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Research paper

Effect of heat pump commissioning faults on energy use in a slab-on-grade residential house

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HIGHLIGHTS

- Commissioning faults in a heat pump installation were simulated.
- Duct leakage, refrigerant undercharge, and others faults are the significant.
- Multi-fault effects may be additive, negligible, or much more than additive.

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ABSTRACT

This study seeks to develop an understanding of the effect of commissioning common faults on the energy consumption of an air-to-air heat pump installed in a single-family, slab-on-grade residential house. Through annual simulations of the house/heat pump system, the study found that duct leakage, refrigerant undercharge, oversized heat pump with nominal 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. Depending on the faults involved, the effects of simultaneous faults were found to be additive, little changed relative to the single fault condition, or well-beyond additive. A significant increase in annual energy use can be caused by lowering the thermostat setting in the cooling mode to improve indoor comfort in cases of excessive indoor humidity levels due to installation faults.

1. Introduction

Space cooling is responsible for the largest share (21.3%) of the electrical energy consumption in the U.S. residential sector [1]. Space heating, for which a significant portion is provided by heat pumps, accounts for an additional 8.7% electricity use. Consequently, there are increasing requirements that space-conditioning equipment be highly efficient to improve building energy efficiency as well as address environmental concerns. To this end, state and municipal governments and utility partners have implemented various initiatives that promote sales of high-efficiency air conditioners and heat pumps. However, there is a growing recognition that merely increasing equipment's laboratory-measured efficiency without ensuring that the equipment is installed and operated correctly in the field is ineffective.

This paper discusses the effect of different commissioning faults on heat pump performance for a single-family, residential, slab-on-grade house. The results presented here were derived from a comprehensive and detailed study by Domanski et al. [2].

2. Installation and maintenance issues

Numerous field studies have documented degraded performance and increased energy usage for typical air conditioners and heat pumps installed in the United States. For example, Proctor [3] performed measurements on a sample of 28 air conditioners newly installed in 22 residential homes in a hot-and-dry climate. Indoor heat exchanger airflow averaged 14% below specifications, and only 18% of the systems had a correct amount of refrigerant. The supply duct leakage averaged 9% of the air handler airflow, and the return leakage amounted to 5%. Rossi [4] presented measured performance data on unitary air conditioners based on observations from routine maintenance and service visits. Out of 1468 systems

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considered in this study, 67% needed service. Of those 15% required major repairs (e.g., compressor or expansion device replacement), and 85% required a tune-up type service (e.g., coil cleaning or refrigerant charge adjustment). Approximately 50% of all units operated with efficiencies of 80% or less, and 20% of all units had efficiencies of 70% or less of their design efficiency. Among others, Parker et al. [5] and Mowris et al. [6] also provided data on performance degradation of air conditioners and heat pumps due to different faults.

3. Technical approach of the study

3.1. Scope

To evaluate the effect of different commissioning faults on energy consumption, we performed annual simulations of energy use by an air-to-air heat pump installed in a slab-on-grade house. We used the annual energy use in a fault-free installation as a reference for normalizing energy use in faulty installations and for indicating the impact of specific faults on energy consumption. The parameters considered in the simulations included duct leakage (unconditioned space), heat pump sizing, indoor coil airflow, refrigerant charge, presence of non-condensable gases, electrical voltage, cooling-mode TXV undersizing, and five US climate zones 2 through 6 from a hot-and-humid climate to a cold climate, represented by five cities (Table 1). We used a building model developed in TRNSYS to simulate the integrated performance of heat pumps in residential applications [7]. The model is driven by typical meteorological year weather data sets TMY3 [8] on a small time-step (e.g., 1.2 min). A detailed thermostat model turns the mechanical systems "on" and "off" at the end of each time step depending on the calculated space conditions.

3.2. Building specifications

The simulated residential building corresponded to a code-compliant house with a Home Energy Rating System (HERS) score of approximately 100 [10] with appropriate levels of insulation and other features corresponding to each climate. It was a 185.8 m^2 three-bedroom structure with a separate attic zone, which was not conditioned (Fig. 1). It had perimeter slab insulation in climate zones 4 and 5. A 'fictitious layer' was added into the resistance between the zone and ground temperature. This fictitious R-value was used to provide the amount of heat loss through the surfaces determined by the F-factor method ($R_{\text{effective}}$), as recommended by Winkelmann [11].

