Accuracy of single-jet and multi-jet water meters under the influence of the filling process in intermittently operated pipe networks

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ABSTRACT

In many areas of the world water distribution systems are operated intermittently. The alternate filling and emptying of the pipe network leads to effects, which have negative impacts on water meter accuracy. For example, air that is present in the pipe network due to the emptying process must exit the network during the subsequent filling process. A part of this air is discharged through service connections and, thus, through water meters. In this paper, a study is presented in which the measurement error of single-jet and multi-jet water meters due to the filling process of an empty pipe is investigated experimentally. From the start of air flow to the steady-state flow of water, several causes of measurement errors can be distinguished, such as pure air flow, the impact of the water front on the impeller, the existence of two-phase flow or unsteady flow conditions. For both meter types, it has been discovered that the measurement error is mainly caused by the air flow. The experimental results show that up to 93% of the air volume in the pipe is registered by the water meters. Based on these results, an approach for estimating the measurement error for both meter types is presented.

Key words | air flow, intermittent water supply, two-phase flow, water meter accuracy

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INTRODUCTION

In water supply systems, single- and multi-jet water meters, which cumulatively determine the volume of water flowing through, are used to measure delivery to the customer. Both water meter types have an impeller on the inside which is set in rotational motion by a single or multiple water jets that flow against the impeller tangentially. The impeller's revolutions are transmitted via gears to a roller counter which displays the volume that flowed through. While all the water flows through the impeller of single-jet water meters, part of the water in a multi-jet water meter goes around the impeller via an adjustable bypass. By variably dividing both flows, multi-jet meters can also be calibrated (Arregui *et al.* 2006).

The accuracy requirements and tolerated limits of error for water meters are regulated in ISO 4064 (2014). The error tolerance is divided into an upper and lower zone with error limits of ±2% and ±5%, respectively. These error limits only apply to calibration in state-approved test facilities. Maximum error limits, which are double those for calibration, i.e. ±4% and ±10%, respectively, apply when installed. A precondition for an accurate measurement is that water meters are used in line with their conceptual design. Among other things, the water meter must be completely filled with water and vented (DVGW worksheet W 406 2012; ISO 4064 2014).

However, in many regions of the world, water distribution systems are operated intermittently. The distribution systems are thus filled with water for a limited time and are not constantly under pressure (De Marchis *et al.* 2010; Klingel & Nestmann 2014). To guarantee constant

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water supply for domestic use, consumers store the water in private tanks. Especially in development countries with high water scarcity and flat-rate tariffs being used by the supply system operator, the consumers try to obtain a higher amount of water by keeping the service connections constantly opened. Hence, the pipe network is partially or completely drained after a supply period, before being refilled in the subsequent period (Farley & Trow 2003; Totsuka *et al.* 2004; Kingdom *et al.* 2006).

If an air-filled distribution system is filled with water, a two-layer water front spreads out in the distribution mains from the entry point. A first, higher speed front forms on the lower side of the pipe and a second lower speed front forms on the upper side of the pipe. Atmospheric pressure is present in the pipe in front of the first (lower) water front. Between the first and second front, the pressure increases linearly, with the pressure within the air volume over the first front being equal to the pressure in the water-filled area (Liou & Hunt 1996; Guizani *et al.* 2006; Hou *et al.* 2014). The advancing front pushes the air present in the system out of the pipe network through, amongst others, service connection pipes. This part of the air flows through the domestic water meters, thus causing them to work contrary to their initial design (Van Zyl 2011).

While some causes of measurement inaccuracies of water meters used in intermittently operated water supply systems have already been exhaustively analysed, such as meter under-registration due to the use of domestic storage by Feldtmann (1985), Rizzo & Cilia (2005), Cobacho *et al.* (2008) and Tamari & Ploquet (2012), increased wear of water meters by Arregui *et al.* (2007) and Criminisi *et al.* (2009), as well as deposits in water meters by Arregui *et al.* (2005), there exist no studies on the extent to which an air flow or a two-phase flow of air and water falsifies water meter measurements. Thus, the authors developed an experimental set-up to analyse measurement errors of water meters during the filling of a pipe under atmospheric pressure. Since the characteristics of single-jet water meters ($Q_3 = 2.5$ R80H) have been described in Walter *et al.* (2017), this article presents the measurement error of multi-jet water meters ($Q_3 = 4$ R80H) and compares the results of both meter types. The study's parameters are the air volume V_{air} before the water meter and pipe pressure $p_{1,stat}$. Since the water meter casing can either be dry or contain an initial amount of water, the basic correlation between measurement error, pipe pressure, and air volume for dry and wet casings is presented.

