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Air and Water Flowrate Optimisation for a Fan Coil Unit in Heat Pump Systems

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Air and Water Flow Rate Optimisation for a Fan Coil Unit in Heat Pump Applications

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ABSTRACT

The degradation in efficiency of auxiliary components in heating/cooling systems when operating at part load is frequently reported. Through the use of variable speed components, the supplied capacity can be reduced to match the required load and hence reduce unnecessary energy consumption. However, for fan coil units, difficulties can arise when optimizing fan and pump speeds at part load. Practically locating optimal water and air flow rates from readily available information and for varying supplied capacities is necessary, in order to reduce the fan coil power consumption. This research attempts to identify whether optimal fan and pump speeds exist for a fan coil unit and how they can be implemented, in a practical manner, in a system control applications. Using an empirical fan coil and pump model, the total power consumption (fan and pump) for different combinations of fan and pump speeds over a range of capacities was calculated. It was observed that, for a given capacity, an optimal combination of fan and pump speeds exists and there was a significant change in power consumption for different combinations of fan and pump speeds supplying the same capacity. A control strategy is described that utilizes a simple fan coil capacity estimation model, coupled with air and water flow rates, along with nominal design data. The pump speed is optimized using PID control to maintain the space temperature at the chosen set-point, which matches the supplied capacity to the required capacity. At set-time intervals, the capacity estimation model is utilized to optimize the water and air flow rates for the required capacity. The control strategy is evaluated, using a full building simulation model for a daily load profile and is compared to two baseline conditions: for no control of the fancoils/pump combination and for PID circulation control of the pump only. The optimal fan and pump speed control resulted in a 43% and 24% decrease in power consumption with compared to the no control baseline and the PID controlled circulation pump strategy, respectively.

1. INTRODUCTION

To date, relatively little work has been undertaken that focuses on optimization of heat pump systems from a building integration perspective. In heat pump systems, auxiliary components, such as circulation pumps and fan coil units, can consume a significant proportion of the total energy used. When operating at part-load, relative auxiliary power consumption can increase even further (Albieri 2008). For fan coil units, this can result in degradation in the water temperature difference across the fan coil, which results in unnecessary pump power consumption (Henze and Floss 2011). Auxiliary energy consumption at part-load can be reduced by matching the supplied and required zone capacities. This can be achieved by cycling the components on/off for nominal pump and fan settings using room temperature bandwidth as a control input or by actively controlling the fan or circulation pump speeds. For fan coil units in particular, Fahlén and Markusson (2011) suggest controlling either the supply water temperature or water flow rate to reduce the supplied load to the building at part-load. For multi-speed fan coil units, fan speed is sometimes controlled using room temperature bandwidth, where the fan speed is increased when the current setting is unable to maintain the room temperature at the specified set-point (Tianyi *et al.*, 2011). Sekhar (2005) studied, for an air handling unit, the tradeoff in terms of power consumption between increasing fan speed or supply air temperature. For practical control of variable speed components such as fans and pumps, PID control is often utilized. Teitel *et al.* (2008) compared the use of variable speed fan control with proportional error compensation to on/off fan control. Fahlén (2011) describes a heat pump system where the water flow rate, supplied to a multi-fan coil heating system, is controlled using PI control with the average zone temperature as an input. In a study by Zhang *et al.* (2011), the water flow rate through a fan coil is also controlled, using PID control to maintain supply air temperature at the set-point as part of a system control strategy. Strategies that use PID control combined with more complex control models for fan coil applications have also been researched (Wang and Xu, 2002) (Soyguder and Alli, 2009). Xu *et al.* (2006) used generalized predictive control to update the gain parameters of the PID controller, which maintained the supply air temperature by controlling the water flow rate. However, when matching the required load using both fan and pump speed control on fan coil units, it is unclear what the optimum combination of water/air flow rate for minimizing power consumption would be. Some methods of finding the optimal fan and pump speed for a required capacity have been reported, such as matching the capacities of the water and air (Fahlen *et al.*, 2006) (Fahlén *et al.*, 2007). Tianyi *et al.* (2011) used a fuzzy control strategy to vary the water flow rate, using valve control and fan speed for a multi-speed fan coil unit, however this method may not result in the optimum combination of fan and pump speeds for reduced power consumption. For larger multi-chiller systems, some studies report on the use of complex system control strategies to minimize power consumption using analytical neural network models and optimization models (Wang and Jin, 2000) (Soleimani-Mohseni *et al.*, 2006) (Kusiak and Li, 2010). These strategies require a large amount of installed sensors or accurate system models, which may not be practical for smaller systems. In order to optimize the water and air flow rate, it is necessary to create a practical control model of the fan coil. Some previously developed control models (Yu *et al.*, 2005) are complex, requiring a large amount of data which may not be available, however, models such as those described by Wang *et al.* (2004) and Markusson *et al.* (2011) can be constructed using information that can be obtained from data sheets. In this paper, a fan coil capacity estimation equation is utilized to develop a control strategy for optimizing the fan and pump speeds for different required capacities. This strategy is then compared to other standard fan coil control strategies using an empirical fan coil, pump and building simulation model.

