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Development and Testing of a Virtual Flow Meter Tool to Monitor the Performance of Cooling Plants

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Abstract

This paper introduces a graphical user interface (GUI) for a virtual flow meter (VFM) Tool that estimates the chilled and condenser water mass flow rates through the evaporator and condenser, respectively, of a chiller. The quasi steady-state thermodynamic mathematical model uses six different scenarios of available sensors, which could be available in a building automation system (BAS) to facilitate the use of the model for a large portion of the building stock. The developed model can be used for reciprocating and centrifugal chillers. A case study from an institutional building is used to demonstrate the use of the VFM Tool during the summer months of 2014. The VFM Tool was able to estimate the chilled and condenser water mass flow rates with a coefficient of variance of the root mean squared error (CV(RMSE)) ranging from 4.9% to 13.4% and the normal mean bias error (NMBE) ranging from -12.2% to -1.4%, depending on the number of sensors available.

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Keywords: Virtual Flow Meter; Chiller; Chilled water system; Measurements;

1. Introduction

The chilled and condenser water mass flow rates of a chiller are important variables for use in ongoing commissioning and fault detection and diagnostics (FDD) of cooling plants. Unfortunately, the chilled and condenser water mass flow rates are not always measured mainly because water flow meters are not installed in most buildings due to budget constraints or space limitations. It is expensive to provide continuous measurements for the

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chilled and condenser water mass flow rates passing through the chiller for ongoing commissioning and FDD using physical water flow meters.

An alternative solution to physical flow meters is to use a virtual sensor to estimate the water flow rates. The idea of virtual sensors is used in many different industries such as the automotive, pulp and paper, and Heating Ventilating and Air Conditioning (HVAC) systems. A virtual sensor estimates or simulates 'measurements' at positions in a system where a physical sensor does not exist, using a mathematical model along with some measurements from other available sensors in the system.

2. Literature Review

The literature review revealed that so far four different models have been developed to estimate the chilled and condenser water mass flow rates in the hydronic loops of an HVAC system of the heating and cooling plant. Two models use information at pump level where the water flow rates are estimated after pumps [1, 2]. The models use the pump head, based on a differential pressure sensor across the pump, and the motor power input along with pump characteristic data, and pump performance curves which are developed from manufacturer data or from in-situ measurements. Two models were developed at the chiller level. Zhao et al. 2012 [3] developed a model that uses the thermodynamic analysis of the chiller to estimate the chilled and condenser water mass flow rates. Wang 2014 [4] uses pressure sensors across the evaporator and condenser with experimentally developed resistance coefficients.

3. Description of Developed Virtual Flow Meter

A new VFM was developed to estimate the chilled and condenser water mass flow rates for a wide range of cooling plants [5,6]. The VFM uses six different scenarios of available sensors that could be available in a BAS. The method requires a maximum ten sensors to estimate the chilled and condenser water mass flow rates. The maximum number of sensors might not always be present in existing buildings. For this method to be implemented into a large portion of the building stock, six scenarios are considered with different amount of sensors: the first scenario uses ten sensors, while the last scenario uses only five sensors. When the amount of available sensors is reduced, manufacturer data can be used with modified subroutines from the HVAC Toolkit [7] that can predict the refrigerant mass flow rate of chillers and the discharge temperature [8]. The sensors and manufacturer data required are shown in Table 1.

Table 1. Scenarios of available measured data

Description of measurement point	Symbol	Scenario					
		1	2	3	4	5	6
Manufacturer data	-	-	-	-	MD-1	MD-1	MD-3
Chilled water supply and return temperature	T_{chws}, T_{chwr}	M	M	M	M	M	M
Condenser water supply and return temperature	T_{cdws}, T_{cdwr}	M	M	M	M	M	M
Pressure in evaporator	$P_{ref,ev}$	M	M	M	M	M	-
Saturation temperature in evaporator	SST	M	M	M	M	M	-
Pressure in condenser	$P_{ref,cd}$	M	M	M	M	M	-
Saturation temperature in condenser	SDT	M	M	M	M	M	-
Suction temperature	T_{suc}	M	M	E	M	E	-
Discharge temperature	T_{dis}	M	MD-2	MD-2	-	-	-
Liquid line temperature	T_{ll}	M	M	E	M	E	-
Power input into the compressor	$\dot{W}_{ac}$	M	M	M	-	-	M

