# Supply Air Temperature Control Using a VFD Pump

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## Abstract

*Traditionally, chilled water pump speed is modulated to maintain the water loop differential pressure set point and the control valve at the air handling unit (AHU) is modulated to maintain the supply air temperature. This paper introduces a new VFD pump speed control algorithm, optimal pump head control strategy, in variable water flow direct return systems. Under this new algorithm, the controlled variable is the most resistant loop air handler supply air temperature instead of the water loop differential pressure. The merits of the new control strategy lie in 1) reducing pump energy consumption at partial loads, 2) reducing pressure disturbance on control valves, which improves control system performance during operations, and 3) providing potentials to reduce control valve initial cost and maintenance cost. An application example is also presented in the paper.*

## Introduction

Variable volume chilled water systems are widely applied today. In such a system, a variable frequency drive (VFD) is installed on the chilled water pump. Usually, the pump speed is modulated to maintain the water loop differential pressure (DP). In a direct return water loop, the differential pressure sensor is commonly located at three fourths of the loop downstream. A constant set point is generally used. The value of the set point is determined by the original control system setup.

Building cooling loads and the amount of outside air intake impact chilled water system loads. Building loads are time-varying since they change with the occupancy, the time of the day, day of the week and season. The amount and temperature of outside air also affect chilled water loads. Therefore, the actual desired pressure at the DP sensor location also changes with loads. At partial loads, the actual desired differential pressure is lower than that at the design condition.

The cooling demand is met by adjusting the chilled water pump speed to deliver the desired chilled water flow. The chilled water pump speed is determined by chilled water pump control methods. Controlling the VFD speed to maintain a constant DP set point, which can satisfy the cooling demand at the design condition, will result in an excessive DP at partial loads. The excessive DP leads to extra pump head and electricity consumption, and may also cause valve leakage. Therefore, constant DP control lacks both energy efficiency and safety.

The most common way to reduce the excessive DP is to reset the DP set point. The reset schedule depends on the system operation and the experience of the control system designer. For example, some systems reset DP set points are based on outside air temperature. Obviously, the outside air temperature is not the only factor that affects the chilled water load. Occupancy, solar radiation and HVAC system operation all impact the chilled water system load. The empirical reset schedule can decrease the energy consumption and increase the reliability of control valves to some extent; however, it is impossible to match the system actual pressure need by the fixed schedule.

Ideally, to maximize energy savings, demand based control should be used. With the demand based control strategy, the chilled water pump will provide the available DP close to the actual demand DP. To achieve this goal, an optimal pump head is discussed in this paper, which is defined as the minimum pump head that can ensure the desired water flow [1]. The optimal pump head idea is developed for the direct return variable flow systems with VFD control, and is applied in a real project. The process to obtain the optimal pump head is described and the application results are provided.

## System Models

Figure 1 presents the general schematic of a direct-return system with $n$ branches. There are a coil, a control valve, and pipe segment on every branch. A circulation pump is equipped to ensure the water flow of the most resistant circuit. A VFD is installed to adjust the pump speed with system loads.

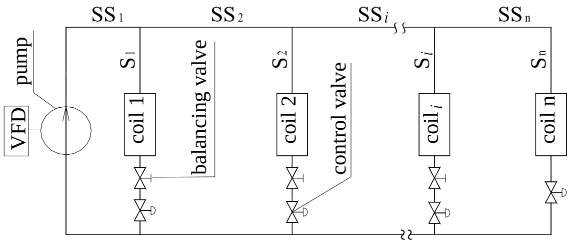

**Figure 1: Schematic of VFD Hydraulic system**

The theoretical pump power ( $HP$ ) is proportional to the product of the pump head and its flow rate. In this study, the pump efficiency is assumed to be constant. The theoretical power is shown in Eq. (1).

$$HP = H \cdot Q_{1-n} / \eta \qquad (1)$$

where,

$HP$ is pump power

$H$ is pump head ;

$Q_{1-n}$ represents the total system water flow;

$\eta$ is pump efficiency.

The pump head equals the pressure loss of the entire loop, which depends on the water flow rate and the pump control method for a certain water loop. When a variable speed drive is used, the pump head varies significantly with control methods.

