# Impact of Installation Faults on Heat Pump Performance

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*Numerous studies and surveys indicate that typically-installed HVAC equipment operate inefficiently and waste considerable energy due to varied installation errors (faults) such as improper refrigerant charge, incorrect airflow, oversized equipment, and leaky ducts. This article summarizes the results of a large United States (U.S.) experimental/analytical study (U.S. contribution to IEA HPP Annex 36) of the impact that different faults have on the performance of an air-source, single-speed heat pump (ASHP) in a typical U.S. single-family house. It combines building effects, equipment effects, and climate effects in an evaluation of the faults' impact on seasonal energy consumption through simulations of the house/ASHP pump system.*

## Introduction

The U.S. technical contribution to Annex 36 (Domanski et al., 2014) explores the impact that typical installation faults have on the performance of a single-speed, 8.8 kW (2.5-ton), ducted, split-system ASHP installed in a single-family house; rated seasonal cooling and heating performance factors (SPFc and SPFh) of 3.81 W/W and 2.26 W/W (U.S. SEER and HSPF of 13 Btu/Wh and 7.7 Btu/Wh), respectively. The laboratory/modeling project combined building, equipment, and climate effects in a comprehensive evaluation of the impact of installation faults on annual energy consumption of the ASHP via seasonal simulations of the house/heat pump system. Faults were evaluated both individually and in combination. The fault parameters evaluated in the study are listed in Table 1. The fault parameters were based on the requirements found in the ANSI/ACCA 5 QI – 2010 Standard "HVAC Quality Installation Specification" (ACCA, 2010), along with two additional faults: excessive liquid line refrigerant subcooling and undersized field-installed thermal expansion valve (TXV). The annual energy consumption analyses were conducted for two different house types (one with a slab foundation and a second with basement foundation) in five locations representative of the range of U.S. climate condition.

*Table 1. Studied faults, definitions, and fault ranges [Source: Domanski et al, 2014]*

| Fault name | Symbol | Definition of fault level | Fault levels (%) |
|---|---|---|---|
| Improper indoor airflow rate | AF | % above or below correct airflow rate | CM: -36, -15, +7, +28<br>HM: -36, -15, +7, +28 |
| Refrigerant undercharge | UC | % mass below correct (no-fault) charge | CM: -10, -20, -30<br>HM: -10, -20, -30 |
| Refrigerant overcharge | OC | % mass above correct (no-fault) charge | CM: +10, +20, +30<br>HM: +10, +20, +30 |
| Excessive liquid line refrigerant subcooling (indication of improper refrigerant charge) | SC | % above the no-fault subcooling value | CM: +100, +200<br>HM: none |
| Presence of non-condensable gases | NC | % of pressure in evacuated indoor section and line set, due to non-condensable gas, with respect to atmospheric pressure | CM: +10, +20<br>HM: +10, +20 |
| Improper electric line voltage | VOL | % above or below 208 V | CM: -8, +8, +25<br>HM: -8, +8, +25 |
| TXV undersizing | TXV | % below the nominal cooling capacity | CM: -60, -40, -20<br>HM: none |
| Duct leakage | DUCT | % of total equipment airflow that leaks out of the duct distribution system (60% supply leakage, 40% return leakage). | CM: +0, +10, +20, +30, +40, +50<br>HM: +0, +10, +20, +30, +40, +50 |
| Heat pump sizing | SIZ | % above or below optimum heat pump capacity | CM: -20, +25, +50, +75, +100<br>HM: -20, +25, +50, +75, +100 |
| | | | **Notes:** CM = Cooling Mode HM = Heating Mode |

### Laboratory Analysis

The undertaken laboratory analyses resulted in correlations that characterize the ASHP performance with no faults (baseline case) and with the first seven faults listed in Table 1. The last two faults in Table 1 were modeled only. Figures 1 and 2 illustrate the indoor and outdoor sections, respectively, of the ASHP as installed in the environmental test chambers at the U.S. National Institute of Standards and Technology (NIST). Figure 3 illustrates the measured impact of indoor air flow faults on the test heat pump COP. Full details and results of the lab tests may be found in Domanski et al. (2014).