2. SIMULATION MODEL

2.1 Simulation Model Development

A simulation model of a fan coil system was developed for evaluating the performance of different control strategies. The overall mathematical model was constructed using experimental data gathered from a test rig of a ground source heat pump system. The fan coil units utilize three speed fans and the deployed water circulation pumps are variable speed. As part of this system model, empirical models were developed for the circulation pumps and fan coil units and integrated with a building model. These models were programmed using MATLAB to create fan coil unit simulation model. Further details of the model are available in Corberan *et al.* (2011).

2.2 Simulation Model Analysis

Using the fan coil system model, the fan coil capacity was calculated for a range of water flow rates at the three fan speed settings for steady state conditions. In Figure 1, the total power consumption (fan and pump) is plotted against the supplied capacity of the fan coil for a range of air and water flow rates. Over the fan coil capacity range, use of different fan speeds for different ranges results in the lowest total power consumption for that range. For a required cooling capacity below 1250 W, fan speed 1 resulted in the lowest overall power consumption, between 1250 and 2000 W, fan speed 2 should be utilized and fan speed 3 is required for a capacity above 2000 W. The difference in power consumption between the three fan speeds for a given supplied capacity is significant and demonstrates the possible savings available through optimizing air and water flow rates. The point at which the optimal fan speed switches is dependent on the non-linear relationship between water/air flow rate and the capacity and power consumption of the pump and fan. For a multi-speed fan coil system, the fan power consumption is given in the manufacturer data sheets for each setting, it is also assumed that the relationship between pump power consumption and water flow rate can be calculated. Therefore to optimize the air and water flow rate, the variation in fan coil capacity with water flow rate for each fan speed is required. A capacity estimation model that can be developed using readily available information from data sheets is described in Section 3, which will ultimately be used as part of the proposed control strategies.

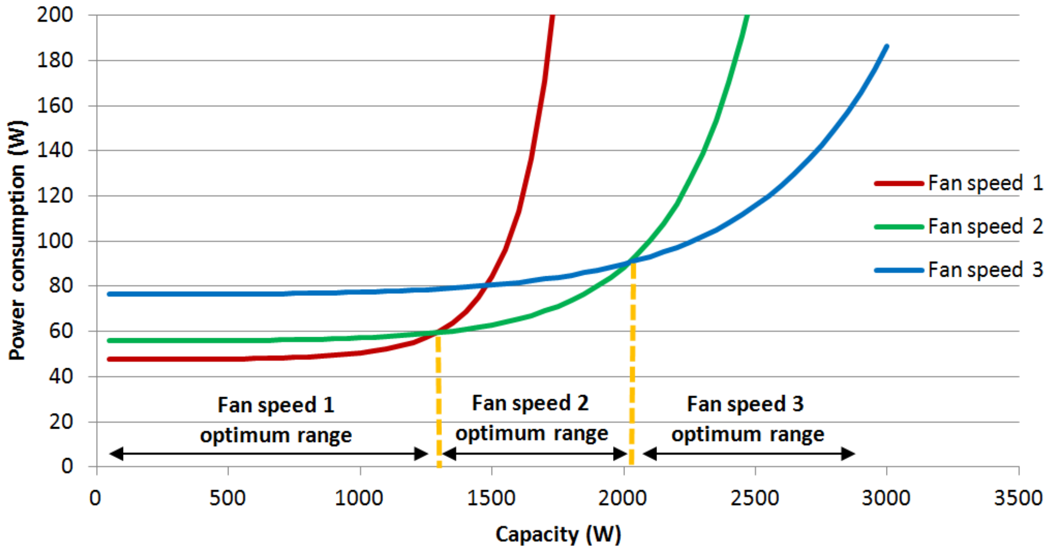

Figure 1: Fan and pump power consumption vs capacity (optimal fan speed for a given capacity).

