Energy Efficiency Strategies for Hydronic Systems through Intelligent Actuators

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Abstract

The degradation of the difference between supply and return water temperature from design values is a condition found in many chilled and hot water distribution plants, leading to a significant waste of distribution and primary system energy. Here, several strategies aimed at preventing delta-T degradation are compared using simulations and field tests. Unnecessarily high flow through the heat exchanger (heating or cooling coil) is one cause of delta-T degradation. Limiting either the delta-T or the flow across the heat exchanger are two known approaches to reduce delta-T degradation on the primary side. A novel strategy, termed flow/delta-T limiting, is introduced and compared to the existing flow and delta-T limiting strategies. It is found that flow limiting is superior when either inlet air or water temperature is fluctuating. Conversely, delta-T limiting is superior when either entering air humidity or airflow rate is fluctuating. Because the numerous variables impacting heat exchanger behavior are typically changing simultaneously, the question arises which strategy is best? Through simulation studies it has been shown that flow/delta-T limiting is the preferred strategy that provides results falling between the flow and delta-T limiting approaches while maintaining acceptable heat exchanger performance. The different approaches have been applied to data sets acquired on two university campuses with the field tests supporting the simulation results.

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1 Introduction

The degradation of the temperature difference between supply and return flow, known as delta-T degradation, in chilled water systems has been widely observed and documented over the last 25 years (Fiorino 1996, Harrell 2009, Hyman 2004, Ma 2010, Reed 2007, Taylor 2002, 2006). Causes include, but are not limited to, the provision of bypass lines, oscillating control loops, and constant speed pumping with three-way valves. Especially under part-load conditions, when the mass flow rate relative to the cooling load increases, an additional chiller and cooling tower may need to be brought online to maintain the flow requirements even though the cooling capacity limits of the operating chillers have not yet been reached. Even though the effect of decreasing waterside temperature difference is typically reported, the real problem is the associated increase in chilled water flow rate (Henze, Henry and Thuillard 2013). While there are numerous contributing factors to delta-T degradation, this paper explores several possibilities of mitigating delta-T degradation with control strategies for individual heat exchangers.

The energy transfer in a heat exchanger without phase change is described by the function,

$$E(\dot{m},\Delta T)=\dot{m}c_p\Delta T \quad (1)$$

where $\dot{m}$ is the fluid mass flow rate [kg/s], c_p the fluid specific heat [J/kgK], and ΔT [K] the change in fluid temperature across the exchanger. A typical application of a heat exchanger in the HVAC domain consists of cooling the air supplied to a zone to a desired temperature to provide comfort under warm weather conditions. The energy transfer from the chilled water to the air stream depends not only on the dimensions of the heat exchanger but also on the fluids' physical states (temperature, enthalpy). At constant air flow and entering conditions, the energy transfer to air increases with larger chilled water flow as shown in Figure 1a. At high flow rates, the energy transfer (solid line) approaches a limit while delta-T (dashed line) degrades asymptotically towards zero. When approaching this limit, any increase in chilled water flow results in only a marginal increase of energy transfer to the air stream. The zone of diminishing returns may be thought of as a waste or saturation zone in which delta-T degradation is caused by an unnecessarily high flow rate and leading to a low return water temperature. In order to reduce a heat exchanger's contribution to delta-T degradation in water distribution systems, it is therefore recommended to avoid operating in saturation. Provided one does not operate significantly below saturation, the associated sacrifice of coil capacity is deemed to be negligible in comparison to the benefits achieved in terms of pump energy savings and improvement of central plant efficiency. This paper introduces and explores a general approach based on curtailing the mass flow rate with three limiting strategies to avoid coil saturation.