METHODOLOGY

Experimental set-up and test procedure

The experimental set-up is represented schematically in Figure 1. A 15 m high water tower with two branches at its foot supplies the measuring section. The first branch goes through valve S3 and a pump to a water-filled tank, thus making the water level in the tower steplessly adjustable. The second branch goes through valve S1 to the measuring section of the experimental rig. Pressure sensor P1 measures pressure p_1 in front of valve S1, while sensor P2 measures pressure p_2 in front of the water meter. When valve S1 is closed, the water level in the water tower or hydrostatic pressure $p_{1,stat}$ is measured. With the opening of valve S1 at the time $t_{p1,start}$, the water column begins to move and pressure p_1 drops abruptly. When the water front reaches P2 at the time $t_{p2,start}$, there is a sudden increase of pressure p_2. If there is no further change in pressure p_2, the unsteady movement of the water column has ended and thus a steady-state flow with constant flow rate is reached at the time $t_{p2,const}$.

The air volume V_{air} in front of the water meter can be varied using hoses of different lengths L_S. This study used calibrated, dry-running single- and multi-jet water meters manufactured by ZENNER International GmbH & Co. KG of type ETKD-N for size $Q_3 = 2.5$ and MTKD-N for size $Q_3 = 4$, respectively, and accuracy class R80H. The water meter determines volume V_{wm}, which comprises a mix of air and water. An optical sensor detects the throughput of each rib of the water meter's low-flow indicator as impulse I_j, so that the flow $Q_{wm}(t)$ can be calculated from the rotation frequency. The flow can be stopped by closing valve S2. The resulting pressure surge at the time $t_{p2,wh}$ is also measured by P2.

A tank with diameter D_t stores the entire volume of water V_t that flows out of the measuring section. Pressure sensor P3 helps to detect the water level in the tank. The

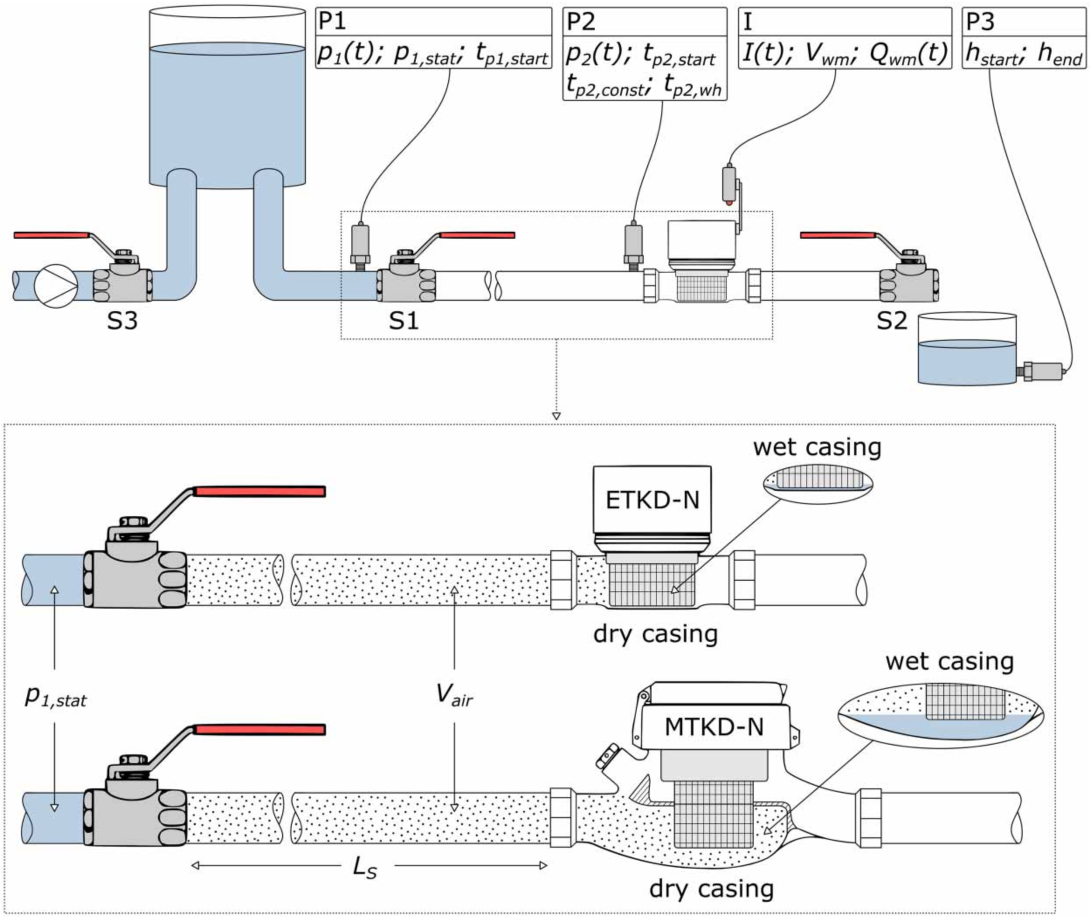

Figure 1 | Experimental set-up and measurement conception.

