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# Study on Applying Differential Pressure in Determining the Flow Rate of Air Conditioning and Heating System

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**Abstract.** The main purpose of this study is to apply regression analysis to build the relationship between flow rate and differential pressure by modeling through experimental data, and specifically use such relationship in interpreting the flow rate of air conditioning water system, in order to establish a lower-cost alternative flow rate interpretation of which the information obtained is more conveniently. For the experimental way, we installed pressure transmitters and paddle wheel flow meters in the condenser side of the chiller, air-handling unit and in the inlet and outlet ends of pump of a small air-conditioning system respectively, and then recorded the values of such device as the pump, the air-handling unit and the condenser under different use conditions as a single pump operation, multi-pumps operation in parallel, and multi-pump operation in variable frequency, to carry out the modeling of relationship between differential pressure and flow rate by actual operation data, and analyze the results. From the experimental results, the modeling equations obtained by the air-handling unit and condenser ends are applicable to a single pump operation, multi-pump operation in parallel and multi-pump operation in variable frequency. The differential pressure obtained to interpret flow rate has a high accuracy and the error value is less than 2%. According to the study results of this experiment, the convenience of flow rate interpretation can be significantly enhanced to facilitate the formulation of air-conditioning energy-saving strategy.

**Keywords:** Air cooled chiller; Comfort; Variable frequency; Energy saving

## 1 Introduction

Energy issues has always been the focus of global concern in recent years; from the analysis at home and abroad, the energy consumption of the building is the main project of human social energy consumption, and the central air-conditioning system within buildings is the core of energy consumption for most of the buildings. Especially living in a subtropical climate, our daily life and work are impacted by the air-conditioning system great. In particular, the domestic electronics industry is booming, the full outside-air clean room is a very energy-consuming building, and how to reduce air conditioning energy consumption and reduce operating costs, will always be the primary goal of the air conditioning practitioners.

An improved air-conditioning system needs appropriate design, excellent construction, correct adjustments and proper maintenance in order to reach such overall construction target as reduction of construction cost, comfortable and convenient use, and inexpensive operating cost. The current air-conditioning energy saving strategy has developed quite mature, but in terms of execution of the air-conditioning energy saving strategy, the expedient allocation and use of water system flow rate will be the key to whether the overall energy strategy is successful or not. To achieve the above object, it can be accomplished through a good control programs; the premise is, however, must have sufficient water flow rate information. The more convenient to obtain water flow rate information, the higher the probability of success of the air conditioning control strategy.

For the existing air-conditioning chiller flow rate information, the value of which is mainly achieved through the flow meter installation; however, the price of the flow meter is not cheap, and there is difficulty in installation, and which is required with appropriate position. Therefore, in most of the air conditioning system, a flow meter will only be mounted on the control node of the main device in accordance with the needs of the overall control of water; however, various types of existing flow meters are difficult to meet the target as demand for more flow rate information obtained at different load ends. In addition, to the commercial construction completed with the system balance adjustment, if it is required to frequently carry out the space uses adjustment in order to meet commercial needs, after the compartment change and rearrangement of air-conditioning system of the building is completed to meet the purpose, whether there is a flow rate information which is easy to get as the reference for re-balance adjustment of overall system, will be the key to air conditioning performance of building to maintain the original design value. For such air conditioning systems as chiller, air-conditioning unit, pump and other equipment, the performance of the device is bound to reduce after three or five years long period of operation; however, most of the air-conditioning system due to the cost and installation convenience, will not be equipped with flow meters for a single air-conditioning equipment, so it should efficiently and easily have obtained the flow rate information to determine single device. Subject to the above practical needs to find a reasonable alternative way to get flow rate information and to take into account the lower construction costs and the convenience of flow rate information is the main motivation for this study.

## 2. Experimental Methods

The required amount of heat transfer for central air-conditioning system to carry out benefit assessment contains the heat dissipation of a condenser and the cooling capacity of a chiller. Therefore, this experiment carries out the measurement to the water inlet and outlet ends of such three sets of equipment as the chilled water coil side of the air-handling unit, the condenser side of the chiller, and inlet/outlet side of pumps, to explore the relationship between differential pressure and flow rate. During the experiment, we use the frequency converter and pipeline balancing valve to adjust the flow rate, recording the differential pressure obtained by measurement and the data change of flow rate one by one. Finally, through regression equation, conduct the training to two sets of data in order to obtain the regression coefficients, and then complete the modeling to establish the relationship of both sets.

2.1 To establish the relationship between flow rate and differential pressure of air-handling unit coils

An air-handling unit is important equipment used to carry out the heat exchange by means of the chilled water supplied by a chiller and indoor cooling load. To understand the amount of heat transfer and the equipment efficiency, we can calculate the temperature difference of coil inlet and outlet of chilled water, and the volume of chilled water flowing through the coil. Therefore, in this experiment, pressure transmitters are installed at coil inlet and outlet sides of the air-handling unit, with the peddled wheel flow meter of chilled water loop to respectively record the measured differential pressure and flow rate, and to simulate the change of flow rate by adjusting the frequency converter and balance valve opening. Its experimental configuration diagram is shown as Figure 1. Due to the practical changes in the flow rate of the air-handling unit coil is mainly reached by the adjustment of proportional two-way valve, therefore in this experiment, we compare two ways of adjusting flow rate, and try to use the differential pressure and flow rate model established by adjusting the frequency converter to predict the flow rate obtained by adjusting the balance valve opening.

