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Replication Studies

Experimental verification of a virtual water flowmeter applicable to air conditioning systems

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ABSTRACT

The main purpose of this research is to suggest a virtual water flowmeter applicable in hydraulic systems with low-cost sensors. Practical procedures for realizing virtual water flowmeters for constant flow pumps (i.e., Cases 1 and 2) and variable flow pumps (i.e., Cases 3 and 4) are proposed in this paper. In Case 1, for measuring the water flow rate through a constant flow pump, the pump head was measured and the water flow rate was estimated using the pump characteristic curve obtained from the manufacturer or by deriving an empirical model based on the field measurement data. In Case 2, the water flow rate through a valve with a constant flow pump was estimated by measuring the pressure head between the valve and the valve opening position. The valve characteristic curve can be obtained by deriving an empirical model based on the initial field test results. The water flow rate through the variable flow pump was calculated, using the pump affinity laws and an empirical model, by measuring the frequency (i.e., Case 3) or input power (i.e., Case 4). The initial setup and test procedures for virtual flowmeters are also proposed in this research for practical use in the field. To verify the proposed procedures, experiments were conducted using constant and variable flow pumps in a pilot system. It was found that the virtual water flowmeters showed 2.9% to 6.7% of root mean square error from Case 1 to Case 4, compared with an ultrasonic water flowmeter, through long-term experimental verification.

1. Introduction

Measurements of water flow (such as chilled water and hot water) have become mandatory to minimize operating energy consumption in buildings and to improve efficiency [1,2], fault detection, and diagnostics [3–6] of heating, ventilating, and air conditioning (HVAC) systems. It is well known that variable flow hydraulic systems can save over 50% of operating energy compared to constant flow systems [7,8]. The commissioning of hydronic systems in HVAC systems provides the opportunity to reduce operating energy consumption by 15–30% [9]. There is an increasing interest in energy management systems for buildings, operating energy savings in hydraulic systems using variable flow approaches, and fault detection and diagnostics in HVAC systems. However, the initial cost for sensors has also increased.

In constant flow hydraulic systems, the water flow rate is measured one time at the initial testing, adjusting, and balancing (TAB) stage using a portable flowmeter because of the high installation, maintenance, and calibration costs associated with the installation of flowmeters in a conventional HVAC system [10]. Moreover, many available conventional water flowmeters cause high pressure losses in HVAC systems and raise the cost of maintenance for air handling unit (AHU) applications [11]. Thus, low-cost flowmeters with acceptable accuracy are strongly required.

A virtual flow sensor uses simple mathematical models with low-cost sensors to measure a difficult quantity or to avoid the need for expensive sensors [12,13]. Since 2003, when Joo et al. [14] developed a virtual fan airflow station to control the return airflow rate by tracking the supply air flow rate, several studies have examined virtual flow sensors for HVAC systems [15–20]. Hammo and Viholainen [15] found that the pressure head measuring method showed better accuracy than the power consumption measuring method for both constant- and variable-volume water flow rates. Ahonen et al. [16] found that the model-based meth-

Abbreviations: AHU, air handling unit; HEX, heat exchanger; HVAC, heating ventilating and air-conditioning; RMSE, root mean square error; TAB, Testing, adjusting, and Balancing.

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Nomenclature

A	Actual measured value
b_X	Systematic standard uncertainty
$F_z(Z)$	Valve characteristics
H_{pump}	Pressure head in pump (Pa)
H_{valve}	Pressure head in valve (Pa)
H_L	Pressure head in loop (Pa)
N	Number of values
n	Frequency (Hz)
P_n	New input power (kW)
P_{ref}	Reference input power (kW)
Q_L	Flow rate in loop (m^3/h)
Q_n	New flow rate in loop (m^3/h)
Q_{ref}	Reference flow rate in loop (m^3/h)
s_X	Random standard uncertainty
U_X	Overall uncertainty
X_s	Simulated value
z	Valve opening

ods for pump operation estimation provide a cost-efficient way to control and analyze the operation of the pump drive. Swamy et al. [17] showed that the uncertainty of virtual water flow measurements was between 1.96% and 7.83%. Song et al. [18] developed a virtual water flowmeter for chilled water flow, and found that their proposed method showed uncertainty similar to that of an ultrasonic water flowmeter. All these studies measured the fluid flow rate by sensing a head and using a curve, without direct physical measurement of the flow rate. On the other hand, Tamminen et al. [19] proposed mixing two model-based control methods for pump operating-point estimation to enhance their usability and accuracy. Ahonen et al. [20] investigated the power consumption and flow monitoring of centrifugal pumps by measuring the motor phase current. Wang et al. [21] developed a virtual pump water flowmeter for implementing building automation systems using a combination of pump affinity laws and polynomial regression models for motor and pump efficiency.