analogue signals of the measuring instruments are recorded and digitized synchronously with a 1,000 Hz sampling frequency by an analogue-to-digital converter with a 12-bit resolution. The experimental set-up is consistent with ISO 4064 (2014) standards.

Determination of measurement error

During an event, i.e. from the start of air flow up to steady-state water flow through the water meter, several causes of measurement errors all adding up to E_{total} can be defined. Once the water front starts moving, air inevitably flows through the water meter. The volume is recorded by the water meter when air flows exclusively is defined as measurement error E_{air}. Using the experimental setup described, all additional causes of measurement errors can only be partially differentiated from one another and are therefore integrated under measurement error E_{rest}. This contains errors arising from the water front impacting the impeller (impulse from an abrupt change in density), air bubbles entering the front of the water column (two-phase flow), the unsteady flow condition (inertial forces of the impeller's rotation), the steady-state flow condition (permissible measuring error according to ISO 4064), and the abrupt stoppage of flow (wake behaviour; only relevant in the experiment).

Comparing the volume V_{wm} registered by the water meter with the actual volume V_t in the tank results in the total measurement error E_{total}. Hereby, the volume V_{water}, which remains between the water meter and valve S2 and is not included in V_t, must be considered. As shown in Equation (1), V_{wm} can be calculated by summing up all Impulses I_j and dividing through the water meter's ratio R_{wm} (ETKD-N: $R_{wm,sj} = 92.57$ ribs per litre;

MTKD-N: $R_{wm,mj} = 48.30$ ribs per litre).

$$E_{total} = V_{wm} - V_t - V_{water} = \sum_{j=t_{p1,start}}^{j=t_{end}} I_j \cdot \frac{1}{R_{wm}} - \pi \cdot \frac{D_t^2}{4} \cdot (h_{end} - h_{start}) - V_{water} \text{ in } L \tag{1}$$

Since $t_{p1,start}$ denotes the start of the water column and $t_{p2,start}$ the arrival of the water column at the water meter, the period of time, during which only air moves through the water meter, can be determined. If a flow is recorded during this time, measurement error E_{air} can be determined by the integration of the flow $Q_{wm}(t)$ or the sum of the impulses I_j using Equation (2).

$$E_{air} = \int_{t_{p1,start}}^{t_{p2,start}} Q_{wm}(t)dt = \sum_{j=t_{p1,start}}^{j=t_{p2,start}} I_j \cdot \frac{1}{R_{wm}} \text{ in } L \tag{2}$$

Since E_{air} is established independent of V_t, the sum of the remaining measurement errors E_{rest} can be calculated using Equation (3).

$$E_{rest} = E_{total} - E_{air} \text{ in } L \tag{3}$$

Test parameters

The illustrated test procedure was conducted for hose lengths of $L_S = 1$, 2, 3, 5, 10, 15, 20 and 25 m that resulted in air volumes of $V_{air} = 0.48$, 0.78, 1.08, 1.67, 3.17, 4.66, 6.15, and 7.65 L for single-jet water meters. For multi-jet water meters V_{air} increases by additional 0.07 L due to the larger volume of the water meter casing. On account of the impeller rotating at very high speeds while air flows through and the filling process of service connections in intermittently operated water distribution systems being consistently marked by small pressures or pressure gradients, pressures $p_{1,stat} = 0.1$ bar up to a maximum of 1.0 bar were analysed in steps of 0.1 bar. If the casing of the water meter is not completely dry, the movement of the impeller is disturbed by the initial water in the casing. This affects the starting behaviour of the impeller and leads to additional dependence of measurement error E_{air} on pressure $p_{1,stat}$. Therefore, measurements were also conducted for the listed volumes using wet casings. Based on the differing geometry of both meter types, single-jet water meters were tested up to $p_{1,stat} = 0.5$ bar, while multi-jet water meters were tested up to $p_{1,stat} = 1.0$ bar. Three measurements were conducted for each parameter combination to calculate the mean value.

