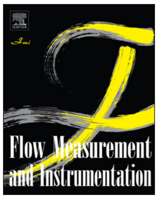
Flow Measurement and Instrumentation 63 (2018) 1–7

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst



Non-invasive estimation of domestic hot water usage with temperature and vibration sensors

N.O. Pirow[a], T.M. Louw[b], M.J. Booysen[a,*]

[a] *MTN Mobile Intelligence Lab and Department of E&E Engineering, Stellenbosch University, South Africa*
[b] *Department of Process Engineering, Stellenbosch University, South Africa*

ARTICLE INFO

Keywords:
Hot water flow estimation
Smart water heaters
Smart grid

ABSTRACT

Electric water heaters are responsible for a large portion of electricity consumption and water usage in the domestic sector. Smart water heaters alleviate the strain on the electricity supply grid and reduce water consumption through behavioural change, but the installation of in-line flow meters is inconvenient and expensive. A non-invasive water flow meter is proposed as an alternative. Non-invasive flow measurement is more common for high flow rates in the industrial sector than for domestic applications. Various non-invasive water measurement methods are investigated in the context of domestic hot water, and a combination of thermal- and vibration-sensing is proposed. The proposed solution uses inexpensive, easily installable, non-invasive sensors and a novel algorithm to provide the same flow measurement accuracy as existing in-line meters. The algorithm detects the beginning and end of water consumption events with an accuracy of 95.6%. Quantitative flow rate estimation was possible for flow rates greater than $5\,\mathrm{L\,min^{-1}}$ with an accuracy of 89%, while volumetric usage estimation had an accuracy of more than 93%. The algorithm limitations were applied to field data, revealing that water consumption could be detected with an error of less than 12% within the limitations of the proposed algorithm. The paper presents a successful proof of concept for a non-invasive alternative to domestic hot water flow rate measurement.

1. Introduction

Water heating with EWHs contributes to 34% of residential electric energy consumption, which can be reduced with the use of smart EWH controllers (SECs) [4]. Based on known hot water demand patterns, individualised heating schedules and temperature set points can be used by SECs to reduce energy consumption due to water heating without affecting user comfort [1,3,9,11]. Widespread use of SECs can decrease the strain on the electricity supply grid through peak shaving by implementing demand-side management, which schedules when EWH heating elements can be active, while taking consumer comfort and hot water demand into account [9,16,17]. SECs can also decrease the total domestic water consumption by providing users with detailed water consumption feedback. Studies have shown that users who receive consumption feedback decrease their water consumption by adjusting their water usage behaviour [6,7,12,15].

A limiting aspect of the large-scale deployment of SECs is the non-trivial and expensive plumbing required to install an in-line water flow meter to measure hot water consumption. A non-invasive, retrofit domestic hot water measurement system removes the expensive plumbing associated with SEC installation. This paper addresses this problem by proposing a novel non-invasive flow sensor that uses vibration and temperature sensing to estimate hot water flow through copper piping.

Several non-invasive technologies were investigated in the context of domestic EWH conditions. A combination of vibration and outlet pipe temperature analysis was determined to be the most practical solution. A non-invasive water flow meter for a smart EWH controller was developed using a novel algorithm that requires temperature and accelerometer data only. The non-invasive flow estimation algorithm was developed using an experimental EWH unit, which was designed to reflect domestic conditions. The selected temperature sensors and accelerometer are inexpensive and readily installed in existing systems, providing an economical retrofit solution.

2. Related work

Table 1 lists relevant investigations into non-invasive water flow sensors. Non-invasive fluid measurement is common in industrial conditions [14]. Larger pipe diameters and higher fluid flow rates are typically present in industrial conditions than can be expected for

---

[*] Corresponding author.
E-mail address: mjbooysen@sun.ac.za (M.J. Booysen).

https://doi.org/10.1016/j.flowmeasinst.2018.07.003
Received 12 March 2018; Received in revised form 24 May 2018; Accepted 15 July 2018

Table 1
Summary of non-invasive water flow rate studies.

	Evans et al. [5]	Bernier and Brennen [2]	Huijsing et al. [8]	Safari and Tavassoli [18]	Jacobs et al. [10]	Nel et al. [13]	**This paper**
Domestic flow rates	×	×	×	✓	✓	✓	✓
Water as working fluid	✓	✓	×	✓	✓	✓	✓
Low-cost sensing	✓	×	✓	✓	✓	✓	✓
Copper pipe supported	✓	×	✓	✓	×	✓	✓
Robust (noise and location)	✓	×	✓	×	×	×	✓

domestic EWH conditions. Data from 34 domestic SEC field units showed maximum measured volumetric flow rates of 30 L $\min^{-1}$ [17]. In contrast, industrial applications discussed by Evans et al. [5] exhibit flow rates between 500 L $\min^{-1}$ and 1500 L $\min^{-1}$ for similar pipe diameters. Lower domestic water flow rates often mean that industrial non-invasive flow measurement methods are not suited.

Ultrasonic and electromagnetic methods are commonly employed for the non-invasive measurement of fluid flow. The use of ultrasonic transducers is technically feasible for domestic use [19], but too expensive for the desired application as components costs alone would exceed current in-line installation method costs. Electromagnetic flow measurement requires an electrically non-conductive inner pipe lining, precluding their use with copper piping [2,20].