* Note M= Measured, E=Estimated, MD= Manufacturer data

The complete description of the models is given in [5,6]. Because of space limitations, only some applications of the proposed VFM are presented in this paper. MD-1 is the required manufacturer data that is used to estimate the refrigerant mass flow rate for scenarios # 4 and # 5. MD-2 is the manufacturer data used to estimate the discharge temperature (T_{dis}) which is the temperature at the exit of the compressor. MD-3 is the manufacturer data used in scenario # 6 to estimate the refrigerant capacity of the system.

3.1. Development of the Graphical User Interface for the VFM Tool

A GUI was developed to provide users with a simple way to enter the required inputs to use the VFM Tool and to provide a quick visual feedback of the results generated by the models of the VFM. The VFM Tool generates a comma-separated file (*.csv) for each chiller alone, as well as for the plant for further analysis and use of the data. The plant, for the case of the VFM Tool, is defined as the combination of all chillers in operation together, and excludes the chilled and condenser water pumps as well as the cooling towers, to simplify the inputs to the model.The main window of the GUI is shown in Figure 1.

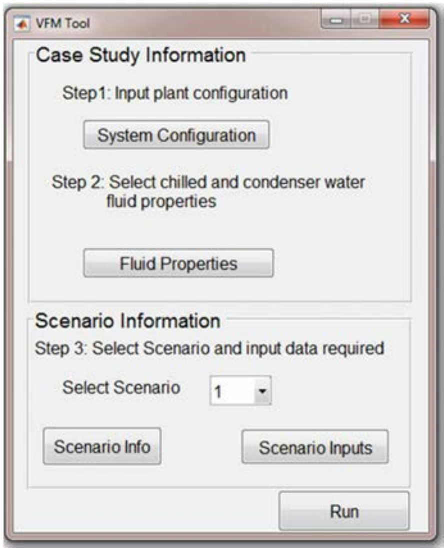

Fig. 1. Main window of the VFM Tool

The system configuration window allows the user to select up to six different chillers to be in combination with each other either in series or in parallel. In the plant configuration menu, there are three drop down menus; (i) the chiller type (ii) chiller refrigerant type and (iii) the part load method. Currently the VFM Tool works for centrifugal and reciprocating chillers. The modified subroutines from the HVAC Toolkit [7] estimate the full-load refrigerant mass flow rate. To model the refrigerant mass flow rate at part load conditions other methods are required to be linked with the results from the HVAC Toolkit [7] like the cylinder-unloading method for reciprocating chillers and the part load ratio method (PLR) and minimum return temperature method (T_{min}) methods for centrifugal chillers [6].

The fluid properties tab is used to select the chilled and condenser fluid that can be water, a calcium-chloride/water solution or a glycol/water solution, each one with the corresponding specific heat capacity. The percentage of brine to water is required and then the specific heat capacity is determined from interpolation within a property table. The cooling fluid of condenser can be water or air. The average temperature from the trend data file is used to estimate the specific heat capacity.

The scenario inputs window is used to input the trend data from the cooling plant. The manufacturer data (MD-1) is used to identify the compressor parameters for scenarios # 4 and # 5 or manufacturer data (MD-3) for scenario # 6. The input trend data is either in excel or (*.csv) files. The table is used to input the superheating and sub-cooling for each chiller for scenario # 3 and # 5.

After all the inputs have been entered, the run button will start the VFM Tool. After completion, the results window appears (Figure 2). The results window consists of a graphic screen and two tables. The graphic screen displays the results from the VFM for three variables: i) the chilled water mass flow rate, ii) the condenser water mass flow rate and iii) the Coefficient of Performance (COP) of the individual chillers or of the chiller plant. By pressing the corresponding tabs located at the top left hand side of the window, it will display the graph for the selected variable. The default graph that appears is of the cooling plant and the results for each individual chiller in operation can be viewed by using the drop down menu. The colored markers highlight the combination of chillers in operation during the point in time when the variable was calculated. This aids the user to visualize the variables with respect to the systems operating conditions. The average properties for the chilled water mass flow rate, condenser water mass flow rate, power demand and COP of each chiller are given in the lower left corner table. For scenarios # 4 and # 5, the identification parameters used to determine the refrigerant mass flow rate, generated from the modified subroutines from the HVAC Toolkit [7], are given as well in the lower right corner table.