3. CONTROL STRATEGY DEVELOPMENT

This section describes the the development of fan coil control strategy using the model described in Section 2.

3.1 Control Model

The capacity estimation model of the fan coil unit was created based on an approach previously described by Markusson *et al.* (2011) which predicts the capacity ratio of a fan coil unit for a change in the water flow rate. The capacity estimation model used for the control model is shown below:

$$y = \frac{F(x) * 2 * \left(\frac{t_{w\,in}}{\theta_d} - \frac{t_{a\,in}}{\theta_d}\right) * x}{x * 2 + F(x) * \left(x * \frac{\Delta t_{a,d}}{\theta_d} + \frac{\Delta t_{w,d}}{\theta_d}\right)} \quad (1)$$

where

$$F(x) = x^m * \frac{1 + \frac{\alpha_{w,d} * A_{w,d}}{\alpha_{a,d} * A_{a,d}}}{1 + \frac{\alpha_{w,d} * A_{w,d}}{\alpha_{a,d} * A_{a,d}} * x^m} \quad (2)$$

$$y = \frac{Q}{Q_d} \quad (3)$$

$$x = \frac{\dot{m}_w}{\dot{m}_{w,d}} \quad (4)$$

The required design data values can be obtained or calculated from a manufacturer's data sheet using one defined design condition. Therefore at a given water flow rate ($\dot{m}_w$), the fan coil capacity (Q) can be estimated using Equations 1 to 4. However, this model is only suitable for a given fan speed. Therefore a separate capacity estimation model was developed for each of the three fan speeds, using the design data at each of the fan speeds specified in the data sheet. The predicted capacity for varying water flow rates at each of the three fans speeds is compared in Figure 2 to the capacity as calculated by the MATLAB simulation model. As can be seen, the predicted and simulated capacities are similar for all fan speeds at varying water flow rate. The water flow rate shown is that through a single fan coil. The maximum absolute error between the capacity values given by the simulation model and the simplified control model for the range of water flow rates and fan speeds is 132 W. This error is only present at the maximum and minimum extremes of water flow rate.

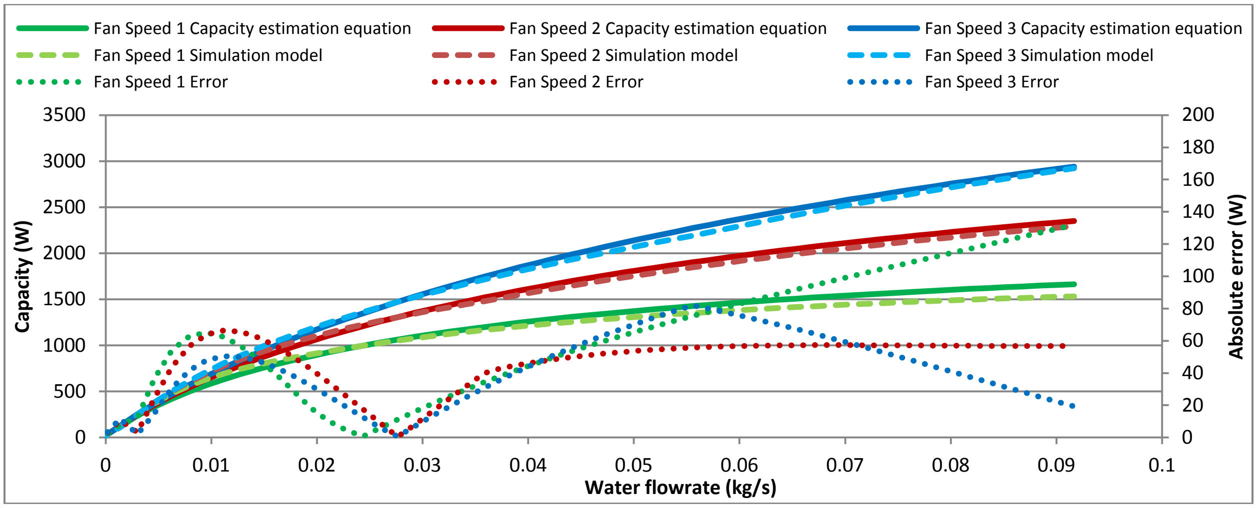

Figure 2: Water flow rate vs fan coil capacity and absolute error (control and simulation model).

