Accuracy of Single-Jet and Multi-Jet Water Meters under the Influence of the Filling Process in Intermittently Operated Pipe Networks

IWA Water IDEAS 2016 Conference, 21.10.2016, Bologna, Italy

David Walter, Miran Mastaller and Philipp Klingel
Purpose and Function of Water Meters

Purpose
- Economic base of water supply
- Determination of delivery to customers
- Determination of water balance and water losses

Function of single-jet and multi-jet meters
- Impeller set in rotational motion by single or multiple jets
- Rotational velocity proportional to flow velocity
- Number of revolutions proportional to cumulative volume
- Low-flow indicator can be used for determining flow over time
- Multi-jet meters use bypasses for calibration
Accuracy of Water Meters in Intermittent Supply

Accuracy of water meters
- Accuracy requirements are regulated in ISO 4064-1: 2014
- Meters have to be used in line with their conceptual design
  → E.g. the meter must be completely filled with water and vented

Intermittently operated water distribution systems
- Pipes are not constantly filled with water and under pressure
- Intermediate storage of water in private tanks
- In areas with high water scarcity and flat-rate tariffs:
  → Service connections constantly opened to access water

Impacts on network and meters
- Pipes drained after each supply period
- Air exits network in subsequent filling process
- Part of the air flows through service connections
  → Meters being used contrary to their initial design
Accuracy of Water Meters in Intermittent Supply

Influences on measurement accuracy

1. Air flow before the arrival of the water front
2. Impact of the water front on the impeller
3. Air intrusion in the front part of the water column
4. Unsteady flow conditions and inertia forces affecting on meter mechanics
Approach

Investigation of water meter accuracy under influence of pipe filling process

- Horizontally mounted single-jet ($Q_3 = 2.5\ \text{R80H}$) and multi-jet ($Q_3 = 4.0\ \text{R80H}$) meters
- Determination of correlation of measurement error, pipe pressure and air volume
- Experimental Parameters:
  - Pipe pressure $p_{1,\text{stat}}$
  - Volume of air in front of the meter $V_{\text{air}} / \text{pipe length } L_S$
  - Dry and wet meter casings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{1,\text{stat}}$</td>
<td>0.1 – 1.0 bar</td>
</tr>
<tr>
<td>$V_{\text{air}}$</td>
<td>0.5 – 7.8 L</td>
</tr>
<tr>
<td>$L_S$</td>
<td>1 – 25 m</td>
</tr>
</tbody>
</table>
Experimental Test Set-Up

Pressure sensor P1
- Hydrostatic pressure $p_{1,\text{stat}}$
- Start of water column movement at pressure drop ($t_{p1,\text{start}}$)

Pressure sensor P2
- Arrival of water front at meter at pressure rise ($t_{p2,\text{start}}$)

Pressure sensor P3
- Determination of real volume (water) $V_t$

Optical sensor I
- Determination of total volume (water + air) $V_{wm}$
- Determination of meter’s flow over time $Q_{wm}(t)$
Experimental Test Set-Up

Pressure sensor P1
- Hydrostatic pressure $p_{1,\text{stat}}$
- Start of water column movement at pressure drop ($t_{p1,\text{start}}$)

Pressure sensor P2
- Arrival of water front at meter at pressure rise ($t_{p2,\text{start}}$)

Pressure sensor P3
- Determination of real volume (water) $V_t$

Optical sensor I
- Determination of total volume (water + air) $V_{wm}$
- Determination of meter’s flow over time $Q_{wm}(t)$
Determination of Measurement Errors

- $E_{\text{total}}$: total error during filling process
- $E_{\text{air}}$: error caused by air flow
- $E_{\text{front}}$: error caused by impact of water front on impeller
- $E_{\text{intr}}$: error caused by air intrusion in front part of water column
- $E_{\text{unsteady}}$: error caused by unsteady flow and inertia forces of meter’s mechanics
- $E_{\text{steady}}$: common meter errors of during steady-state flow (ISO 4064-1: 2014)

No precise differentiation with described test set-up
Determination of Measurement Errors

- $E_{\text{total}}$
- $E_{\text{air}}$
- $E_{\text{front}}$
- $E_{\text{intr}}$
- $E_{\text{unsteady}}$
- $E_{\text{steady}}$
Determination of Measurement Errors

- $E_{\text{total}}$
  \[ E_{\text{total}} = V_{wm} - V_t - V_{\text{water}} \]
  total error during filling process

- $E_{\text{air}}$
  \[ E_{\text{air}} = \int_{t_{p1,\text{start}}}^{t_{p2,\text{start}}} Q_{wm}(t) \, dt \]
  error caused by air flow