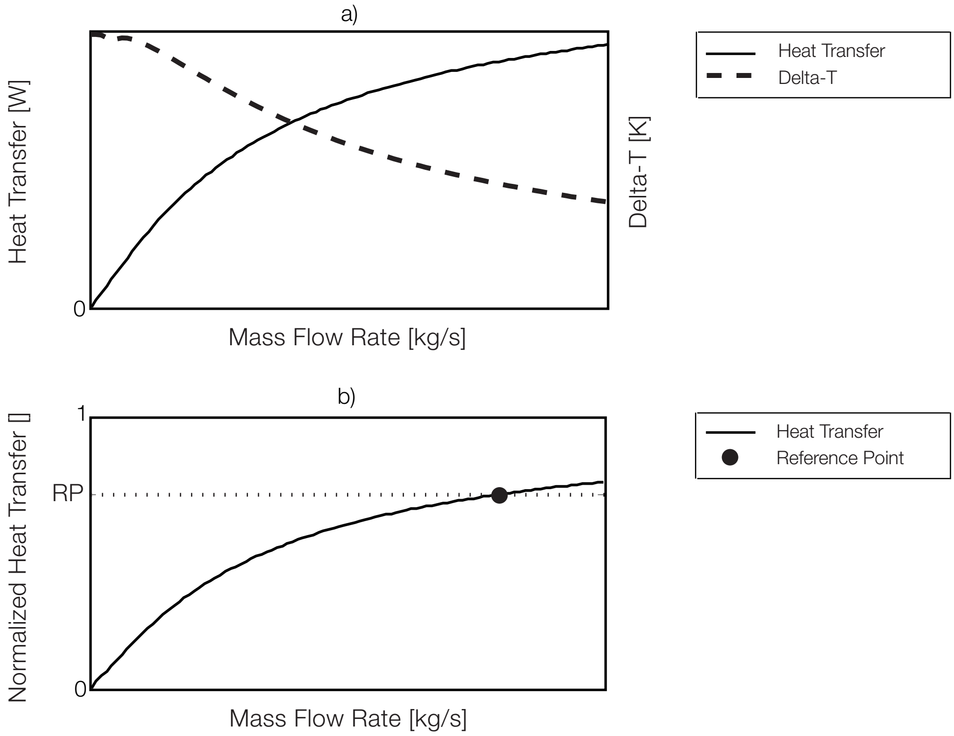

Figure 1: (a) Absolute and (b) normalized heat transfer capacity at design conditions. (The dip in the upper left corner of (a) is due to flow regime transition)

2 Strategies for Managing Desired Coil Performance

A delta-T limiting strategy field study has been performed at the Massachusetts Institute of Technology (MIT) library (Henze, Henry, and Thuillard 2013). This study involved the use of pressure independent control devices incorporating magnetic flow meters, temperature sensors in both waterside supply and return lines, and microprocessors to apply and monitor a delta-T limiting strategy. Unique delta-T threshold control values were determined for each coil after recording and analyzing data using a software tool. Describing the tool would go beyond the scope of this paper. The result at MIT was a doubling of the delta-T of the water entering and leaving the library relative to pre-retrofit conditions supporting the assertion that limiting strategies have a positive impact on delta-T syndrome. Very good results were also observed during the field experiments when implementing flow limiting. Even during the high summer days, the limiting strategies did not have a negative impact on comfort. Equation 1 contains two variables, flow and delta-T. Limiting one of the two variables will impact the other, suggesting both different strategies may have merit in addressing delta-T degradation. This article proposes a new strategy to reduce delta-T degradation by combining both the flow and delta-T into a single variable, the ratio of flow to delta-T. This limiting strategy is referred to in the rest of this article as the flow/delta-T limiting strategy. Three sensors are required to implement the flow/delta-T strategy. Two temperature sensors measure the change in temperature across the coil, and a flow sensor determines the chilled water flow rate.