3.2 Control Strategies

The control strategy developed aims to reduce the overall energy consumption of the fans and circulation pump for a multi-zone system with multiple fan coils by controlling the fan and pump speeds. The strategy operates as follows; firstly the supplied capacity to the building is reduced to match the requirement of the maximum capacity zone, which is done by controlling the circulation pump speed. The pump speed is controlled using PID control to maintain the room temperature of the zone with the maximum load requirement at the set-point temperature. At a specified time interval, the water and air flow rates are optimised to minimise the power consumption for the prevailing supplied capacity. The operation of this strategy and other tested strategies are described in detail in the following sections.

3.2.1 Standard Control

The pump speed is not controlled and remains at the nominal frequency of 50 Hz, the fan coils are also not controlled. A room temperature bandwidth is utilised to maintain the room air temperature around the set-point. For cooling, when the room air temperature is cooled to the lower bandwidth, a two-way valve diverts the circulation water away from the fan coil. When the room air temperature reaches the upper bandwidth, the water flow is reverted through the fan coil. The fan and pump remain in operation regardless as to whether the fan coil water supply is diverted or not. In the current paper, this control acts as a baseline reference case.

3.2.2 PID Control of Circulation Pump

The circulation pump speed is controlled to maintain the room temperature of the zone with the maximum required capacity at the room temperature set-point using PID control. At the beginning of a heating/cooling daily cycle, one room is arbitrarily chosen as the maximum capacity zone. All other zones operate by cycling the water supply to the fan coils, as described for the standard control case. For cooling, a third bandwidth above the upper room temperature bandwidth is also specified (PID bandwidth). If the load of a zone surpasses that of the current maximum capacity zone, the room temperature of that zone will continue to increase beyond the upper set-point temperature. When the room temperature rises above the PID bandwidth, the room temperature error for that zone will become the input signal for the pump PID controller. Limits are put on the pump speed to insure it does not exceed set values, in this case a lower limit of 20 Hz and an upper limit of 70 Hz. The fan speed of each fan coil is not controlled.

3.2.3 PID Control of Circulation Pump and Fan Speed Optimisation

For this control strategy, the pump speed is controlled using PID control as described above. However the capacity estimation model is utilised at a specified time interval to optimise the fan and pump speed. When optimisation is initiated, the fan coil capacity of the zone with the maximum load is calculated using the capacity estimation equation for the given water flow rate and fan speed. At this capacity, the optimiser calculates the required water flow rate at the three fan speeds using the capacity model for each speed. The power consumption of the three different options are calculated and the fan speed that results in the lowest power consumption is set for the maximum capacity zone. The water flow rate will then adjust to the desired level automatically using the PID control.

In particular cases, the fan coil may not be capable of matching the required load for a low fan speed. At a reduced fan speed setting as zone capacity increases, the pump speed may increase to its maximum level, if this happens, the capacity will not be met and the calculated capacity will be incorrect during the optimisation phase. Therefore when the pump speed reaches its maximum level, the fan speed of the maximum capacity zone is increased automatically. To avoid the optimisation running before the water flow rate and room temperature has settled to the set-point, the counter for the optimiser is reset each time the maximum capacity zone is changed. Due to the inertia of the room fan coil unit, the time period between each optimisation update should be large enough to allow the room temperature to reach the set-point temperature.

4. RESULTS

4.1 Simulation description

The control strategies mentioned above were tested using the fan coil system simulation model. The simulations were run for a daily cooling cycle with an average external temperature of 28°C and a maximum and minimum of 32°C and 24°C, respectively. The room set-point temperature is set to 25°C with a bandwidth of ±1°C. The supply water temperature is constant at 7°C. For the standard control strategy and the pump control strategy, the fan speed in all zones is set to the highest value for the duration of the simulation. This was done to insure the required capacity of the zones would always be satisfied. For the water/air flow rate control strategy, the time between each optimisation was set to 20 minutes. The building load profile is shown in Figure 3. This profile was chosen to represent high and low capacity zones with realistic load steps and a change in zone with the maximum load. The building load chosen is based on experimental load data from the installed test demonstration site, on July 13 2010, and represents an average part load ratio of 0.6.

