New York State Energy Research and Development Authority

# Air Bypass in Vertical Stack Water Source Heat Pumps

Final Report

August 2011

No. 11-16

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# Air Bypass in Vertical Stack Water Source Heat Pumps

Final Report

Prepared for the

**New York State Energy Research and Development Authority**

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# Abstract

Vertical stack water source heat pumps are widely used to provide both comfort cooling and heating to buildings. The problem of air bypass, in which some return air does not pass over the indoor coil of the heat pump, can occur causing performance degradation of the heat pumps. This paper quantifies the air bypass problem in vertical stack water source heat pumps, and associated impacts. Field testing at five different sites was performed and results show that air bypass occurred in all five installations. Three methods are proposed to detect and diagnose the air bypass problem. By sealing air bypass locations after the diagnostics, the improvement in cooling efficiency ranged from 7% to 17% and averaged 12.8%, and the improvement in heating efficiency ranged from 16% to 19% and averaged 17.5%. Based on the locations of air bypass, it is shown that 55.1% of bypassed air was passing through the locations, which are common in all types of water source heat pumps.

*Keywords:* Water source heat pumps, Air bypass, Heating and cooling capacity, Energy efficiency

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# Summary


Taitem Engineering performed testing at five sites throughout New York State to determine the effects of "air bypass" on the performance of vertical stack water source heat pumps. "Air bypass" is the phenomenon of air bypassing the indoor coil and being supplied to the living space without being conditioned. The five testing sites included two hotels, a multifamily residential building, a dorm, and a student apartment building. The testing was performed over three-day periods at each site, starting in the winter of 2009 and extending to the summer of 2010.

Vertical stack water source heat pumps (VSWSHP) are a particular type of water source heat pump and are commonly found in apartment buildings, dorms, and hotels. A VSWSHP is used for both heating and cooling and is constructed in such a way that the main components are stacked on top of each other, allowing the unit to be tall and thin. Because of this construction, VSWSHPs do not require much space and so are popular in apartments, dorms, and hotels. Taitem Engineering found that due to their construction, VSWSHP are prone to air bypass. Because of air bypass, the air is just being re-circulated through the living space without being heated or cooled, making the VSWSHP work harder to condition the space. Through testing and investigation, the areas identified that most contribute to air bypass include sheet metal seams, gaps, holes, and open cell gasketing. In addition, because VSWSHP are typically built into small spaces, they are designed so that the main components can be easily removed for servicing. This design feature, while convenient and practical, creates sealing problems that allow for air bypass.

The testing at each of the five sites was performed on a single VSWSHP per building, and with the combination of the five sites, three separate manufacturers' VSWSHP were tested. Although quantities of air bypass varied between sites, the overall findings were that air bypass existed at every site, and that due to air bypass the unit efficiency was reduced at every site. Furthermore, results showed that with a minimal amount of air sealing, unit efficiency could be measurably increased at every site.

Testing at all sites included measuring the quantity of the air bypass by measuring air flows at various locations using three testing methods, measuring temperatures of the air at various locations, and measuring the energy consumption of the VSWSHP.

A test plan was first developed. A summary of the testing procedure is as follows:

1. Visual inspection of the unit potential locations of air bypass determined
2. Take baseline measurements using the three testing methods and log energy consumption
3. Incrementally air seal identified locations of air bypass. Take measurements and log energy consumption after each location of air bypass is sealed
4. Take final measurements and log energy consumption once all air sealing has been completed.

With the data that was gathered, Taitem Engineering was able to calculate the decrease in VSWSHP efficiency due to air bypass. Said another way, Taitem Engineering was able to calculate the potential increase in efficiency as a result of various air sealing measures. By sealing air bypass locations after the diagnostics, the improvement in cooling efficiency ranged from 7% to 17% and averaged 12.8%, and the improvement in heating efficiency ranged from 16% to 19% and averaged 17.5%.

While testing was only performed on VSWSHP, Taitem Engineering found that the locations of air bypass can be separated into two types, type 1 and type 2. Type 1 are the locations only found in VSWSHP and type 2 are the locations common to all Water Source Heat Pumps (WSHP). Results from the testing show that more than half of the total air bypass can be classified as type 2 (common to all WSHP). It can therefore be estimated that by air sealing WSHP, we can expect an increase on the order of 5% and 7% in cooling and heating efficiency respectively.

# 1 Introduction

## Nomenclature

$T_{in}$ return air temperature (F)

$T_C$ air temperature leaving the indoor coil (F)

$T_{out}$ supply air temperature (F)

V volumetric air flow rate at the end of supply the duct ($ft^3$/min)

$h_{in}$ enthalpy of the return air (Btu/ $lb_{dry\ air}$)

$h_{out}$ enthalpy of the supply air (Btu/ $lb_{dry\ air}$)

☐ specific volume of the supply air ($ft^3$/ $lb_{dry\ air}$)

$W_{out}$ specific humidity of the supply air ($lb_{water}$/$lb_{dry\ air}$)

$P_{hp}$ instantaneous heat pump power (kW)

$c_{pa}$ specific heat of moist air (Btu/( $lb_{dry\ air}$ -F))

COP coefficient of performance of heat pump

EER energy efficiency ratio of heat pump

TCC total cooling capacity (Btu/hr)

SCC sensible cooling capacity (Btu/hr)

LCC latent cooling capacity (Btu/hr)

THC total heating capacity (Btu/hr)

## Background

Approximately 14% of the total energy and 32% of the electricity generated in the United States are consumed by heating, ventilating, and air conditioning (HVAC) systems to meet heating and cooling demands of residential and commercial buildings (DOE, ASHRAE). Among all HVAC systems, water source heat pumps (WSHP) in particular are increasingly popular, especially in high performance buildings. According to the U.S. census bureau, 180,100 water source heat pumps were shipped in 2009 alone.

Many HVAC systems fail to match the performance criteria envisioned at design. A study performed by Proctor, in the United States, of over 55,000 air conditioning units showed that more than 90% were operating with one or more kinds of faults. Another study of over 13,000 air conditioning units showed that 57% of the systems were either undercharged or overcharged for refrigerant, causing them to operate below their designed efficiency (Downey). In a survey, over 1,400 roof top units were studied, and the results showed that the average operating efficiency of the units was 80% of designed performance (Rossi). A modeling study performed on air conditioning units showed that increases in supply and return duct leakage from 0% to 11% decreased cooling capacity by 34% and the combined effects of a 30% undercharged unit with 30% duct leakage decreased the capacity over 50% (Walker).

This report addresses the specific problem of air bypass in Vertical Stack Water Source Heat Pumps (VSWSHP) that are a specific type of WSHP. VSWSHP are commonly found in apartment buildings, dormitories, and hotels. VSWSHP are constructed in such a way that the main components are stacked on top of each other, allowing the unit to be tall and thin. Because of this construction, VSWSHP do not require much space and therefore are popular in apartments, dormitories, and hotels. Taitem Engineering found that due to their construction, VSWSHP are prone to air bypass. Air bypass is the phenomenon of air bypassing the indoor coil and being supplied to the living space without being conditioned. Because of air bypass, the air is just being re-circulated through the living space without being heated or cooled, making the VSWSHP work harder to condition the space. This phenomenon reduces the overall system efficiency and therefore requires more energy.

There are a variety of methods that exist to identify the failures of HVAC systems to perform at their peak rated operating efficiency. The two most common methods are fault detection and diagnostic (FDD) and HVAC system commissioning. Fault detection is a process to determine the faults in a HVAC system and fault diagnostics involve the reasons and identification of a fault. HVAC system commissioning is used to evaluate the performance of an HVAC system and is typically performed on a whole building level. FDD and commissioning are both used to detect and diagnose HVAC system faults and their causes at an early stage in order to prevent energy waste and potential damage to the system. Still, though FDD and commissioning are widely used to improve the performance of HVAC systems, FDD models and standard commissioning tests such as measurement of supply airflow, measurement of the refrigerant pressure of the system, and thermostat response tests might not identify air bypass. The literature survey indicates that air-bypass in WSHP systems does not appear to have previously been identified as an issue. This paper presents the impact of air bypass on the performance of VSWSHP and proposes three methods to identify air bypass. Field testing was performed at five different sites where the VSWSHP systems were installed, and locations of air bypass were identified. Hereafter in this paper, heat pump will be used in lieu of VSWSHP.

# 2 Fault Description

Air bypass is a problem in which some return air does not pass over the indoor coil of a heat pump. A fraction of the return air is pulled into the cabinet through gaps and holes such as through piping penetrations behind the heat pump, through the heat pump front panel, and at junctions where the heat pump is supposed to seal with the equipment cabinet as it slides in. There are several impacts of air bypass on the performance of heat pumps.