Figure 1. ASHP test unit in chamber – indoor section

Figure 2. ASHP test unit in chamber – outdoor section

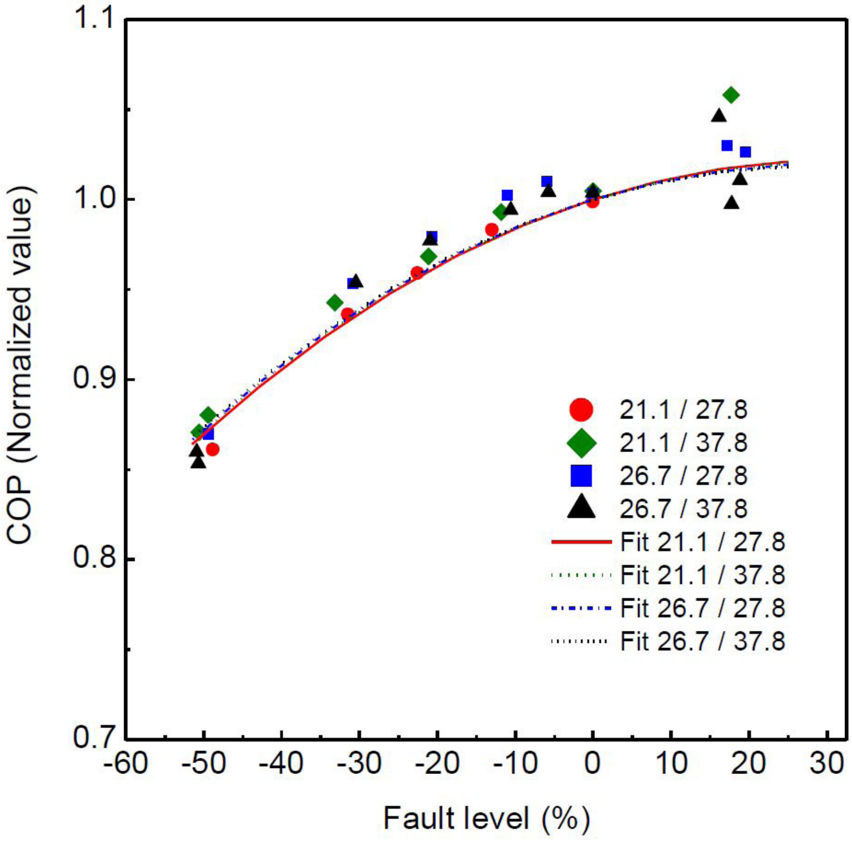

*Figure 3. ASHP measured cooling COP vs. faults in indoor airflow (from -50 % to +20 % of the design flow; the legend denotes indoor dry-bulb / outdoor dry-bulb temperatures, °C)*

## Simulations of Building / ASHP Systems with Installation Faults

These simulations, using the laboratory-determined performance correlations, estimated the annual energy consumption (combined heating and cooling) of the subject ASHP for both normal (baseline or no fault) operation and for various intensities of the studied installation faults. The simulations focused strictly on system performance issues; no effort was made to quantify impacts on occupant comfort, indoor air quality, noise generation (e.g., airflow noise from air moving through restricted ducts), equipment reliability/robustness (number of starts/stops, etc.), maintainability (e.g., access issues), or costs of initial installation and ongoing maintenance.

A building model developed in TRNSYS was used to simulate the integrated performance of the subject ASHP/house systems in this study (CDH Energy Corp., 2010). The model is driven by typical meteorological year weather data sets TMY3 (Wilcox and Marion, 2008) on a small time-step (e.g., 1.2 minutes).

A detailed thermostat model turns the heat pump "on" and "off" at the end of each time step, depending on the calculated space conditions. Table 2 lists the climates with representative locations and house structures considered in this study. The selected cities represent U.S. climate zones 2 through 6 as shown in Figure 4. This selection enabled prediction of how different faults will affect ASHP performance in the most prevalent climates in the U.S.

Two 190 m² (2,000 ft²) three-bedroom houses were modeled: a slab-on-grade house, and a house with a basement. A 2-zone model was employed for the slab-on-grade foundation house – living space and attic zones. A 3-zone model was developed for the basement foundation house – living space, attic, and basement zones. The basement was not directly conditioned, but coupled to the main living space via zone-to-zone air exchange. These buildings corresponded to code-compliant houses with appropriate levels of insulation and other features corresponding to each climate (Domanski et al., 2014). The slab-on-grade houses were modeled with air distribution ducts located in the attic. The houses with basements were modeled with ducts located in the semi-conditioned basement space. For Houston, TX, only a slab-on-grade house was studied because houses with basements are rarely built in this location.