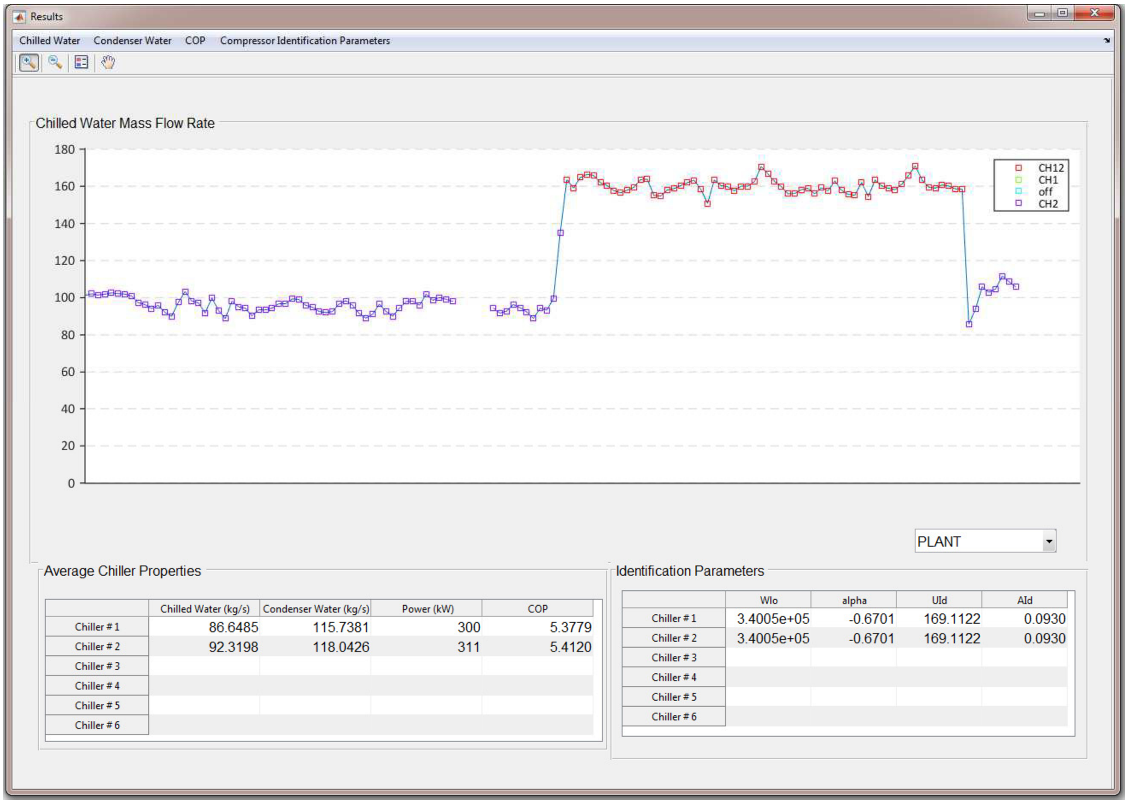

Fig. 2. Results window for VFM Tool during the summer of 2014

The results window is used to provide quick feedback to verify how well the VFM Tool estimated the chilled water and condenser water mass flow rates. It gives the user the opportunity to verify if large discrepancies exists between the estimated values and the design or manufacturer data. Once the chilled and condenser water mass flow rates are accepted by the user, they can be used for further analysis of the cooling plant with the developed comma-separated files (*.csv).