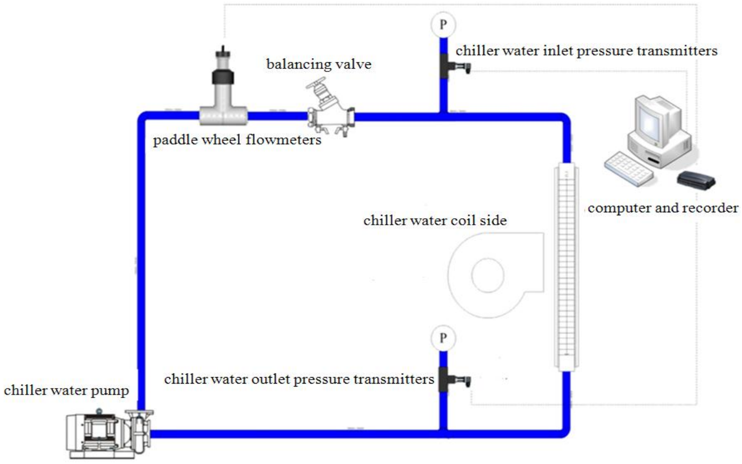


Figure 1. Experimental configuration diagram of air-handling unit's differential pressure and flow rate

2.2 To establish the relationship between flow rate and differential pressure of condenser coils

The condenser of a chiller is a heat transfer element discharging the heat absorbed by a particular space and the waste heat of a compressor to the atmosphere. To understand the amount of heat transfer, we can calculate the temperature difference of coil inlet and outlet of chilled water, and the volume of cooled water flowing through the coil. Therefore, in this experiment, pressure transmitters are installed at coil inlet and outlet sides of the condenser, with the peddled wheel flow meter of chilled water loop to respectively record the flow rate, and by means of multiple cooling water pumps in parallel and adjusting the inverter frequency of pumps to respectively record the relationship between the differential pressure of condenser inlet and outlet and the flow rate under changes of flow rate. Its experimental configuration diagram is shown in Figure 2.

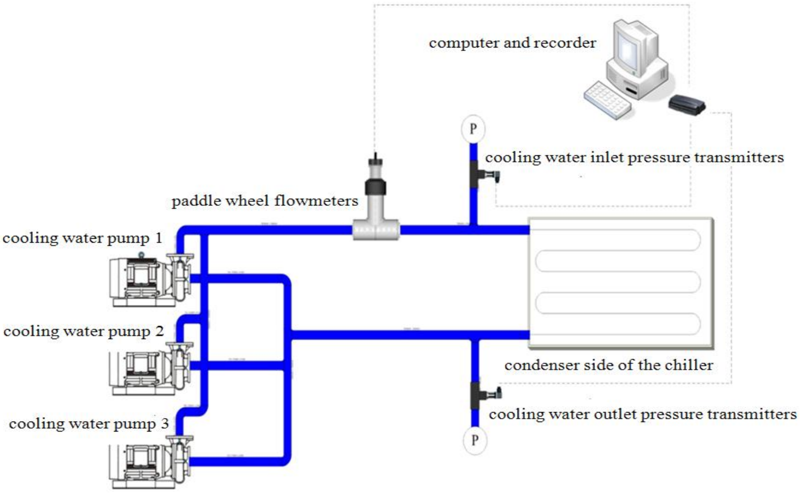


Figure 2. Experimental configuration diagram of condenser's differential pressure and flow rate

2.3 To establish the relationship between flow rate and differential pressure of pump inlet and outlet

A pump is the equipment in air-conditioning system to drive the flow of fluid; currently in the prevailing energy-saving strategy, both the chilled water secondary pump and cooling water pump are able to adjust the load changes through the frequency converters. Therefore, to understand the cooling capacity or the amount of heat dissipation about the system can be learned from understanding the flow rate of pumps. Hence, in this experiment, pressure transmitters are installed at coil inlet and outlet sides of pumps, in order to analyze the relationship between differential pressure of each pump inlet and outlet and changes of flow rate when a single pump operates and multiple parallel pumps operate. Its experimental configuration diagram is shown in Figure 3.

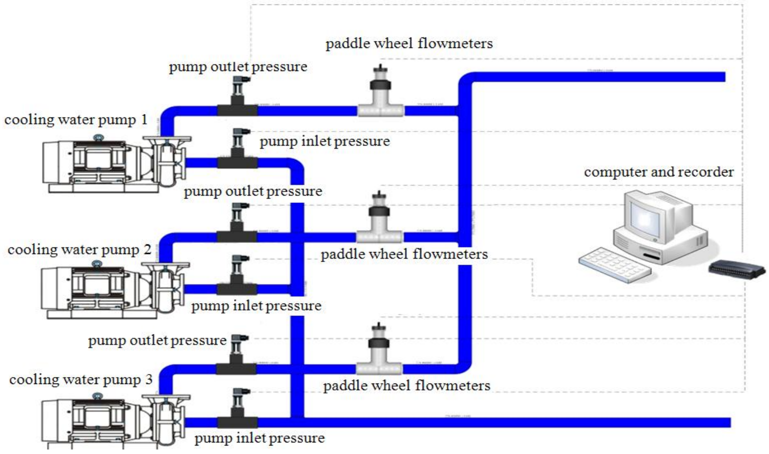


Figure 3. Experimental configuration diagram of pump sides differential pressure and flow rate

## 3. Results and Discussion

The experiment equipment used in this study is a small air-conditioning system, including a chiller, an air-handling unit, a cooling tower, a chilled water pump, and a cooling water pump. For the power and control parts, include the power providing 110 V and 220V, and a frequency converter control panel. The detailed specifications of equipment are as shown in Table 1.

