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# Development of By-pass Blending Station System

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## ABSTRACT

A new building blending station system named by-pass blending station (BBS) has been developed to reduce building pump energy consumption in both district heating and cooling systems. Theoretical investigation demonstrated that the BBS can significantly reduce building pump power for a typical cooling system when constant water flow is maintained in the building side. When differential pressure reset is applied in the building side, more pump energy can be saved. The BBS also reduces the pump size and therefore results in lower initial system cost. A case study was also performed and demonstrated 42% of annual chilled water pump energy savings for constant building water flow, and 82% of annual chilled water pump savings for differential pressure resetting at Omaha, Nebraska.

## NOMENCLATURE

- C: Constant  
 M: water flow rate (GPM or kg/s)  
 T: Temperature (°F or °C)  
 W: Pump power (kW)  
 $\bar{Q}$ : Building load ratio  
 $\Delta p$ : Differential pressure (Psi or Pa)  
 $\beta$ : Ratio of the pump power savings over the design pump power  
 $\phi$ : Ratio of the building loop differential pressure over the loop differential required under design flow.  
 $\varphi$ : Ratio of the blending water flow over the building water flow.

Subscripts:

- b: building  
 d: design, full load  
 o: Optimal, BBS  
 p: district systems, pump  
 r: Return  
 s: Supply  
 min: minimum

## INTRODUCTION

Districting heating and cooling has been revived since 1984 in USA [Mornhed and Gasten, 1995]. Many new district heating and cooling systems have been established and existing systems have been expanded in recent years. Industry and federal government have agreed that cooling, heating, and power (CHP) systems are a key support for electric grid of the future; as much as eight gigawatts by the year 2020 [Sweetser, 2002]. Many more existing and new buildings are likely to receive chilled water and/or hot water from district cooling systems in the future.

When buildings are directly connected to the central heating or cooling systems, blending stations are required. District cooling or heating systems often require higher temperature difference of the supply and return in order to reduce the pumping cost [ASHRAE, 2000]. For example, the district cooling system may require the return water temperature be 17°F higher than the supply water temperature. The cooling coils in air-handling units (AHUs) are often designed to rise the supply water temperature by 10 or 12°F. When the district chilled water is directly supplied to the cooling coil, the building return water temperature is often significantly lower than the value required by the district plant. To maintain the required return water temperature, a blending station is used to mix the district supply water and the building return water. The blending stations control the amount of return water backflow to the building to maintain the return water temperature at the required value by the district system.

Building end users are designed with the same temperature rise or drop as the district systems, the blending stations are also required to maintain the constant return water temperature under partial load conditions. In this case, the blending station has no function at the design load condition. However, the heating and the cooling system mostly work on partial load conditions. Under partial load conditions, most building end users cannot maintain the same differential temperature since the no-linearity of the

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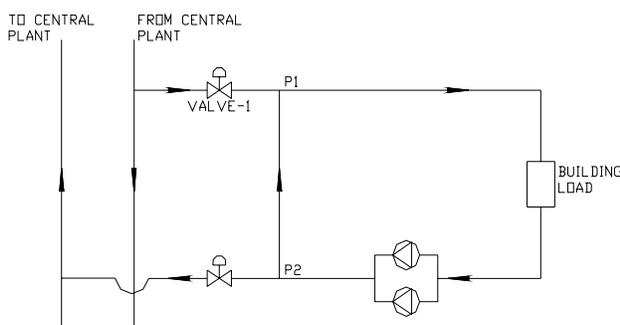
coil heat transfer. Unfortunately, the differential temperature is often smaller under the partial load conditions. The blending stations are often designed and used for practical reasons. For example, the blending station may be used to maintain building comfort when a building has significant water balance problems. Blending station is required for both constant water flow and variable water flow system in order to maintain required return water temperature.

ASHRAE [2000] recommends installing building circulation pump on the building return water line and installing a by-pass to connect the return and the supply line. This design has two drawbacks: (1) the pump design flow must be the same as the total building flow although the return water flow for mixing is much less than the total water flow, and (2) the pump will have to provide the entire head required by the water circulation in the building loop, although the primary loop may have the required differential pressure available.

This paper first discusses the ASHRAE recommended blending station design, and then presents an innovative blending station system named as by-pass blending station (BBS). The pump energy models are developed and subsequently used to compare the energy performance. A case study is finally presented using the actual building data to demonstrate the potential annual pump energy savings.