RESULTS AND DISCUSSION

Measurement error E_{rest}

Compared to the total measurement error E_{total}, error E_{rest} results in low values that mostly fluctuate around zero and may be positive or negative. For all tested combinations of V_{air} and $p_{1,stat}$ there was a positive mean value of $E_{rest,mv} = +0.10$ L and a negative mean value of $E_{rest,mv} = -0.14$ L. Regarding the low values of E_{rest} it can be concluded that, E_{total} depends substantially on measurement error E_{air}, which is described below in more detail.

Measurement error E_{air} for single-jet water meters and dry casing

In Figure 2(a) E_{air} is plotted for various pressures $p_{1,stat}$ dependent on the air volume V_{air} using a dry meter casing. E_{air} is relatively independent of pressure $p_{1,stat}$ for $p_{1,stat} \geq 0.2$ bar and, therefore, depends only on air volume V_{air}. The measurement error increases continuously with an increase in air volume. Starting at $V_{air} = 1.08$ L a linear relationship between V_{air} and E_{air} is recognisable. E_{air} decreases nonlinearly for smaller volumes and must inevitably end at zero, since there is no air volume in front of the water meter $t_{p1,start} = t_{p2,start}$ and, thus, $E_{air} = 0$ is valid.

Occasionally, measurement error E_{air} for $p_{1,stat} = 0.1$ bar is comparatively low. A reason for this may be the relatively unstable build-up of the water front. For lower pressures $p_{1,stat}$ and, thus, lower flow rates, the front shows a more marked development and both layers of the front form with a greater distance between them. Once the forward layer of the front reaches the pressure sensor P2 at time $t_{p2,start}$, pressure p_2