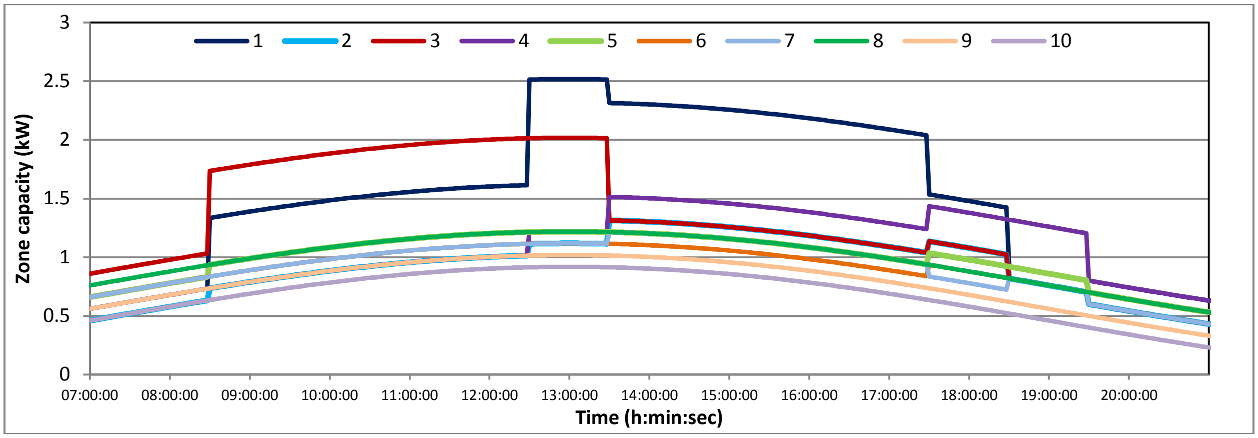

Figure 3: Zone load profile between 7 am – 9 pm.

4.2 Simulation Results

The results shown are for the daily simulation between the hours of 7 am – 9 pm. Figure 4 shows the total power requirement of the fan coils for the tested control strategies. For the beginning of the simulation, zone 3 has the largest load requirement, which is surpassed by zone 1 after 12:30 pm. For the standard control strategy, a constant power requirement is observed as fan and pump speeds are unchanged. For the pump control strategy, the pump is adjusted to match the maximum load, therefore the pump speed can be seen to increase as the part load does. The water/air flow rate optimisation strategy results in a reduced power requirement, particularly for low part load ratios which are present at the beginning of the simulation. However as the load increases, the pump speed can increase significantly if the fan speed is at a low setting, this results in an increase in total power requirement for a short period of time before the water/air flow rate optimisation control is activated. The saving potential is highly dependent on the part load ratio of the building and individual zones.

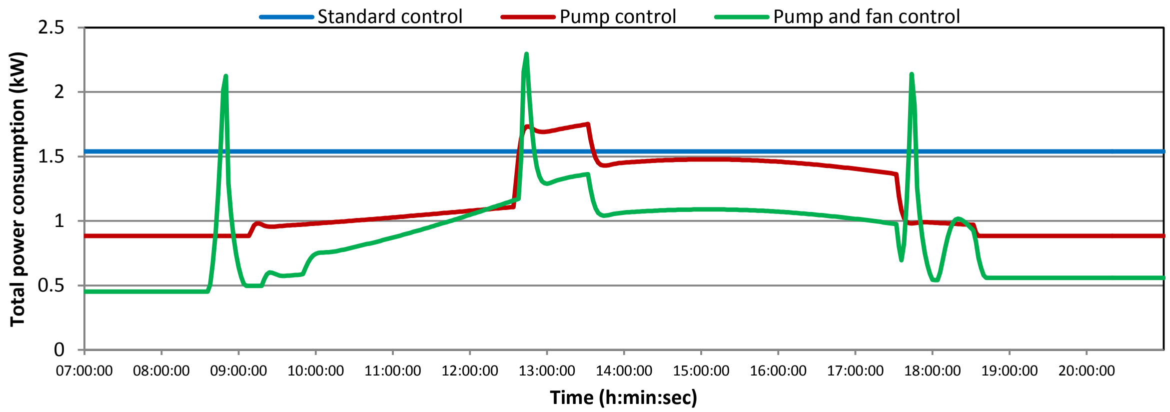

Figure 4: Total power consumption from 7.00 am – 9.00 pm for the three tested control strategies.

