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Energy Saving Analysis of Variable Primary Flow System with Screw Chiller

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Abstract. This paper focuses on energy-saving operation and use of the variable primary flow (VPF) of a central air-conditioning system chiller, by means of regression analysis to determine the relationship equation of chiller power consumption and cooled water flow rate, cooled water supply temperature, cooling water return temperature, and partial load, and the relationship equation of the cooled water pump power consumption and the cooled water flow rate. Take the relationship equations as basis to identify the power consumption change curve of loads in different flow rates, and calculate the most energy-saving cooled water flow rate of the chiller and the cooled water pump in various loads.

Keywords: Chiller、Variable Primary Flow、VPF

1 Introduction

With the enhancement of the standard living of human, the space comfort requirements of residential building environment also will increase. In order to create a comfortable environment space, often need the help of the central air-conditioning system to maintain indoor comfort conditions; however, it is accompanied by a large amount of energy consumption. All such devices constituting the central air-conditioning system as chiller, cooled water pump, cooling water pump, cooling water tower and blower are power consumption devices, their power consumption typically accounting for most of total building power consumption. The power consumption of the cooler unit accounts for over half of total central air-conditioning system power consumption, so a high-efficiency cooler unit indeed can effectively reduce the total annual power consumption of the system. For buildings of different forms and uses, under the premises as the conditions to meet the comfortable environment requirements, there are a variety of different planning and choices in design of the central air-conditioning system. The design of an air-conditioning system with variable primary flow (VPF) has been widely adopted in Europe and United States [3], and the use cases of which have increased year by year.

The most direct influence of the VPF changes of an central air-conditioning system on power consumption is the reduced power consumption of the cooled water pump; however, in terms of the chiller, it will change the evaporation temperature, the cooled water return/supply temperature, and the evaporation temperature difference, and also affect the amount of heat transfer in the evaporator, and influence the coefficient of performance (COP) of the chiller. This study, therefore, aims at tackling the analysis carried out to the influence of changed VPF on various data, to find the optimal operation value of VPF.

2. Chilled water system in an central air-conditioning system

2.1 Chilled water system

As shown in Figure 1, the chilled water system consists of a chiller, a chilled water pump, a chilled water piping and a blower. The chilled water pump made the chilled water circulate between the chiller and the blower; the 7℃ chilled water absorbed the space heat in the air-handling unit, so that the chilled water temperature rose to 12℃, and the 12℃ chilled water was returned to the chiller, cooling to 7℃ through the chiller evaporator, and then continued to the air-handling unit by the chilled water pump to effect the cooling function in the air-conditioning room.

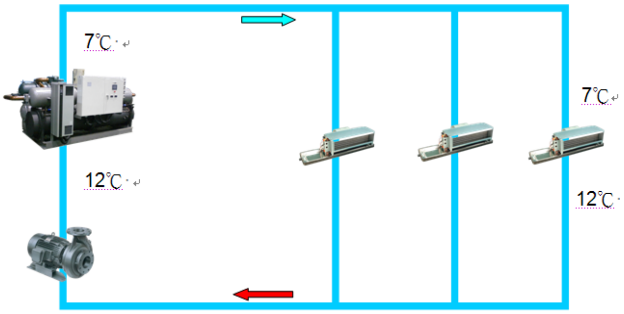

Figure 1. Concept of chilled water action

2.2. Primary Only System (POS)

Actually, when the chilled water system operates, the loads are different depending on ambient temperature, personnel access, lighting and other peripherals. The POS controls the chilled water flow by a three-way valve; when the load is low, the flow through the blower becomes small, and the excess flow through bypass pipe bypasses the blower; the flow rate through the blower and the sum of bypassing flow are unchanged, so to maintain the constant flow of entire chilled water system. This system is the primary only system (POS), as shown in Figure 2.

For this system, the chilled water flow through the chiller is constant, and the chilled water flow through the splitter of every air-handling unit is constant too. The

POS maintains the whole system with the constant circulating volume of chilled water. In this system, it is no need to control the chilled water pump, as long as renders the same to operate; however, in load shedding, the excess chilled water will still circulate, resulting in a waste of energy.