The use range and accuracy of peddled wheel flow meters used in this experiment are shown in Table 2.

The use range and accuracy of pressure transmitters used in this experiment are shown in Table 3.

Table 1 Specifications of Experimental Equipment

| Equipment | Items | Specifications |
|---|---|---|
| Chiller | Cooling capacity | 21 kW |
| | Refrigerant | R-22 |
| | Compressor | Scroll |
| | power of compressor | 4.8 kW |
| | COP | 4.38 |
| | chilled water flow | 3.66 m3/hr |

| | | |
|---|---|---|
| | rate | |
| | cooling water flow rate | 4.44 m3/hr |
| Pump | power of primary chilled water pump | 1 HP |
| | power of secondary chilled water pump | 1 HP |
| | cooling water pump power | 1 HP |
| Air-handling unit | Cooling capacity | 21 kW |
| | fan | 0.75 HP |
| | Air flow rate | 2210 m3/hr |
| Cooling tower | Type | Counter flow |
| | Cooling capacity | 28 kW |
| | Air flow rate | 4500 m3/hr |

Table 2 Specifications of peddled wheel flow meter

| item | Specifications |
|---|---|
| flow rate | 0.3~0.6 m/s |
| Materials | Main body--CPVC,PTFE,SUS316L |
| | 6-lobe rotator--ECTFE fluorine plastic |
| | Axis and bearing -High-density ceramic |
| Accuracy | ±0.5% |
| pressure | Within 10bar |

Table 3. Specifications of Pressure Transmitter

| Item | Specifications |
|---|---|

| | |
|---|---|
| Pressure range | -1~10 bar |
| Pressure-sensitive component | Ceramic piezoresistive pressure-sensitive core |
| Accuracy | ±0.5% |
| temperature range | -10~85℃ |

3.1 Air-handling unit

For the relationship (as shown in Formula 1) between flow rate $Q_{AHU}$ and differential pressure $\Delta P_{AHU}$ established by the water inlet and outlet ends of the air-handling unit, the coefficient obtained from its modeling results is shown in Table 4; comparing the differential pressure, which are calculated by controlling the frequency converter after modeling, to the data collected by the peddled wheel flow meter, the average error rate is 1.7%.

$$Q_{AHU} = a_0 + a_1 \Delta P_{AHU} + a_2 \Delta P_{AHU}^{0.5} \qquad (1)$$

Table4. Modeling results of air-handling unit coils' differential pressure and flow rate

| Methods of adjusting flow rate | a0 | a1 | a2 | $R^2$ | The average error rate |
|---|---|---|---|---|---|
| Adjusting frequency converter | -0.10444 | 2.84157 | 4.82475 | 0.991 | 1.7% |

| | | | | | |
|---|---|---|---|---|---|
| Adjusting balance valve | -2.63062 | -8.00204 | 15.4985 | 0.976 | 1.2% |

In the experiment, two ways to adjust flow rate are using the frequency converter to control flow rate, and adjusting the balance valve to control flow rate. The relationship between the simulated values and the actual values by frequency converter is shown in Figure 4.

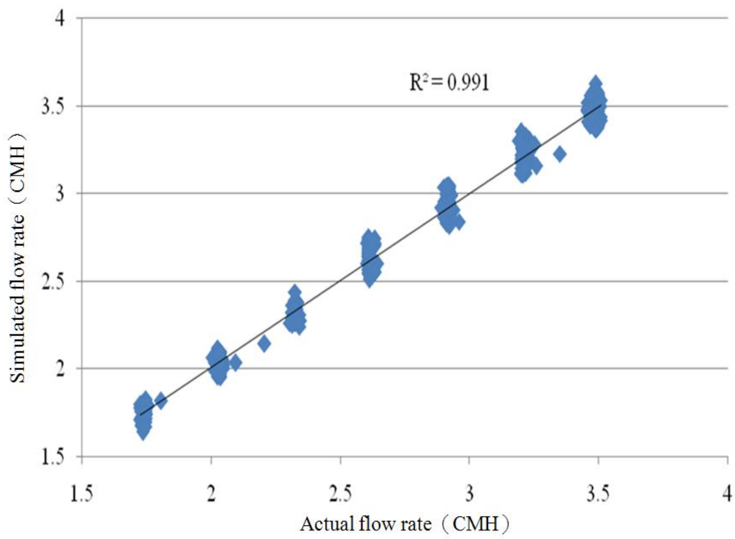


Figure 4. The flow rate relationship between actual values and simulated values after adjusting frequency converter

In control of the flow rate by frequency converter, it was to make the RPM control of chilled water pump from 60Hz to collect the flow rate data in inlet and outlet ends of the air-handling unit, and then by gradual reduction of 5Hz to collect the data of different flow stages in 55Hz, 50Hz, 45Hz, 40Hz, 35Hz, and 30Hz. It would not be reduced after 30Hz, because practically it is seldom to reduce the frequency less than 50% rated frequency in control of frequency inverter.

The relationship between the simulated values and actual values by balance valve is as the result shown in Figure 5. In operation, first adjusted the flow rate of 4-ring balance valve opening, and then gradually adjusted to 1.5 rings by half ring as interval. Then, the flow rate was very low about 2.5CMH~3CMH. When the flow rate was adjusted by balance valve, the valve opening and the flow rate were not changed in proportion that the flow rate decreased small in the initial adjustment of one ring, and the changes in the flow rate increased significantly after adjusting valve opening change in the middle. When the coefficients obtained by entire differential pressure modeling used to compare the flow rate of flow meter, the average error rate is 1.2%.