A simulation tool based on the HVAC toolkit code by Brandemuehl, Gabel and Andersen

(Brandemuehl 1993) was developed to generate performance maps for counter-cross flow heat exchangers based on established relationships for dry and wet cooling coils in order to establish expected coil behavior for a range of operating conditions. This tool was developed because the complex behavior of heat exchangers depends on several inputs: air pressure, inlet water and air temperature, humidity, mass flow rates, material properties of the two fluids, and the heat exchanger geometry and material properties. In particular, the model accounts for condensate mass transfer experienced in wet and partially wet cooling coils during dehumidification. For the purposes of this study, the only variables discussed further are inlet water and air temperature, inlet air humidity, and air mass flow rate; all other parameters are held constant.

The three limiting strategies are discussed and compared using normalized capacity, a variable developed to study heat exchanger behavior. The normalization is achieved by dividing the absolute heat transfer curve by the maximum heat transfer of the coil for the given input fluid states at very large water flow rates as shown in Figure 1b. The domain of the normalized heat transfer values is therefore between zero and one. A reference point (RP) is selected on the normalized heat transfer curve at design conditions for the cooling coil. The reference point serves as a basis for comparison. As the operating conditions change during the year, the maximum normalized coil operating point imposed by the limiting strategies varies as seen in Figures 2 to 4. In this study, physical parameters are changed one at a time and their effect is discussed. For the numerical simulations, design conditions represent the high heat transfer summer condition experienced at the MIT campus library. The RP in this paper has been selected for illustrative purposes and represents a point on the normalized heat transfer curve for which the coil is 85 percent saturated. At these design conditions, the reference point does not only define a normalized capacity limit of the heat transfer, but also defines the flow, delta-T, or flow/delta-T specific controller thresholds. The result that most closely maintains the normalized capacity limit while exceeding the minimum acceptable coil performance is deemed the superior strategy.

Case 1: Inlet Temperature Fluctuations

Assuming constant inlet air temperature, humidity, and flow rate, simulations show that, for a large range of supply water temperatures, the normalized coil capacity curves are almost independent of the water supply temperature while, absolute cooling output varies. Figure 2a furnishes an example of a heat exchanger at two different water supply temperatures. The normalized heat transfer curves (Figure 2b) overlap quite closely as do the flow limit and RP. In other words, the shape of the normalized heat transfer curve is independent of the water supply temperature.

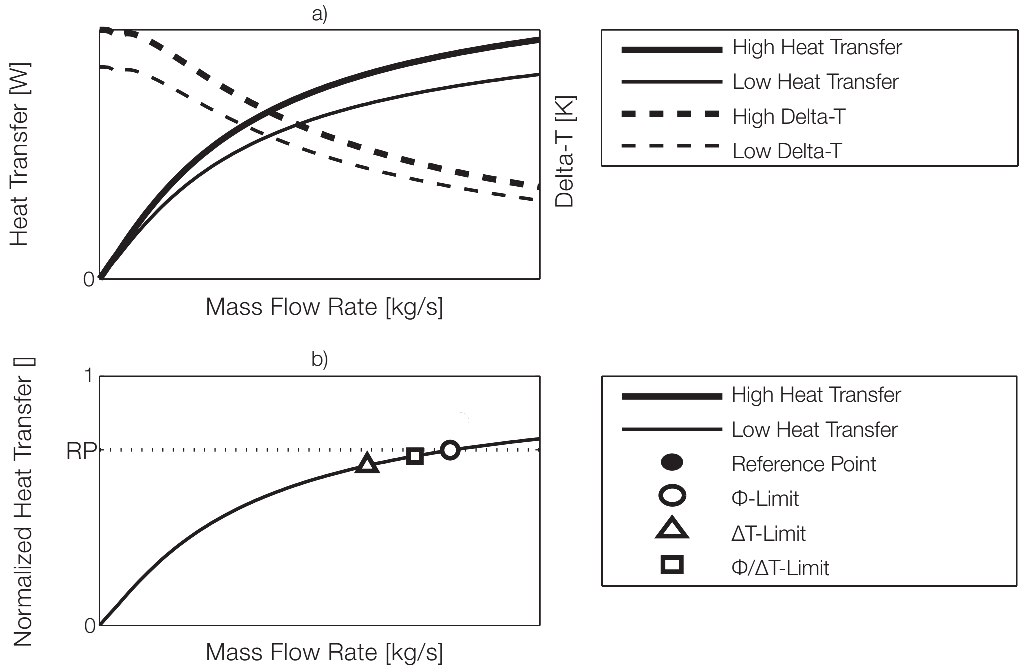

Figure 2: (a) Absolute and (b) normalized heat transfer capacity with flow, delta-T and flow/delta-T limiting results, assuming a 2K increase in chilled water supply temperature from 6 to 8°C.