In this study, an optimal pump head model is used in order to avoid the impact of the improper pump control methods. An optimal pump head ( $H$ ) is defined as the minimum pump head that can meet the system load demand [1]. An optimal pump head will require at least one branch control valve to be fully open. In a variable flow system, an optimal pump head is determined by the pressure drop of the most resistant circuit (MRC) with the control valve fully open, as shown by:

$$\begin{aligned} H &= Max(H_i) \\ H_i &= P_i + SS_1 Q_{1\sim n}^2 + SS_2 Q_{2\sim n}^2 + \cdots + SS_i Q_{i\sim n}^2 \\ &= P_i + \sum_{j=1}^{i} SS_j Q_{j\sim n}^2 \qquad (2) \\ P_i &= S_i Q_i^{\ 2} \end{aligned}$$

where

$P$ is the differential pressure across a branch;

The subscripts, $i$ and $n$ indicate the branch location in the water loop.

$S$ is the branch resistance factor;

$SS$ is the total flow resistance of supply and return mains.

For a system with a constant DP set point, $Ps$, the pump head is:

$$H_S = P_S + \sum_{j=1}^{i} SS_j Q_{j\sim n}^2 \qquad (3)$$

Comparing the constant set point method and the optimal pump head method, the pump head difference is expressed as:

$$\Delta H = Ps - P_i \qquad (4)$$

And the energy saving by using the optimal pump head method is:

$$\Delta HP = \cdot \Delta H \cdot Q_{1-n} / \eta \qquad (5)$$

To achieve the optimal pump head, it is important to fully open the most resistant loop control valve. The location of the most resistant water loop is determined by both the system layout and cooling load distributions. The most resistant loop may not be the most remote loop when the load of this loop is relatively smaller than those loops before it.

In order to realize the optimal pump head, the first step is to find the most resistant loop. The second step is to fully open the control valve in this loop. The final step is to adjust the pump speed to provide the actual desired pressure to ensure the air handler unit supply air temperature.

## Case Study

The optimal pump head control was applied in a real project. The studied case is a ten-floor office building. The gross floor area is about 200,000 ft$^2$. Four identical variable air volume air handling unit systems provide the conditioned air to terminal boxes serving the main office areas. The cooling system is a direct return chilled water system. The chilled water pump with a motor power of 50 HP delivers the chilled water to air handling unit cooling coils. Building cooling loads are approximately evenly distributed to every air handling unit. A VFD is installed on the chilled water pump. Direct digital controllers are used in the building HVAC systems. Figure 2 depicts the chilled water system schematic.

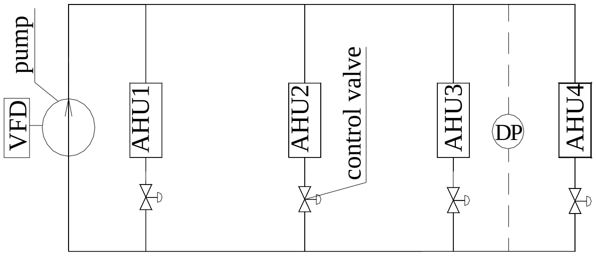

**Figure 2: Schematic of the real project chilled water system secondary loop**

Before May, 2004, the chilled water system pump speed was modulated to maintain the DP at its set point, 8 psi. The original set point can be manually adjusted by operators. Since it was manually adjustable, it was usually kept at the constant value.

Investigating the system, the optimal pump head control was applied to the system. To achieve the optimal pump head, the control valve on the most resistant water loop is desired to be fully open or almost fully open. This is performed by changing the conventional VFD pump controlled variable. Traditionally, the controlled variable of a VFD pump speed control loop is the water loop DP. The proportional and integral (PI) control loop is used to maintain the DP set point. The DP set points may be reset based on the outside air temperature, pump speed, valve positions, etc. Since there is no linear relationship between the cooling load and the optimal pump head; although the set point can be reset when the load changes to minimize the pump head to some extent, it is difficult to reset the DP set point to match the optimal pump head. In this building, the chilled water system is a direct return system and the cooling loads of the air handling units are similar. Therefore, in this project, the VFD pump controlled variable is changed to the supply air temperature of the most resistant water loop air handling unit. The control valve is close to fully open during operation based on the cooling coil valve characteristics.

In the control valve PI control loop, the controlled variable is supply air temperature. The direct action is used in the PI loop. Therefore, the higher the controlled variable input deviates from its reference, the larger the control signal is. Making use of this feature, a fake set point, which is lower than the actual desired supply air temperature, is used to enlarge the control error. The enlarged error makes the control valve fully open automatically. The actual desired supply air temperature set point is the reference of the VFD speed control loop. The VFD control PI loop will maintain the real supply air temperature set point of the most resistant water loop.

Figure 3 shows the application results. As shown in the figure, the actual DP is much lower than the original set point. As a result, the reduction of the DP decreases the pump head and pump electricity consumption.

