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ABSTRACT

The type of heating, ventilation and air conditioning (HVAC) system has a large impact on the heating and cooling energy consumption in multifamily residential buildings. This paper compares the energy performance of three HVAC systems: a direct expansion (DX) split system, a split air source heat pump (ASHP) system, and a closed-loop water source heat pump (WSHP) system with a boiler and an evaporative fluid cooler as the central heating and cooling source. All three systems use gas furnace for heating or heating backup. The comparison is made in a number of scenarios including different climate conditions, system operation schemes and applicable building codes. It is found that with the minimum code-compliant equipment efficiency, ASHP performs the best among all scenarios except in extremely code climates. WSHP tends to perform better than the split DX system in cold climates but worse in hot climates.

1. INTRODUCTION

According to the Residential Energy Consumption Survey (EIA 2005), about 22% of the US households live in apartments. These apartment units account for about 15% of total energy consumption by residential buildings. Of all energy end-use categories, heating and cooling contribute more than 50% of the energy consumption in multifamily residential buildings (i.e., apartment buildings). Because the HVAC system has a large impact on the heating and cooling energy consumption, it is important to understand the energy performance of different HVAC systems for apartment buildings. In literature, most system performance studies focus on commercial buildings. There is only very limited work on HVAC system performance specifically for multifamily residential buildings (Chua and Chou 2010). This paper intends to add some knowledge to the above area by comparing three types of HVAC systems that are usually found and regarded as applicable to apartment buildings. The remainder of this paper is organized as follows. Section 2 describes the building model used to facilitate the system performance comparison with energy simulation programs. The simulation scenarios are discussed in Section 3, following which the simulation results are presented and analyzed in Section 4. This paper ends with some conclusions and recommendations for future work.

2. BUILDING DESCRIPTION

A hypothetical apartment building is employed in this study to investigate the energy performance of different heating and air conditioning systems. This building prototype mainly comes from the mid-rise apartment building benchmark model developed by the U.S. Department of Energy (DOE 2010a). It has four floors and a total floor area of 3130 m^2. Each floor has eight equally sized apartment units (about 88 m^2). The building has an aspect ratio of 2.74 and an overall window wall ratio of 15% (Figure 1). The SE unit on the first floor is assigned as the combined space for office and lobby.

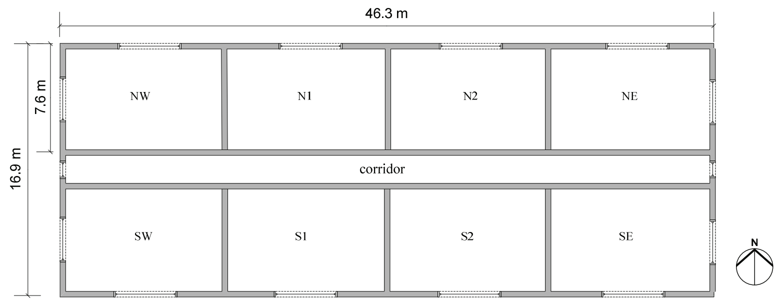

Figure 1: Floor layout of the apartment building

The building has the following opaque envelope constructions: steel-framed exterior walls, a flat roof with insulation entirely above metal deck, and a slab-on-grade concrete floor with carpets. All exterior opaque assembly constructions are configured according to Appendix A in ASHRAE Standard 90.1 (ASHRAE 2004a). For example, the steel-framed wall consists of the following layers in sequence from outside to inside: 19-mm stucco cladding, 16-mm gypsum board sheathing, steel framing with fiberglass insulation in stud cavities, rigid insulation, and 16-mm gypsum board finishing. The thickness of the rigid insulation layer depends on the required thermal transmittance (U-value). Drywalls are used for interior partitions. The window construction is selected from a database (NREL 2009) according to the required U-value and SHGC value. Because the database has a limited number of window entries, the selected window construction may not have exactly the same performance as the required U and SHGC values. However, the difference is less than 7%.