Considering only water temperature variations, limiting the water flow rate is the superior strategy to prevent water flow from entering too far into the saturation zone. In contrast, the delta-T limiting leads to deviations furthest from the reference point. The flow/delta-T limiting falls in between the flow and delta-T limiting strategies. The same behavior is observed for varying supply air temperatures; the energy transfer normalized by the maximum transfer limit is independent of the air supply temperature with similar control results.

Case 2: Inlet Air Flow Rate and Humidity Fluctuations

If inlet water temperature, air temperature and humidity are held constant, while the mass flow rate is changed, the normalized cooling capacity curves for high and low heat transfer develop distinctly different shapes as shown in Figure 3.

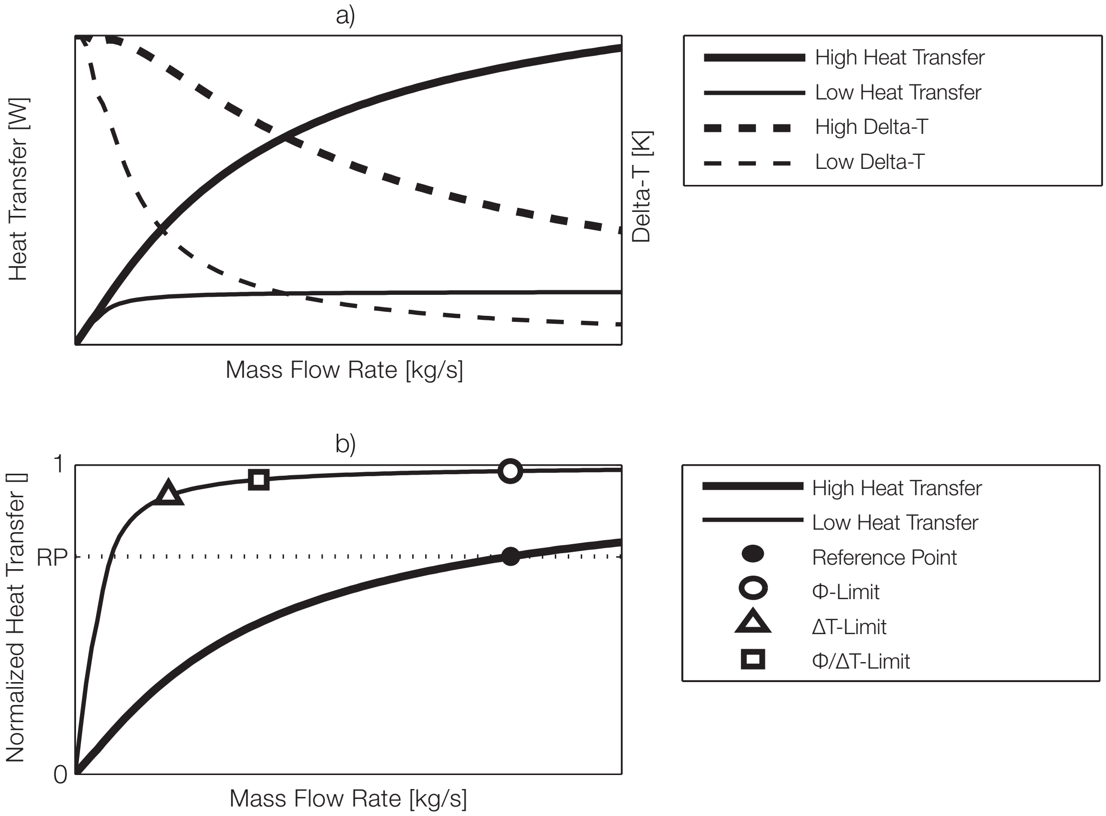

Figure 3: (a) Absolute and (b) normalized heat transfer capacity with flow, delta-T and flow/delta-T limiting results, assuming a factor 6 reduction in mass air flow rate.