Figures 5 shows the total power consumption and zone capacity for the three tested control strategies and the room temperature and air and pump state for the fan/pump speed optimization strategy from 8:00 am to 10:00 am. It should be noted that a time lag is observed to exist between any change in the zone load and the associated zone temperature. Before 8:30 am, the pump control strategy has a lower power consumption than the no control scenario, due to the reduced pump speed. Fan/pump optimization control has a lower power consumption, again due to the reduced fan speed. At 8:30 am, the load of zones 1 and 3 increase with zone 3 having the largest required capacity. The room temperature of zone 3 can be seen to increase beyond the PID bandwidth and pump control is set to that zone. For the pump/fan optimization control, the pump speed is increased to reduce the room temperature, however, at the low fan speed setting the fan coil is unable to match the required capacity and the pump speed increases to the maximum level at 8:48 am. When this occurs, the fan speed is automatically increased to speed 3 to insure capacity is matched which results in the room temperature for that zone decreasing to the lower bandwidth temperature. All zones begin to cycle within the upper and lower bandwidth, therefore the pump speed is not controlled by any zone temperature and reduces to the minimum value of 20 Hz. At 9:15 am, zone 3 exceeds the PID bandwidth and control reverts to that zone, resulting in an increase in pump speed as before. The room temperature stabilizes at the set-point and at 9:48 am the fan/pump speed optimizer is utilized. As a result of the optimizer the fan speed is reduced from 3 to 2 to reduce the overall power consumption and the room temperature is again stabilized by increasing the pump speed.

Figure 6 shows the total energy consumption of the circulation pump and fan coils for the three tested control strategy. For the standard control strategy, the fan and pump are not under control and hence are in constant operation. Although individually, the fan coil units consume a small proportion of the total energy consumption of a system, the combined energy consumption of the ten fan coils are larger than that of the circulation pump. For the pump control strategy, the energy consumed by the fans is not reduced as the fan speeds are not controlled. However the pump energy consumption is significantly reduced due to the reduced pump speeds when operating at part load. At a part load of 1, the circulation pump would be operating at the nominal frequency and no energy saving arise. For the water/air speed optimisation strategy, the pump energy consumption is increased however the fan energy consumption is reduced when compared to pump speed control alone. This results in an overall reduction in energy consumption due to the optimised fan/pump speed delivering the same required capacity. A 43% and 24% decrease in power consumption is observed when comparing air/water flow rate control strategy to a no control baseline and a PID controlled circulation pump strategy, respectively.

The control strategies were tested on different sample days to assess performance for varying load profiles. The simulated load profiles and the experimental profiles they are based on are shown in figure 7. The two sample days chosen represent lower load profiles than that described above. As can be seen from figure 8 the total energy consumption using the standard control is constant regardless of the load profile, however pump control and fan/pump control result in reduced energy consumption for a reduced load profile. The pump energy consumption in both cases is reduced substantially; however, the fan coil energy consumption is still relatively large due to the significant fan power consumption even when operating at the lowest speed, which is the case for fan/pump control.

5. CONCLUSIONS

For a given required fan coil capacity there exists a combination of fan and pump speed that result a minimum power consumption. The potential energy savings by operating at the optimal water and air flow rates can be significant. However, to practically calculate the optimal water/air flow rate, both the capacity and power consumption need to be calculated from available data and simple system measurements. A control strategy has been developed that reduces the supplied capacity to that of the maximum zone capacity using variable speed pump control. At given intervals, the optimal combination of fan and pump speed for reduced power consumption at a given capacity is calculated and the fan speed is updated. This control strategy resulted in a 43% and 24% decrease in power consumption with compared to a no control baseline and a PID controlled circulation pump strategy, respectively. For a reduction in part load the total energy consumption using pump control and pump/fan control can be reduced significantly. As the part load decreases the power consumed by the fans constitutes a high proportion of the total energy used which results in a greater savings potential by controlling fan speed.

