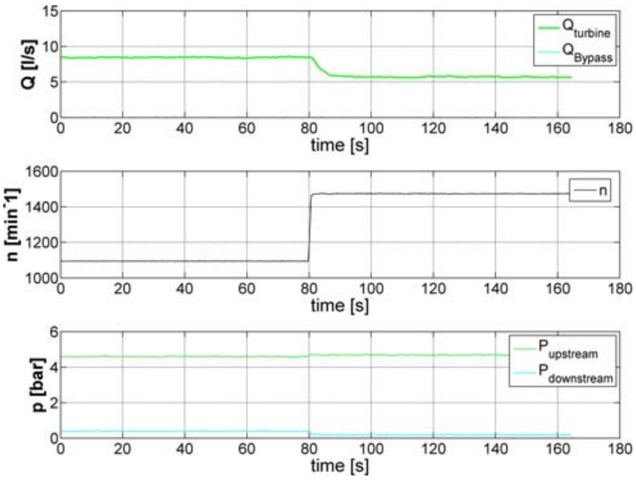

Figure 7: water hammer investigations of the PAT-multitec in the case of a load rejection. Subfigures: 6a: flow rate; 6b: rotational speed; 6c: pressure.

The lengths of the pipes in the test bench are quite short and the pressure hammer is reduced due to reflections and opposite extinction of the pressure waves. For this reason, a theoretical approach of the maximum pressure height after Joukowsky is carried out. The following parameters are relevant to this theoretical approach:

- Flow rate change and durability,
- Pipe diameter (d_i and d_a),
- Pipe length,
- Wall thickness,
- Modulus of elasticity (Fluid and Pipe-material).

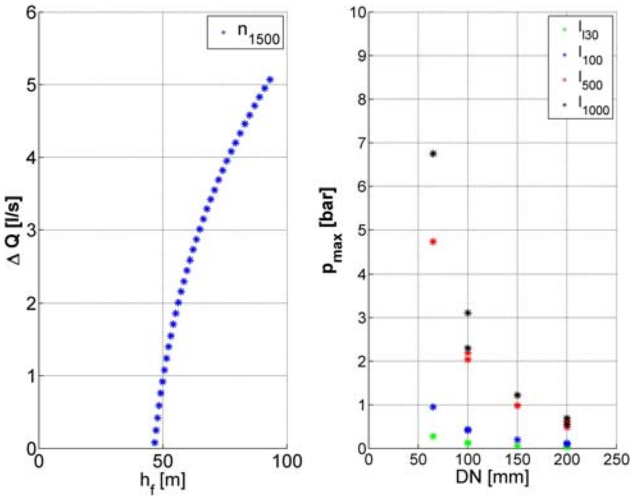

Figure 8: Assessment of the maximum water hammer in case of load rejection dependent on pipe diameter and pipe length.

The flow rate change in the case of a run-through of the turbine from synchronous speed is shown in the left subfigure of figure 7. For the calculation of the water hammer, the maximum flow rate change (5 l/s) is used. In the second subfigure, the maximum water hammer is shown, which is calculated based on the Joukowsky approach and dependent on the pipe diameter and the pipe length (30 m, 100 m, 500 m, 1000 m). The water hammer reaches its maximum in the case of small pipe diameters and large pipe lengths.

Turbine effects on the discharge measurement of water meters

The functionality and reliability of water flow meters in the water distribution system have to be ensured in case of the implementation of a turbine upstream of water meters. A uniform and low turbulent approaching flow is crucial. The homogeneity is also dependent of the length of the straight pipe section upstream the flow meter. Two variants regarding the distance between turbine and water flow meter are investigated:

- Setup 1: distance between turbine and meter: 1000 mm,
- Setup 2: distance between turbine and meter: 2000 mm.

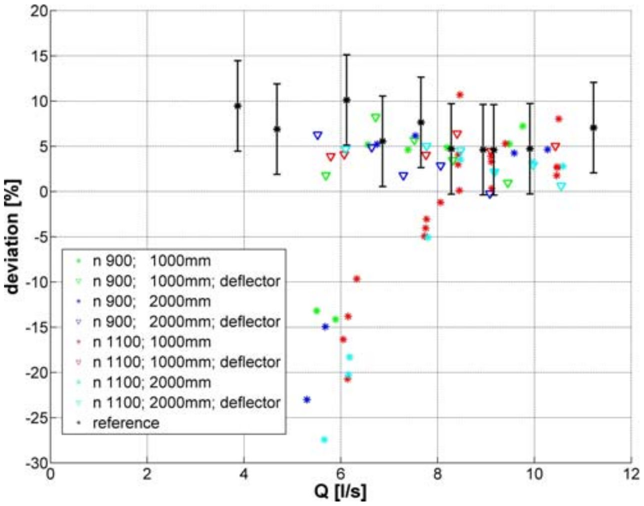

Figure 9: deviation of the flow measurement downstream the turbine.

The percentage of deviation of the measured data is shown in figure 8. In addition to the modification of the distance between the turbine and water meter, a variation of rotational speed and the effects of a flow straightener is investigated. It is apparent that due to the observable swirled inflow, a considerable deviation of the measured flow rate is independent from the distance between the turbine and water meter as well as from the rotational speed.

The inflow condition can be optimized with the installation of a cross-shaped deflector of 500 mm length (equates to 2.5 * DN) upstream of the water flow meter. The results indicate clearly an improvement of the discharge measurement and the measured data are within the tolerance extent (black bars) of the water flow meter.

Conclusions

In the research project “implementation studies of small energy converters in water supply systems”, the possibilities of energy recovery at currently unused sites in the water supply sector are demonstrated. This contributes to a more efficient handling with regards to the energy resources of the system.
Pressure reducing valves are often located in transfer chambers of the water distribution network to dissipate excess pressure energy. These valves can be replaced with small energy converters. By a given cost effectiveness, the choice of the turbine depends primarily on the hydraulic conditions. Further decision criteria are the operating behaviour as well as the available space in the transfer chamber.

The operating behaviour of the PAT-multitec in case of a disturbed inflow is tested due to the fact that a straight pipe section upstream of the turbine cannot be realized. It should be noted that no considerable changes in the degree of effectiveness compared with the undisturbed inflow situation are recorded. An additional point of interest is the turbine behavior under abnormal conditions. The run-through and braking characteristics of the PAT-multitec are measured and the maximum pressure head upstream the turbine in case of a load rejection is calculated using a theoretical approach.

In addition, the effects of turbine operation on the discharge measurement of water flow meters are investigated. In these investigations, the parameters distance between turbine and water flow meter, rotational speed and the discharge are varied. The deviations of the discharge measurements could be minimized with the implementation of a cross-shaped deflector upstream of the flow meter.

The investigations carried out provide an important contribution to future exploration of the currently unused potential in drinking water supply systems.

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