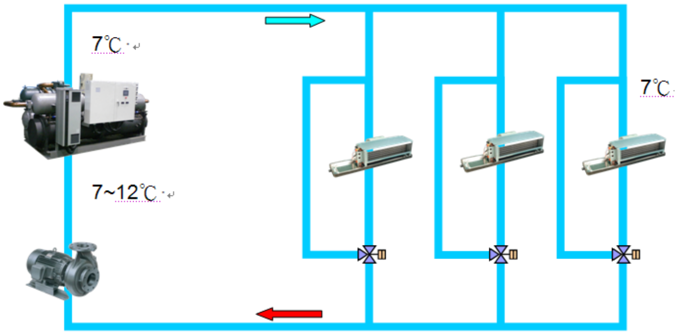

Figure 2. Primary only system

2.3. Primary/secondary system

Primary/secondary system is also known as decoupling system, as shown in Figure 3. The primary pump is of constant frequency to keep the chiller with constant flow rate, and the secondary pump is of variable frequency control to coordinate with the size of the load to regulate the flow rate, in order to achieve the energy saving effect. This system is mainly to improve the energy waste of chilled water in load shedding caused by the secondary constant flow rate. The bypass pipe is used to automatically adjust the chilled water volume, so that when the load changes, the problem of different primary and secondary chilled water circulating volume can be overcome. When the maximum load of secondary flow comes out, the demanded chilled water flow rate and the primary circulation volume are same, then the flow rate of the bypass pipe is close to zero; when the load of secondary flow rate reduces, the secondary flow rate will be lower than the primary flow rate, and the excess primary flow rate will directly return to the chiller through the bypass pipe. For this design, when the load is small, reducing the secondary flow rate can achieve the energy saving purpose of the secondary pump; however, the primary flow rate is still constant, resulting in the energy waste of the primary pump.

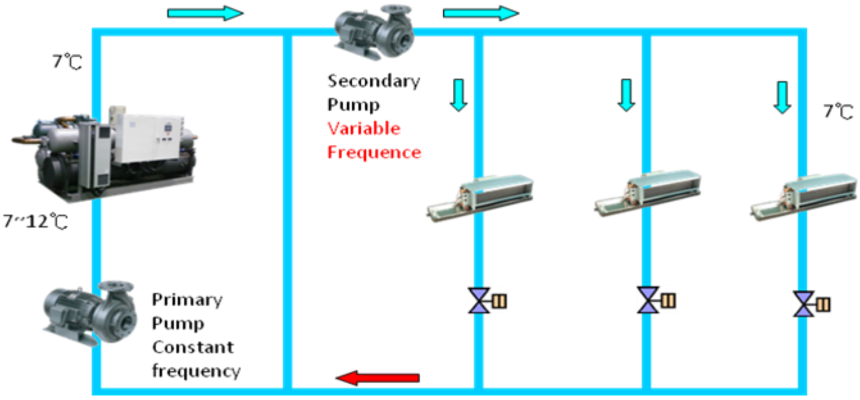

Figure 3. Primary constant/Secondary variable flow system

2.4. VPF system

Generally speaking, the number of days required with full load operation in a year will not be more than 10 days; most of the time, the operation is under partial load mode. With the variable primary flow design, pumps have more time to operate in low water volume and low power consumption. Because the pump power consumption is directly proportional to the third power of flow rate, so when the water volume is lowered, there will be considerable large proportion of energy saving amount.

The chilled water pump saves energy, but at the same time, the power consumption of the chiller changes. Under overall consideration, should or should not drop the primary flow rate, and how much of the drop can be the most energy-efficient? This is the focus to be discussed in this paper. First of the following is to instruct how to install the VPF system.

2.4.1 Modified by the old system

At present, most of the chilled water system is primary/secondary system; as long as installing a frequency converter in the primary pump can become a VPF system, as shown in Figure 4. However, a proportional valve should be installed in the bypass pipe, with the changes of load, to adjust the flow rate of the bypass pipe [4].