For internal loads, there are many studies in literature reporting the energy use density and profile for lighting, appliances and miscellaneous equipment for residential buildings (Chiou 2009; Hendron 2008). This paper follows the work done for Building America benchmark research (Hendron 2008) to set up the internal loads for this apartment building. Although the Building America benchmark model was developed particularly for single-family houses, the internal load use patterns should be reasonably similar between single-family houses and multi-unit apartment buildings. Assuming that each apartment unit has two bedrooms, the internal loads for each unit have the following characteristics (DOE 2010b; Hendron 2008):

- Occupant: 2.5 people per unit, 113 W/people for the heat gain, sensible fraction at 57%.
- Peak lighting density (hard-wired lighting only): 3.88 W/m^2
- Peak plug load density (including plug-in lighting): 6.71 W/m^2
- The typical schedules for occupancy, lighting and plug equipment are illustrated in Figure 2. These schedules apply throughout the whole year without further division between weekdays and weekends. This simplification will not affect the findings from this study.

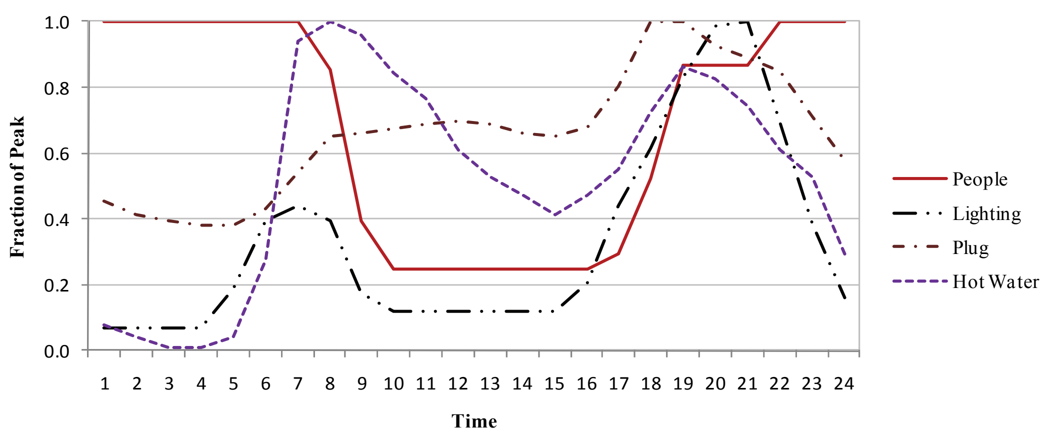

Figure 2: Profiles for the internal loads and hot water consumption

An electric water heater is used in each apartment unit. The water tank has a volume of about 110 L and a skin loss coefficient of about 1.64 W/K. Each unit consumes 208 L hot water per day supplied at 49 °C. The hot water consumption profile is presented in Figure 2. More details on domestic hot water (DHW) consumption can be found in the Building America benchmark model (DOE 2010b; Hendron 2008).

The three alternative HVAC systems considered in this work include a split DX system, a split air-source heat pump system (ASHP), and a closed-loop water source heat pump system (WSHP). Split DX system with gas or electric for heating is the most common system type for apartment buildings (EIA 2005). Each apartment unit has a split DX system. The building energy consumption for the split DX system serves as the baseline to compare with the other two systems. Split air-source heat pump system with a gas or electricity furnace as heating backup is also commonly used in apartment buildings, especially in temperate climates. In heating mode, the heat pump absorbs heat from outside air and transfers the heat to the space. In the cooling mode, the heat pump absorbs heat from the space and rejects the heat to the outside air. In contrast to the split air source heat pump system, the water source heat pumps in all apartment units are linked together by a closed water piping loop. Each individual water source heat pump may draw energy from the circulating water loop to provide space heating or reject energy into the water loop to provide space cooling. When the total load on the water loop system cannot maintain the loop outlet temperature within a predefined setpoint deadband (18 °C for heating and 30 °C for cooling), a gas-fired condensing hot water boiler and an evaporative fluid cooler are used, respectively, as the heating and the cooling source for the water loop. The boiler has a thermal efficiency of 90%.