### EXISTING BUILDING BLENDING SYSTEMS

Figure 1 presents the schematic of a typical building blending station based on ASHRAE (ASHRAE Handbook Systems, 2000). The blending station consists of a control valve on the building supply pipe, a by-pass line, and building circulation pumps.



**Figure 1: Schematic of Existing Building Blending Station**

The control valve (Valve-1) is designed or selected to consume the primary loop differential pressure. Very often, special pressure throttling devices are designed to assist the control valve to consume the excessive differential pressure provided by the district systems. The by-pass pipe provides the physical pass of the return water back flow. The pump is designed or selected based on the design water flow and the building loop pressure loss under the building design water flow.

During normal operation, the control valve (Valve-1) located on the chilled water supply consumes the entire differential pressure provided by the district systems and is modulated to maintain the required return water temperature from the building. If the building return water temperature is lower than the required value, the control valve will close more to allow more return water backflow and vice versa. The valve maintains the pressure at the supply side ( $p_1$ ) rather than on the return side ( $p_2$ ) thus allowing the water from the building return to be blended with the supply from the central plant. The pump runs at full speed and uses the same amount of pump power regardless of the load conditions.

This system provides good control over the  $\Delta T$  required by the district systems. However, several improvements can be performed on this system. First, the differential pressure provided by the district systems may be used since it is wasted by the control valve. Second, the water flow through the pump may be reduced since the return water back flow is significantly less than the building circulation rate. An innovative system named by-pass blending station (BBS) is developed to improve the blending system performance by implementing these features.

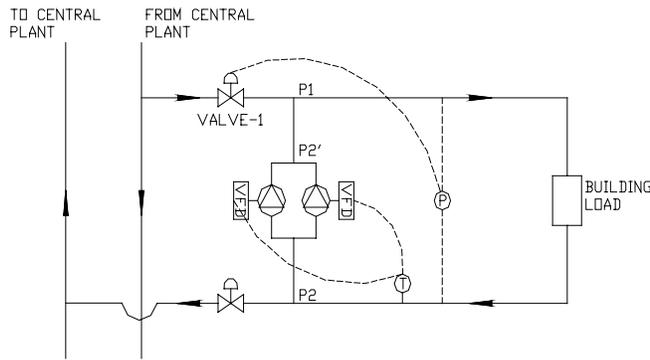
### BY-PASS BLENDING STATION (BBS)

Figure 2 shows the schematic for the proposed BBS design. The pumps are located in the by-pass line. VFDs are added to the pumps. A differential pressure sensor is added to the building loop. The sensor can either be installed at the end of the loop or at the entrance to the building loop.

The control valve (Valve-1) is designed and selected based on building circulation and smaller differential pressure, which equals the difference of the maximum available district loop differential pressure and the maximum building loop pressure loss. The pump design water flow equals the maximum return water backflow rate, which can be significantly less than the building design water flow

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rate. The pump head equals the building loop pressure loss.



**Figure 2: Schematic Diagram of the BBS System**

During normal operation, Valve-1 is modulated to maintain the building  $\Delta P$  set point depending upon the load required by the building. The pump speed is controlled to maintain the required return water temperature. If the return water temperature is lower than the set point, the VFD speeds up the pump to increase the building supply water temperature, and vice versa.

In the BBS system, the primary loop differential pressure is fully used to circulate the “primary water”. The pump is only used to circulate the “backflow water”. Therefore, the BBS system uses much less pump power than the existing systems. The amount of pump power savings depends on the amount of water re-circulation. Less water circulation results in more pump power savings.

The BBS system allows the building differential pressure reset and variable flow due to the use of VFD. Implementing an optimal building differential pressure reset can result in significant additional pump savings.

It is important to note that the BBS system can only be designed and installed where the differential pressure of the district loop is higher than the building loop pressure loss.

### Energy Performance Analysis

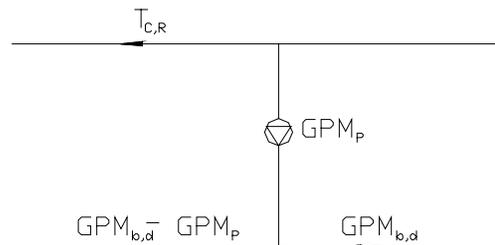
The pump power is proportional to the product of the water flow and the pump head when the impact of the pump efficiency is ignored. Therefore, the pump power of the base system and the BBS system are expressed using Equations 1 and 2 respectively.

$$W_b = C \cdot \Delta P_{b,d} \cdot M_{b,d} \quad (1)$$

$$W_o = C \cdot \Delta P_{b,d} \cdot M_p \quad (2)$$

Notice that the water flow rate is a variable in Equation 2 for the BBS system. To correlate the flow with design flow and water temperatures, an energy balance analysis is performed.