Impacts of air bypass are:

- Low suction pressure in cooling
- High condensing pressure in heating
- Low efficiency in heating and cooling
- Vulnerability to freeze up in cooling
- Vulnerability to high pressure trip in heating

Vulnerability to freeze up in cooling mode, is the most dramatic. If a heat pump is running in cooling mode, the indoor coil has the potential to freeze and the heat pump will stop working (Figure 2-1). Air bypass causes this occurrence because reduced return airflow over the indoor coil reduces the refrigerant temperature in the coil and the coil surface temperature below the level expected in the manufacturer's design. If the surface of the indoor coil drops below 32 F, and the unit continues to run in cooling mode, condensate on the coil may cause ice formation on the surface. As is shown in Figure 2-1, due to the air bypass problem, a solid block of ice was formed over the indoor coil of a heat pump within an hour of startup. Figure 2-2 shows the variation of return air temperature ($T_{in}$), air temperature leaving the indoor coil ($T_C$), and supply air temperature ($T_{out}$) over time.

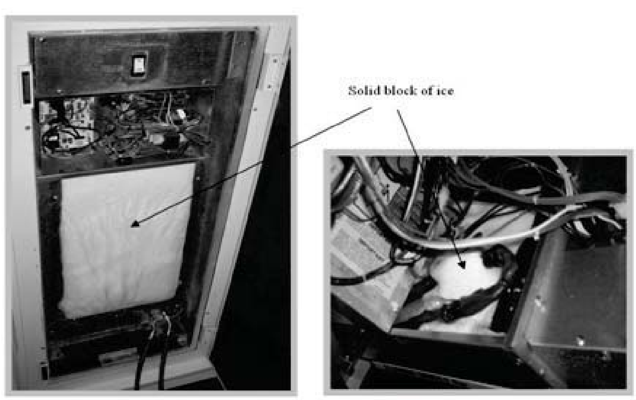


**Figure 2-1: A solid block of ice over the indoor coil and in the control box**

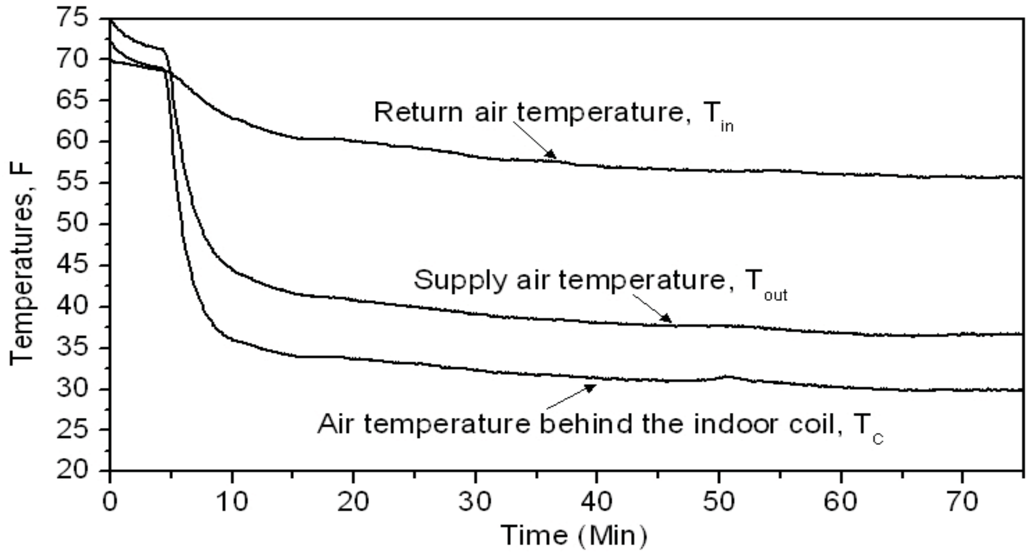


**Figure 2-2: Temperature variations of supply air, return air, and the air leaving the indoor coil before the sealing**

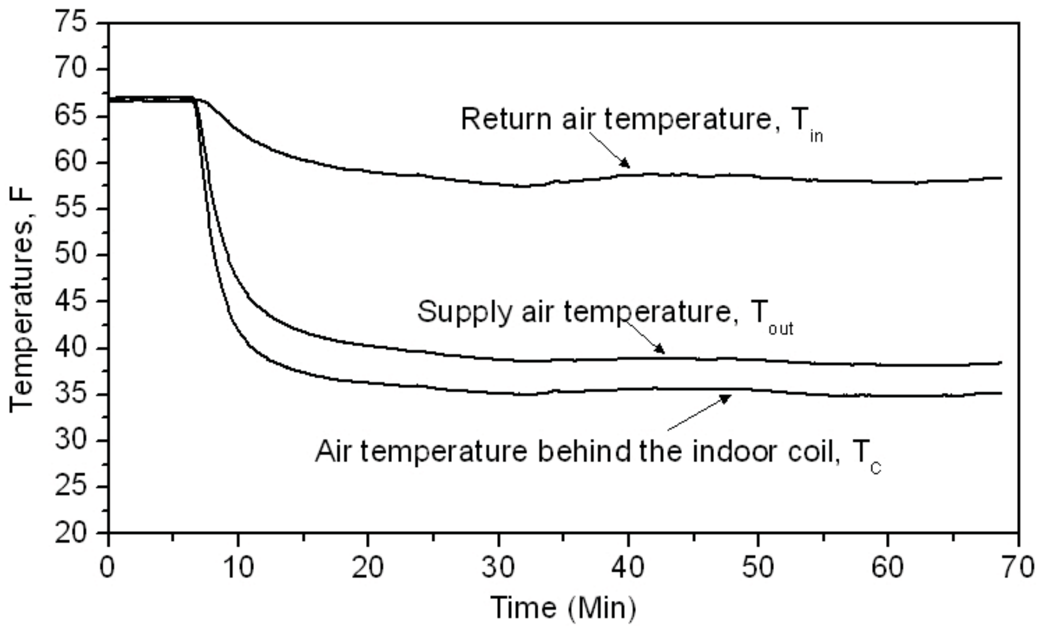


**Figure 2-3: Temperature variations of supply air, return air and the air leaving the indoor coil after the sealing. The heat pump was running in cooling mode.**

It can be noted in the graph that the air temperature leaving the indoor coil rapidly dropped below 32 F and continued to decrease, which caused ice formation over the indoor coil. Figure 2-3 shows the variations of $T_{in}$, $T_C$ and Tout after blocking air bypass, and it can be noted that after preventing the air bypass, the temperature of air leaving the coil ($T_C$) stayed above 32 F.

After coil freeze-up in cooling mode, the next most serious impact of air bypass is high pressure trip in heating. Since the volume of air passing over the coil is lower than expected due to air bypass, there is not proper heat exchange with the refrigerant in the coil. Therefore, the refrigerant pressure on the discharge side of the compressor becomes too high because it cannot reject enough heat to the air passing by and the unit shuts itself down (trips) due to high pressure. This shut down occurs as a way for the unit to protect itself. Once the shut down has occurred the unit will not function until it is manually reset.

# 3 Details of Field Experiments

Field experiments were executed during 2009 and 2010 in five buildings to investigate the air bypass problem in heat pumps. A typical schematic of a heat pump is presented in Figure 3-1. The water-to-air heat pumps typically consist of an aluminum fin and copper tube heat exchanger on the air side, double tube heat exchanger with inner convoluted tube and the refrigerant flowing in the annular space on the water side, a hermetic compressor, thermostatic expansion valve, a reversing valve, and a control system.

The heat pumps investigated in this study had total cooling capacities between 1.5 and 3.5 tons and all units were 208v/230v single phase. Field test conditions for all five sites are presented in Table 3-1. All the heat pumps were fairly new, installed within the past three years by three different major heat pump manufacturers. Each heat pump unit had a user-controlled thermostat to maintain the indoor air temperature at a desired set-point. Thermostats were located on the wall about five feet off the floor. Heated or cooled air was delivered to the designated areas through supply ducts with wall or ceiling-mounted supply registers. Return air entered into the unit by passing around the access door on front of the unit. The heat pumps were located inside of a drywall enclosure. Inside of the enclosure, there was a sheet metal cabinet in which the chassis was located. The cabinet and the chassis were manufactured products, while the drywall assembly was site built. The heat pumps were mounted in the drywall chase and the interior of the sheet metal cabinet was covered with insulation. Water pipes were typically copper and entered the unit from the rear.

As mentioned before, only VSWSHPs have been selected in this investigation. These heat pumps can be divided in two main parts; a cabinet comprised of a control system and blower, and a chassis, containing the full refrigeration circuit, and that slides into the cabinet. Based on the locations of air bypass, the sources of air bypass can broadly be divided in two types. Type1 are the locations which can only be found in VSWSHPs such as the junction where the heat pump is supposed to seal with the cabinet as it slides into place; and type 2 are the locations which are common to all types of water source heat pumps. These locations of air bypass are: water pipe penetrations, condensate pipe penetrations, cabinet seams, electrical connections, control connections, etc. (Figure 3-2). Initially, the locations of air bypass in the heat pumps were identified at each site by using the smoke flow visualization technique and were sealed one by one. Visual inspection and smoke testing were also performed before and after each sealing. This allowed an assessment of the quality of air sealing before moving on to each subsequent test. For all tests, the relative quantities of air bypass were disaggregated for the different types of bypass. This disaggregation was done through repeated measurement of air bypass after each type of hole was sealed and visually inspected.