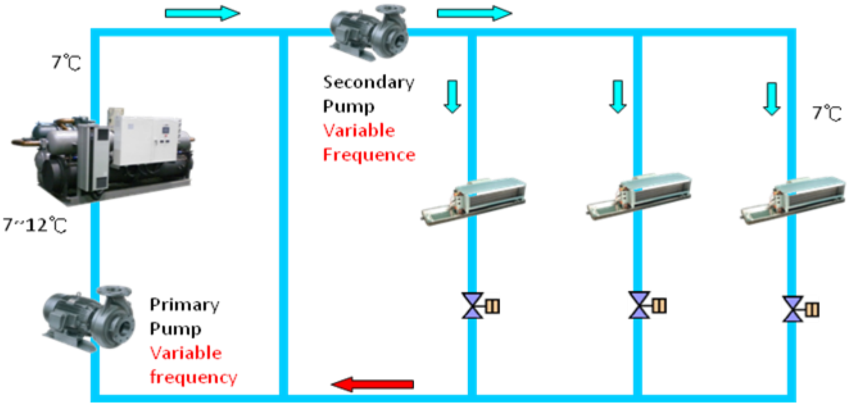

Figure 4. Primary/secondary chilled water circulation system

2.4.2 New system

The variable primary flow system was used to cancel the secondary water pump, and the primary constant frequency pump was replaced with the high lift variable frequency pump, as shown in Figure 5. And a dedicated controller was used to control the operation and frequency of the water pump; the controller calculated the secondary load by temperature difference and flow rate, and sent commands to the water pump inverter, to supply the chilled water flow suitable for the load.

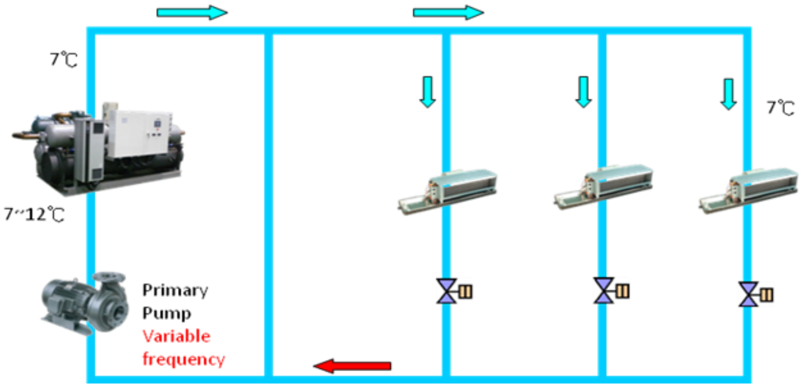

Figure 5. Primary chilled water circulation system

3. Prediction of power consumption

3.1 The chiller power consumption mode

The prediction of the chiller power consumption was taking the actual measured operation data by statistical software to obtain regression equation coefficient, in order to establish the chiller power consumption mode as follows:

$a_0 \sim a_{19}$: Regression coefficient

Pchiller: chiller power consumption (kW)

Tchws: chilled water supply temperature (℃)

Tcwr: cooling water return temperature (℃)

LPM: chilled water flow rate (Liter/minute)

PLR: partial load ratio (%), the actual refrigerating capacity of the chiller divided by the rated refrigerating capacity.

And the actual refrigerating capacity of the chiller is:

Q: refrigerating capacity (kW)

△T: chilled water return/supply temperature difference (℃)

LPM: chilled water flow rate (Liter/minute)

Cp: Heat capacity at constant pressure (Kcal/Kg · ℃)

C: Constant

3.2 The pump power consumption mode

Through the law of similarity, for a pump, the power consumption is proportional to the third power of speed, and flow rate is proportional to the speed, so we can see the water pump power consumption is proportional to the third power of flow rate. The water pump power consumption mode established by liner egression is as follows:

$b_0 \sim b_3$: Regression coefficient

Pchp: water pump power consumption

4. Experimental Exploration and Analysis

In this experiment, an office building was taken for the experimental area, and the actual data collected by a monitoring system was analyzed. Table 1 shows the specifications of this system. The sampling time for this experiment is 12 days. Sampling data and operation range of the various parameters of the chiller are shown in Tables 2 and 3.