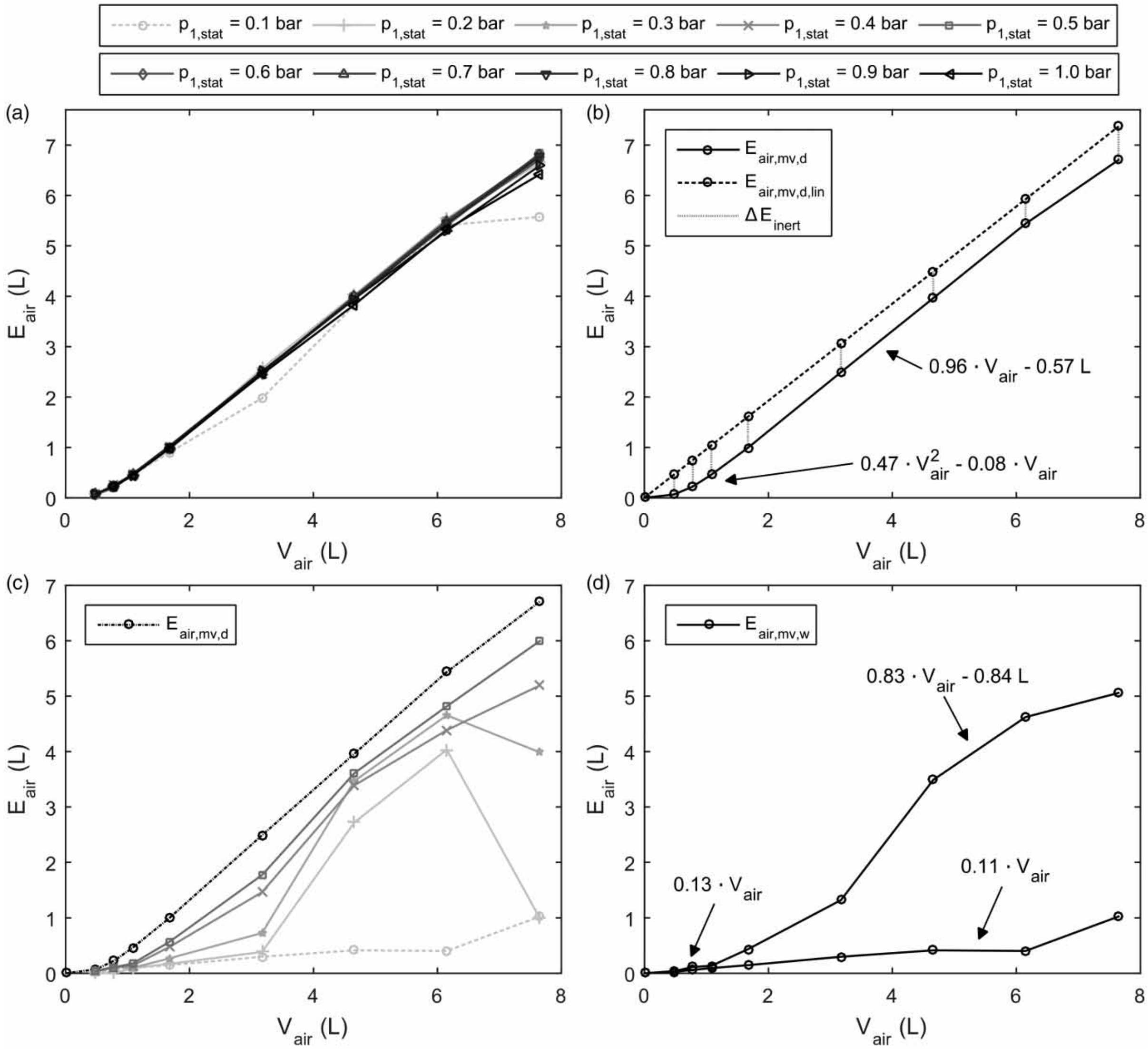

Figure 2 | Single-jet water meters: E_{air} dependent on V_{air} and $p_{1,stat}$ (a) and $E_{air,mv,d}$, $E_{air,mv,d,lin}$, and ΔE_{inert} dependent on V_{air} (b) for dry meter casings. E_{air} dependent on V_{air} and $p_{1,stat}$ (c) and $E_{air,mv,w}$ for the upper and lower range dependent on V_{air} (d) for wet meter casings.

rises and the recording of air flow stops. Therefore, the air volume above the first layer is not contained in volume E_{air}. Consequently, it can be inferred that the conclusions drawn here regarding E_{air} are valid for $p_{1,stat} \geq 0.2$ bar.

The mean values $E_{air,mv,d}$ of all measurements with $p_{1,stat} \geq 0.2$ bar from Figure 2(a) are plotted in Figure 2(b). The gradient of $E_{air,mv,d}$ in the linear range, and thus the deviation in volume due to the medium of air, is 96%. In addition, a linear function $E_{air,mv,d,lin}$ with the same gradient but running through the origin is illustrated. The vertical offset of the curve $E_{air,mv,d}$ compared to $E_{air,mv,d,lin}$ can be explained by the starting resistance of the impeller which leads to an additional deviation in volume. When air flow starts, the inertial forces of the impeller and the register must be overcome. Thus, the front part of the air column flows through the water meter being under-registered. The vertical distance between $E_{air,mv,d}$ and $E_{air,mv,d,lin}$ therefore constitutes the mean value of the volume ΔE_{inert} not registered due to the inertial forces of the impeller ($\Delta E_{inert} =$ 0.57 L in the linear range).

An air volume $V_{air} < 1.08$ L results in a non-linear relationship between air volume and measurement error. The decline of ΔE_{inert} for small air volumes can be explained by the compression of the air that inevitably occurs directly in front of the water front. This leads to a density and pressure gradient in the air column. For short hose lengths L_S, this compressed part of the air column flows through the water meter while the impeller starts up. Additional acceleration occurs as a result of the pressure gradient, thus letting the impeller start turning earlier. The specific approximations for the linear and non-linear range of $E_{air,mv,d}$ can be found in Figure 2(b).

The results presented in Figure 2 describe the measurement error of a specific single-jet water meter. For a more general estimation of the error, a second water meter of the same type has been tested in a further measurement series. Since the results are very similar, the specific error curves of only one water meter are presented in this paper. A detailed presentation of both measurement series can be found in Walter *et al.* (2017). For establishing Equations (4) and (5) the specific error curves of both measurement series has been combined. To estimate E_{total} the minor influence of E_{rest} can be neglected ($E_{rest} \approx 0$).

$$E_{total} = E_{air} + E_{rest} = 0.93 \cdot V_{air} - 0.56\,\mathrm{L} + E_{rest} \quad \text{for } V_{air} \geq 1.08\,\mathrm{L} \tag{4}$$

$$E_{total} = E_{air} + E_{rest} = 0.4 \cdot V_{air}^2 - 0.04 \cdot V_{air} + E_{rest} \text{ for } V_{air} < 1.08\,\mathrm{L} \tag{5}$$

Measurement error E_{air} for single-jet water meters and wet casing

Dependent on the air volume V_{air}, measurement error E_{air} in Figure 2(c) is plotted for various pressures $p_{1,stat}$ using a wet meter casing. $E_{air,mv,d}$, the mean value error curve for a dry casing from Figure 2(b), is also plotted. Compared to $E_{air,mv,d}$, a significantly smaller volume E_{air} results from $p_{1,stat} = 0.1$ bar. Starting from a pressure of $p_{1,stat} = 0.3$ bar, abruptly larger volumes E_{air} are recorded, which come closer to $E_{air,mv,d}$ with increasing pressure. Volumes of E_{air} for $p_{1,stat} = 0.2$ bar, are partly in the range of the results for $p_{1,stat} = 0.1$ and 0.3 bar. Hence, the error curve can be divided in an upper and a lower range with $p_{1,stat} = 0.2$ bar being the border between the ranges. In spite of the additional dependence on pressure, there is mostly also an approximately linear relationship between V_{air} and E_{air}.