**Table 3-1: Field Test Conditions at Sites**

| Parameters | | Site 1 | Site 2 | Site 2 | Site 4 | Site 5 |
|---|---|---|---|---|---|---|
| Entering water temperature (EWT, °F) | | 81 | 60 | 70 | 66 | 89 |
| Indoor air temperature | Baseline (°F) | 73 | 74 | 73 | 72 | 71 |
| | After sealing (°F) | 76 | 72 | 74 | 76 | 68 |
| Indoor air relative humidity | Baseline (%) | 58 | 25 | 58 | 27 | 49 |
| | After sealing (%) | 53 | 29 | 72 | 29 | 56 |
| Outdoor air temperature | Baseline (°F) | 31 | 44 | 49 | 31 | 79 |
| | After sealing (°F) | 30 | 45 | 41 | 53 | 89 |
| Outdoor air relative humidity | Baseline (%) | 49 | 71 | 36 | 36 | 71 |
| | After sealing (%) | 51 | 81 | 19 | 47 | 57 |

An ALNOR balometer (model-ABT703) was used to measure volumetric air flow rates of total return air to the heat pump, total supply air and air entering the indoor coil. A data logger (Onset Computers, model: H22001) in conjunction with four temperature and relative humidity sensors (Onset Computers, model: S-THBM002) were used to measure the dry-bulb temperatures and relative humidity of the return air, the air leaving the indoor coil, the supply air, and the ambient air. Temperatures and relative humidity data were sampled at one second intervals. In order to calculate the efficiency (EER in cooling or COP in heating) of the heat pump, instantaneous power at the location where the main power supply enters the unit (L1 and L2 terminals) inside the electrical panel of the heat pump, was measured. A 3-phase power transducer (Veries Industries, model no. H8044) in conjunction with a data-logger were used to measure the power consumption of the heat pump.

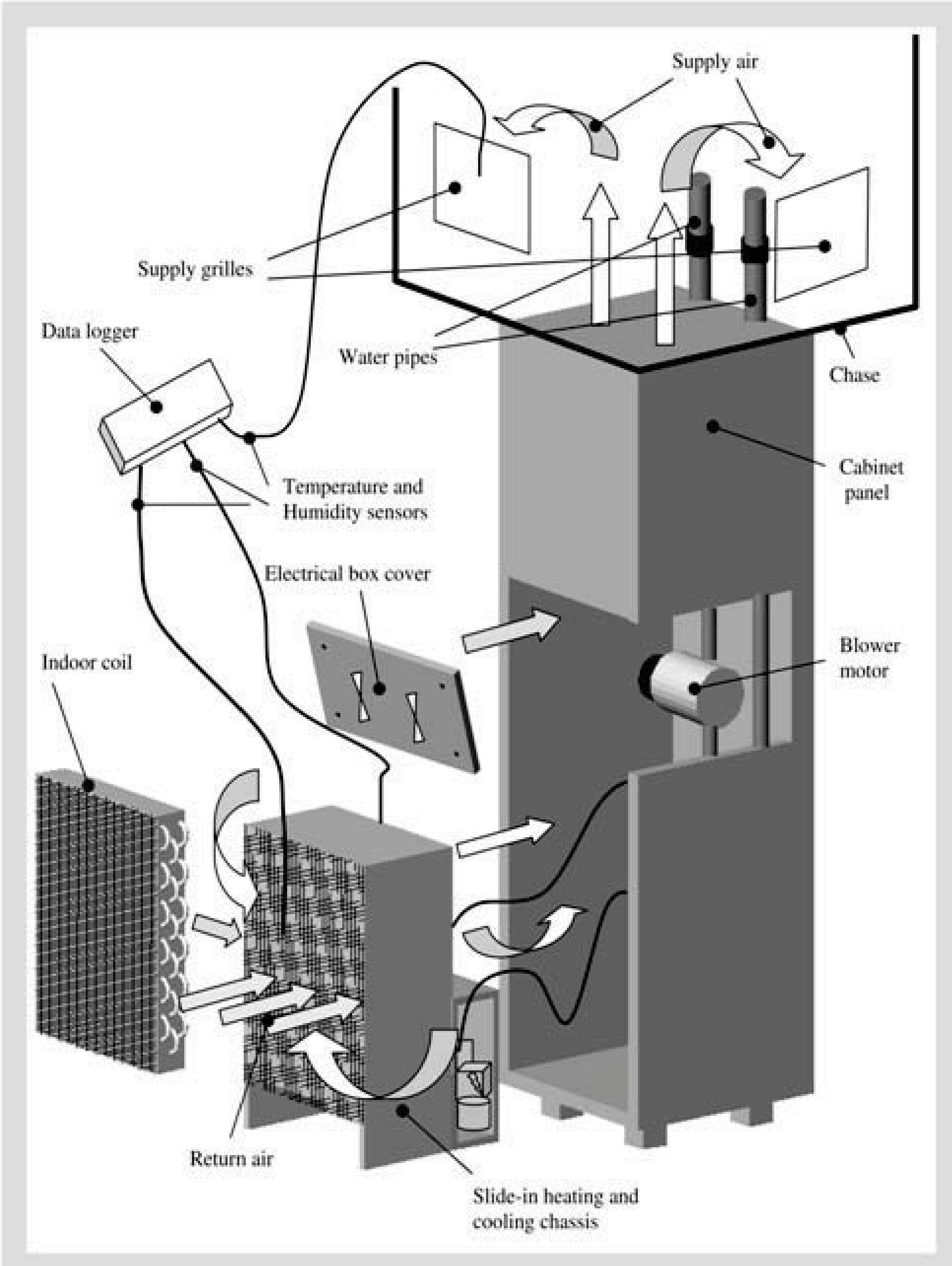


**Figure 3-1: Schematic of a vertical stack water source heat pump**

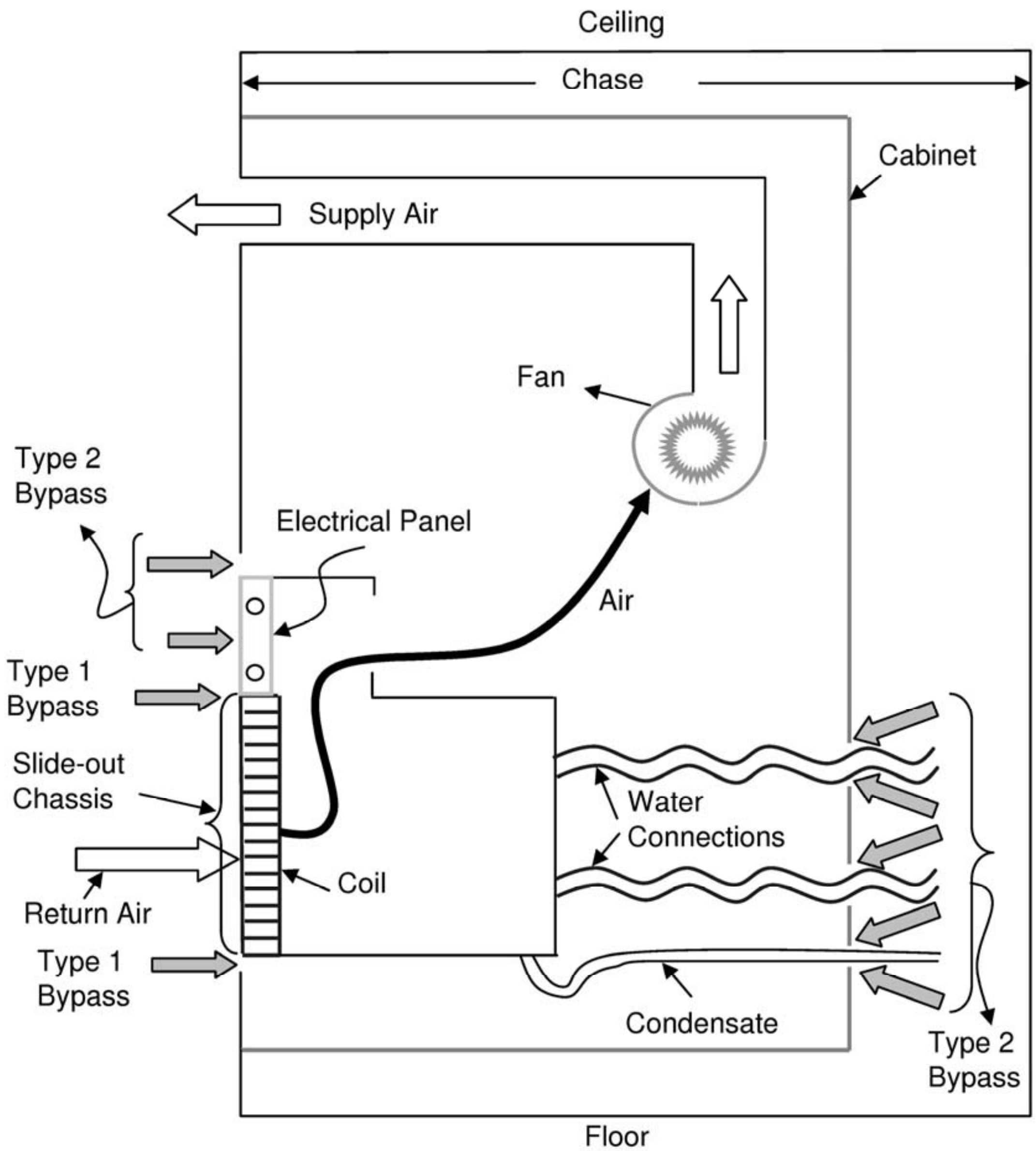


**Figure 3-2: Potential locations of air bypass in a vertical stack water source heat pump**

# 4 Methodology

In order to diagnose the air bypass problem, three different methods have been employed: volumetric air flow tests (direct measurement of airflow), an air temperature mixing test, and a blocked coil method. Visual inspection and smoke testing were performed before measurements were taken, and again after each incremental improvement, to assure proper sealing. In particular, visible holes in the chase or areas where dust had accumulated as an indication of bypass were found. Three methods were used to evaluate air bypass:

## Balometer Air-Flow Testing Method

A series of balometer tests were performed on the heat pump units. These included a baseline test (before sealing), followed by a series of tests to measure the effect of incremental sealing aimed at reducing bypass. In each test, a balometer was used to measure the total supply airflow, total return airflow, and the air flow just across the indoor coil (plate fin heat exchanger). This allowed us to separate air bypass associated with the face of the unit and air bypass occurring in other parts of the cabinet.