The above-ground portions of the houses had exterior walls with layers of drywall, insulation (R(SI)-2.3 or R(SI)-3.3, depending on the climate zone), and stucco as the outside surface. Windows took up approximately 22% of all of the exterior walls; 10.2 m^2 on the north and south facing walls, and 6.5 m^2 on east and west facing walls. The ceiling (i.e. boundary between main zone and attic) was made up of a layer of drywall, framing and insulation (R(SI)-5.3 or R(SI)-6.7, depending on the climate zone). The attic had gable walls on the east and west sides and roof surface on the north and south sides. The roof was sheathed in plywood and then covered with asphalt shingles. The east and west surfaces (gables) are made up of plywood on the inside surface with stucco on the outside surface.

The AIM-2 infiltration model [12,13] relates infiltration to wind and indoor–outdoor temperature difference for each time step. An equivalent leakage area (ELA) of 0.0633 m^2 was chosen to provide the desired seven air changes per hour (ACH) at 50 Pa pressure differential (ACH50 for the main zone in each building model). The attic used the same AIM-2 equations to determine leakage as a function of wind and temperature difference. The attic ELA was set to be 0.366 m^2 for each of the climate zones, or about 5 times the leakage rate for the HERS 100 house [14].

The ducts were modeled to be in the attic space and all the air leakage and thermal losses/gains go into that zone. Duct leakage was assumed to be 10% of flow; 6% on the supply side and 4% on the return side. Duct insulation was assumed to be R(SI)-1.1 with a supply duct area of 50.5 m^2 and a return duct area of 9.3 m^2 for a 10.6 kW heat pump nominal cooling capacity. The nominal duct areas were increased and decreased proportionally based on the size (or nominal tonnage) of the heat pump unit.

The window model in Type 56 uses the window parameters generated by LBNLs WINDOW5 software, which is considerably more detailed than the NFRC rating values generally used in residential practice and building codes. The LBNL WINDOW5 inputs for this project were determined following the methodology developed by Arasteh et al. [15].

The scheduling or profile of internal heat and moisture generation was taken from the Building America Benchmark Definition [16]. Sensible gains from all sources were assumed to be 76.7 MJ/day. Internal moisture generation from all sources was specified as 5.4 kg/day, or less than half of the ASHRAE Standard 160 moisture generation rate of 14.2 kg/day for a three-bedroom house [17]. The ASHRAE 160 value is meant to be a 'worst case' design condition and therefore does not correspond to average conditions.

The only mechanical ventilation option considered in this study is an exhaust fan. The fan operated continuously to provide sufficient ventilation to the house. The fans provided an average flow rate of 98.5 m^3 h^1 required by ASHRAE Standard 62.2 [18] for the 185.8 m^2 three-bedroom house. The exhaust fan power was assumed to be 0.85 kJ m^{-3}. The duct leakage was always a net out, so that additional net flow was an exhaust. All detailed house design specifications are given by Domanski et al. [2].

3.3. Heat pump specifications and modeling

Fault effects were measured and correlated for a conventional heat pump unit with a 13 SEER and 7.7 HSPF rating. The cyclic degradation coefficient, C_D, of the heat pump was approximately 0.15 in both cooling and heating mode. For determining the performance of a faulty heat pump, we applied dimensionless multipliers to the fault-free heat pump performance parameters

Table 1
IECC US climates and locations considered with thermostat set points and electricity cost.

Zone	Climate	Location	Thermostat set point (°C)		Electricity cost	
			Cooling	Heating	$/MJ	$/kWh
2	Hot and humid	Houston, TX	25.6	22.2	0.306	0.085
3	Hot and dry climate	Las Vegas, NV			0.454	0.126
4	Mixed climate	Washington, DC	24.4	21.1	0.508	0.141
5	Heating dominated	Chicago, IL			0.461	0.128
6	Cold	Minneapolis, MN			0.389	0.108

Note: Electric costs from Form 826 data for local utility in 2010 for residential sector [9].