It is technically feasible to use either gas or electric furnace for heating or backup heating in the three HVAC systems considered. The choice is normally location dependent according to the utility infrastructure and tariffs. In this study, however, only gas furnace is considered to reduce the impact of fuel changes on results of the analysis.

3. SIMULATION SCENARIOS

System performance usually varies with climate conditions. Hence, it is desirable to compare the performance of the three considered HVAC systems in different climate conditions. ASHRAE Standard 90.1 (ASHRAE 2004a) provides a classification of climate zones according to the heating and cooling degree days and the atmospheric moisture. This classification covers eight major climate zones from 1 to 8 with increasing heating degree days and decreasing cooling degree days. A major climate zone may be further divided into humid, dry, and marine climate types which are labeled as A, B and C, respectively. For example, climate zone 3 is characterized as warm climate and it has three subcategories: 3A for humid climate; 3B for dry climate and 3C for marine climate. The above classification leads to a total of 17 climate zones. Following the study by Briggs et al. (2003), we select a city to represent each climate zone. Because no cities in the U.S. are representative of the climate zones 1B and 5C, two cities outside of the U.S. are selected to provide a complete picture of the system performance in all climate zones. An overview of the 17 climate zones and their representative cities is listed below:

- 1A (very hot, humid): Miami, FL
- 1B (very hot, dry): Riyadh, Saudi Arabia
- 2A (hot, humid): Houston, TX
- 2B (hot, dry): Phoenix, AZ
- 3A (warm, humid): Memphis, TN
- 3B (warm, dry): El Paso, TX
- 3C (warm, marine): San Francisco, CA
- 4A (mixed, humid): Baltimore, MD
- 4B (mixed, dry): Albuquerque, NM
- 4C (mixed, marine): Seattle, WA
- 5A (cool, humid): Chicago, IL
- 5B (cool, dry): Boise, ID
- 5C (cool, marine): Vancouver, Canada
- 6A (cold, humid): Burlington, VT
- 6B (cold, dry): Helena, MT
- 7 (very cold): Duluth, MN
- 8 (subarctic): Fairbanks, AK

How the HVAC system operates would have a significant impact on energy consumption of the apartment building. There are a number of surveys (e.g., Chua and Chou 2010) on the system usage pattern in typical residential households. They found that most people turn on their air conditioning system at night. The average running times were found to be around 5 hours during daytime and 7 hours at night. To investigate how the system performance varies with different usage patterns, this study explores the following three operation schemes:

- System operation scheme 1: Continuous running fan without thermostat setback and setup. The supply fan for each system always runs no matter whether the space has heating or cooling load. The outdoor air ventilation complies with the fan operation. This means that outdoor air is supplied continuously. According to ASHRAE Standard 62 (ASHRAE 2004b), the ventilation rate is set at 0.026 m^3/s for each apartment. In this operation scheme, all apartment units except for the SE unit used as the facility office maintain the same thermostat setpoints: 21.7 °C for heating and 24.4 °C for cooling.

- System operation scheme 2: Cycling fan without thermostat setback and setup. The supply air fan cycles on and off together the heating or cooling coil to meet the space load. Thus, outdoor air ventilation is available only when the space has heating or cooling load. The thermostat setpoints are the same as those in the first operation scheme.

- System operation scheme 3: Cycling fan with thermostat setback and setup. In comparison with the second operation scheme, this scenario has thermostat setback and setup. Between 7:00 and 18:00, the thermostat setpoint is reset to 18.3 °C for heating and 26.7 °C for cooling.