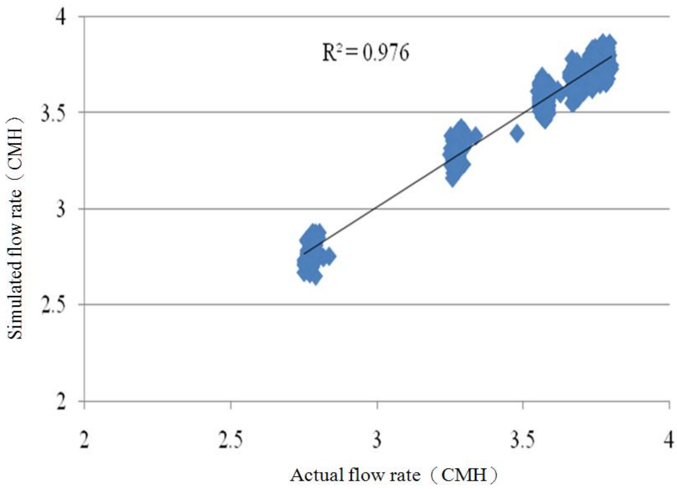


Figure5. The flow rate relationship between actual and simulated values after adjusting the balance valve

Because the variable energy-saving control of air-handling unit is by means of a proportional two-way valve with a frequency converter to control the chilled water flow rate of the air-handling unit in order to achieve the energy saving effect, therefore, the differential pressure and flow rate model established by adjusting the frequency converter can be used to predict the flow rate obtained by adjusting the opening degree of a balancing valve. The trend graph of actual values and simulated values is shown in Figure 6, and the average error rate of this predication value is 1.8%.

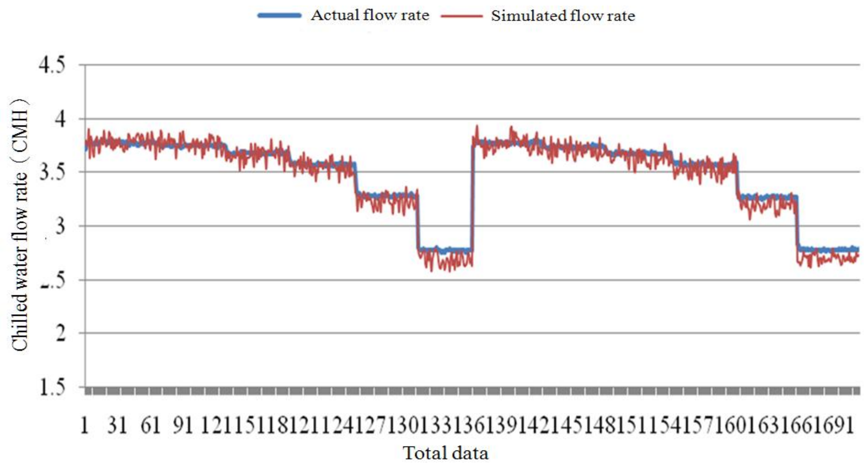


Figure 6. Actual and simulated flow rate changes after adjusting the opening degree of the balance valve

3.2 Condenser coils

The relationship between the flow rate of condenser coils $Q_{cond}$ and differential pressure $\Delta P_{cond}$ (2) is established by adjusting the flow rate through the operation cooling water pumps in parallel with a frequency converter.

$$Q_{cond} = a_0 + a_1 \Delta P_{cond} + a_2 \Delta P_{cond}^{0.5} \quad (2)$$

The coefficient achieved from its modeling results is shown in Table 5. It can be learned from the table, regardless of a single pump operation or multiple pumps in parallel operation, the cooling water pumps still present same linear relationship between differential pressure of cooling water coils and flow rate; the model analysis of the actual values and simulated values is shown in Figure 7.

Table 5 The modeling results of condenser coils differential pressure and flow rate

| $a_0$ | $a_1$ | $a_2$ | $R^2$ | The average error rate |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| -1.68505 | -0.30007 | 7.98711 | 0.990 | 1.9% |

For the collection of flow rate data from condenser sides, first the RPM of cooling water pumps from 60Hz was controlled to collect the flow rate data of condenser inlet and outlet ends, and then by gradual reduction of 5Hz to collect the data of different flow stages in 55Hz, 50Hz, 45Hz, 40Hz, 35Hz, and 30Hz. It will not be reduced after 30Hz.

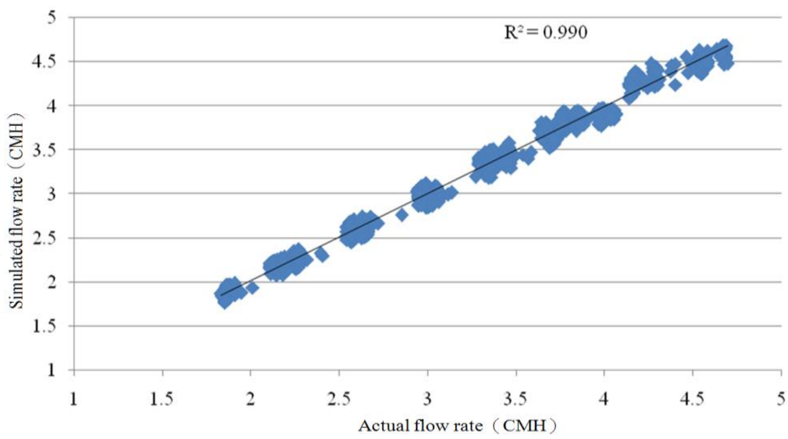


Figure 7. The relationship between simulated values and actual values of condensers

The data presented in Figure 7 include the conditions of a single pump operation and the multi-pump operation in parallel. Using the coefficients obtained by differential pressure modeling of condenser sides to compare the flow rate of flow meter, the average error rate is 1.2%.