Generally, two methods for virtual water flow measurement are available for constant flow pumps: measuring the pressure head with the valve in the opening position and measuring only the pressure head [15–18]. The former is used for valve-side flows or branches, and the latter is used for the primary flow on the pump side. A variable flow pump also has two available methods: measuring the frequency and measuring the input power, using either pump affinity laws or empirical models [18–21].

In this research, test procedures for virtual water flowmeters were developed for constant and variable flow pumps. For water flow measurement in constant flow pumps, the pump head (Case 1) and the head and valve in the opening position (Case 2) measuring methods were used. To measure the water flow rate in variable flow pumps, the pump frequency (Case 3) and power (Case 4) measuring methods were applied. Furthermore, the proposed procedures for field engineers who need to apply virtual water flowmeters were explained, and the proposed methods were verified using initial experimental data and long-term operation.

2. Virtual water flowmeter for HVAC systems in buildings

2.1. Estimation methods

In Case 1, the water flow rate was estimated by measuring the pump head. The test-pump performance curves can be obtained from the manufacturer; however, the field test conditions are usually different from the pump test conditions. To obtain the installed pump performance curve in the field, which is related to the water flow rate and is a function of the pump head, a multiple linear regression model was used. Various order regression models were derived and compared to observe any accuracy enhancement.

To estimate the water flow rate modulated by the valve in branch or bypass pipelines, the valve characteristic ($F_z(z)$) and pressure head across the loop (H_L), as shown in Eq. (1) [18] were measured. The valve characteristic can be obtained by the valve characteristic curve, which is a function of the valve opening position (z). From the literature [18], it was found that the valve characteristic curve should be obtained through an empirical approach at the installation site. In Case 2, the valve characteristic curve was obtained using an empirical approach with multiple linear regression models, and then, the water flow rate was calculated using Eq. (1).

$$Q_L = F_z(z)\sqrt{H_L} \tag{1}$$

The affinity laws are commonly used to predict the volumetric flow rate of a pump. Eqs. (2) to (5) are assumed with a constant impeller diameter. The pump motor speed is modulated by changing the frequency of a variable frequency drive. Measuring the shaft speed of a pump is not easy, but estimating it is easily done by measuring its frequency, because the shaft motor speed is linearly related to its frequency. The actual shaft motor speed shows a 2.7–3% deviation from the frequency, which is caused by slip [22]. However, this slip occurs across the whole frequency range, and thus, the frequency measurement can efficiently represent the shaft speed. In this research, the frequency was used instead of shaft speed for applying the affinity laws.

In Case 3, the flow rate was calculated using the affinity laws by measuring the frequency, which is proportional to the flow rate (Eq. (2)). In Case 4, the flow rate was determined by measuring the input power using the affinity laws, as shown in Eq. (3), or using the linear regression model. The reference values for flow rate (Q_{ref}), power (P_{ref}), and frequency (n_{ref}) use their respective allowable maximum values. This equation is obtained such that the input power is proportional to the cube of the frequency from Eq. (4). In cases where the virtual flowmeter using the affinity laws showed low accuracy, the empirical approach with linear regression models was used to calculate the water flow rate. The root mean square error (RMSE) was used to evaluate quantitatively the difference between the measured and virtual water flow values in each Case (Eq. (5)) [23,24].

$$Q_n = \left(\frac{n_n}{n_{ref}}\right) Q_{ref} \tag{2}$$

$$Q_n = \left(\frac{P_n}{P_{ref}}\right)^{1/3} Q_{ref} \tag{3}$$

$$P_n = \left(\frac{n_n}{n_{ref}}\right)^{3} P_{ref} \tag{4}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum\left(\frac{X_S - A}{A}\right)^2}{N}} \times 100 \tag{5}$$

2.2. Virtual water flowmeter test procedure

These test guidelines cover the virtual water flowmeter for constant and variable flow pumps. This test method is applicable to HVAC systems in buildings and includes five major steps: test planning, test set-up, initial test procedure, analysis, and report.