Figure 3 presents the flow balance in a blending station. Equation 3 states that the energy of the building supply water equals the sum of the energy of the primary supply water and backflow water. Equation 4 states that the building energy consumption equals the district system energy loss.



**Figure 3: Schematic Diagram of Water Balance**

$$M_p \cdot T_{p,r} + (M_{b,d} - M_p) \cdot T_{c,s} = M_{b,d} \cdot T_{b,s} \quad (3)$$

$$M_p \cdot (T_{c,r} - T_{c,s}) = M_{b,d} \cdot (T_{b,s} - T_{c,s}) \quad (4)$$

From equations 3 and 4, the water backflow is expressed as:

$$M_p = M_{b,d} \cdot \left( \frac{T_{b,s} - T_{c,s}}{T_{c,r} - T_{c,s}} \right) \quad (5)$$

To introduce equation 5 into equation 2, the pump power of the BBS system is deduced as:

$$W_o = C \cdot \Delta P_{b,d} \cdot M_{b,d} \cdot \left( \frac{T_{b,s} - T_{c,s}}{T_{c,r} - T_{c,s}} \right) \quad (6)$$

If the constant building circulation is assumed for both the existing and the BBS systems, the potential pump power savings can be expressed as the ratio of the pump power savings over the design pump

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power. According to equations 1 and 6, the pump power savings is deduced as equation 7.

$$\beta = 1 - \frac{W_o}{W_b} = 1 - \frac{T_{b,s} - T_{c,s}}{T_{c,r} - T_{c,s}} = 1 - \phi \quad (7)$$

The building blending ratio can be correlated with the building load ratio and the minimum blending ratio. Equation 8 is developed by performing energy balance analysis.

$$\phi = 1 - \bar{Q}(1 - \phi_{\min}) \quad (8)$$

Where:

$$\phi_{\min} = \frac{T_{b,s,d} - T_{c,s}}{T_{c,R} - T_{c,s}} \quad (9)$$

The minimum blending ratio is the blending rate when building has full load. The minimum blending ratio depends on the district and building design water temperatures, design air conditions, and the coil properties.

To introduce equation 8 into equation 7, the pump power savings is expressed using the minimum blending ratio and the building load ratio.

$$\beta = \bar{Q}(1 - \phi_{\min}) \quad (10)$$

When the BBS system is used, the differential pressure reset may be used to reduce the pump power. Assuming constant resistance characteristics of the building water loop, the building loop water flow can be correlated using the differential pressure set points.

$$M_b = M_{b,d} \sqrt{\frac{\Delta P_b}{\Delta P_{b,d}}} \quad (11)$$

The pump flow rate for the BBS system is then expressed by equation 12 based on equation 5.

$$M_p = M_b \cdot \left( \frac{T_{b,s} - T_{c,s}}{T_{c,r} - T_{c,s}} \right) \quad (12)$$

Introducing Eq. (11) into Eq. (12), the pump flow rate,  $M_p$ , is:

$$M_p = M_{b,d} \cdot \sqrt{\frac{\Delta P_b}{\Delta P_{b,d}}} \cdot \left( \frac{T_{b,s} - T_{c,s}}{T_{c,R} - T_{c,s}} \right) \quad (13)$$

Inserting Eq. (13) into Eq. (2), gives the pump power for the new blending station under variable building pressure loss conditions:

$$W_o = C \cdot M_{b,d} \cdot \Delta P_{b,d} \left( \frac{\Delta P_b}{\Delta P_{b,d}} \right)^{3/2} \phi \quad (14)$$

Finally, the potential pump power savings is expressed by equation 15.