Table 1 Specifications of experimental air-conditioning system

Item	Specifications
evaporator type	Flooded type
compressor type	Spiral type (dual pressure)
Refrigerant type	R134a
chiller refrigerating capacity	220 RT
chiller rated power	174 kW
rated chilled water flow rate	2200 LPM
Horse power of chilled water pump	20 HP

Table 2 Sampling dates and climate data of the experiment

Date	Sun. to Mon.	temperature range ℃	Humidity range %
2012/5/17	Thu.	23.4~28.5	83.5~98.6
2012/5/18	Fri.	26.9~30.0	60.0~79.4
2012/5/21	Mon.	25.4~27.6	68.6~83.8
2012/6/26	Tue.	27.2~33.7	68.7~96.3

2012/6/27	Wed.	28.8~33.3	68.3~85.0
2012/6/28	Thu.	30.1~34.6	59.5~81.1
2012/7/12	Thu.	31.0~36.5	51.3~73.5
2012/7/13	Fri.	31.2~36.5	46.5~68.8
2012/7/16	Mon.	27.5~34.2	64.8~100.0
2012/7/17	Tue.	29.2~34.8	63.2~100.0
2012/7/19	Thu.	30.9~34.1	63.8~79.0
2012/7/20	Fri.	31.8~35.6	63.6~96.7

Table 3 Sampling data range of the chiller

Item	Range
PLR(%)	23~102%
T_{chws} (℃)	5～20℃
T_{cwr} (℃)	23～40℃
Chilled water flow rate (LPM)	1000~2360 LPM

The independent variables in this experiment are partial load ratio, chilled water supply temperature, chilled water return temperature, chilled water flow rate, and the regression equation coefficients obtained by the statistical software as shown in Table 4. The regression results show that the R^2 value is 0.9914, and the average error rate is 2.67%, indicating the accuracy is quite high which is available for prediction. Figure 6 shows the comparison of the actual chiller power consumption and simulative power consumption.

Table 4 The regression coefficients of the chiller power consumption mode

regression coefficients	Value	Variables
a_0	-359.8886954	constant
a_1	753.5186042	PLR
a_2	53.64333133	T_{chws}
a_3	10.08311737	T_{cwr}
a_4	0.151590106	LPM
a_5	-80.51994968	PLR^2
a_6	0.00496408	$T_{chws}{}^2$
a_7	0.061237284	$T_{cwr}{}^2$
a_8	5.37E-06	LPM^2
a_9	-77.76634553	$PLR \times T_{chws}$
a_{10}	-15.0755124	$PLR \times T_{cwr}$
a_{11}	-0.320926157	$PLR \times LPM$
a_{12}	-1.893852713	$T_{chws} \times T_{cwr}$
a_{13}	-0.023946452	$T_{chws} \times LPM$
a_{14}	-0.005589775	$T_{cwr} \times LPM$
a_{15}	2.590653335	$PLR \times T_{chws} \times T_{cwr}$
a_{16}	0.039563671	$PLR \times T_{chws} \times LPM$
a_{17}	0.010126365	$PLR \times T_{cwr} \times LPM$

a_{18}	0.000807989	$T_{chws} \times T_{cwr} \times LPM$
a_{19}	-0.00128231	$PLR \times T_{chws} \times T_{cwr} \times LPM$

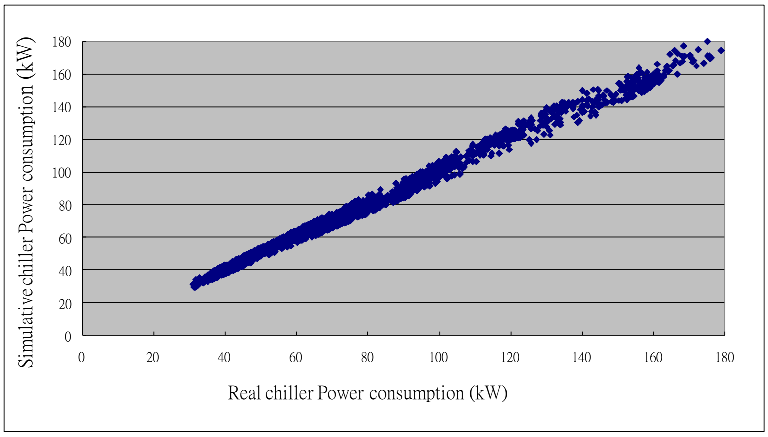

Figure 6 Comparison of actual chiller power consumption and simulative power consumption