3.3 Pumps

The relationship between differential pressure and flow rate in pumps of parallel operation must be discussed separately under various combinations. Figure 8 shows the relationship between total flow rate of three pumps in parallel operation and individual flow rate of three pumps operation, respectively showing the relationship between flow rate controlled by adjusting the frequency converter with individual operation of each pump, two pumps in parallel and three pumps in parallel operation. The total flow rate of three pumps operated at same time was about 5CMH, but the flow rate of individual pump was approximately less than 2CMH. Same situation is displayed in two pumps in parallel that total flow rate closed 5CMH, and the flow rate of individual pump was slightly higher than 2CMH. Comparing total flow rate of two pumps operating in parallel with the same of three pumps operating in parallel, we find almost the same between the two that is because total flow rate limited by the diameter has nearly saturated in two pumps in parallel, and three pumps in parallel will increase the power consumption only; moreover, it will not increase the transfer amount of the cooling water. In practical applications, the transfer information of total flow rate obtained through this measurement is available for operation reference to avoid the operation of power consumption.

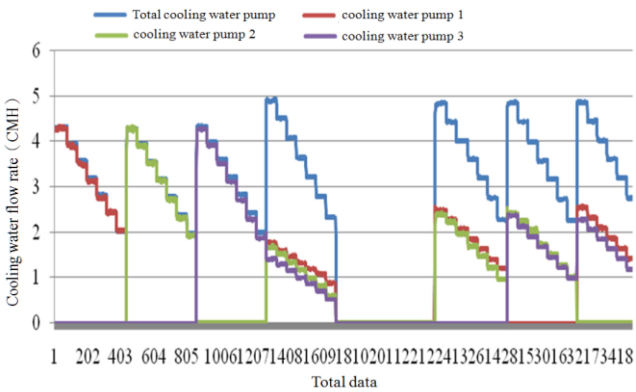


Figure 8. The relationship of flow rate changes in tree pumps in parallel operation

It can be learned from Figures 9 to 11 that when pumps operate in parallel, the relationship between differential pressure and flow rate reflected under the conditions of various combinations by number of pumps are different. Therefore, to apply the differential pressure to deduce flow rate, a differential pressure turning flow rate model for every pump under the combination of different number of pumps must be established. The modeling results are shown in Table 6, by which for applications of operation in parallel, using differential pressure to deduce flow rate must select the model by combination types.

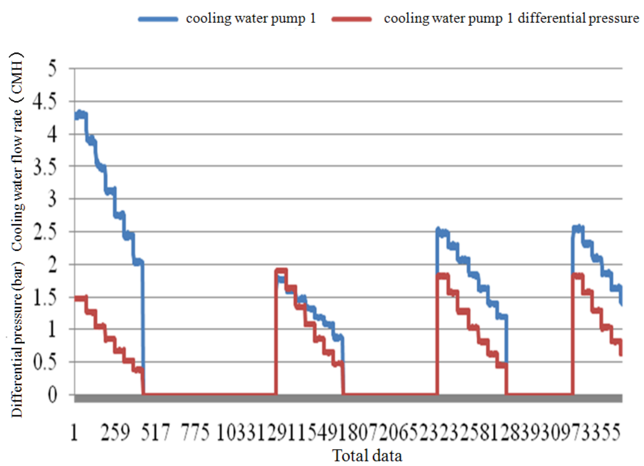


Figure 9. The relationship between flow rateand differential pressure when the cooling water pump 1 is in parallel operation

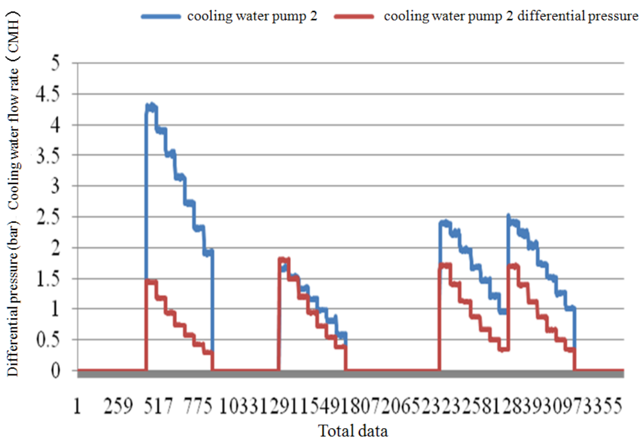

Figure 10. The relationship between flow rate and differential pressure when the cooling water pump 2 is in parallel operation

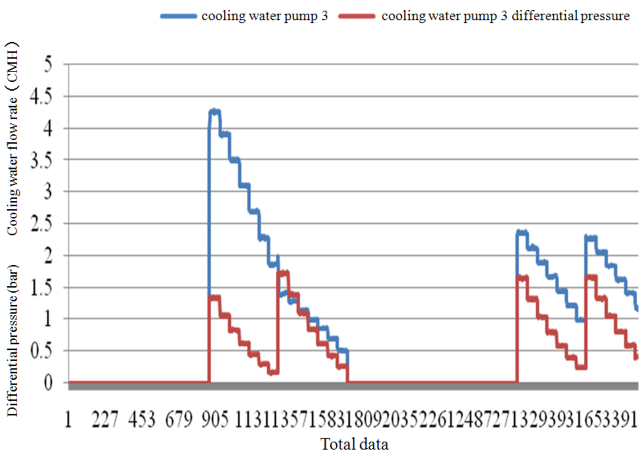


Figure 11. The relationship between flow rate and differential pressure when the cooling water pump 3 is in parallel operation