## Air Mixing Method

Air temperature mixing tests were taken by placing temperature and relative humidity probes in front of the indoor coil to measure the temperature and relative humidity of the return air, air properties of the air leaving the indoor coil, and temperature and relative humidity of the supply air. The locations of the sensors are shown in Figure 3-1. Data were recorded continuously throughout the process, and results were obtained after each air sealing. Based on the following calculation, the fraction of air bypass was estimated:

$$\text{Air bypass} = \frac{T_{out} - T_c}{T_{in} - T_c} \times V \qquad (1)$$

where V ($ft^3$/min) was the volumetric flow rate at the supply grille.

## Blocked Coil Method

Another method, the blocked coil approach, was also used to examine air bypass. In this method, the return air on the front face of the indoor coil was blocked and the volumetric air flow at the supply grille was measured, which essentially represented all bypasses, as no airflow was being allowed through the coil. Since the coil was blocked, the blower would be operating at a higher pressure. As a result, this measurement was expected to be high, and thus less accurate than the other two methods.

The combination of the three methods allowed verification of our results by checking the data from each method against the others.

## Uncertainty Analysis

Uncertainty analysis is required to indicate the accuracy of the experiments. An uncertainty analysis was performed using the method described by Holman (2001) which states:

$$e_Y^2 = \left(\frac{\partial Y}{\partial X_1}\right)^2 e_{X_1}^2 + \left(\frac{\partial Y}{\partial X_2}\right)^2 e_{X_2}^2 + \ldots\ldots\ldots\ldots + \left(\frac{\partial Y}{\partial X_J}\right)^2 e_{X_J}^2 \qquad (2)$$

where $e_Y$ represents the overall uncertainty, Y are the calculated results, $Y = Y(X_1, X_2, \ldots X_J)$, and $e_{X_{1\ldots J}}$ represent the individual uncertainties in the variables $x_{1\ldots j}$. The instrumentation ranges and their uncertainties are presented in Table 4-1. In the present study, the temperatures, relative humidity, flow rates, and instantaneous power were measured with instruments described above. Total cooling capacity, LCC, SCC, SHR, EER, total heating capacity, and COP were calculated using equations given below.

$$TCC = \frac{60 \times V \times (h_{in} - h_{out})}{\nu \times (1 + W_{out})} \qquad (3)$$

$$LCC = \frac{60 \times 1060 \times V \times (W_{in} - W_{out})}{\nu \times (1 + W_{out})} \qquad (4)$$

$$SCC = \frac{60 \times V \times c_{pa} \times (T_{in} - T_{out})}{\nu \times (1 + W_{out})} \qquad (5)$$

The sensible heat ratio is defined as the ratio of the sensible cooling capacity to the total cooling capacity,

$$SHR = \frac{SCC}{TCC} \qquad (6)$$

Energy efficiency ratio of the heat pump is defined as,

$$EER = \frac{3.412 \times TCC}{P_{hp}} \qquad (7)$$

The total heating capacity, THC, was obtained using the following equation,

$$THC = 1.08 \times V \times (T_{out} - T_{in}) \qquad (8)$$

and the COP of the heat pump was obtained using the following equation,

$$COP = \frac{THC}{P_{hp}} \tag{9}$$

The total uncertainties of the measurements are estimated to be $\pm$ 0.38$^0$F for the temperatures, $\pm$ 2.50% for the relative humidity, $\pm$ 3.00% for flow rates, and $\pm$ 1.00% for instantaneous power of the heat pump.

**Table 4-1: Instrumentation range and uncertainty**

| Instrument | Range | Uncertainty |
|---|---|---|
| 1. Balometer | 50 to 1200 CFM | $\pm$ 3.00% |
| 2. Temperature sensor | 32$^0$F to 122$^0$F (0$^0$C to 50$^0$C) | $\pm$ 0.38$^0$F ($\pm$ 0.21$^0$C) |
| 3. Relative humidity sensor | 10 to 90 % | $\pm$ 2.50 % |
| 4. kWHr transducer | 0 to 100 kW | $\pm$ 1.00% |

The uncertainties of the total cooling capacity, and efficiency (EER) for all sites, and total heating capacity, and efficiency (COP) for sites 4 and 5 were calculated on the basis of measured uncertainties of temperature, relative humidity, heat pump power, and volumetric flow rates (Table 4-2).

$TCC = f\,( T_{in}, T_{out}, RH_{in}, RH_{out}, V)$, and (10)

$EER = f\,( T_{in}, T_{out}, RH_{in}, RH_{out}, V, P_{hp})$ (11)

$THC = f\,( T_{in}, T_{out}, V)$, and (12)

$COP = f\,( T_{in}, T_{out}, V, P_{hp})$ (13)

$RH_{in}$ and $RH_{out}$ are the relative humidity of the return and supply air, respectively. In the uncertainty calculations on EER and COP, the uncertainty due to entering water temperature is neglected.

**Table 4-2: Relative Uncertainties for TCC, THC, EER and COP**

| | Parameter | Uncertainty |
|---|---|---|
| Cooling Mode | Total Cooling Capacity | $\pm$ 5.36% to $\pm$ 10.81% |
| | EER | $\pm$ 5.93% to $\pm$ 10.86% |
| Heating Mode | Total Heating Capacity | $\pm$ 3.46% to $\pm$ 4.22% |
| | COP | $\pm$ 8.91% to $\pm$ 14.18% |

It is also noted that the uncertainty discussed above is limited to the operation ranges of return and supply air temperatures, return and supply air relative humidity, and volumetric flow rate at the supply grille. If the temperatures, relative humidities, and volumetric flow rate are considerably away from the test conditions mentioned in Table 3-1, the uncertainties of the parameters presented in Table 4-3 are expected to be different. In addition, both TCC and THC are dependent on some of the test conditions such as $T_{in}$, EWT, entering wet bulb temperature (EWB), and V. For a given site, EWT was approximately constant before and after the sealing. Nevertheless, on the sites, the $T_{in}$ and the $RH_{in}$ varied slightly before and after the sealing (Table 3-1). While calculating TCC, THC, EER, and COP of the heat pumps, instantaneous test conditions were considered. Nevertheless, due to the difference in test conditions ($T_{in}$, $RH_{in}$ etc.) before and after the sealing, their effects on the improvements of measured parameters (TCC, THC, EER etc.) are neglected in the subsequent analysis.

# 5 Results and Discussion

Extensive testing at each site was done, however, for brevity; only the data collected at the fifth site is discussed in detail in this section. Additionally, summary results for all five sites are presented in this section. Detailed results from sites one through four can be found in appendix A.

## Test Results

The three testing methods were performed at all five sites as described in section 4. A baseline measurement to determine the air bypass was performed before sealing air bypass locations. After taking these baseline readings, a series of measurements were performed to determine the reduction in air leakage as a result of incremental improvements. After each air sealing step, a smoke test was conducted to ensure that the sealing of the target area was complete. There were four general locations of air bypass found, which are  in Table 5-1. These locations are outlined in Figure 5-1 below.