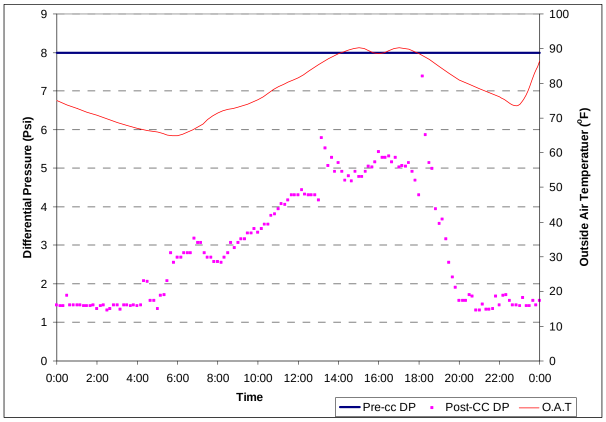

**Figure 3**: May 24, 2005 (Tuesday) the most resistant water loop differential pressure

Based on measurement data and calculation results, the pump power consumption between the new and the existing control algorithm is compare

In this building from 6:00 to 18:00, the HVAC systems run in occupied mode, and four identical air handlers operate together. From 18:00 to 6:00, the HVAC system is in unoccupied mode; and two identical air handlers are in use.

At one occupied moment, the total system water was 1,050 gpm, and the pressure differential at the DP sensor location was 5.61 psi. Since the control valve after the DP sensor is fully open, the resistance factor of the most resistant branch is approximately a constant; therefore, the water flow rate corresponding to all the DP shown in Figure 3 can be calculated considering the building occupancy mode. The DP difference between pre-CC and post-CC is also the pump head difference. According to Eq.(5), the theoretical pump power savings in the unit of HP can be calculated after CC. The pump efficiency used in the calculation is 0.65. Figure 4 shows the saving results.

Changing the fixed DP control method to the optimal pump head method can provide significant electricity savings. The savings are especially remarkable during occupied hours as shown in Figure 4.

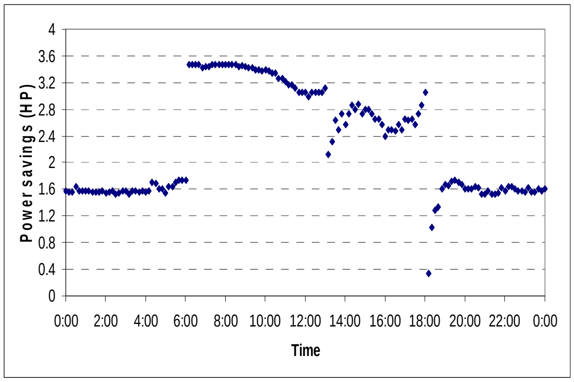

**Figure 4:** May 24, 2005 (Tuesday) calculated chilled water pump electricity savings

The reduction of DP also improves control valve performance. For a system with a fixed DP set point, since the actual desired DP of the water loop reduces with the reduction of water flow, the control valves must absorb the extra pressure when water flow decreases. The additional DP across a valve is the difference between the fixed DP set point and actual desired DP. Therefore, when controlling a VFD pump to maintain a fixed pressure set point, the differential pressure across control valves increases at partial loads. The increase in DP across a control valve results in control valve distortion. The valve distortion leads to more flow through the control valve at the same valve position, which worsens the control valve performance. Using the optimal pump head control strategy, the DP across the control valves is less than the DP in the system with a fixed DP set point. This implies the system with the optimal pump head control algorithm has less control valve distortion. Therefore, the system with optimal head VFD control improves the control performance.

This control strategy also allows the control valve to be selected with lower close-off pressure. The close-off pressure is the maximum DP seen by the control valve as it closes [2]. Higher DP can cause control valve leakage, result in higher requirements in the selection of valve actuators. In contrast, reduced close-off pressure can reduce valve leakage and also reduce the pressure requirement on the valve actuator selection. Therefore, adjusting VFD speed to maintain the supply air temperature set point can reduce the control valve initial cost by allowing the selection of a lower close-off pressure control valve and can save maintenance cost by reducing leakage.

## Conclusions

The application of the optimal pump head concept to a real project by adjusting pump speed to maintain the supply air temperature set point can:

1. save pump electricity energy;
2. improve control valve control performance;
3. reduce control valve initial cost;
4. save maintenance cost.

## References

[1] Zheng B., Liu M. (2004). Impacts of balance valves on pump energy and control performance in variable water flow systems. Proceedings of Solar 2004

[2] ASHRAE. (1998). Fundamentals of HVAC control systems. pp. 3:3-3:23