- $E_{\text{rest}}$
  \[ E_{\text{rest}} = E_{\text{total}} - E_{\text{air}} \]
  remaining error ($E_{\text{front}} + E_{\text{intr}} + E_{\text{unsteady}} + E_{\text{steady}}$)
Measurement Error $E_{rest}$

- Very low positive and negative values near zero
- No dependence of $V_{air}$ or $p_{1,stat}$
- $E_{rest}$ can be neglected for estimating $E_{total}$

\[
E_{rest} \approx 0 \\
E_{total} \approx E_{air}
\]
Measurement Error $E_{\text{air}}$ for Single-Jet Meters and Dry Meter Casing

- $E_{\text{air}}$ is independent of $p_{1,\text{stat}}$ for $p_{1,\text{stat}} \geq 0.2$ bar
- Linear correlation between $E_{\text{air}}$ and $V_{\text{air}}$ for $V_{\text{air}} \geq 1.08$ L
- Non-Linear correlation between $E_{\text{air}}$ and $V_{\text{air}}$ for $V_{\text{air}} < 1.08$ L
- $E_{\text{air}}$ is dependent of $p_{1,\text{stat}}$ for $p_{1,\text{stat}} = 0.1$ bar due to unstable build-up of water front
Measurement Error $E_{\text{air}}$ for Single-Jet Meters and Dry Meter Casing

- $E_{\text{air}}$ is independent of $p_{1,\text{stat}}$ for $p_{1,\text{stat}} \geq 0.2$ bar
- Linear correlation between $E_{\text{air}}$ and $V_{\text{air}}$ for $V_{\text{air}} \geq 1.08$ L
- Non-Linear correlation between $E_{\text{air}}$ and $V_{\text{air}}$ for $V_{\text{air}} < 1.08$ L
- $E_{\text{air}}$ is dependent of $p_{1,\text{stat}}$ for $p_{1,\text{stat}} = 0.1$ bar due to unstable build-up of water front
Measurement Error $E_{\text{air}}$ for Single-Jet Meters and Dry Meter Casing

- $E_{\text{air,mv,d}}$ as mean value error curve
- Gradient and deviation in volume measurement of 96% in linear range
- Constant vertical offset of $\Delta E_{\text{inert}}$ in linear range due to starting resistance of impeller
- Decline of $\Delta E_{\text{inert}}$ in non-linear range due to compression of air in front of the water column

![Graphs showing error curves and deviation](image)
Measurement Error $E_{air}$ for Single-Jet Meters and Dry Meter Casing

- $E_{air,mv,d}$ as mean value error curve
- Gradient and deviation in volume measurement of 96% in linear range
- Constant vertical offset of $\Delta E_{inert}$ in linear range due to starting resistance of impeller
- Decline of $\Delta E_{inert}$ in non-linear range due to compression of air in front of the water column

![Graph showing error and volume measurement relationship](image)

- $E_{air,mv,d}$ as mean value error curve
- Gradient and deviation in volume measurement of 96% in linear range
- Constant vertical offset of $\Delta E_{inert}$ in linear range due to starting resistance of impeller
- Decline of $\Delta E_{inert}$ in non-linear range due to compression of air in front of the water column
Measurement Error $E_{air}$ for Single-Jet Meters and Dry Meter Casing

Estimation of $E_{total}$

\[
E_{total} = E_{air} + E_{rest} = 0.93 \cdot V_{air} - 0.56 \text{ L} + E_{rest}
\]

for $V_{air} \geq 1.08 \text{ L}$ (1)

\[
E_{total} = E_{air} + E_{rest} = 0.4 \cdot V_{air}^2 - 0.04 \cdot V_{air} + E_{rest}
\]

for $V_{air} < 1.08 \text{ L}$ (2)
Measurement Error $E_{air}$ for Single-Jet Meters and Wet Meter Casing

- Significantly smaller values of $E_{air}$ for $p_{1,stat} = 0.1$ bar $\rightarrow$ water remains in meter casing
- Abruptly larger values of $E_{air}$ for $p_{1,stat} = 0.3$ bar $\rightarrow$ water being pushed out of meter casing
- Fluctuating values of $E_{air}$ for $p_{1,stat} = 0.2$ bar $\rightarrow$ unstable condition

$\rightarrow$ Mean value error curve can be divided in an upper and a lower range
Measurement Error $E_{\text{air}}$ for Single-Jet Meters and Wet Meter Casing

