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Development of a virtual pump water flow meter with a flow rate function of motor power and pump head

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ABSTRACT

Water flow rates are key operating variables in chilled and hot water systems. The water flow rate through a pump can be virtually measured using available motor power and pump head with projected motor and pump efficiencies. In general, motor efficiency is implicitly determined by motor power while pump efficiency is given as a function of water flow rate. As a result, the water flow rate has to be calculated through a numerical method, which is difficult to apply in building automation systems (BAS). The objective of this paper is to develop a virtual pump water flow meter, which can be implemented in BAS with an explicit expression of motor power and pump head. First, motor efficiency is regressed as a function of motor power by consolidating multiple dependent factors, then pump efficiency function is reconstructed with pump shaft power and head, and finally experiments are conducted to develop and validate a virtual pump water flow meter on a chilled water pump. The experimental results show that the virtual flow measurements agree well with the flow measurement by a physical meter. The measurement standard deviation is 0.5 L/s for a pump with the design flow rate of 37.9 L/s.

1. Introduction

Airflow and water flow rate are key operating variables for optimal operation, fault detection and diagnosis (FDD), and energy metering in heating, ventilating and air-conditioning (HVAC) systems. Gao et al. [1] pointed out that energy efficient pump control strategies should maintain the water flow rate in the secondary loop equal to or lower than the water flow rate in the primary loop in decoupled chilled water systems. Zhao et al. [2] and Zhao [3] developed several effective FDD methods for chillers, which heavily depend on the water flow rates of evaporators and condensers. Celenza et al. [4] demonstrated that water flow measurement contributes the uncertainty of direct heat meters three times more than water temperature measurement.

Conventionally airflow and water flow rates are often measured by differential pressure meters, such as Pitot tubes, Orifice plates or Venturi meters, which normally require long, straight pipes or duct unobstructed by valves, dampers, bends and fittings for accurate measurements [5]. Wang [6] gave an example that the total straight pipe length should be at least 3.89 m (13.8 ft) without any parts for a DN250 (NPS10) pipe. Unfortunately, these conditions are difficult to satisfy in actual systems and the accuracy of the physical flow meter is in jeopardy.

On the other hand, a component of HVAC systems may have a physical correlation of air or water flow rate with other measurable variables. For example, the pressure drop of a cooling coil is correlated to the water flow rate and the pressure drop of a control valve is correlated to the water flow rate as well as the valve position. Therefore, the flow rate can be virtually obtained by measuring other available variables. Zhao et al. [3] developed a virtual water flow meter to determine the water flow rate in chillers using available chiller onboard measurements. Wang [6] developed a method to determine the water flow rate through chillers by combining pipe resistance coefficients and online pressure difference. Song et al. [7] developed a virtual water flow meter to determine the water flow rate through the cooling coil of AHUs based on pressure difference as well as control valve positions.

Moreover, motor-driven fans and pumps are essential components installed in HVAC systems and share same governing laws. Since the fans and pumps have dynamic loads, variable-frequency drives (VFDs) are widely applied on the motors of fans and motors. The VFDs adjust the output frequency to proportionally reduce motor speed and consequently reduce motor mechanical load to pumps or fans. Meanwhile the VFDs also adjust the output voltage

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Nomenclature

f VFD frequency (Hz)

H	pump head (Pa or Psi)
Q	pump water flow rate (L/s or GPM)
s	motor slip
V	VFD voltage (V)
W_{motor}	motor power (kW)
W_{shaft}	pump shaft power (kW)
W_{water}	mechanical work received by water (kW)
η_{motor}	motor efficiency
η_{pump}	pump efficiency
ω	pump speed

Subscripts:

imp	implicit

to reduce motor electrical input power. The air or water flow rate through a fan or pump has a correlation with fan or pump head, shaft power, and speed. Therefore, a virtual flow meter can be developed on fans and pumps to determine the fan or pump flow rate by available fan or pump head, shaft power, and speed [8]. In general, the fan or pump head can be accurately measured by a differential pressure transducer, the fan or pump shaft power is easily obtained from the connected VFD, and the motor speed can be obtained from the VFD frequency command in BAS.

Liu [9] proposed the first fan airflow meter that determines fan airflow rate using measured fan head and speed associated with an in-situ fan head curve in 2003. Then a power-based fan airflow meter using measured fan power and speed was developed to eliminate the errors caused by the flat section of head curves in 2005 since the power curve is steep in the flow range where the head curve is flat in general [8]. Liu [10] demonstrated applications of both virtual fan and pump flow meters based on either head or shaft power in 2006. Besides the flat head and shaft power curves within a certain flow range, actual fan or pump speeds have to be applied to create actual correlations between head or shaft power and flow rate under actual speeds from the in-situ curve for both head-based and power-based virtual flow meters. Therefore, the fan or pump speed is a dominant variable that affects the accuracy of head-based and power-based virtual flow meters among all input variables. Unfortunately, the VFD frequency command does not always represent the motor speed, which is proportional to the fan or pump speed, especially in the low speed range.