*Table 2. Climates, locations and structures considered [Source: Domanski et al., 2014]*

| Zone | Climate | Location | Slab-on-grade house | House with basement |
|---|---|---|---|---|
| 2 | Hot and humid | Houston, TX | Yes | No |
| 3 | Hot and dry climate | Las Vegas, NV | Yes | Yes |
| 4 | Mixed climate | Washington, DC | Yes | Yes |
| 5 | Heating dominated | Chicago, IL | Yes | Yes |
| 6 | Cold | Minneapolis, MN | Yes | Yes |

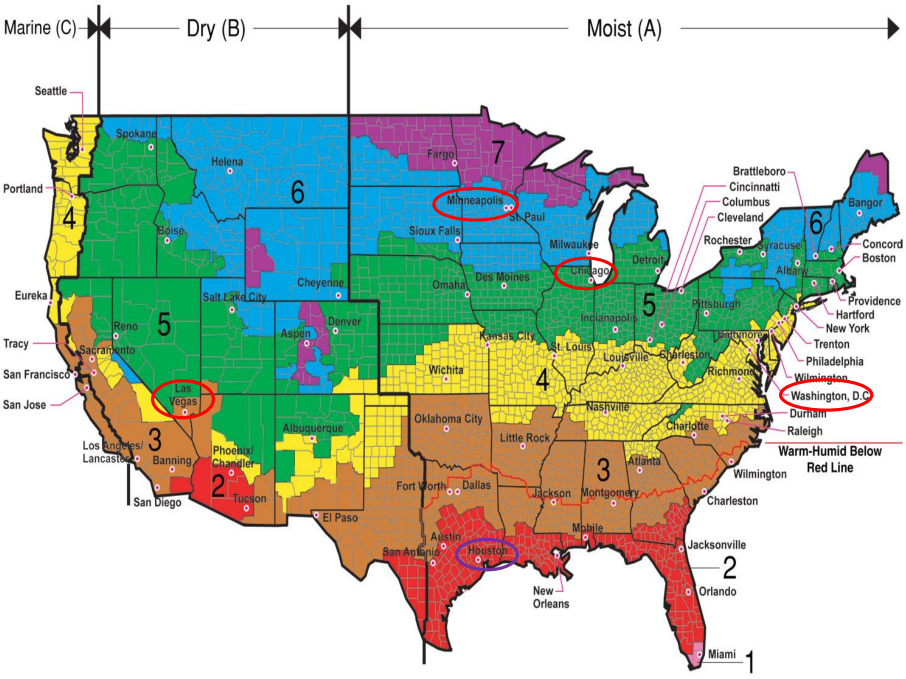

*Figure 4. U.S. climate zones with locations for simulation indicated*

## Impact of Single Installation Faults on Heat Pump Performance

Table 3 shows representative impacts of the studied faults on ASHP annual energy use (relative to "no fault" energy use). It is anticipated that the selected levels of individual faults reflect an installation condition which might not be noticed by a poorly-trained or inattentive technician.

In most cases, the effect of installation faults is similar for both house types. Duct leakage faults (DUCT) in the slab-on-grade house can cause the highest increase in energy use among the faults studied, especially in the colder locations. It is expected that duct leakage will also result in some increase of energy use for the basement house; however, the modeling approach employed could not discern this increase.

The next most influential faults were refrigerant undercharge (UC), refrigerant overcharge (OC), and improper airflow across the indoor coil (AF). For the 30 % undercharge fault (UC) level, the energy use increase is on the order of 20 %, regardless of the climate and building type. Refrigerant overcharge (OC) can also result in a significant increase in energy use, 10 - 16 % at the 30 % overcharge fault level. Improper indoor airflow (AF) can affect similar performance degradation. [Note: Excessive refrigerant subcooling (SC) correlates to refrigerant overcharge (OC); 100 % subcooling is approximately equivalent to 20 % refrigerant overcharge.] An oversized heat pump (SIZ) coupled with undersized air ducts can cause >10 % energy use increases in the hot climate locations. The undersized cooling TXV fault (TXV) also has the potential to significantly increase the energy use in the hot locations.

*Table 3. Annual energy use impacts for an ASHP due to each individual studied installation fault vs. a fault-free installation [Derived from: Domanski et al., 2014)]*