The relationship between flow rate $Q_{pump_1}$ and differential pressure $\Delta P_{pump_1}$ (bar) established by a single cooling water pump operation with a frequency converter to adjust flow rate is shown as Formula (3).

$$Q_{pump_1} = a_0 + a_1 \Delta P_{pump_1} + a_2 \Delta P_{pump_1}^{0.5} \quad (3)$$

The coefficient obtained from the results of single pump operation modeling is shown in Table 6. The distribution completed by the single pump operation modeling for three cooling water pumps respectively is shown in Figure 12, 15, and 18, and the average error rate is 1.07%, 0.93%, and 0.85% respectively. The relationship between flow rate $Q_{pump_2}$ and differential pressure $\Delta P_{pump_2}$ established by two cooling water pumps operation with frequency converter to adjust flow rate is shown as Formula (4).

$$Q_{pump_2} = a_0 + a_1 \Delta P_{pump_2} + a_3 \Delta P_{pump_2}^{0.5} \quad (4)$$

The coefficient obtained from the results of single pump operation modeling is shown in Table 6.The distribution completed by two pumps operation modeling for three cooling water pumps respectively is shown in Figures 13, 16, and 19, and the average error rate is 1.06%, 1.96%, and 1.99% respectively. The relationship between flow rate $Q_{pump_3}$ and differential pressure $\Delta P_{pump_3}$ established by three cooling water pumps operation with the frequency converter to adjust flow rate is shown as Formula (5).

$$Q_{pump_3} = a_0 + a_1 \Delta P_{pump_3} + a_2 \Delta P_{pump_3}^{0.5} \quad (5)$$

The coefficient obtained from the results of three-pump operation modeling is shown in Table 6. The distribution completed by three-pump operation modeling for three cooling water pumps respectively is shown in Figures 14, 17, and 20, and the average error rate is 1.9%, 1.6%, and 1.19% respectively.

Table 6. Modeling results of differential pressure and flow rate in pump inlet and outlet

| Combi-nation mode | pump No. | $a_0$ | $a_1$ | $a_2$ | $R^2$ | The average error rate |
|---|---|---|---|---|---|---|
| single operation | 1 | 0.345479 | 0.802401 | 2.46988 | 0.995939 | 1.07% |
| | 2 | -0.525726 | -0.660325 | 4.80106 | 0.997683 | 0.93% |
| | 3 | 0.426052 | -0.166922 | 3.54008 | 0.997193 | 0.85% |
| Two-pump operation | 1 | 0.0336918 | 0.144093 | 1.74915 | 0.995223 | 1.06% |
| | 2 | -0.582129 | -0.488579 | 2.93947 | 0.992821 | 1.96% |
| | 3 | 0.110518 | -0.011727 | 1.73978 | 0.992059 | 1.99% |
| Three-pump operation | 1 | 0.117814 | 0.055519 | 1.18097 | 0.989663 | 1.9% |
| | 2 | -0.672357 | -0.43351 | 2.32236 | 0.994541 | 1.6% |
| | 3 | -0.201255 | -0.22833 | 1.53338 | 0.996656 | 1.19% |

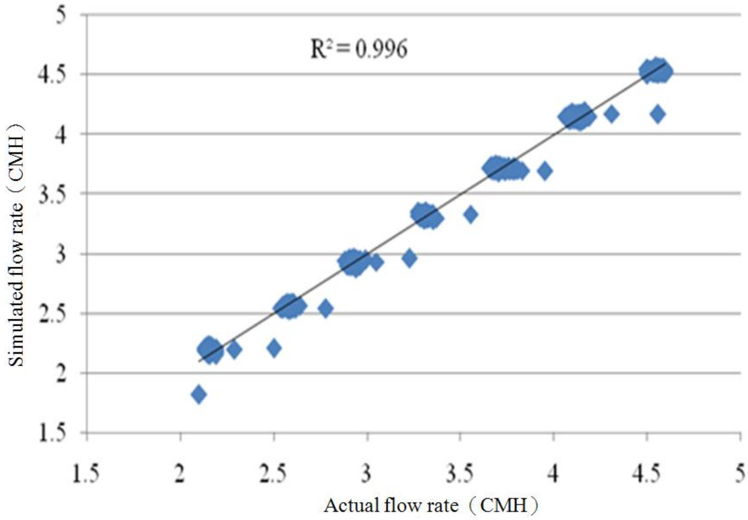


Figure12. Model analysis of differential pressure and flow rate modeling of cooling water pump 1 in single-pump operation

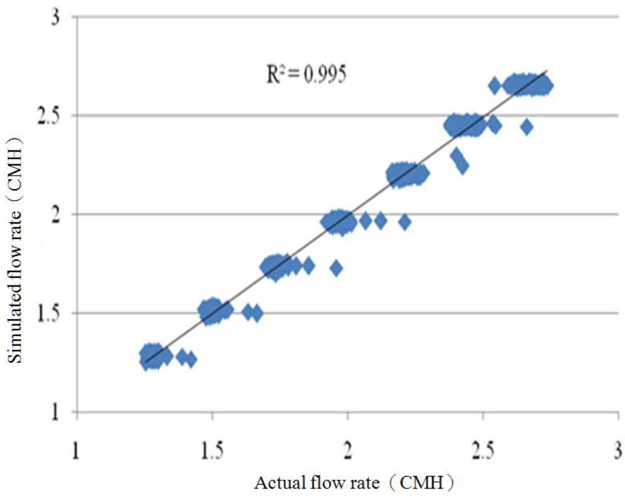


Figure13. Model analysis of differential pressure and flow rate modeling of cooling water pump 1 in two-pump operation