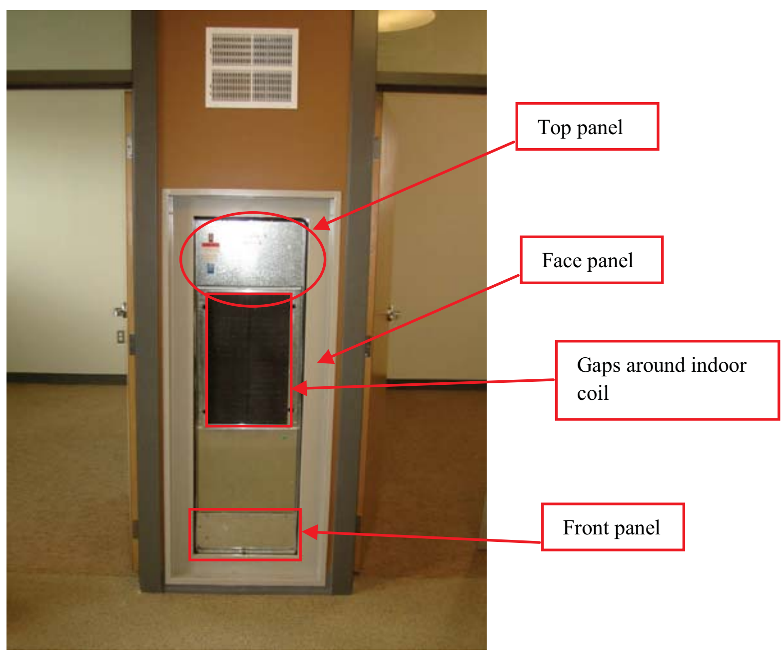


**Figure 5-1: General locations of air bypass at site #5**

The reduction in air bypass using the blocked coil method is presented in Table 5-1. The blocked coil test is useful because it can be employed as a quick commissioning test; if the air is not bypassing the coil, there will be no air flow at the supply after blocking the indoor coil. The blocked coil method is expected to give exaggerated results, because blocking the coil itself affects air pressures throughout the system. Therefore, uncertainty analysis for this method is not presented.

**Table 5-1: Reduction in air bypass using blocked coil method (site 5)**

| Order of sealing | Reduction in air by-pass ($ft^3$/min) |
|---|---|
| 1. Holes at the top panel and the open cell foam gasket between the cabinet and the face panel | 6 |
| 2. Gaps around the edges of the front panel and bottom left corner | 20 |
| 3. Gaps around the indoor coil | 35 |
| 4. Pipe penetrations through the rear of the cabinet | 90 |

The baseline balometer test showed that the supply airflow was 675 $ft^3$/min and the return flow over the coil was 513 $ft^3$/min. The balometer test was repeated after each air sealing step. Once the measurements were taken for each air sealing step, the reduction in air bypass for each location was determined. Table 5-2 presents the supply air flow, air flow over the indoor coil, and reduction in air bypass after sealing each location. Uncertainty in air flow measurement caused by the balometer is also presented in Table 5-2.

Table 5-3 presents the reduction in air bypass using the air mixing method. Equation 1 is used to calculate reduction in air bypass, and equation 2 is used to calculate uncertainty in the reduction in air bypass using air mixing method. It can be seen in Table 5-2 and Table 5-3 that both methods showed similar reduction in air bypass after sealing all locations of air bypass. It can also be noted in Table 5-2 that, after sealing the final location of air bypass, there is still a significant difference in total supply air flow and the air flow over the indoor coil. This results from the fact that the unit was located in a drywall chase and the interior of the sheet metal cabinet was covered with insulation so that not all parts of the sheet metal cabinet could be inspected or accessed for sealing.

**Table 5-2: Air flow measurements using balometer (Site 5)**

| Order of sealing | Total supply air flow ($ft^3$/min) | Air flow over the indoor air coil ($ft^3$/min) | Reduction in air bypass ($ft^3$/min) |
|---|---|---|---|
| 1. Baseline measurement | $675 \pm 20.254$ | $513 \pm 15.386$ | N.A. |
| 2. Holes at the top panel and the open cell foam gasket between the cabinet and the face panel | $666 \pm 19.981$ | $527 \pm 15.814$ | 0 to 36.074 |
| 3. Gaps around the edges of the front panel and bottom left corner | $665 \pm 19.954$ | $531 \pm 15.927$ | 0 to 40.157 |
| 4. Gaps around the indoor coil | $675 \pm 20.254$ | $550 \pm 16.504$ | 14.437 to 59.563 |
| 5. Pipe penetrations through the rear of the cabinet | $678 \pm 20.342$ | $570 \pm 17.104$ | 33.986 to 80.023 |

**Table 5-3: Reduction in air bypass using air temperature mixing method (Site 5)**

| Order of sealing | Reduction in air by-pass ($ft^3$/min) |
|---|---|
| 1. Holes at the top panel and open cell foam gasket between the cabinet and the face panel | 0 to 54.265 |
| 2. Gaps around the edges of the front panel and bottom left corner | 0 to 58.407 |
| 3. Gaps around the indoor coil | 15.333 to 67.162 |
| 4. Pipe penetrations through the rear of the cabinet | 34.858 to 82.601 |

**Table 5-4: Comparative results (Site 5)**

| Method | Total Bypass Before Sealing (CFM) | Total Bypass Before Sealing | Total Bypass After Sealing (CFM) | Total Bypass After Sealing | Total Reduction in Bypass (CFM) | Total Reduction in Bypass (%) |
|---|---|---|---|---|---|---|
| Balometer Testing | 162 | 24.0 % | 108 | 15.9 % | 54 | 8.1 % |
| Temperature Mixing | 119 | 17.57 % | 63 | 9.22 % | 56 | 8.3% |
| Blocked Coil | 275 | 40.7 % | 185 | 27.3 % | 90 | 13.4% |

Throughout the tests, we noted some unexpected results. For example, the blocked coil tests show lower air bypass after the first one or two steps of air-sealing, when we would expect higher air bypass compared to the other two methods (Table 5-1, 5-2, and 5-3). In general, taking measurements under field conditions proved challenging. Balometers themselves have an accuracy of 3%, even when calibrated, and beyond that can show readings that fluctuate by several CFM within a given test, due to airflow turbulence. Sealing the balometer at its edges around the surface against which it is mating can also be difficult. Temperature measurements for the air temperature mixing method are ostensibly affected by radiation from nearby cold and hot surfaces (for example, the coil itself). Comparative results from three different methods are shown in Table 5-4.

## Cooling Calculations

The indoor air enthalpy method has been used in this study to calculate total cooling capacity of the heat pumps. The performance of the heat pumps was studied by measuring the air flow rates (supply and return), temperatures of supply and return air, temperature leaving the indoor coil, and total power consumption when the heat pump was running. The heat pump unit was allowed to run long enough so that it could come to a quasi-steady state.

Readings were taken when the unit was running in cooling mode with a setpoint temperature of 66.2 F. After several minutes of testing, temperature and relative humidity were recorded along with the unit's power consumption (kW). Power readings were used for the efficiency calculations when the return air temperature was 66.8 F.

Table 5-5 shows improvement in the efficiency (EER) of the heat pump after each sealing step. Equations 3 and 7 are used to calculate efficiency of the heat pump after each sealing step. Overall, a 14.4% improvement in cooling efficiency was obtained.

**Table 5-5: Efficiency of heat pump after sealing each step (site 5)**

| Order of sealing | Efficiency (EER) |
|---|---|
| 1. Baseline measurement | $11.373 \pm 0.601$ |
| 2. Holes at the top panel and the open cell foam gasket between the cabinet and the face panel | $11.802 \pm 0.651$ |
| 3. Gaps around the edges of the front panel and bottom left corner | $12.675 \pm 0.662$ |
| 4. Gaps around the indoor coil | $12.946 \pm 0.681$ |
| 5. Pipe penetrations through the rear of the cabinet | $13.008 \pm 0.679$ |

## Heating Calculations

A similar approach was considered to examine the effect of air bypass on the performance of the heat pump when it was running in heating mode. The total heating capacity, THC, was obtained using the following equation:

(14)

and the COP of the heat pump was obtained using the following equation:

(15)

Table 5-6 presents the efficiency of the heat pump before and after all air-sealing. Based on uncertainty analysis for COP presented in Table 8, a range from 6.581% to 31.633% and averaged 19.107% improvement in COP efficiency was obtained after sealing all accessible locations of air bypass.

**Table 5-6: Efficiency (COP) of heat pump in heating mode (Site 5)**

| Test | Efficiency (COP) |
|---|---|
| 1. Baseline measurement | $2.554 \pm 0.162$ |
| 2. After all sealing | $3.042 \pm 0.191$ |

# 6 *Psychrometric Analysis (Cooling Mode)*

Figure 6-1 shows a psychrometric representation of the air bypass problem in cooling mode. Three state-points in the unit were analyzed. State points 1', 2', and 3' represent the air properties of return air, air leaving the indoor coil and supply air respectively when a fraction of the air was bypassing the indoor coil. State points 1, 2 and 3 represent the air properties of return air, air leaving the indoor coil, and supply air respectively when the possible areas of air bypass were sealed. The analysis presented below at these state points is based on the data collected for a typical warm day with the heat pump running in cooling mode. In both cases, before and after the sealing, ambient air temperature was set at 66.2 F using a manually controlled thermostat. The design loads of the heat pump are 1.67 tons for the total cooling load, 1.27 tons for the sensible load, and 0.4 tons for the latent load. The design volumetric flow rate of the unit was 630 $ft^3$/min. The design efficiency of the heat pump in cooling mode (energy efficiency ratio, EER) was 17.2 and in heating mode (coefficient of performance, COP) was 4.4.