$$\beta = 1 - \phi^{3/2} [1 - \bar{Q}(1 - \phi_{\min})] \quad (15)$$

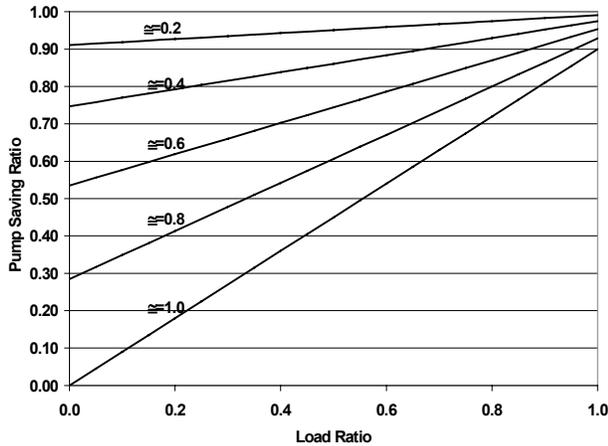
Where:

$$\phi = \frac{\Delta P_b}{\Delta P_{b,d}} \quad (16)$$

Equation 10 shows that the pump power savings depends on the building load ratio and the minimum blending ratio when the constant loop flow is used. Equation 15 shows that the pump power savings depends on both the building load ratio and the building loop differential set point. Figure 4 shows the theoretical pump energy savings ratio ( $\beta$ ) of the BBS system versus the building chilled water supply temperature for various building loads. The minimum blending ratio is assumed to be 10%. At constant differential pressure set point or constant building water flow,  $\phi=1$ , the pump power savings increases as the building load increases. When the building differential pressure reset is used, the pump power savings is much higher. For example, the pump power savings is increased from 36% to 70% when the differential pressure is reset from 100% to 60% under 40% of the building load.

The lower differential pressure can be used under lower building load ratio. Based on the theoretical results presented in Figure 4, the pump power savings can be maintained at higher than 50% all times. Therefore, the BBS can reduce building pump power by at least 50% when the differential pressure reset is properly implemented. The optimal building differential pressure reset and its impacts will be presented in a separate paper. The potential annual energy savings is demonstrated in the next section using a case study.

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**Figure 4: Simulated pump energy savings ratio versus the building load ratio and the differential pressure ratio (The minimum blending ratio is assumed to be 10%)**

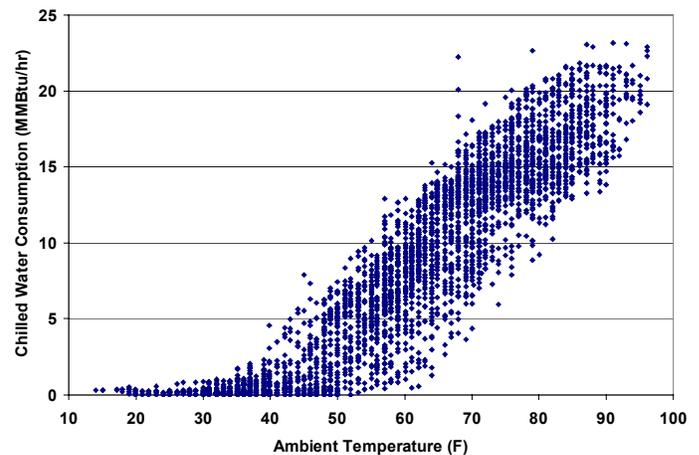
**CASE STUDY**

The case study is a 500,000 square feet medical facility located at Omaha, Nebraska. The facility has 34 AHUs. The AHUs were designed to rise the chilled water temperature from 42°F to 52°F. The building is connected with the district system through a traditional blending station. The district cooling system provides chilled water temperature at 39°F and requires return water temperature be higher than 57°F.

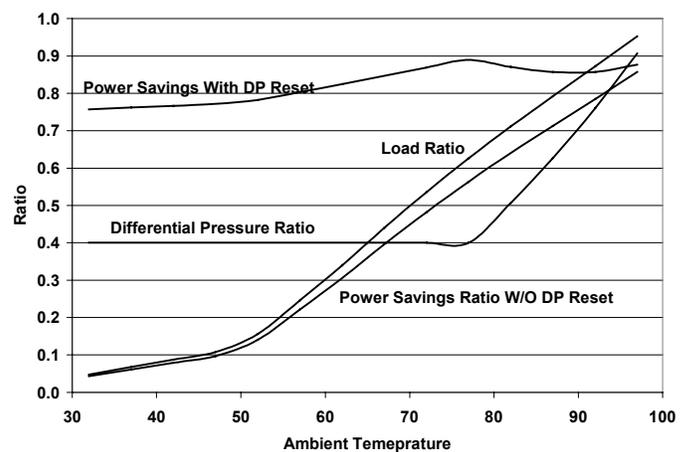
Figure 5 presents the measured hourly chilled water consumption versus the ambient air temperature. When the outside air temperature is lower than 30°F, the chilled water consumption is negligible. When the outside air temperature reaches 100°F, the hourly chilled water energy consumption is as high as 25 MMBtu/hr. In order to use bin method to analyze the annual potential pump energy savings, the simplified load profile is generated using the detailed hourly measured data. The load ratio is calculated as the ratio of the average load in the bin over the maximum cooling load (25 MMBtu/hr). The number of hours in each bin is taken from ASHRAE bin data [Degelman 1984].