Estimation of $E_{\text{total}}$

$$E_{\text{total}} = E_{\text{air}} + E_{\text{rest}} = 0.76 \cdot V_{\text{air}} - 0.63 \, \text{L} + E_{\text{rest}}$$

for $V_{\text{air}} \geq 1.08 \, \text{L}; \ p_{1,\text{stat}} \geq 0.3 \, \text{bar}$ (3)

$$E_{\text{total}} = E_{\text{air}} + E_{\text{rest}} = 0.19 \cdot V_{\text{air}} + E_{\text{rest}}$$

for $V_{\text{air}} < 1.08 \, \text{L}; \ p_{1,\text{stat}} \geq 0.3 \, \text{bar}$ (4)

$$E_{\text{total}} = E_{\text{air}} + E_{\text{rest}} = 0.11 \cdot V_{\text{air}} + E_{\text{rest}}$$

for $p_{1,\text{stat}} = 0.1 \, \text{bar}$ (5)
Measurement Error $E_{\text{air}}$ for Multi-Jet Meters and Dry Meter Casing

- $E_{\text{air}}$ is dependent of $p_{1,\text{stat}}$ and becomes smaller with higher values of $p_{1,\text{stat}}$ for $p_{1,\text{stat}} \geq 0.2$ bar
- Decrease of $E_{\text{air}}$ for $p_{1,\text{stat}} = 0.1$ bar due to unstable build-up of water front
- Separation of error curves in linear and non-linear section between $V_{\text{air}} = 1.74$ L
- Gradient in linear range of 58% for 1.0 bar to 150% for 0.2 bar
- Dependency of $E_{\text{air}}$ on $p_{1,\text{stat}}$ may caused by vibrations of the impeller and existence of bypass
Measurement Error $E_{\text{air}}$ for Multi-Jet Meters and Dry Meter Casing

**Estimation of $E_{\text{total}}$**

$$E_{\text{total}} = E_{\text{air}} + E_{\text{rest}}$$

$$= (1.73 - 1.15 \cdot p_{1,\text{stat}}) \cdot V_{\text{air}} - (2.05 - 1.5 \cdot p_{1,\text{stat}}) + E_{\text{rest}}$$

for $V_{\text{air}} \geq 1.74 \text{ L}$  \hspace{1cm} (6)

$$E_{\text{total}} = E_{\text{air}} + E_{\text{rest}}$$

$$= (0.24 - 0.1 \cdot p_{1,\text{stat}}) \cdot V_{\text{air}}^2 + (0.15 - 0.13 \cdot p_{1,\text{stat}}) \cdot V_{\text{air}} + E_{\text{rest}}$$

for $V_{\text{air}} < 1.74 \text{ L}$  \hspace{1cm} (7)

$p_{1,\text{stat}}$ in bar

---

![Graphs showing $E_{\text{air}}$ vs $V_{\text{air}}$ for different pressures.](image)
Measurement Error $E_{air}$ for Multi-Jet Meters and Wet Meter Casing

- Significantly smaller values of $E_{air}$ for all pressures $\rightarrow$ water remains in meter casing
- Velocity of air flow not high enough to lift initial water out of the lower chamber

**Estimation of $E_{total}$**

$$E_{total} = E_{air} + E_{rest} = 0.15 \cdot V_{air} + E_{rest}$$  \hspace{1cm} (8)
Conclusion

1. **Single-jet and multi-jet water meters, dry and wet meter casing:**
   Measurement error $E_{rest}$ consists of very low values that fluctuate around zero
   $\rightarrow E_{rest}$ can be neglected for estimating the total error $E_{total}$

2. **Single-jet water meters, dry meter casing:**
   The error is independent of pipe pressure $p_{1,stat}$ and only depends on the air volume $V_{air}$$\rightarrow$ Estimation of total error via equation (1) and (2)

3. **Single-jet water meters, wet meter casing:**
   Additional dependence of error on pressure $p_{1,stat}$ for small pressures caused by increase of the impeller’s starting resistance by initial water
   $\rightarrow$ Estimation of total error via equation (3), (4) and (5)

4. **Multi-jet water meters, dry meter casing:**
   The error is dependent of pipe pressure $p_{1,stat}$ since the impeller starts vibrating and the air flow shifts towards the bypass
   $\rightarrow$ Estimation of total error via equation (6) and (7)

5. **Multi-jet water meters, wet meter casing:**
   The error is independent of pipe pressure $p_{1,stat}$ since the initial water remains in the chamber and affects the rotational motion of the impeller for all tested pressures
   $\rightarrow$ Estimation of total error via equation (8)