| Fault type | Fault level | Relative energy use (%) [100 is baseline] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Slab-on-grade house installation (Air ducts located in unconditioned attic) | | | | | Basement house installation (Air ducts in conditioned basement) | | | |
| | **%** | **HOU** | **LV** | **WAS** | **CHI** | **MIN** | **LV** | **WAS** | **CHI** | **MIN** |
| AF | **- 36** | 112 | 113 | 114 | 113 | 111 | 111 | 112 | 112 | 110 |
| UC | **- 30** | 121 | 122 | 123 | 120 | 117 | 120 | 121 | 119 | 117 |
| OC | **+ 30** | 110 | 110 | 114 | 113 | 112 | 111 | 116 | 115 | 113 |
| SC | **+ 200** | 118 | 116 | 119 | 118 | 116 | 118 | 120 | 120 | 119 |
| NC | **+ 10** | 102 | 102 | 101 | 101 | 101 | 102 | 101 | 101 | 101 |
| VOL | **+ 8** | 102 | 101 | 102 | 102 | 101 | 101 | 102 | 102 | 102 |
| TXV | **- 40** | 114 | 110 | 107 | 105 | 107 | 109 | 105 | 103 | 102 |
| DUCT | **+ 30** | 118 | 117 | 124 | 126 | 126 | 100* | 100* | 100* | 100* |
| SIZ# | **+ 50** | 115 | 113 | 105 | 101 | 99 | 114 | 108 | 104 | 102 |

U.S. cities included in the study: **HOU** → Houston, TX **LV** → Las Vegas, NV **WAS** → Washington, DC **CHI** → Chicago, IL **MIN** → Minneapolis, MN

* duct leakage into basements assumed to have no energy impact

\# coupled with undersized air ducts

*Table 4. Combinations of studied faults [Source: Domanski et al., 2014]*

| Fault combination case | Level of fault A | Level of fault B |
|---|---|---|
| A | Moderate | Moderate |
| B | Moderate | Vorst |
| C | Worst | Moderate |
| D | Worst | Worst |

*Table 5. Impact of combined refrigerant undercharge and air duct leakage faults on ASHP energy use in three U.S. locations*

| Air duct leakage + low refrigerant charge (Houston) | | 20% Duct leakage | 40% Duct leakage |
|---|---|---|---|
| | | 109% | 128% |
| 15% Undercharge | 105% | **115%** | **136%** |
| 30% Undercharge | 121% | **132%** | **156%** |
| **Air duct leakage + low refrigerant charge (Washington, DC)** | | **20% Duct leakage** | **40% Duct leakage** |
| | | 112% | 139% |
| 15% Undercharge | 105% | **117%** | **146%** |
| 30% Undercharge | 123% | **137%** | **172%** |
| **Air duct leakage + low refrigerant charge (Minneapolis)** | | **20% Duct leakage** | **40% Duct leakage** |
| | | 113% | 140% |
| 15% Undercharge | 103% | **116%** | **144%** |
| 30% Undercharge | 117% | **132%** | **162%** |

## Impact of Dual Installation Faults on Heat Pump Performance

The combination of two faults, A and B, were considered in the following four combinations as listed in Table 4 above.

The 'moderate level' is the value at the middle of the range, while the 'worst level' is the highest (or lowest) probable level of the fault value (see Table 1). In the full study (Domanski et al., 2014), simulations of 14 fault combinations were conducted: duct leakage coupled with system oversizing, restricted air flow, refrigerant overcharge or undercharge, or noncondensible gases; system oversizing coupled with refrigerant undercharge or overcharge, or noncondensible gases; restricted air flow coupled with refrigerant undercharge or overcharge, or noncondensible gases; and undersized TXV coupled with duct leakage, system oversizing, or restricted airflow. The results indicated that the impact of combinations of two faults on annual energy use may be additive (A+B), less than additive (<A+B), or greater than additive (>A+B). Figure 5 illustrates simulation results for the combination of duct leakage and refrigerant undercharge for Houston, Washington, and Minneapolis (spanning the range of U.S. climate conditions from hot to very cold). For the lower refrigerant undercharge fault, the combined impact is approximately additive in all locations. At the greater undercharge fault level, the combined impact is slightly amplified.

## Selected Findings

Extensive simulations of house/heat pump systems in five U.S. climatic zones lead to the following conclusions:

- Duct leakage, refrigerant undercharge, oversized heat pump with undersized ductwork, low indoor airflow due to undersized ductwork, and refrigerant overcharge have the most potential for causing significant performance degradation and increased annual energy consumption.
- The effect of different installation faults on annual energy

use is similar for a slab-on-grade house and a basement house, except for the duct leakage fault.

- The effect of two simultaneous faults can be additive (e.g., duct leakage and non-condensable gases), little changed relative to the single fault condition (e.g., low indoor airflow and refrigerant undercharge), or beyond additive (e.g., duct leakage and refrigerant undercharge).
- The laboratory and modeling results from this fault analysis on an 8.8 kW (2.5 ton) heat pump are considered to be representative of all unitary equipment, including commercial split-systems and single package units.

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