Simulations show that coil capacity scales almost perfectly with delta-T as indicated by the delta-T limit (Figure 3b) most closely approaching the reference point value. Therefore, delta-T limiting is the superior control strategy to avoid the zone of diminishing coil returns. Flow limiting restricts mass flow rate too late, i.e. well within the saturation zone. Flow/delta-T limiting produces a result that falls in between the results of flow and delta-T limiting.

The scaling of normalized curves with respect to humidity depends largely on whether the exchanger heat transfer is sensible only (the air passing through the heat exchanger never cools to the dew point temperature), or if there is latent energy transfer in the form of dehumidification. When mass transfer occurs (dehumidification), as is typically observed in cooling application, the results are fairly similar to changing air mass flow rate. Delta-T limiting is the superior solution when only humidity is changing.

It is common in variable air volume applications that the chilled water and entering air conditions change simultaneously during operation. In this case, what is the best strategy? Results at constant air volume mirror those found for a variable air volume system where flow/delta-T limiting is the superior strategy as shown in the following section. Care must be taken with the proper choice of the delta-T limit: When all variables fluctuate simultaneously, delta-T limiting may limit the heat transfer capacity in some instances too early. On the other hand, flow limiting may lead to the inverse effect, limiting the flow too late in comparison to the reference point. We found that limiting the ratio flow/delta-T is a strategy that prevents the flow from entering the zone of low return while meeting or exceeding normalized coil performance at large loads.

3 Application to Measured Field Data

A field study was conducted on the campuses of the Massachusetts Institute of Technology (MIT) and the University of Colorado Boulder (UCB) during the cooling season of 2011. During this field study, high resolution heat exchanger data were collected. The variables, recorded at 30-second intervals, included the delta-T across the heat exchanger and the mass flow rate of water through the coil. Using these data sets, the three coil management strategies are applied and compared as illustrated in Figures 4 (MIT) and 5 (UCB). For the data shown in these figures, coil flow was intentionally not restricted during actual operation, and the management strategies were applied in a subsequent simulation analysis in order to reveal the restriction that would have occurred if said strategies had been implemented.