The power consumption of the water pump under the condition of constant system pressure drop relates to water volume only; the obtained regression equation coefficients are shown in Table 5. From similarity theorem that power consumption is proportional to the third power of water volume, but the obtained third power coefficient b_3 is 0, so the modeling by the second power is as follows:

$$P_{chp} = b_0 + b_1 LPM + b_2 LPM^2 \qquad (1)$$

$b_0 \sim b_2$: Regression coefficient
P_{chp}: water pump power consumption (kW)

Table 5. The regression coefficients of the chiller water pump power consumption

regression coefficients	Value	Variables
b_0	2.03343	constant

b_1	-0.00263171	LPM
b_2	3.57953E-06	LPM^2

The regression analysis shows that the R^2 value is 0.988 and the average error rate is 4.46%; Figure 7 shows the comparison of actual power consumption of chilled water pump and simulative power consumption. From the figure, it shows the accuracy of the chilled water pump modeling is quite high and available for prediction.

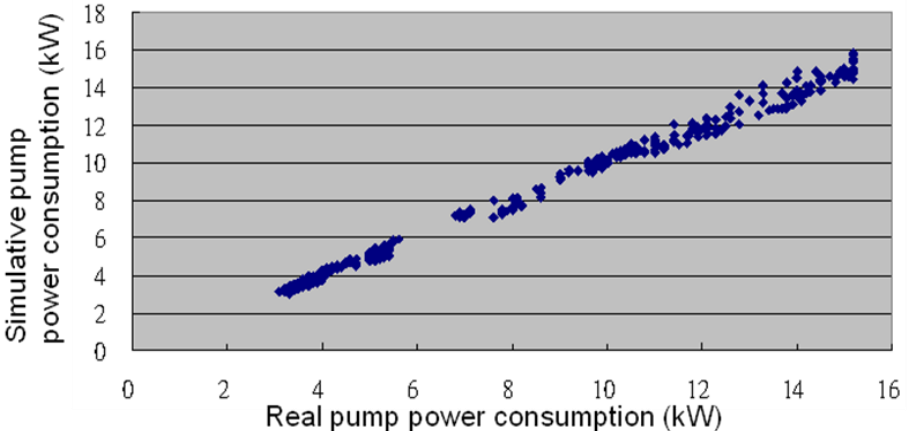

Figure 7. Comparison of actual power consumption of chilled water pump and simulative power consumption

5. Meta-analysis of the chiller and the chilled water pump power consumption

There is only one independent variable in the regression equation of the chilled water pump power consumption, which is the chilled water flow rate. Figure 8 shows the power consumption curves of 1000~2400LPM.