The speed of the water front and thus, the speed of the air column depends on pressure $p_{1,stat}$. For measurements with $p_{1,stat} = 0.1$ bar, the speed of the air column at the beginning is too low to push a significant part of the water out of the casing. As a result, the rotational motion of the impeller is affected by the initial water during air flow, which is resulting in very low values for E_{air}. When $p_{1,stat} \geq 0.3$ bar the speed is high enough to carry a part of the water out of the casing. Larger volumes are registered for E_{air} as a result of the freer rotational motion of the impeller. With increasing pressure, a larger part of the water is displaced from the casing, thus suggesting a correlation between E_{air} and $p_{1,stat}$.

The mean values $E_{air,mv,w}$ of all measurements using a wet casing for the range above and below 0.2 bar is illustrated in Figure 2(d). The specific approximations are also given in each case, in which only the approximations in the upper range, analogous to a dry meter casing, must be divided into two sections. With a wet casing, the average error curves for small air volumes can also be described sufficiently using linear approximations.

Analogous to the analysis of a dry meter case, a second measurement series for testing wet meter cases was executed. By combining the specific error curves of both measurement series, the Equations (6)–(8) can be formulated. For an estimation of E_{total} the minor influence of E_{rest} can be neglected ($E_{rest} \approx 0$).

$$E_{total} = E_{air} + E_{rest} = 0.76 \cdot V_{air} - 0.63\,\mathrm{L} + E_{rest} \quad \text{for } V_{air} \geq 1.08\,\mathrm{L};\ p_{1,stat} \geq 0.3\,\text{bar} \tag{6}$$

$$E_{total} = E_{air} + E_{rest} = 0.19 \cdot V_{air} + E_{rest} \quad \text{for } V_{air} < 1.08\,\mathrm{L};\ p_{1,stat} \geq 0.3\,\text{bar} \tag{7}$$

$$E_{total} = E_{air} + E_{rest} = 0.11 \cdot V_{air} + E_{rest} \quad \text{for } p_{1,stat} = 0.1\,\text{bar} \tag{8}$$

Measurement error E_{air} for multi-jet water meters and dry casing

In Figure 3(a) E_{air} is plotted for various pressures $p_{1,stat}$ dependent on the air volume V_{air} using a dry meter casing. Unlike the results of the single-jet water meter, there exists a correlation between E_{air} and $p_{1,stat}$. With higher pressures $p_{1,stat}$ the gradient of the error curve decreases continuously and error E_{air} becomes smaller. Analogous to single-jet water meters, each error curve can also be divided into a linear and a non-linear section. The smallest error results from $p_{1,stat} = 1.0$ bar with a gradient in the linear range of 58% and the highest error results from $p_{1,stat} = 0.2$ bar with a gradient in the linear range of 150%. The results for $p_{1,stat} = 0.1$ bar do not follow this behaviour and show slightly smaller values for E_{air} since the build-up of the water front has an additional influence on E_{air}.

A possible explanation for the dependence of E_{air} on $p_{1,stat}$ may be found in the rotational motion of the impeller and the existence of the bypass. The bearing and the axis of