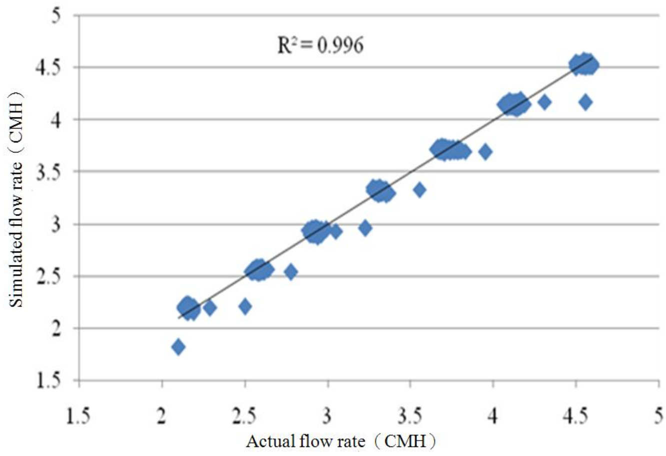


Figure14. Model analysis of differential pressure and flow rate modeling of cooling water pump 1 in three-pump operation

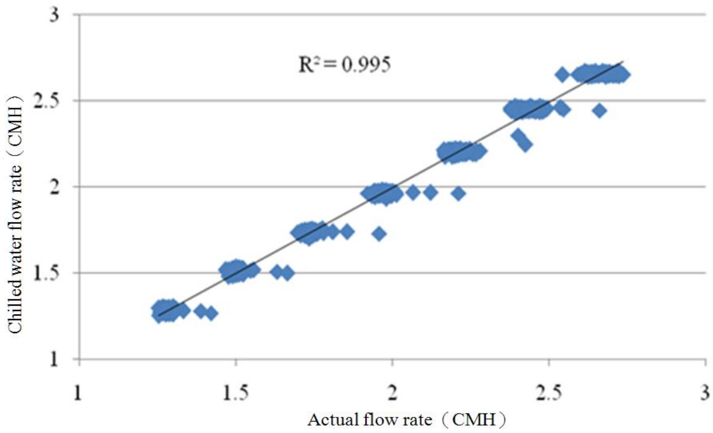


Figure15. Model analysis of differential pressure and flow rate modeling of cooling water pump 2 in single-pump operation

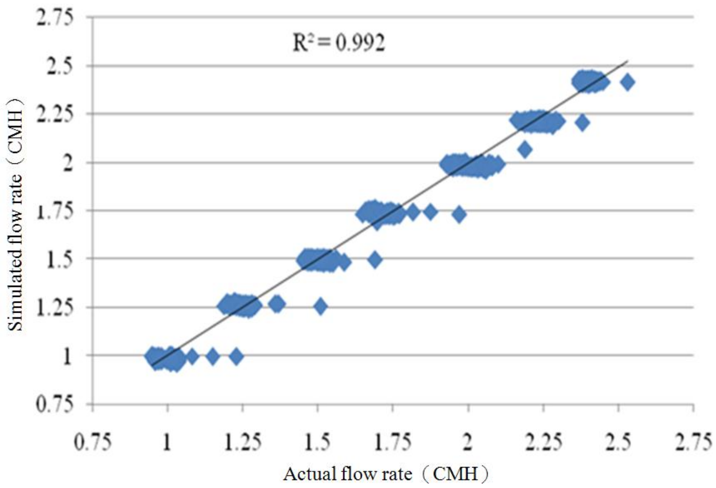


Figure16. Model analysis of differential pressure and flow rate modeling of cooling water pump 2 in two-pump operation

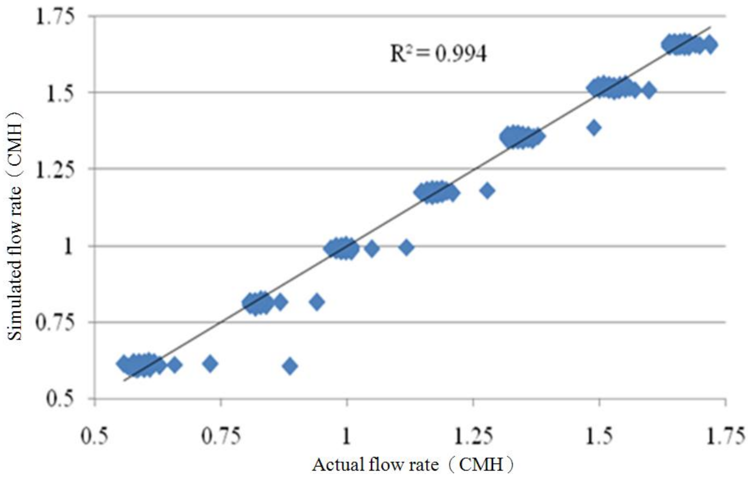


Figure17. Model analysis of differential pressure and flow rate modeling of cooling water pump 2 in three-pump operation