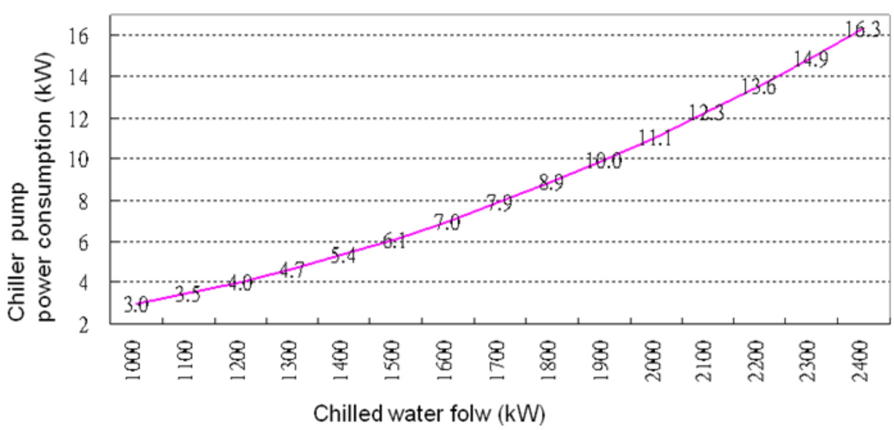

Figure 8. The chilled water pump power consumption

There are four independent variables of the regression equation of the chiller power consumption, including partial load ratio, chilled water supply temperature, cooling water return temperature, and chilled water flow rate. This paper took the constant chilled water supply temperature 7℃, and cooling water return temperature 25℃ for analysis. First, the partial load rate was fixed as 100%, as shown in Table 6. The changes of the water pump power consumption, the chiller power consumption, and total power consumption when the chilled water flow rate varied between 1000 to 2400LPM were illustrated as shown in Figure 9. The blue curve below refers to the chiller power consumption, and the purple curve above refers to total power consumption. Found out the chilled water flow of the lowest power consumption among total power consumption as the optimal flow rate of total power consumption. Using the triangle-point as mark, total power consumption curve was a smiling curve, and the optimum flow rate of the lowest power consumption among total power consumption was at the lowest point of 1800LPM smiling curve. The flow rate started to decrement from 2200LPM and decremented 100LPM every time until 1000LPM. The separation distance of two curves refers to the water pump power consumption; it can be found that the smaller the flow rate, the smaller the separation distance, refers the smaller the water pump power consumption.

Table 6 The power consumption analysis of the chilled water flow changes when the chiller load is of 100%

PLR %	T_{chws} (℃)	T_{cwr} (℃)	Chilled water flow rate (LPM)	Chiller power consumption (kW)	COP	Pump power consumption (kW)	Total power consumption (kW)
100%	7.0	25.0	1000	155.7	4.97	3.0	158.6
100%	7.0	25.0	1100	153.8	5.03	3.5	157.3
100%	7.0	25.0	1200	152.1	5.09	4.0	156.1
100%	7.0	25.0	1300	150.5	5.14	4.7	155.1
100%	7.0	25.0	1400	149.0	5.19	5.4	154.3
100%	7.0	25.0	1500	147.6	5.24	6.1	153.7
100%	7.0	25.0	1600	146.3	5.29	7.0	153.3
100%	7.0	25.0	1700	145.1	5.33	7.9	153.0
100%	7.0	25.0	1800	144.0	5.37	8.9	152.9
100%	7.0	25.0	1900	143.0	5.41	10.0	153.0
100%	7.0	25.0	2000	142.2	5.44	11.1	153.2
100%	7.0	25.0	2100	141.4	5.47	12.3	153.7
100%	7.0	25.0	2200	140.7	5.50	13.6	154.3
100%	7.0	25.0	2300	140.2	5.52	14.9	155.1
100%	7.0	25.0	2400	139.8	5.53	16.3	156.1

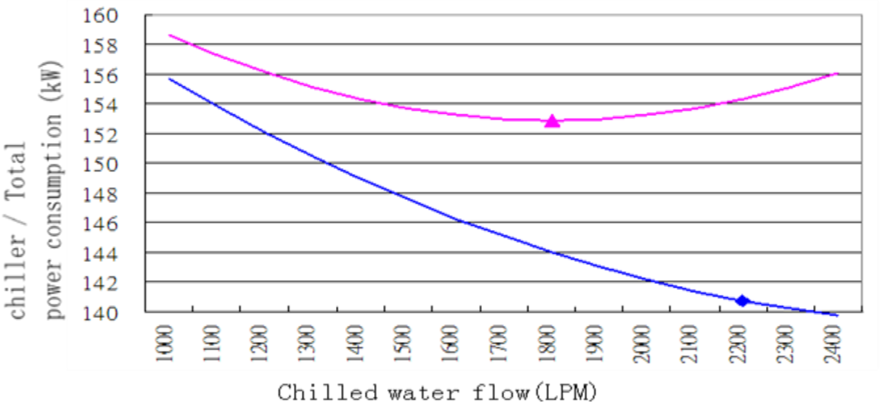

Figure 9 The power consumption changes when the chilled water flow rate changes (the chiller load is of 100%)

Analyzed the state of partial load ratio at 90%, 80%, 70%, 60%, 50%, 40%, 30%, and 25%, and compiled the power consumption message of various loads at rated flow and the optimum flow rate, as shown in Table 7. It can be seen from Table 7, under the load from 25% to 100%, there was always energy saving effect of reducing chilled water flow rate, with the energy saving volume between 1.4kW to 9.6kW, and the energy saving rate was from 0.9% to 3.6%. When the load was 100%, the energy saving rate was 1.4kW (0.9%) only; the smaller the load, the smaller the optimum flow rate, and the greater the energy saving volume, and the greater the energy saving rate as well. The energy saving rate was obtained from the energy savings divided by total power consumption of rated flow at the said load, and the energy savings were up to 23.6%. If always takes the total power consumption 154.3kW of rated flow at 100% loads as basis, the energy saving rate is of 0.9% to 6.2%.