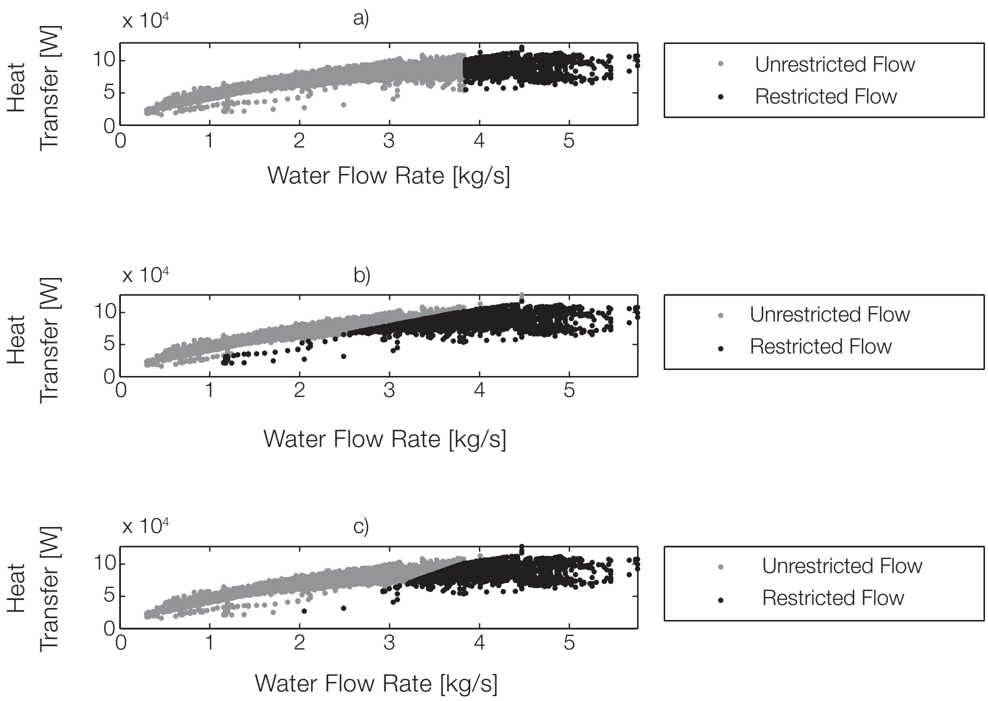

Figure 4: (a) Flow limiting (b) delta-T limiting and (c) flow/delta-T limiting coil management strategies applied to data from MIT air handling unit.

We can observe in Figure 4 the coil capacity increasing with chilled water mass flow rate in an exponential fashion, revealing saturation at high flow rates. The application of the coil management strategies is clearly indicated by the separation of the light and dark data markers. Looking at Figure 4a one can see that the point of saturation is different for the upper and lower bounding envelope curves. While favorable results were observed at MIT applying both flow and delta-T limiting strategies, it is clear from the simulation results shown in Figure 4 that flow/delta-T limiting would have yielded favorable results that fall in between the flow and delta-T strategies.

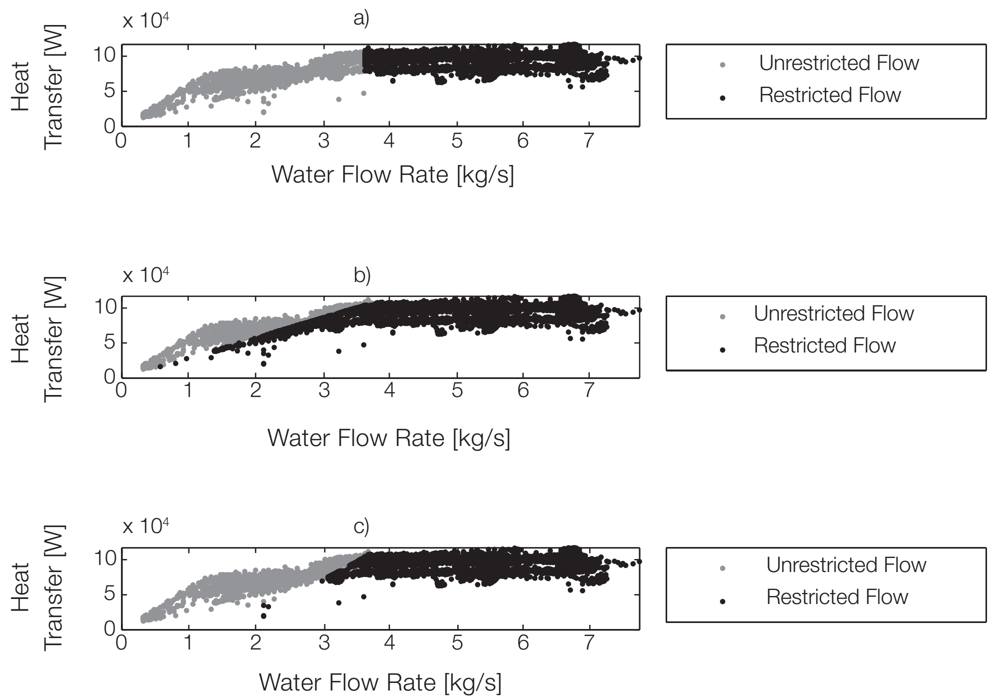

Figure 5: (a) Flow limiting (b) delta-T limiting and (c) flow/delta-T limiting coil management strategies applied to data from UCB air handling unit.