Thermal methods are generally used to measure gas flow rate [14]. Thermal mass (or thermal dispersion) flow measurement was used by Huijsing et al. [8] to measure low flow rate liquid flows (below 0.6 L $\min^{-1}$) in small diameter pipes (the measuring tube has an inner diameter of 13 mm). Thermal event detection and volumetric estimation were incorporated in an EWH energy usage model by Nel et al. [13] using a non-invasive temperature sensor installed on the outlet pipe. The data sample rate used was 1 min and the described system was more effective for longer duration flow events (7–10 min) and the minimum duration of a detectable usage event was 3 min.

Domestic water flow conditions are almost exclusively turbulent. Rapid velocity fluctuations generated by turbulent flow results in vibrations on the pipe surface, and the magnitude of these vibrations are correlated to the average fluid velocity in the pipe [5]. An empirically derived quadratic relationship was found between the standard deviation of the vibrations measured using an accelerometer and fluid velocities ranging between 1.82 m s^{-1} and 5.48 m s^{-1} [5]. These velocities are common in industrial conditions, but greater than that found in domestic applications where the maximum fluid velocity is approximately 0.64 m s^{-1}. Another study utilizing condenser microphones to detect vibrations found either linear or quadratic correlations, depending on the sensor position [18]. Time and frequency domain analysis were used to estimate water flow using a piezoelectric transducer installed on a tap outlet, but transitional water flow rates could not be estimated accurately [10].

From the above information, a combination of vibration and thermal water flow estimation was identified as being the most promising method for low-cost non-invasive flow measurement and were further investigated in the context of domestic EWH conditions.

3. Experimental unit

3.1. Hardware

A 150 L EWH with a 3 kW heating element and a 600 kPa water supply, as is commonly found in domestic installations, was selected. A diagram of the experimental unit is shown in Fig. 1. A Raspberry Pi 3 was used to sample the sensors, store acquired data, and perform scheduled water usage events for controlled experimental conditions. Water flow rate was controlled using a manually operated ball valve and scheduled water usage (flow events) were controlled by fully opening or closing an electrically operated solenoid valve. Water flow rate was measured using an in-line positive displacement Misol flow meter with a volumetric measurement resolution of 380 pulses per litre and general purpose input/output (GPIO) interrupt handler in software.

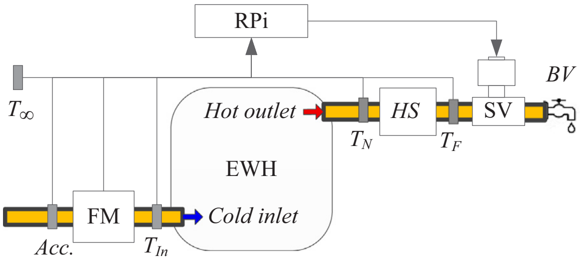


Fig. 1. Diagram showing the experimental unit. Outlet pipe temperature sensors (near and far - T_N and T_F respectively), inlet pipe temperature sensor (T_{In}), ambient air temperature sensor (T_∞), heatsinks (HS), electrically operated solenoid valve (SV), manually operated ball valve (BV), flow meter (FM), EWH tank, LSM303 accelerometer and Raspberry Pi (RPi) are shown.

Two temperature sensors were mounted on the EWH outlet pipe: one ‘near’ (T_N) and one ‘far’ (T_F) a short distance away from the EWH outlet. Inlet pipe (T_{In}) and ambient air (T_∞) sensors were also installed, but were not required for the designed system to function. Texas Instruments TMP275 digital temperature sensors were selected due to their relatively low cost, listed accuracy of ± 1 °C without calibration, inter-integrated circuit (I^2C) communication, and maximum resolution of 12-bit which equates to 0.0625 °C. Heatsinks were installed on the outlet pipe to maximize the longitudinal temperature difference on the outlet pipe between the upstream and downstream sensors. The heatsinks were milled to have a 22 mm mounting surface to enclose the outlet pipe. This was to provide a ‘best case’ scenario for thermal investigations. The study indicated that sufficient thermal data was available for the experimental unit that heatsinks and ‘far’ temperature sensors were not required - but this cannot be confirmed for other installations until field tests are performed. A n LSM303 3-axis accelerometer was installed on the inlet pipe, sufficiently far from upstream and downstream disturbances to ensure fully developed turbulent flow was measured.

3.2. Software

A python script was executed on the Raspberry Pi to control the water flow for experiments using the solenoid valve, sample the temperature sensors and accelerometer using I^2C, measure the water flow rate using GPIO pulses, and to store the acquired data in a MySQL database. Data sampling was performed at 1 s intervals. Accelerometer sweeps were performed at ≈ 1 kHz and the standard deviation σ of 250 g-force readings per accelerometer axis were stored. The σ values were filtered using a centre-shifted rolling mean (moving average) filter with a window length of 10 s to smooth the signals while maintaining temporal accuracy. Experiments with automated flow events were controlled using the Raspberry Pi and solenoid valve to ensure repeatable conditions.

3.3. Experimental plan

Three separate experiments were performed using the EWH unit to