Table 7. The power saving analysis

PLR	Rated flow rate		Opimum flow rate					saving	%
	$P_{chiller}$	P_{total}	Flow (LPM)	%	$P_{chiller}$	P_{pump}	P_{total}	kW	
100%	140.7	154.3	1800	82%	144.0	8.9	152.9	1.4	0.9%
90%	130.8	144.4	1700	77%	134.4	7.9	142.3	2.1	1.4%
80%	119.3	132.9	1600	73%	123.0	7.0	130.0	2.9	2.2%
70%	106.2	119.7	1500	68%	109.8	6.1	115.9	3.8	3.2%
60%	91.4	105.0	1500	68%	94.0	6.1	100.1	4.9	4.6%
50%	75.1	88.6	1400	64%	77.2	5.4	82.6	6.1	6.8%
40%	57.1	70.7	1300	59%	58.6	4.7	63.3	7.4	10.5%
30%	37.5	51.1	1200	55%	38.2	4.0	42.3	8.8	17.3%
25%	27.1	40.7	1200	55%	27.1	4.0	31.1	9.6	23.6%

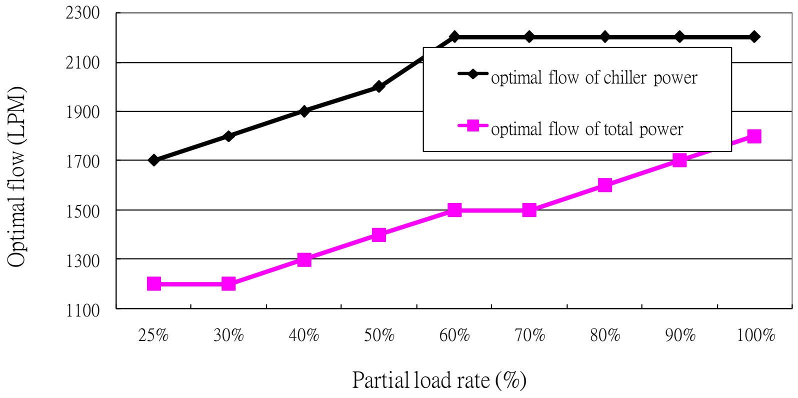

Figure 10. Optimal flow rate tracking

Integrated the optimum flow rate of the lowest power consumption at different loads into Figure 10; when the load was greater than 60%, the chiller's optimum flow rate was the rated flow rate, and when the load was less than 60%, the chiller's optimum flow rate gradually reduces. Figure 10 shows the chiller's rated flow is not the optimum flow rate, the lower the load, the lower the optimum flow rate.

6. Conclusions

The control of the chiller was based on the supply temperature of chilled water. During the experiment, when the chilled water flow rate changed, the chiller cannot knew the flow rate changes, but only through the change of flow rate leading to changes of temperature that the chiller will react. So, when the flow rate changes, the control of the chilled water temperature will be relatively unstable; to change the speed of the chilled water flow rate must consider the chiller's reaction speed to avoid too much devotion of temperature from the set point to affect the system stability.

VPF system is used to save energy by low flow rate. If the chilled water return/supply temperature difference is great, and the return water temperature is higher than the same of primary only system, the chiller will misjudge low load into high load in terms of stage-backwater control, resulting in too low return temperature, and in severe case, may cause the chilled water freezing. It is recommended that to use VPF for energy saving, using the free-stage supply water control of the chiller is better.

Too low chilled water flow rate will affect the heat exchange efficiency of the chilled water in the evaporator. For the minimum flow rate restrictions, please refer to 2~3ft/s, the minimum requirement of variable primary flow system in flow velocity of the chiller evaporator mentioned by MaQcay International [2]. The users cannot know the internal design of the evaporator, and so no way of knowing the flow velocity of cooper pipe of the evaporator. The best is to ask chiller manufacturer provide the flow rate and flow velocity table as the reference for variable flow rate operation.

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