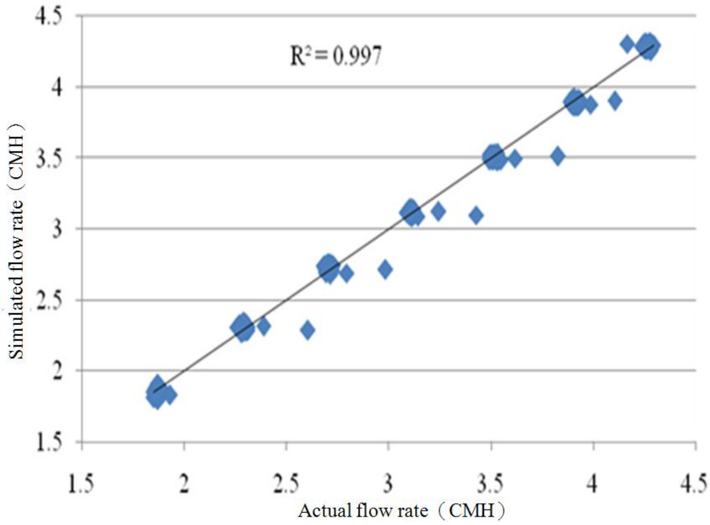


Figure18. Model analysis of differential pressure and flow rate modeling of cooling water pump 3 in single-pump operation

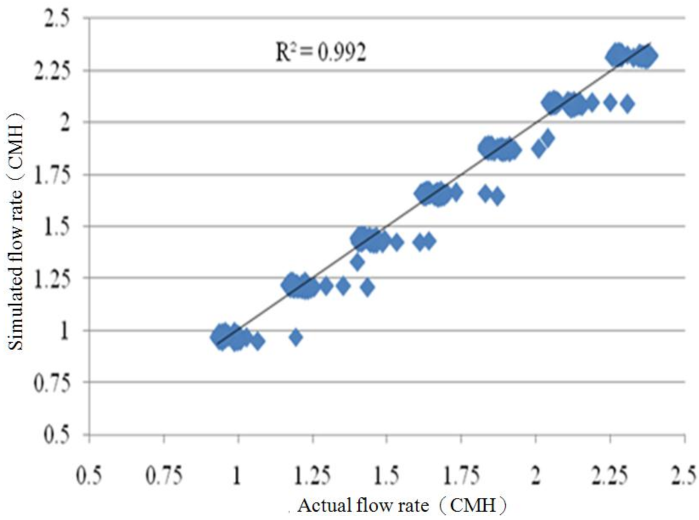


Figure19. Model analysis of differential pressure and flow rate modeling of cooling water pump 3 in two-pump operation

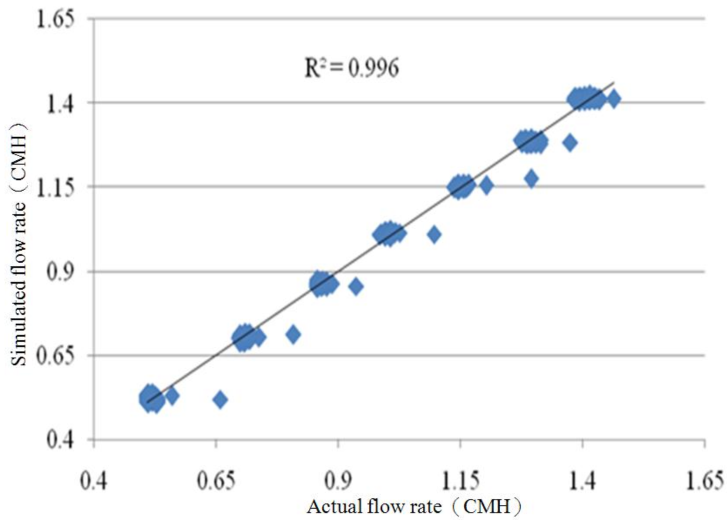


Figure20. Model analysis of operation differential pressure and flow rate modeling of cooling water pump 3 in three-pump

## 4. Conclusions

By means of the pressure transmitter which is much cheaper than ultrasound flow meter, applied differential pressure in central air-conditioning system to carry out the flow rate calculation and from the actual data obtained, using regression analysis modeling to compare the values of the peddled wheel flow meter that has very high accuracy in application. In this study, the measurement test is carried out at the position of the critical equipment affecting the energy consumption of central air-conditioning system, and of the equipment where the flow meter should be usually erected. The following conclusions are obtained:

（1） For the modeling data completed by pressure transmitters, whether at the air-handling unit inlet and outlet ends, the chiller's condenser side, or cooling water pump inlet and outlet ends, under the single-pump operation and the multi-pump operation in parallel, comparing the obtained values of flow rate to actual flow meter, the average error rate is within 2%, so there is very high accuracy.

(2) For the modeling data completed by pressure transmitters, taking the data modeling obtained from the frequency converter operation in 60Hz and 30Hz to carry out the error comparison to whole data that whether at the air-handling unit inlet and outlet ends, the chiller's condenser side, or the cooling water pump inlet and outlet ends, under the single-pump operation and the multi-pump operation in parallel, comparing the obtained values of flow rate to actual flow meter, the average error rate is about within 2%, so that there is still very high accuracy.

(3) In the experiment applying differential pressure to deduce the flow rate at chiller condenser coil or evaporator coil, the same can collect the modeling data by operating the pump frequency converter to adjust flow rate. The test results show that regardless of how many pumps in parallel operation, the modeling completed by the relationship between the differential pressure of condenser coil and flow rate is applicable to different number of operating pumps.

(4) To use the differential pressure at pump inlet and outlet to carry out the flow rate relationship modeling, need to consider whether there is the setting of pump parallel operation mode. Since pumps in parallel will produce pipeline impedance effect sometimes, so the modeling must be carried out respectively to different number of operating pumps; the modeling coefficient obtained from a pump single operation and multiple pumps in parallel operation is not the same.

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