In addition to the climate conditions and the system usage patterns, the code compliance situation also has an important impact on the HVAC system performance. This study follows the ASHRAE Standard 90.1 to set up two code compliance scenarios: one for Standard 90.1-2004 and the other for the potential Standard 90.1-2010. Because Standard 90.1-2010 is still under development, applicable addenda are considered. For example, Addendum bb to Standard 90.1-2007 is referred in this work to set the building envelope requirements, although that addendum is still in public review. These two versions of Standard 90.1 are selected in this work for two reasons: 1) 90.1-2004 has been adopted by many states in the US and it was used as the baseline in many high performance building design studies; and 2) 90.1-2010 is expected to have much more stringent requirements in order to achieve the goal of 30% energy cost savings than its previous version. For this apartment building, the major differences with the two code compliance scenarios lie in building envelope requirements and equipment efficiency. Table 1 lists the required minimum performance of the DX air conditioners and heat pumps. Different performance metrics such as SEER and HSPF are converted to the simulation inputs using the approach by Wassmer and Brandemuehl (2006).

Table 1: Minimum efficiency for air conditioners and heat pumps in Standard 90.1

Standard 90.1	Mode	Split DX	Split ASHP	WSHP
2004	Cooling	10.0 SEER	10.0 SEER	11.2 EER
	Heating	NA	6.8 HSPF	4.2 COP
2010	Cooling	13.0 SEER	13.0 SEER	11.2 EER
	Heating	NA	7.7 HSPF	4.2 COP

Overall, each climate zone has the following six scenarios used to compare system performance:

- 2004ConNoreset: Standard 90.1-2004 + system operation scheme 1
- 2004CycNoreset: Standard 90.1-2004 + system operation scheme 2
- 2004CycReset: Standard 90.1-2004 + system operation scheme 3
- 2010ConNoreset: Standard 90.1-2010 + system operation scheme 1
- 2010CycNoreset: Standard 90.1-2010 + system operation scheme 2
- 2010CycReset: Standard 90.1-2010 + system operation scheme 3

4. SIMULATION RESULTS AND ANALYSIS

The energy consumption of this apartment building was estimated with the simulation program EnergyPlus for all scenarios. Figure 3 shows the site energy end use split with the three HVAC systems under the 2004ConNoreset scenario. Not all climate zones are presented in that figure for the sake of clarity. It can be seen from Figure 3 that the total annual site energy use intensity (EUI) ranges from 400 to 870 MJ/m^2 for the split DX system. Heating, DHW, and plug loads are the three major energy end uses for the climate zone s from 4 to 8, whereas cooling, plug and DHW are the three major energy end uses for the climate zones 1 and 2. Because fan is continuously running, fan energy is also a noticeable part of the total EUI for all climate zones. In this case, for a given climate zone, the difference of building energy consumption with the three HVAC systems comes only from heating and cooling.