To avoid using inaccurate motor speeds, power-head-based fan and pump flow meters were developed. The power-head-based flow meters determines fan or pump flow rate based on measured fan/pump head and motor power as well as projected motor efficiency and fan/pump efficiency without using the motor speed. Motor efficiency is applied to calculate fan/pump shaft power from available motor power, which is read from the connected VFD. Meanwhile, fan/pump efficiency correlates fan/pump flow rate to calculated shaft power and measured head, which is measured by a differential pressure transducer. Therefore, accurate motor and fan/pump efficiency calculation is essential to develop power-head-based virtual flow meters.

The latest power-head-based fan flow meter was developed by Wang et al. [8]. Andiroglu et al. [11] applied the same principle to develop and validate a virtual pump flow meter in 2013. Typically, the fan/pump efficiency curve normally is given as a function of flow rate under a design speed by manufacturers as same as the fan/pump head and shaft power curves. According to affinity laws, each point on the given efficiency curve under a design speed represents a series of equivalent points under different speeds, which have same efficiency as well as an identical ratio of fan/pump head to flow rate squared. Since the inaccurate fan/pump speed has to be avoided, the fan/pump efficiency was constructed as a function of the ratio of fan/pump head to flow rate squared through a calibration process in the latest power-head-based flow meters [8,11].

Even though it is very common to assume constant motor efficiency for motor energy calculation [12], accurate motor efficiency calculation is needed in virtual flow meter development for a better accuracy. The MotorMaster+ motor system management software developed by the U.S. Department of Energy's (DOE) Industrial Technologies Program provides motor efficiency at different loads at the rated frequency for nearly 30,000 industrial electric motors [13]. In fact, not only motor power but also VFD frequency affects motor efficiency [14–16]. Motor efficiency at variable frequencies can be accurately estimated using the motor equivalent circuit theory recommended by Institute of Electrical and Electronics Engineers (IEEE) [17]. The latest power-head-based flow meters applied this method to calculate motor efficiency [8,11].

The water flow determined by the developed virtual water flow meter agrees well with the ultrasonic water flow meter measurement indicated by the coefficient of determination or *R*-squared of 0.97 and the standard deviation of 0.5 L/s (7 GPM) for instant measurement [11]. However, two iterations in virtual flow calculation are barriers to implement the developed virtual flow meters in building automation systems (BAS). First, VFD voltage, frequency and motor slip are independent input variables to calculate motor power and efficiency using the motor equivalent circuit method [17–19], therefore, motor efficiency has to be implicitly determined by motor power, VFD frequency and voltage by a numerical method. Second, since fan and pump efficiencies were calibrated as a function of the ratio of fan or pump head to flow rate squared, the unknown flow rate presents on both the side of the basic flow correlation equation. As a result, the flow rate has to be calculated from available pump/fan shaft power and head through another numerical process. Two numerical processes to calculate the motor efficiency and flow rate make it impossible to achieve the virtual flow rate calculation in BAS for current HVAC applications, which has less mathematic calculation capacity.

The objective of this paper is to develop and validate a virtual head-power-based pump flow meter, which is easily implemented in BAS, by constructing an explicit water flow expression of available motor power and pump head to eliminate these two barriers. In the paper, first the motor efficiency is regressed as an explicit function of motor power by consolidating dependent factors, including motor power, VFD frequency and voltage; then the pump efficiency is regressed as a function of pump shaft power and head without water flow rate; and finally experiments are conducted to develop, calibrate and validate a virtual pump water flow meter on a chilled water pump based on motor power and pump head along with regressed motor and pump efficiency functions.

2. Theory for virtual pump flow meters

VFDs are widely installed on the motor of pumps in HVAC systems to reduce pump shaft power by reducing VFD frequency and reducing motor power by reducing VFD voltage at partial flow rates. Fig. 1 shows the configuration of a VFD–motor–pump system. The VFD receives the power at the rated frequency and voltage, and transforms it into the power at variable frequencies and voltages. The motor receives the power with variable frequencies and voltages from the VFD and drives the pump at variable speeds with reduced pump shaft power and motor power. The pump creates water pressure increase or pump head and generates water flow driven by the shaft power from the motor.