4. Case Study of a University Campus

The VFM Tool was used to estimate the chilled and condenser water mass flow rates for the cooling plant of a university campus during the summer from May to October 2014. The cooling plant consists of two (3165 kW) centrifugal chillers connected in parallel with two constant speed pumps that are connected in parallel. This case study represented a common case of existing buildings where a limited amount of sensors and manufacturer data are available. For this case, only scenarios # 5 and # 6 were used to estimate the chilled and condenser water mass flow rates.

The results are separated into three modes of operation: i) chiller # 1, ii) chiller # 2, and iii) both chillers in operation. The average chilled and condenser water mass flow rates with the overall uncertainty due to propagation of measurement errors are given in Tables 2 and 3, respectively. The uncertainty is determined by using developed equations for the propagation of measurement errors for each parameter [6]. During the summer of 2014 the chilled and condenser mass flow rates were verified using a portable ultrasonic flowmeter. The measured chilled water mass flow rates were 87.8 ± 2.7 kg/s (chiller #1), 90.1 ± 2.7 kg/s (chiller # 2), and 151.7 ± 3.5 kg/s (chillers #1 and #2). The estimated chilled water mass flow rates for scenario # 5 agreed well with the measured values; the average estimated values were 92.3 ± 12.5 kg/s (chiller #1), 94.2 ± 11.9 (chiller #2), 157.8 ± 29.2 (chillers #1 and #2). The average estimated values for scenario # 6 were 96.2 ± 13.1 (chiller #1), 100.6 ± 12.7 (chiller #2), 169.2 ± 31.3 (chiller #1 and #2).

Scenario # 5 proved to provide more accurate estimates for the chilled water mass flow rate than scenario # 6 for this case study where the average CV(RMSE) ranged from 5.2% to 7.4% and the NMBE ranged from -4.5% to -2.2%. For scenario # 6, the average CV(RMSE) ranged from 9.0% to 12.8% and the NMBE ranged from -11.8% to -6.8 %.

Table 2. Average chilled water mass flow rate during the summer of 2014

		VFM model B (Scenario #5)			VFM model C (Scenario #6)			Measured
	Month	Average (kg/s)	CV(RMSE) (%)	NMBE (%)	Average (kg/s)	CV(RMSE) (%)	NMBE (%)	Average (kg/s)
CH 1	May	92.7	8.3	-3.3	96.3	9.3	-7.3	
	June	91.0	7.1	-1.4	95.5	8.9	-6.4	
	July	92.8	7.2	-3.4	97.2	9.5	-8.2	
	August	92.6	5.9	-3.1	95.6	7.9	-6.4	
	September	-	-	-	-	-	-	
	Average	92.3 ± 12.5	7.4	-2.2	96.2 ± 13.1	9.0	-6.8	87.8 ± 2.7
CH 2	May	-	-	-	-	-	-	
	June	-	-	-	-	-	-	
	July	93.0	5.7	-3.3	100.0	11.7	-11.0	
	August	94.7	6.8	-4.4	100.6	12.6	-11.8	
	September	94.9	8.0	-5.4	101.1	13.4	-12.2	
	Average	94.2 ± 11.9	6.8	-4.5	100.6 ± 12.7	12.8	-11.8	90.1 ± 2.7
CH 1 & 2	May	158.5	5.3	-4.5	170.4	13.1	-12.4	
	June	158.3	5.3	-4.4	169.8	12.7	-11.9	
	July	157.2	5.5	-3.6	168.7	12.2	-11.2	
	August	157.5	4.9	-3.8	168.7	12.0	-11.2	
	September	157.3	5.1	-3.7	168.4	11.8	-11.1	
	Average	157.8 ± 29.2	5.2	-3.8	169.2 ± 31.3	12.1	-11.3	151.7 ± 3.5

The measured condenser water mass flow rates for scenario # 5 were 112.4 ± 2.2 kg/s (chiller # 1) and 117.0 ± 2.3 kg/s (chiller # 2). The estimated values were 116.2 ± 12.2 kg/s (chiller # 1) and 115.9 ± 12.6 kg/s (chiller # 2). For scenario # 6, the average condenser water mass flow rates were 121.7 ± 12.8 kg/s (chiller # 1) and 122.9 ± 13.4 kg/s (chiller # 2). As for the chilled water mass flow rate, scenario # 5 proved to provide more accurate estimates for the condenser water mass flow rate than scenario # 6, for this case study. The average CV(RMSE) ranged from 3.8% and 7.5%, and the NMBE ranged from -3.4% and -1.1% for chiller # 1 and chiller # 2, respectively. For scenario # 6, the average CV(RMSE) ranged from 6.4% and 10.2% and the NMBE ranged from -11.8% and -6.8 % for chiller # 1 and chiller # 2, respectively.