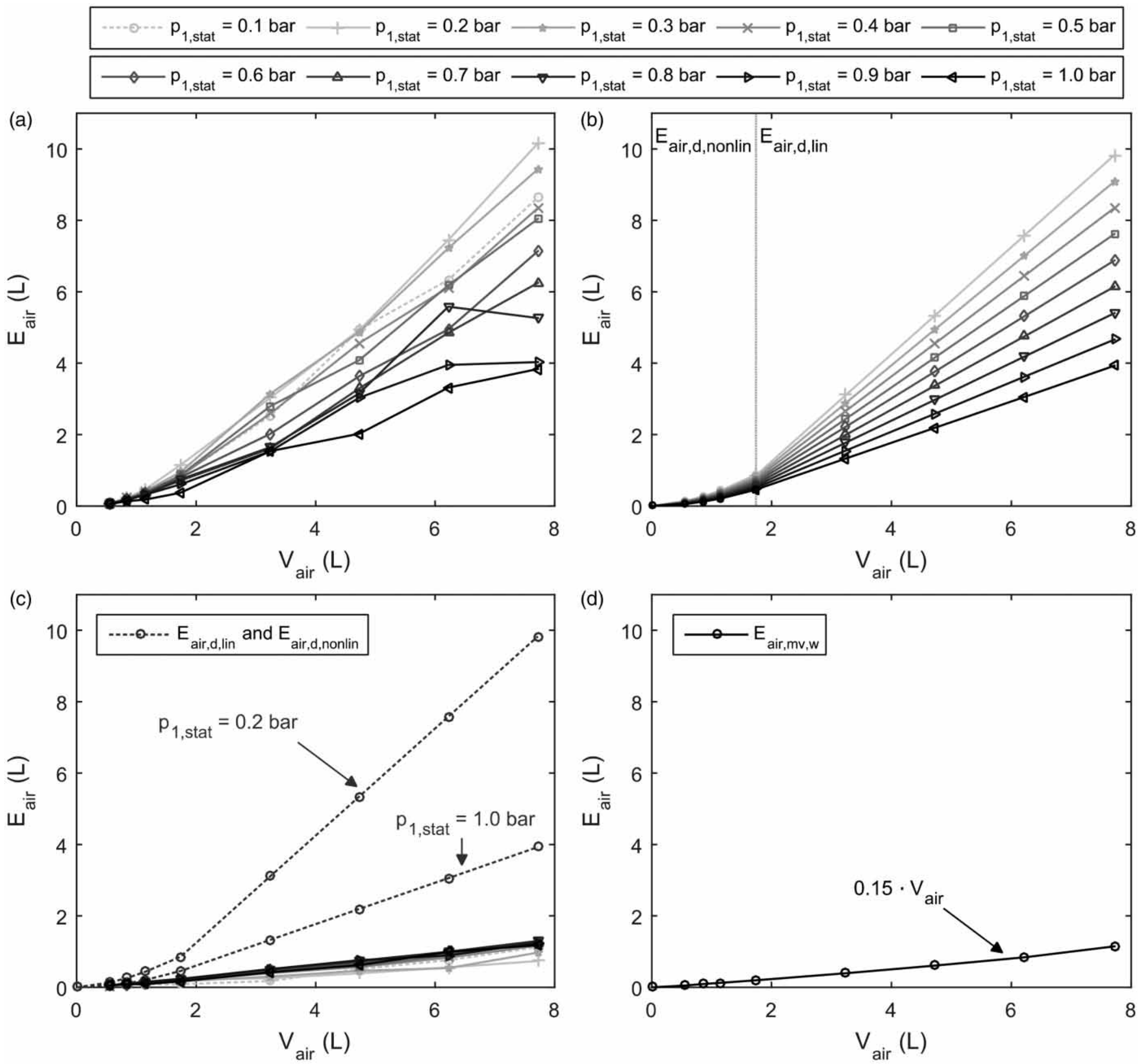

Figure 3 | Multi-jet water meters: E_{air} dependent on V_{air} and $p_{1,stat}$ (a) and $E_{air,d,lin}$ and $E_{air,d,nonlin}$ dependent on V_{air} and $p_{1,stat}$ (b) for dry meter casings. E_{air} dependent on V_{air} and $p_{1,stat}$ incl. $E_{air,d,lin}$ and $E_{air,d,nonlin}$ for $p_{1,stat} = 0.2$ and 1.0 bar (c) and $E_{air,mv,w}$ dependent on V_{air} (d) for wet meter casings.

the impeller are designed to operate in water, a medium with a density a thousand times higher than air. Especially for high pressures, when the impeller has a high rotational velocity, a vibrational sound can be detected. A vibration of the impeller or the axis would increase the turning resistance of the impeller and, thus, leads to a higher pressure loss for the flow through the impeller. Hence, more air would flow through the bypass, not being registered by the water meter. For very low pressures, an oppositional effect could occur. If, during a low air flow, a smaller air volume flows through the bypass than when the meter is filled with water as a result of e.g. compressible effects, a disproportionate measurement of volume would occur compared to the calibrated state.

Within measurements with the same parameter combination and a dry casing, single-jet water meters have a very high reproducibility of the values for E_{air} but for multi-jet water meters there is a greater dispersion of the values for E_{air}. Therefore, several outliners can be observed in the linear section of E_{air} in Figure 3(a). However, a linear approximation $E_{air,d,lin}$ for $V_{air} \geq 1.74$ L and a non-linear approximation $E_{air,d,nonlin}$ for $V_{air} < 1.74$ L has been established and plotted in Figure 3(b) to describe E_{air} as a function of V_{air} and $p_{1,stat}$.