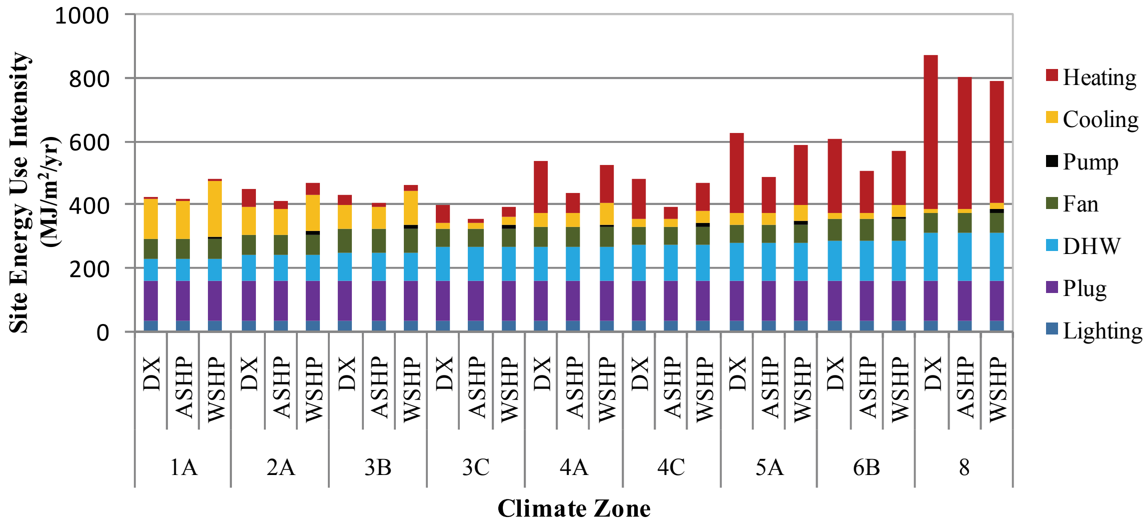

Figure 3: Site energy end use splits for selected climate zones

With the split DX system as the baseline, Figures 4 and 5, respectively, show the percentage of total site energy use difference for the ASHP and WSHP system under the three considered operation schemes in compliance with Standard 90.1-2004. These two figures lead to the following observations:

- ASHP performs better than the split DX system for all cases except when the supply fan cycles together with the heating or cooling coil load in extremely cold climate conditions. ASHP generally achieves about 5%-20% site energy savings than the baseline for climate zones from 3 to 7. The percentage of energy savings is usually much higher when the fan runs continuously than the case when the fan cycles. This is because longer system running time means more energy difference between the two systems. The same reason can be used to explain why ASHP has a slightly higher percentage of energy saving than the split DX system in the case of no thermostat setback and setup. Thermostat setup and setback reduces the system running time and thereby reduces the energy consumption gap between the two systems.

- The performance of WSHP relative to the split DX system varies with climate zones. In general, WSHP performs better in heating dominated climate zones (5-8). The percentage of energy savings can reach about 10% for the case of continuously running fan. In contrast, WSHP performs worse in cooling dominated zones (1-3) and there is as high as about 15% energy increase over the split DX system.

- Using the equipment that just meets the minimum code requirement of Standard 90.1-2004, WSHP usually performs worse than ASHP for apartment buildings. Combining Figures 4 and 5 shows that WSHP may perform better than ASHP only in very cold locations including the climate zones 7 and 8.

The above observation of WSHP performance in different climate conditions is similar to the findings by Lian et al. (2005), where they found that a closed–loop WSHP system performs better than a conventional air conditioning system in cold climates but worse in hot climates. The underlying reason can be further analyzed as follows:

- The particular advantage of heat recovery accompanied with WSHP cannot be fully realized in apartment buildings. Because the space thermal loads of residential buildings heavily depend on the weather, it is usually the case that all apartment units require heating or cooling simultaneously.

- In many actual operating conditions, WSHP usually has a lower cooling efficiency and a higher heating efficiency than ASHP and the split DX system. This can be illustrated with two extreme climate zones: 1A for

Miami and 8 for Fairbanks. Figures 6 and 7 show the profile for the outdoor air temperature (T_{oa}) and the source water supply temperature (T_w) for the WSHP in those two climate zones, respectively. T_{oa} is also the entering air condenser temperature for the ASHP and the DX system. It can be seen that in Miami, T_w takes the same value as the standard rating condition at 30 °C for WSHP in most operating hours while T_{oa} is lower than the standard rating condition at 35 °C for both ASHP and DX coil. In Fairbanks, however, T_w is higher than the standard rating condition at 20 °C for WSHP in most operating hours while T_{oa} fluctuates around the standard rating condition at 8.3 °C for ASHP. The above deviations imply that the WSHP has a lower cooling COP and a higher heating COP than the standard rating performance. For example, for the system serving the SE apartment unit in the middle floor, detailed simulation outputs show that in Miami, the annual average cooling COP is only 2.42 for WSHP while it is 3.58 for ASHP. In Fairbanks, the annual average heating COP is 3.72 for WSHP while it is 2.24 for ASHP.