Table 3. Average condenser water mass flow rate during the summer of 2014

		VFM model B (Scenario # 5)			VFM model C (Scenario # 6)			Measured
	Month	Average (kg/s)	CV(RMSE) (%)	NMBE (%)	Average (kg/s)	CV(RMSE) (%)	NMBE (%)	Average (kg/s)
CH1	May	119.8	13.0	-6.6	123.8	14.2	-10.2	
	June	116.3	8.1	-3.6	121.4	10.7	-8.1	
	July	114.9	3.2	-2.3	120.9	7.9	-7.5	
	August	115.5	4.3	-2.5	121.4	8.6	-8.0	
	September	114.6	2.8	-2.0	121.1	7.9	-7.7	
	Average	116.2 ± 12.2	7.5	-3.4	121.7 ± 12.8	10.2	-8.2	112.4 ± 2.2
CH2	May	118.4	3.2	-1.2	124.7	7.3	-6.6	
	June	114.3	3.0	2.3	121.8	5.2	-4.1	
	July	116.1	2.9	0.8	123.6	6.4	-5.6	
	August	115.1	4.8	1.6	122.1	6.5	-4.4	
	September	116.0	3.6	0.8	122.7	6.3	-4.9	
	Average	115.9 ± 12.6	3.8	1.1	122.9 ± 13.4	6.4	-5.0	117.0 ± 2.3

5. Conclusion

This paper presented a graphical user interface (GUI) which uses the VFM Tool to estimate the chilled and condenser water mass flow rates that pass though the evaporator and condenser, respectively, of a chiller. The VFM Tool allows users a quick graphical visualization of the water flow rates in the system over time, and the system Coefficient of Performance through time to track and monitor changes in performance.

The VFM Tool provides a low-cost, non-intrusive method for the ongoing commissioning of existing central cooling plants. The VFM Tool estimated well the average chilled and condenser water mass flow rates, during the summer of 2014 for the cooling plant of a university campus, with a CV(RMSE) less than 7.5% and NMBE less than -4.5% for scenario # 5, and a CV(RMSE) less than 12.8% and NMBE less than -11.8% for scenario # 6.

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References

[1] Song L, Joo IS, Wang G. Uncertainty analysis of a virtual water flow measurement in building energy consumption monitoring. HVAC and R Research. 2012;18(5):997-1010.
[2] Wang G, Liu M, Claridge DE. Development of an energy meter using a pump flow station. ASHRAE Transactions. 2010;116(PART 2):569
[3] Wang H. Water flow rate models based on the pipe resistance and pressure difference in multiple parallel chiller systems. Energy and Buildings. 2014;75:181-8.
[4] Zhao X, Yang M, Li H. Development, evaluation, and validation of a robust virtual sensing method for determining water flow rate in chillers. HVAC and R Research. 2012;18(5):874-89.
[5] McDonald E, Zmeureanu R. Virtual Flow Meter to Estimate the Water Flow Rates in Chillers. ASHRAE Transactions. 2014; SE-14-017
[6] McDonald, E. Development and Testing of a Virtual Flow Meter for Use in Ongoing Commissioning of Commercial and Institutional Buildings. (Master of Science). 2014; Concordia University, Montreal, Quebec, Canada.
[7] Bourdouxhe JP, Grodent M, and Lebrun J. HVAC 1 Toolkit: A Toolkit for Primary HVAC System Energy Calculations. 1994; ASHRAE, Atlanta, Georgia.
[8] Carrier Corporation. 'Open-Drive Compressors and 09RH Water-Cooled Condensers'. 2001; Catalogue No. 510-505