In Figure 5, similar trends are observed at UCB as compared to MIT in Figure 4. In particular, the delta-T management strategy appears to limit flow prematurely for the selected reference point. The data suggest that flow/delta-T limiting is slightly superior to the flow limiting management strategy. During field application, the selection of the reference point is of utmost importance. Because the purpose of the limiting management strategies is to the find the proper balance between coil performance and energy optimization, it needs to be chosen carefully. Improper limit selection, particularly where the coil is not yet approaching saturation, should be avoided.

4 Conclusions

Heat exchangers exhibit a behavior of diminishing returns: above a certain value increasing the flow results in a marginal increase of the energy transfer. Implementing a strategy to avoid aforementioned zone of diminishing returns provides several benefits. The efficiency of the central plant is increased by the reduced flow and increased return water temperature. Pumping energy is also reduced by avoiding the saturation zone of the heat exchanger. This study has investigated three coil management strategies to restrict the flow of chilled water through a heat exchanger in an effort to avoid saturation. Heating and cooling coil behavior is complex and varies as a function of inlet water and air temperature, humidity, and fluid mass flow rate. Each of the presented limiting strategies has a different impact depending on which variable changes dominate the heat transfer process. Table 1 offers a ranking of management strategies when individual variables fluctuate, where 1 signifies the preferred option.

Table 1. Coil Management Strategy Summary

Fluctuating Variable(s))	Flow Limiting	Delta-T Limiting	Flow/Delta-T Limiting
Water inlet temp.	1	3	2
Air inlet temp.	1	3	2
Air inlet humidity	3	1	2
Air mass flow rate	3	1	2

It has been shown that flow limiting is the preferred strategy when only water or air temperature is changing. When humidity or air mass flow rate changes dominate the heat transfer, delta-T limiting is the preferred solution to control coil performance. When all of the inlet conditions are changing simultaneously as seen in Figures 4 and 5, flow/delta-T limiting suggests itself as the solution that most effectively maintains good coil performance and avoids saturation.

Nomenclature

E = energy transfer rate of the heat exchanger
$\dot{m}$ = mass flow rate though the heat exchanger
ΔT = fluid temperature difference across the heat exchanger
c_p = specific heat of the controlled fluid through the heat exchanger

References

Brandemuehl, M.J., Gabel, S., and I. Andersen. 1993. A toolkit for secondary HVAC system energy calculations (629-RP). ASHRAE

Fiorino, D.P. 1996. Twenty-five ways to raise your chilled-water temperature differential. AHSRAE Transaction. 102(1): 567-572.

Harrel, J.M. and J.A. Mathias. 2009. Improving efficiency in a campus chilled water system using exergy analysis. ASHRAE Transactions. 115(1): 507-522.

Henze, G.P., Henry, W., and M. Thuillard. 2013. Improving campus chilled water systems with intelligent control valves: A Field Study, pp. 103-112. Proceedings of the 2013 ASCE Architectural Engineering Conference, April 2-5, 2013, State College, PA.

Hyman, L.B. and D. Little. 2004. Overcoming low delta-T, negative delta-P, at large university campus. ASHRAE Journal. February. 28-34.

Ma, Z. and S. Wang. 2010. Enhancing the performance of large primary-secondary chilled water systems by using bypass check valve. Energy. doi:10.1016/j.energy.2010.10.042.

Reed, M.A., and C. Davis. 2007. Chilled water plant savings at no cost. Energy Engineering. 105(2): 59-76.

Taylor, S.T. 2002. Degrading chilled water plant delta-T: causes and mitigation. ASHRAE Transactions. 108(1): 641-653.

Taylor, S.T. 2006. Chilled water plant retrofit – a case study. ASHRAE Transactions. 112(2): 187-197.