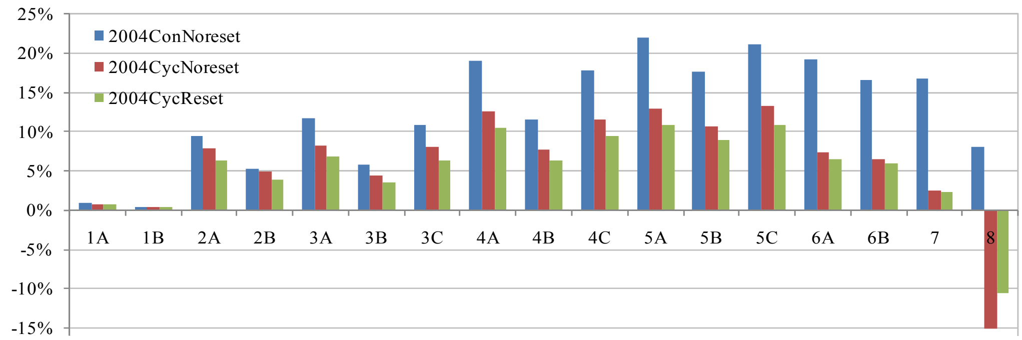

Figure 4: Site energy saving percentage for ASHP against the split DX system (90.1-2004 compliant)

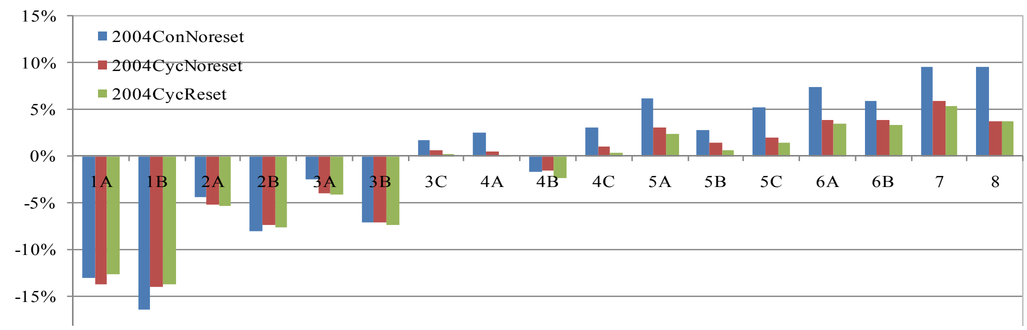

Figure 5: Site energy saving percentage for WSHP against the split DX system (90.1-2004 compliant)