Mean Equations (9) and (10) can be formulated for assessing the total measurement error E_{total} during an event. For an estimation of E_{total} the minor influence of E_{rest} can be neglected ($E_{rest} \approx 0$).

$$\begin{aligned} E_{total} &= E_{air} + E_{rest} \\ &= (1.73 - 1.15 \cdot p_{1,stat}) \cdot V_{air} - (2.05 - 1.5 \cdot p_{1,stat}) + E_{rest} \\ &\quad \text{for } V_{air} \geq 1.74 \text{ L} \end{aligned} \tag{9}$$

$$\begin{aligned} E_{total} &= E_{air} + E_{rest} \\ &= (0.24 - 0.1 \cdot p_{1,stat}) \cdot V_{air}^2 + (0.15 - 0.13 \cdot p_{1,stat}) \cdot V_{air} + E_{rest} \\ &\quad \text{for } V_{air} < 1.74 \text{ L} \end{aligned} \tag{10}$$

Measurement error E_{air} for multi-jet water meters and wet casing

Depending on air volume V_{air}, measurement error E_{air} in Figure 3(c) is plotted for various pressures $p_{1,stat}$ using a wet meter casing. The error curves for a dry meter casing with $p_{1,stat} = 0.2$ and 1.0 bar from Figure 3(b) and thus, the upper and lower limits of the error range are also plotted. Compared to these error curves, a significantly smaller volume for E_{air} is registered for all tested pressures. There is a linear correlation between V_{air} and E_{air} and E_{air} shows no dependence on $p_{1,stat}$. A sudden rise of the values for higher pressures, as seen for single-jet meters, cannot be observed. This behaviour can be explained by the structure of the measuring chamber of the multi-jet water meter (Figure 1). The measuring chamber is divided into a lower and an upper chamber connected by the impeller. Therefore, the water or the air must flow vertically from the lower chamber to the upper chamber through the impeller. For the initial water in the lower measuring chamber, the velocity of the air flow within the tested pressures is not high enough to lift the water up from the lower chamber. Hence, the rotational motion of the impeller is disturbed while the total volume of air is measured resulting in very low values for E_{air}.

The mean value $E_{air,mv,w}$ of all measurements using a wet meter casing is illustrated in Figure 3(d). Here, the specific approximation can be described for the entire range by means of a linear relationship.

Mean Equation (11) can be formulated for assessing the total measurement error E_{total} during an event. For an estimation of E_{total} the minor influence of E_{rest} can be neglected ($E_{rest} \approx 0$).

$$E_{total} = E_{air} + E_{rest} = 0.15 \cdot V_{air} + E_{rest} \tag{11}$$

CONCLUSION

This article presents a study in which the influence of a water front driven air flow on the measurement accuracy of single- and multi-jet water meters with dry and wet meter casings was investigated experimentally. The experiment leads to the following conclusions:

1. The measurement error E_{rest} consists of very low positive and negative values that fluctuate around zero. The total measurement error E_{total} thus results significantly from the measurement error E_{air}. Therefore, E_{rest} can be neglected in Equations (3)–(11) for estimating E_{total}.
2. For single-jet water meters and dry meter casings the measurement error is independent of pipe pressure $p_{1,stat}$ and only depends on the air volume V_{air} in front

of the water meter. Depending on V_{air}, measurement error E_{total} can be estimated using Equations (4) and (5).
3. For single-jet water meters and wet meter casings, there is an additional dependence on pressure $p_{1,stat}$, because the initial water in the casing causes a substantial increase of the impeller's starting resistance. This dependence is distinctive for $p_{1,stat} = 0.1$ bar, but decreases with increasing pressure. Depending on V_{air}, error E_{total} can be approximated using Equations (6)–(8).
4. For multi-jet water meters and dry meter casings, the measurement error depends on pipe pressure $p_{1,stat}$ and air volume V_{air}. With higher pressures, the error E_{total} becomes continuously smaller. For estimating E_{total} depending on $p_{1,stat}$ and V_{air}, Equations (9) and (10) can be used.
5. For multi-jet water meters and wet meter casings, there is no dependence on pipe pressure, since, on account of the geometry of the measuring chamber, the initial water remains in the chamber for all tested pressures and affects the rotational motion of the impeller in each case. Depending on V_{air}, measurement error E_{total} can be approximated using Equation (11).

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