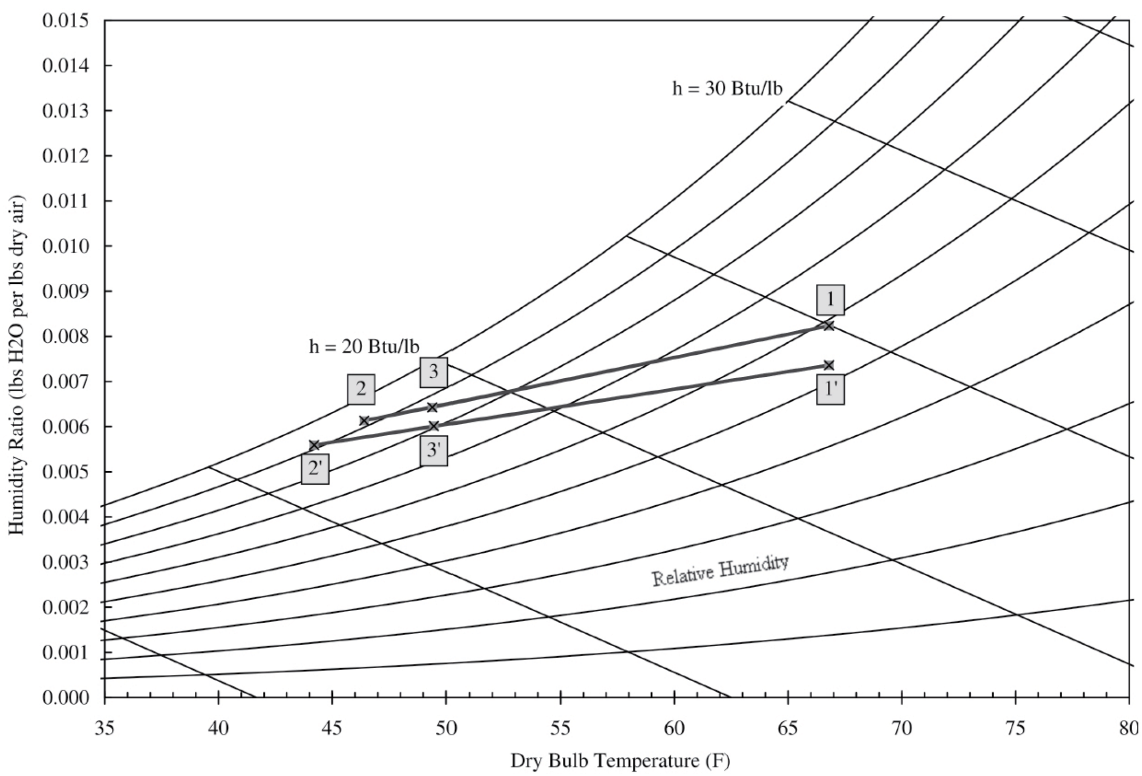


**Figure 6-1: Psychrometric presentation of the air conditioning process before and after blocking the areas of air bypass**

## Psychrometric Analysis Before Sealing

State point 1' represents the return air conditions in steady state. A sensor is used to measure the temperature and relative humidity of the return air, which were, $T_{in}$ = 66.86 F and $RH_{in}$ = 52.5% with a corresponding humidity ratio of Win = 0.007359 $lb_{water}/lb_{dry\ air}$. Total enthalpy associated with the return ambient air to the unit was 24.2 Btu/ $lb_{dry\ air}$. The volumetric air flow rate of the supply air to the room was 675 $ft^3$/min. State point 2' represents the temperature and relative humidity of the air leaving the indoor coil. The temperature and relative humidity at point 2' were 44.2 F and 91.5% respectively with a corresponding humidity ratio of WC= 0.005592 $lb_{water}/lb_{dry\ air}$. Total enthalpy associated to the air leaving the indoor coil was 16.74 Btu/lb. State point 3' represents the supply air conditions. The temperature and relative humidity of the supply air were 49.46 F and 80.6% respectively with a corresponding humidity ratio of $W_{out}$ = 0.006012 $lb_{water}/lb_{dry\ air}$. Total enthalpy associated to the supply air was 18.46 Btu/lb.

## Psychrometric Analysis After Sealing

State point 1' represents the return air conditions after sealing. At the state point 1', temperature and relative humidity of the air were 66.81 F and 59.0% respectively with a corresponding humidity ratio $W_{in}$ = 0.008234 $lb_{water}/lb_{dry\ air}$ and total enthalpy of the return air was 25.14 Btu/lb. State point 2' shows the properties of the air leaving the indoor coil. The temperature and the relative humidity were 46.2 F and 92.2% respectively with a corresponding humidity ratio WC = 0.006132 $lb_{water}/lb_{dry\ air}$. Total enthalpy associated to the air was 17.8 Btu/lb. State point 3' represents the properties of the supply air. Temperature and relative humidity of the supply air were 49.38 F and 86.3% respectively. The volumetric air flow rate of the supply air to the room was 678 $ft^3$/min after sealing, which, given the margin of error of the measuring equipment, is equal to the volumetric air flow rate prior to sealing. Humidity ratio, $W_{out}$, was 0.006427 $lb_{water}/lb_{dry\ air}$ and the enthalpy associated to the supply was 18.89 Btu/lb.

After the sealing, the sensible heat ratio decreased, the latent capacity of the unit increased, and the total cooling capacity increased. Further, as shown on the psychrometric chart (Figure 6-1), the temperature leaving the indoor coil after the sealing increased by 2 F, however the supply air temperature did not change at all. This is due to the fact that when the air was bypassing the indoor coil, a fraction of the total return air was mixing with the air leaving from the indoor coil. As a result, before blocking the areas of air bypass, the temperature of the air leaving the indoor coil was 2 F lower than the air temperature leaving the coil after the sealing.

# 7 Summary of the Field Test Results

As mentioned above, heat pumps at five sites were tested. Results of all the sites are summarized in this section. Figure 7-1 shows percentage reduction in air bypass obtained at all five sites. A 5% to 17% reduction in air bypass after sealing all accessible locations of air bypass was obtained. Figure 7-2 shows percentage improvements in cooling efficiency at all five sites chosen in this study. A 7% to 17% improvement in the efficiency was obtained in cooling mode and a 5% to 11% improvement was obtained in total cooling capacities (Figure 7-3). Similarly, tests in heating mode were performed at sites 4 and 5, and results showed 16% and 19% improvement in efficiency at site 4 and 5 respectively.

Though the heat pump units are primarily designed to either cool or heat the space, these units also dehumidify the air. The total cooling capacity, TCC, comprises two separate components: the sensible capacity, SCC, which is associated with lowering the dry bulb temperature of the air and the latent capacity, LCC, which is associated with removing moisture from the air. The sensible heat ratio, SHR, is the ratio of the SCC to TCC. The SHR of the heat pumps typically vary between 0.68 to 0.80, which is necessary to maintain humidity level in the space by continuously removing moisture from the air, because high humidity can cause discomfort, surface material deterioration, condensation, and corrosion. In this study, it was found that due to air bypass problem, the SHR of the heat pumps increased. Figure 7-4 shows percentage reduction in SHR at each site after the sealing. A 2.8% to 12.0% reduction in SHR was observed.

Table 7-1 shows a summary of air bypass at each site. It should be noted in Table 7-1 that all locations of air bypass could not be sealed. Detailed description of air bypass after each sealing step, by using all three methods, is provided in Appendix A. An average of 54.5% air bypass was reduced. A significant amount of air was bypassing from other inaccessible holes. Using a linear approximation, we speculate that if the majority of bypass (including inaccessible hidden bypass) is reduced, the efficiency of the heat pumps might be improved as much as 25%.

As mentioned above, the bypass locations can be divided into two types: locations that can be found only in VSWSHPs, and locations that are common in all types of WSHPs. Table 7-2 shows that 44.9% air was bypassing through gaps and holes that can be found only in VSWSHPs and the rest (55.1%) air was bypassing through locations that can be identified in any type of WSHP.

A natural question is “Who should seal the air bypass”? Most of the air bypass relates to the design of the heat pumps themselves, at sheet metal seams, control and electrical devices, etc. Some of the air bypass sites relate to the installation, for example where the water pipes penetrate the cabinet. These penetrations need to allow pipe movement due to thermal expansion and contraction, so instructions from manufacturers typically call for the contractor to seal the penetrations. Still the holes are large and are consistently sealed poorly. It is recommended that manufacturers use some form offlexible seal, such as a boot (similar to the seal on automobile stick-shifts), that provides air sealing while allowing for pipe movement. Efficiency testing of heat pumps for ratings should require use of factory-shipped sealing of the heat pumps, rather than simulation of what the installing contractor will do to air-seal the units, because we speculate that the air bypass is not being captured in efficiency testing by manufacturers.