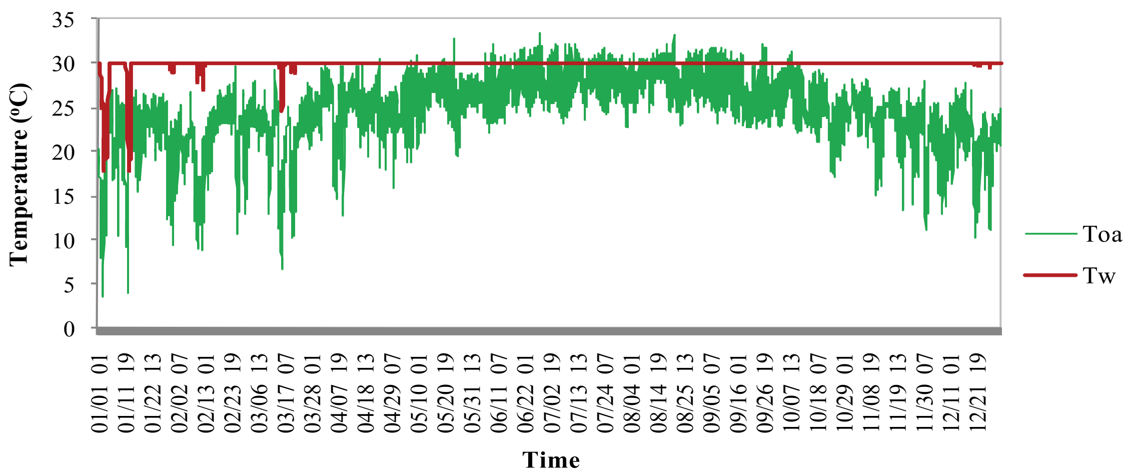

Figure 6: Temperature profile for outdoor air and supply water for WSHP in Miami

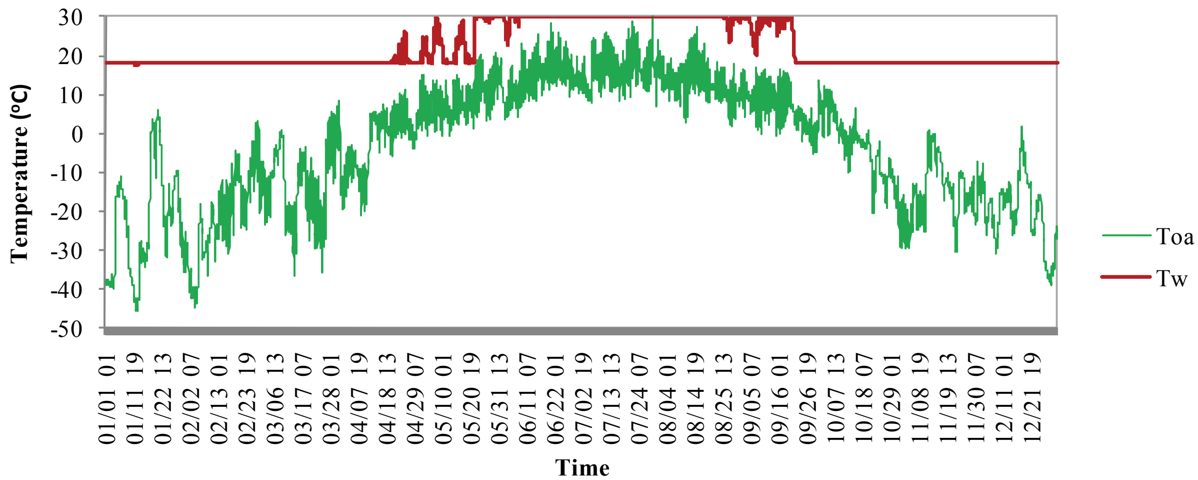

Figure 7: Temperature profile for outdoor air and supply water for WSHP in Fairbanks

For the case of code compliance with Standard 90.1-2010, Figures 8 and 9 show the percentage of energy savings for ASHP and WSHP in comparison with the split DX system. The general trends are similar to the previous case on code compliance with 90.1-2004. However, the magnitudes of relative performance differ in the following aspects:

- ASHP has a lower percentage of energy savings for 90.1-2010 than it did for 90.1-2004. The maximum percentage of saving decreases from 22% to about 19% if the supply fan runs continuously while it decreases from 13% to 8% if the fan cycles. The reduction is caused by the stringent building envelope requirement in 90.1-2010. High performance building envelope may weaken the saving potential from an energy efficient HVAC system.

- WSHP rarely performs better when the supply fan cycles. In comparison with the results for 90.1-2004 (Figure 5), WSHP no longer has energy savings in the climate zones 3C, 4A, and 5B for the first system operation scheme. The percentage of increased energy consumption becomes higher in hot climates. The major reason is that the cooling efficiency does not change between Standard 90.1-2004 and 90.1-2010 for WSHP while it increases for both ASHP and the split DX system.