Figure 6 presents the load ratio, the differential pressure reset ratio, and the power savings ratio against the ambient temperature. The cooling load ratio increases from 5% to 95% when the ambient temperature increases from 30°F to 100°F. The differential pressure ratio was determined as the

square of the building load ratio provided it is higher than 0.4. The minimum differential pressure ratio is set as 0.4. Based on the theoretical models, the pump power saving ratio is determined under both constant building flow and the differential pressure reset conditions. When the constant building water flow is maintained, the pump power savings ratio is slightly less than the building load ratio since the 10% minimum blending ratio is assumed. When the differential pressure reset is implemented, the pump power savings ratio varies from 76% to 89%. Under partial load conditions, the BBS can significantly increase the pump power savings.



**Figure 5: Measured Hourly Chilled Water Energy Consumption versus the Ambient Air Temperature in the Case Study Building**

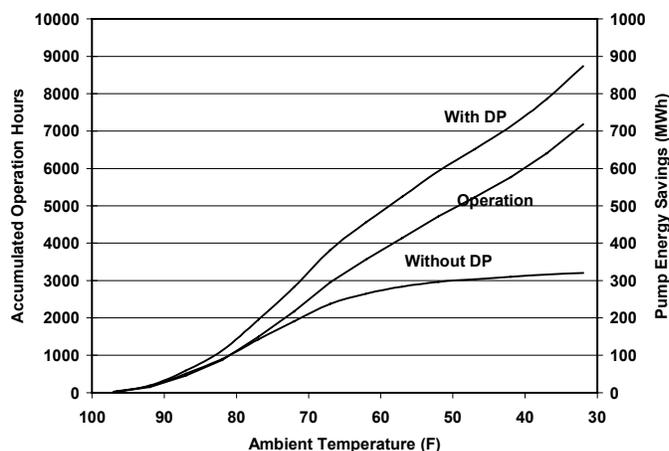


**Figure 6: Load Ratio, Differential Pressure Reset Ratio, and Pump Power Savings Ratio versus the Ambient Air Temperature**

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Figure 7 presents the accumulated pump operating hours and the accumulated pump energy savings against the ambient air temperature. The pump energy savings was determined as the product of the pump power savings and the number of hour operation in each bin. The design pump power is 200 hp. When the ambient temperature decreases from 100°F to 52°F, the accumulated pump operating hours are 4,723 hours. The accumulated pump energy savings are 296 MWh (42%) if the differential reset is not used. When the differential pressure reset is used, the accumulated pump energy savings are 593 MWh (84%). If the electricity price is assumed to be \$0.08/kWh, the annual energy cost savings are \$23,680 for the constant building water operation, and \$47,440/yr for differential pressure reset.

When the ambient temperature decreases to 32°F, the accumulated chiller operation time is 7,185 hours. The accumulated pump energy savings are 320 MWh (30%) for constant building flow and 873 MWh (82%) for differential pressure reset. The potential annual energy cost savings are \$25,600/yr for constant building water flow operation, and \$69,840 for differential pressure reset. Obviously, the BBS system provides a very attractive energy retrofit for the case study building.



**Figure 7: Accumulative Pump Operating Hours and Accumulated Pump Energy Savings versus Ambient Temperature**

## CONCLUSIONS

The BBS system has been developed. It installs the pump in the building by-pass line and uses a VFD on the pump. The BBS system has smaller pumps and provides “power of the recirculation water” only.

A case study demonstrated a minimum 42% annual pump energy savings when constant building water flow is maintained. When the differential pressure reset is implemented, the annual pump energy savings can be as high as 84%.

The actual energy savings may be slightly lower in actual design operation since the model analysis did not account for the VFD power loss. It must be pointed out that the BBS system cannot be implemented in places where the primary loop differential pressure is less than the building loop pressure loss.

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