**Table 7-1: Summary of air bypass at each site**

| Location | Air bypass before sealing (%) | Air bypass after sealing (%) | Reduction in air bypass | Improvement in EER (%) |
|---|---|---|---|---|
| Site 1 | 29.2 | 17.1 | 12.1 | 17.0 |
| Site 2 | 23.0 | 7.1 | 16.9 | 13.0 |
| Site 3 | 15.3 | 7.3 | 8.0 | 13.0 |
| Site 4 | 17.1 | 12.0 | 5.1 | 12.5 |
| Site 5 | 24.0 | 15.9 | 8.1 | 14.4 |
| Average | 21.7 | 11.8 | 10.0 | 14.0 |

**Table 7-2: Percentage distribution of air bypass associated with the types of locations in VSWSHP**

| Types of locations | Type 1 | Type 2 |
|---|---|---|
| % distribution | 44.9 | 55.1 |

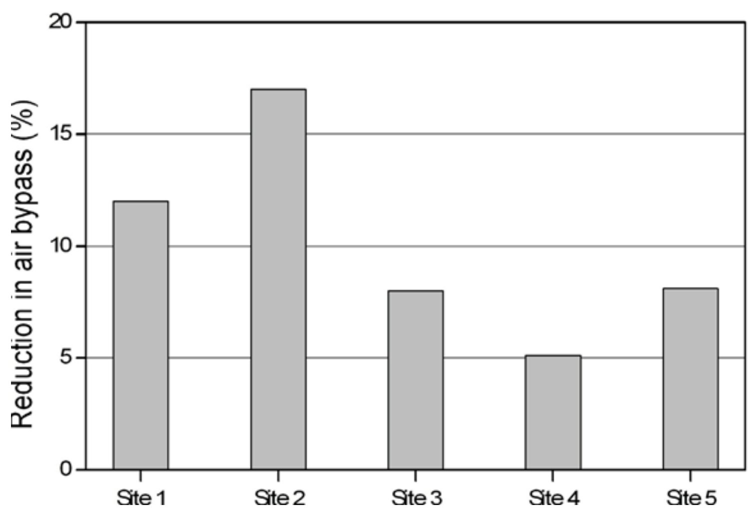


**Figure 7-1: Reduction in air bypass after sealing accessible holes**

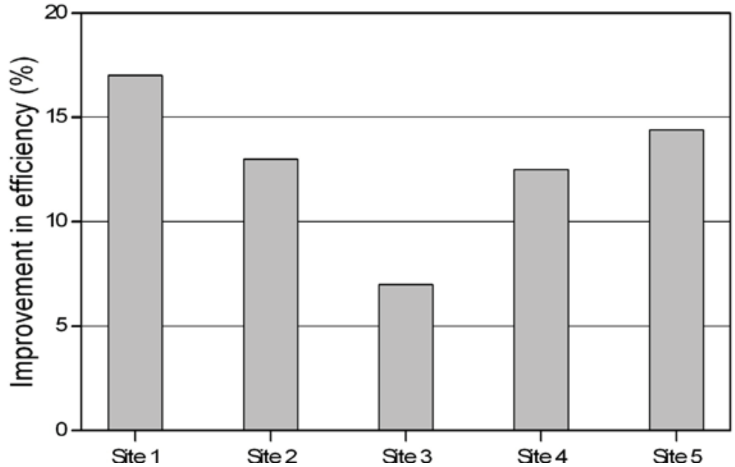


**Figure 7-2: Improvement in efficiency (EER) when the heat pumps were running in cooling mode**

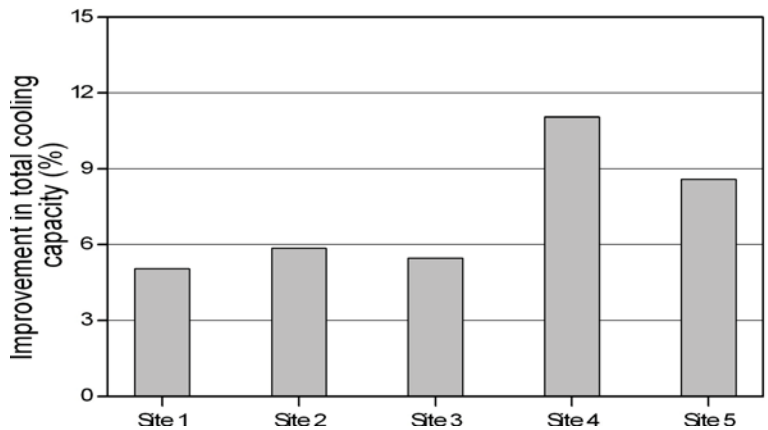


**Figure 7-3: Improvement in total cooling capacity (TCC) after blocking potential areas of air bypass**

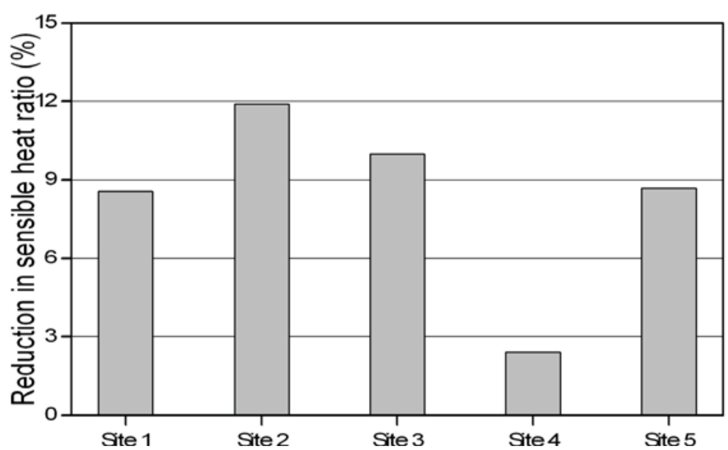


**Figure 7-4: Reduction in sensible heat ratio (SCC/TCC) after blocking potential areas of air bypass**

# 8 Benefits of Reducing Air Bypass

There are several benefits that can be achieved by eliminating air bypass from heat pumps.

## Energy Benefits

Energy benefits derive from eliminating multiple types of energy losses that result from air bypass:

1. In cooling, the refrigerant suction pressure drops, and so the compressor works across a higher pressure difference. Likewise, in heating, the discharge pressure rises due to air bypass, causing an increase in energy usage. In addition, it is generally accepted that high discharge pressures are dangerous for compressors and can shorten the compressor lifespan.
2. In both heating and cooling, the heat pump capacity drops due to air bypass, making the heat pump run longer and less efficiently.
3. In cooling, the indoor coil can freeze (Figure 2-1), leading to zero capacity by stopping or significantly reducing cool air output from the system, while the heat pump compressor would run continuously.

Similar to duct losses in HVAC systems, which have been a major focus of recent efforts in the industry, and which might result in 10% to 20% losses, equipment air bypass losses could likely reach 25% or more, based on the findings in our field work.

## Environmental Benefits

Environmental benefits result from reduced energy losses. Indoor comfort will be improved where air bypass problems are so severe that heat pumps cannot meet the building heating and cooling loads. Further, better dehumidification will also improve indoor air quality.

## Economic Benefits

Reduced energy losses will result in reduced costs in buildings where heat pump air bypass is eliminated.

# 9 Conclusion

The study investigates the air bypass problem in VSWSHPs. It is shown that air bypass can significantly increase VSWSHP energy usage. Blocking areas of air bypass in heat pumps in both cooling and heating modes seems a direct and attractive approach, and can lead to energy savings. In this paper, three methods are proposed to detect and diagnose the air bypass problem. Five sites were selected for testing where VSWSHPs were installed and used to provide both heating and cooling to designated areas of the buildings. Several different air bypass routes were found, each of which contributed significantly to the problem. It is also shown that the air bypass problem caused performance degradation of the heat pump in both cooling as well as in heating. The test results showed 5% to 11% improvement in total cooling capacity, 7% to 17% improvement in cooling efficiency (EER) and 16% to 19% improvement in heating efficiency (COP) of VSWSHPs compared to the baseline system, when air bypass areas were sealed. Of the three methods to detect and diagnose air bypass were tested, the balometer method appears to be the most accurate, while the blocked-coil method might be the most useful for commissioning and diagnostic tests.

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# Appendix A—Test results from sites 1 through 4

## Site #1—Test results

### Table A-1: Site #1 Balometer test results

| Balometer Testing | Air Bypass |
|---|---|
| 1). Correcting the cabinet deformities. This includes straightening the cabinet lip and installing drain pan clips, installing the Schrader valve cover, and installing front panel screws | 34 CFM |
| 2). Add ¼" seal on the front edge of the chassis and around the drain pan | 3.6 CFM |
| 3). Sealing the condensate drain hole. | No change* |
| 4). Sealing holes in the back of the unit. These are the plumbing penetrations at the water loop supply and return. | No change* |
| 5). Sealing the four corners at the front access panel | 5.4 CFM |
| 6). Sealing the four sides of the access panel where it connects to the cabinet. | 17 CFM |
| 7). Caulking the sheet metal seams on the bottom of the cabinet<br>* No change indicates a number <1 | No change* |

### Table A-2: Site #1 Air Temperature Mixing Method test results

| Air Temperature Mixing Method | |
|---|---|
| 1). Average bypass before sealing. | 94 CFM |
| 2). Average bypass after sealing the unit as well as we can | 55 CFM |
| Total change due to air sealing | 39 CFM |

### Table A-3: Site #1 Blocked Coil Method test results

| Blocked Coil Method* | |
|---|---|
| 1). Total bypass with the return coil blocked and the unit air sealed | 50 CFM |
| *Based on testing only one unit. | |