It must be stressed that the above findings and analysis are made at the following conditions: the equipment efficiency just meets the minimum code requirement; the water loop temperature control is not optimized; the WSHP is not coupled with ground, water wells, and surface water sources such as rivers and lakes. There are many water source heat pumps currently available that have much higher efficiency than the minimum standard requirement. The performance comparison results may no longer be valid if a higher efficiency WSHP is used with optimal control or coupled with ground water sources.

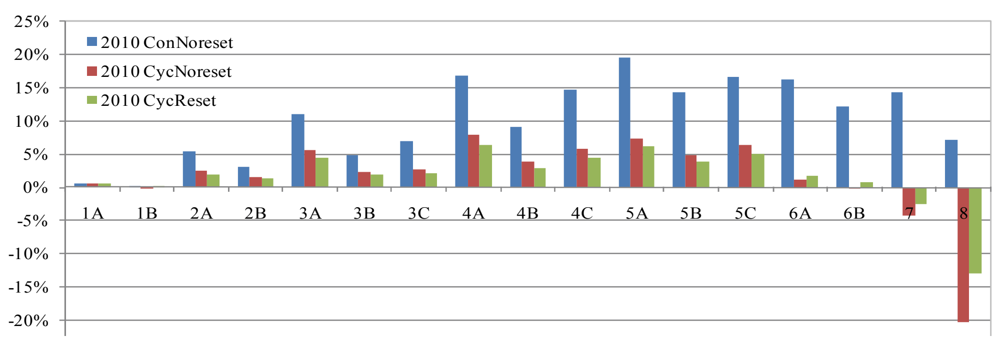

Figure 8: Site energy saving percentage for ASHP against the split DX system (90.1-2010 compliant)

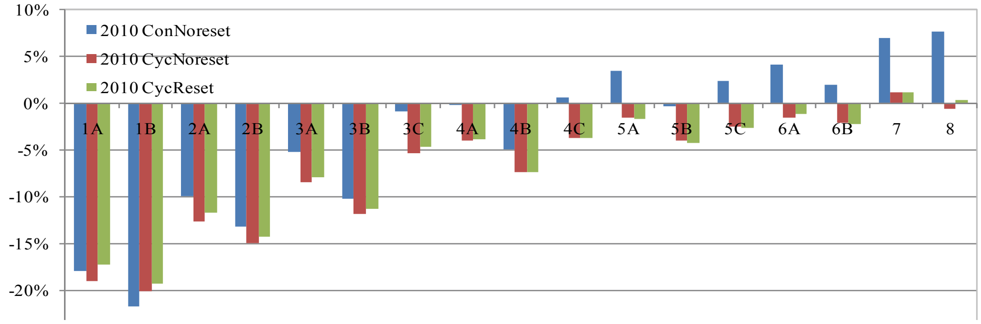

Figure 9: Site energy saving percentage for WSHP against the split DX system (90.1-2010 compliant)

5. CONCLUSIONS

Detailed energy simulation is used to investigate the performance of three HVAC systems for typical mid-rise apartment buildings in the U.S. For a building that just meets the ASHRAE Standard 90.1 requirement in terms of the envelope, air conditioners and heat pumps, the simulation results show that ASHP performs better than WSHP and the split DX system in all scenarios except in very hot and cold climates (zones 1, 7 and 8). ASHP and split DX systems have comparable energy performance in climate zone 1. For a building in compliance with Standard 90.1-2004, WSHP performs better than the split DX system in heating dominated locations (climate zones 5-8) but it performs worse in cooling dominated locations (climate zones 1, 2, 3A and 3B). However, for a building in compliance with Standard 90.1-2010, WSHP may perform better than the split DX system in a small number of cold climates only when the supply fan runs continuously. For future work, it would be worthwhile to investigate how the results change by increasing WSHP efficiency, using the ground source coupled system, and altering the number of floors in the apartment building.

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