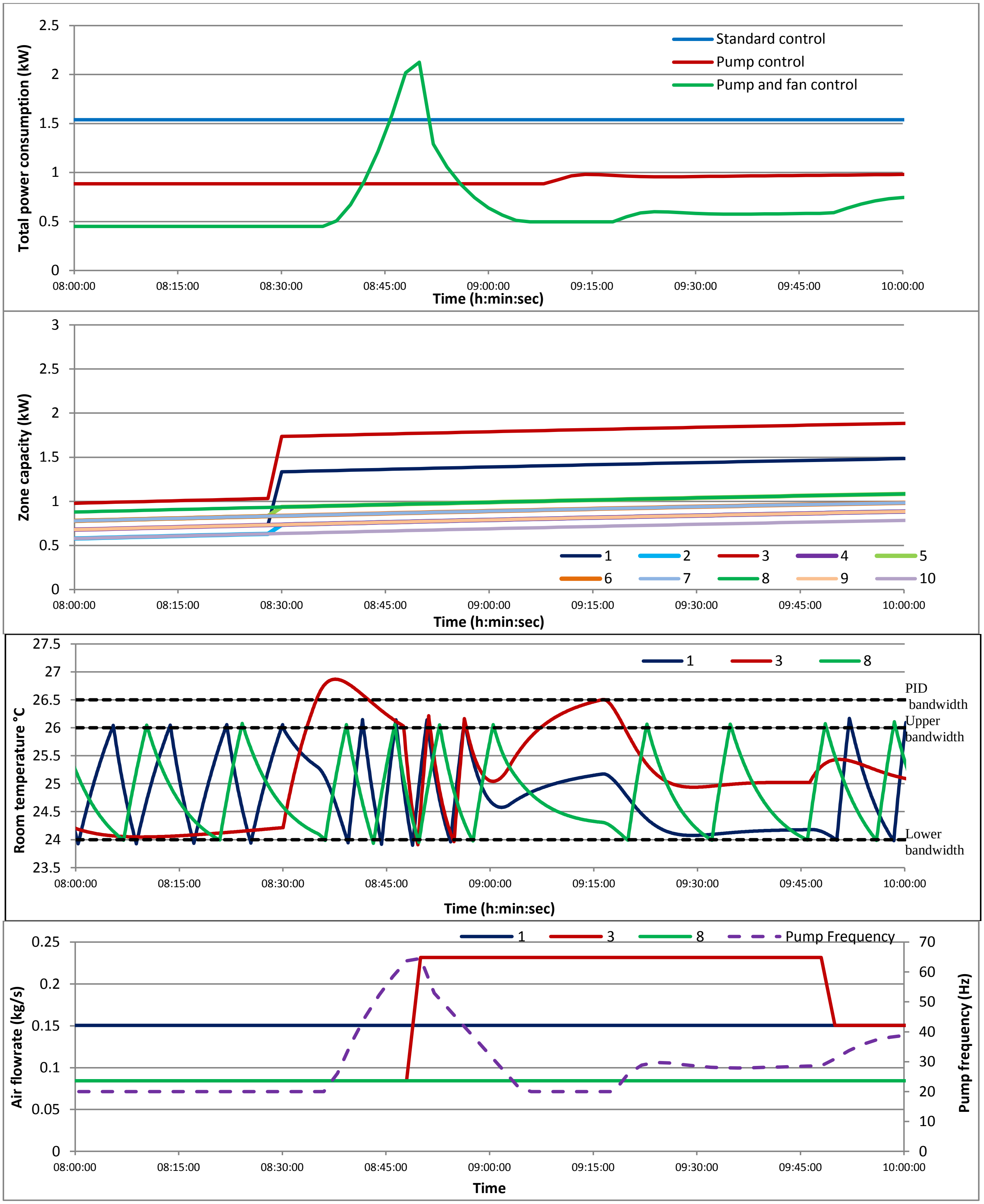

Figure 5: Total power consumption, zone capacity, room temperature, air and pump state from 8:00 pm – 10:00 pm for the three tested control strategies.

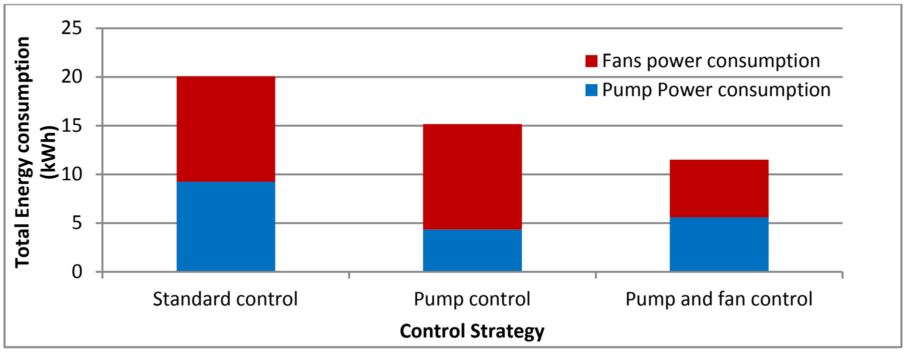

Figure 6: Fan and pump power consumption 7 am – 9 pm for the three control strategies.