### Table A-4: Site #1 Comparative results of various testing methods

| Comparative Results | | | | | | |
|---|---|---|---|---|---|---|
| Method | Total Bypass Before Sealing | Total Bypass Before Sealing | Total Bypass After Sealing | Total Bypass After Sealing | Total Reduction in Bypass | Total Reduction in Bypass |
| Balometer Testing | 105 CFM | 29% | 63 CFM | 17% | 42 CFM | 12% |
| Temperature Mixing* | 94 CFM | 26% | 55 CFM | 15% | 39 CFM | 11% |
| Blocked Coil* | Not available | - | 50 CFM | 14% | - | - |
| *The temperature mixing and block coil tests use an average flow rate of 364 CFM | | | | | | |

## Site #2—Test results

### Table A-5: Site #2 Balometer test results

| Balometer Testing | Air Bypass |
|---|---|
| 1). The bottom of the front face of the chassis | 98 CFM |
| 2). Around the Schrader valves | No change* |
| 3). Around the electric panel | No change* |
| 4). Pipe penetrations on the back of the unit | 37 CFM |
| 5). Drain penetrations on the back of the unit | No change* |
| * No change indicates a number <1 | |

### Table A-6: Site #2 Air Temperature Mixing Method test results

| Air Temperature Mixing Method | |
|---|---|
| 1). The bottom of the front face of the chassis | 20 CFM |
| 2). Around the Schrader valves | 3 CFM |
| 3). Around the electric panel | 15 CFM |
| 4). Pipe penetrations on the back of the unit | 10 CFM |
| 5). Drain penetrations on the back of the unit | 0 CFM |

### Table A-7: Site #2 Blocked Coil Method test results

| Blocked Coil Method | |
|---|---|
| 1). The bottom of the front face of the chassis | 0 CFM |
| 2). Around the Schrader valves | 9 CFM |
| 3). Around the electric panel | 7 CFM |
| 4). Pipe penetrations on the back of the unit | 67 CFM |
| 5). Drain penetrations on the back of the unit | 19 CFM |

### Table A-8: Site #2 Comparative results of various testing methods

| Comparative Results | | | | | | |
|---|---|---|---|---|---|---|
| Method | Total Bypass Before Sealing | Total Bypass Before Sealing | Total Bypass After Sealing | Total Bypass After Sealing | Total Reduction in Bypass | Total Reduction in Bypass |
| Balometer Testing | 74 CFM | 23% | 20 CFM | 7% | 54 CFM | 17% |
| Temperature Mixing | 86 CFM | 27% | 53 CFM | 17% | 33 CFM | 8% |
| Blocked Coil | 180 CFM | 57% | 78 CFM | 26% | 102 CFM | 32% |

**Table A-9: Site #2 Efficiency increase as a result of air sealing**

| Efficiency | COP |
|---|---|
| 1). Baseline | 4.48 |
| 2). After sealing the bottom of the front face of the chassis | 4.72 |
| 3). After sealing around the Schrader valves | 4.66 |
| 4). After sealing around the electric panel | 4.55 |
| 5). After sealing the pipe penetrations on the back of the unit | 4.80 |
| 6). After sealing the drain penetration on the back of the unit | 5.05 |

# Site #3—Test results

**Table A-10: Site #3 Balometer test results**

| Balometer Testing | Total Return Airflow | Return over coil air flow | Air Bypass Reduction |
|---|---|---|---|
| 1) Holes at the top of the front panel | 365 CFM | 304 CFM | 14 CFM |
| 2) Gap at the bottom of the front panel between the panel and the chassis | 364 CFM | 318 CFM | 15 CFM |
| 3) All edges around coil opening | 360 CFM | 322 CFM | 8 CFM |
| 4) All remaining gaps and holes in the face panel | 357 CFM | 328 CFM | 9 CFM |
| 5) Pipe penetrations through the rear of the cabinet | 366 CFM | 332 CFM | Negligible |

**Table A-11: Site #3 Air Temperature Mixing Method test results**

| Air Temperature Mixing Method | |
|---|---|
| 1) Holes at the top of the front panel | Negligible |
| 2) Gap at the bottom of the front panel between the panel and the chassis | 4 CFM |
| 3) All edges around coil opening | Negligible |
| 4) All remaining gaps and holes in the face panel. | 6 CFM |

**Table A-12: Site #3 Blocked Coil Method test results**

| Blocked Coil Method | |
|---|---|
| 1) Holes at the top of the front panel | 27 CFM |
| 2) Gap at the bottom of the front panel between the panel and the chassis. | 4 CFM |
| 3) All edges around coil opening | 31 CFM |
| 4) All remaining gaps and holes in the face panel | Negligible |
| 5) Pipe penetrations through the rear of the cabinet | Negligible |

**Table A-13: Site #3 Comparative results of various testing methods**

| Comparative Results | | | | | | |
|---|---|---|---|---|---|---|
| Method | Total Bypass Before Sealing (CFM) | Total Bypass Before Sealing | Total Bypass After Sealing (CFM) | Total Bypass After Sealing | Total Reduction in Bypass (CFM) | Total Reduction in Bypass |
| Balometer Testing | 58 | 15.3% | 26 | 7.3% | 32 | 8% |
| Temperature Mixing | 93 | 24.6% | 87 | 24.6% | 6 | 0% |
| Blocked Coil | 149 | 39.4% | 89 | 25.1% | 60 | 14% |

**Table A-14: Site #3 Efficiency increase as a result of air sealing**

| Efficiency | EER |
|---|---|
| 1) Baseline | 8.98 |
| 2) After sealing holes at the top of the front panel | 9.41 |
| 3) After sealing gap at the bottom of the front panel between the panel and the chassis | 9.53 |
| 4) After sealing all edges around coil opening. | 9.44 |
| 5) After sealing all remaining gaps and holes in the face panel. | 9.6 |

Due to a compressor failure we were not able to take kW readings for the last air sealing. Therefore we are only able to report on the unit EER up through the air sealing of the all remaining gaps and holes in the face panel. Given the results from the balometer test and the blocked coil test, we can assume that the sealing of the pipe penetrations in the rear of the cabinet will have a negligible effect on the unit EER.

## Site #4– Test results

The baseline balometer test resulted in total supply airflow 1050 CFM and return over the coil was 990 CFM.

**Table A-15: Site #4 Balometer test results**

| Balometer Testing | Total supply air flow (CFM) | Air flow over the indoor coil (CFM) | Total reduction in air bypass (CFM) |
|---|---|---|---|
| 1) Baseline measurement | 1050 | 990 | N.A. |
| 2) After sealing holes at the corners of the front panel made during installation | 1111 | 1050 | 60 |
| 3) After sealing the gap around the edges of the front panel and bottom left corner | 1093 | 1130 | 140 |
| 4) After sealing electrical switches and Schrader valves | 1103 | 1145 | 155 |
| 5) After sealing pipe penetrations through the rear of the cabinet | 1088 | 1270 | 280 |

**Table A-16: Site #4 Air Temperature Mixing Method test results**

| Air Temperature Mixing Method | |
|---|---|
| 1) Holes at the corners of the front panel made during installation | Negligible |
| 2) Gap around the edges of the front panel and bottom left corner | 13 CFM |
| 3) Electrical switches and Schrader valves | 26 CFM |
| 4) Pipe penetrations through the rear of the cabinet | Negligible |

**Table A-17: Site #4 Blocked Coil Method test results**

| Blocked Coil Method | |
|---|---|
| 1) Holes at the corners of the front panel made during installation | Negligible |
| 2) Gap around the edges of the front panel and bottom left corner | 178 CFM |
| 3) Electrical switches and Schrader valves | 36 CFM |
| 4) Pipe penetrations through the rear of the cabinet | 200 CFM |

**Table A-18: Site #4 Comparative results of various testing methods**

| Comparative Results | | | | | | |
|---|---|---|---|---|---|---|
| **Method** | **Total Bypass Before Sealing (CFM)** | **Total Bypass Before Sealing** | **Total Bypass After Sealing (CFM)** | **Total Bypass After Sealing** | **Total Reduction in Bypass (CFM)** | **Total Reduction in Bypass (%)** |
| Balometer Testing (1) | 280 | 22.0% | N.A. | N.A. | 280 | 22% |
| Temperature Mixing | 190 | 17.1% | 132 | 12% | 6 | 5.1% |
| Blocked Coil | 675 | 64.3% | 298 | 27.4% | 60 | 36.9% |

Due to problems with the balometer testing, described in the report, all balometer measurements are relative to the baseline test. We presume that there is in fact additional bypass that was not measured, but just do not know for sure.

**Table A-19: Site #4 Efficiency increase as a result of air sealing (cooling mode)**

| Efficiency (Cooling Mode) | |
|---|---|
| **Test** | **Efficiency (EER)** |
| 1) Baseline | 6.37 |
| 2) Holes at the corners of the front panel made during installation | 6.59 |
| 3) Gap around the edges of the front panel and bottom left corner | 6.73 |
| 4) Electrical switches and Schrader valves | 6.94 |
| 5) Pipe penetrations through the rear of the cabinet | 7.16 |

**Table A-20: Site #4 Efficiency increase as a result of air sealing (heating mode)**

| Efficiency (Heating Mode) | |
|---|---|
| **Test** | **Efficiency (COP)** |
| 1) Baseline, before sealing | 1.66 |
| 2) After sealing | 1.93 |

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