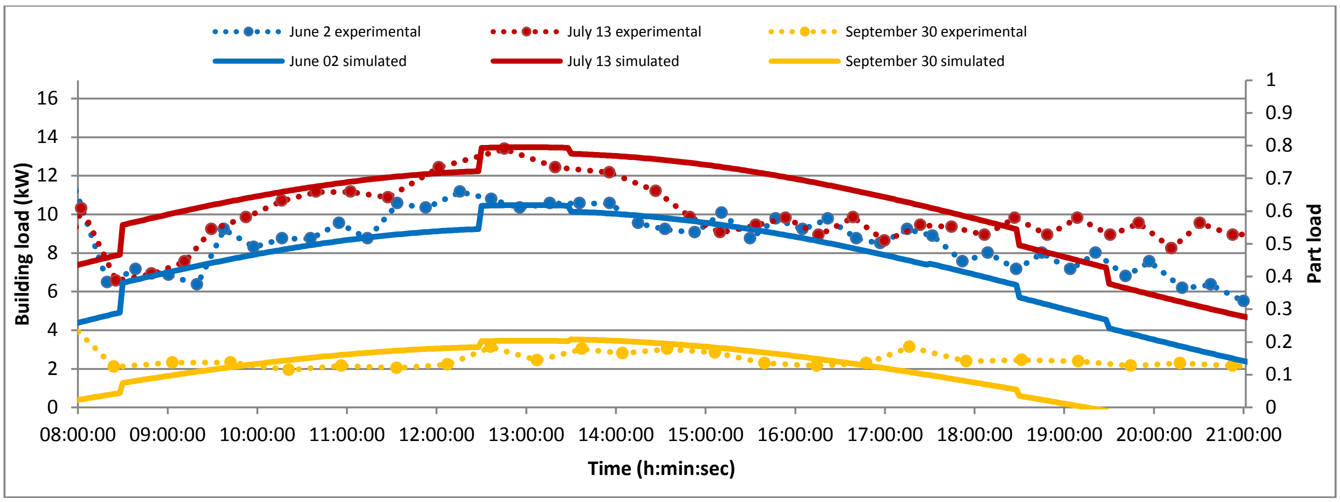

Figure 7: Experimental and simulated building load between 8am – 9 pm for the three tested days.

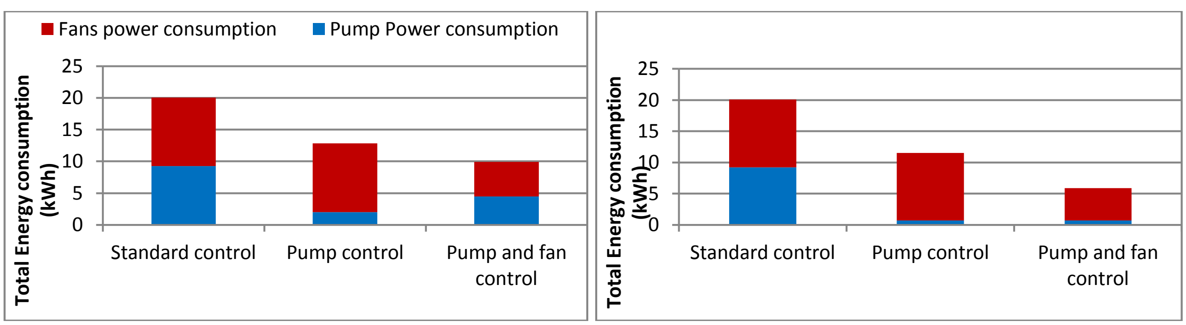

Figure 8: Fan and pump power consumption 8 am – 9 pm for June 02 and September 30, respectively.

NOMENCLATURE

A	Cross-sectional area	(m^2)
Q	Capacity	(W)
$\dot{m}$	Mass flow rate	($kg\cdot s^{-1}$)
n	Flow related heat transfer exponent	(-)
t	Temperature	(K)
θ	HE mean temperature	(K)
Δt	Inlet outlet temp difference	(K)
∝	Convection heat transfer coefficient	($W\cdot m^{-2}\cdot K^{-1}$)

Subscripts

a	air	d	design
in	inlet	w	water

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