Field testing of two prototype air-source integrated heat pumps for net zero energy home (nZEH) application

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Integrating multiple functions into a single system offers potential efficiency and cost reduction benefits. Oak Ridge National Laboratory (ORNL) and its partners have designed, developed, and tested two air-source heat pump designs that not only provide space heating and cooling, but also water heating, dehumidification, and ventilation functions. Details on the design, simulated performance, prototype field test, measured performance, and lessons learned are provided.

Introduction

The US Department of Energy's Building Technologies Office (DOE-BTO) defines a net zero energy building (nZEB) as "an energy-efficient **building** where, on a **source energy** basis, the actual **annual delivered energy** is less than or equal to the on-site renewable **exported energy**" [1]. Achieving nZEB performance requires both maximizing the building envelope efficiency and minimizing energy use for space heating and cooling (SH, SC), water heating (WH), and indoor humidity control. ORNL has been working with BTO and manufacturer partners to develop advanced integrated heat pump (IHP) technologies to help meet this challenge.

Systems description

An IHP is a heat pump system with multiple functions - e.g., SH, SC, WH, dehumidification (DH), etc. This article summarizes the development and field testing of two prototype air-source integrated heat pumps (AS-IHPs). One (AS-IHP 1) uses a single variable speed (VS) compressor and fans, illustrated schematically in Figure 1. An optional ventilation (V) air intake can be included to provide pre-conditioned fresh air through the heat pump air handler section. However, the field test prototype did not include dedicated V or DH modes [2]. Figure 2 is a photograph of the prototype in the field test house in Knoxville, TN, USA.

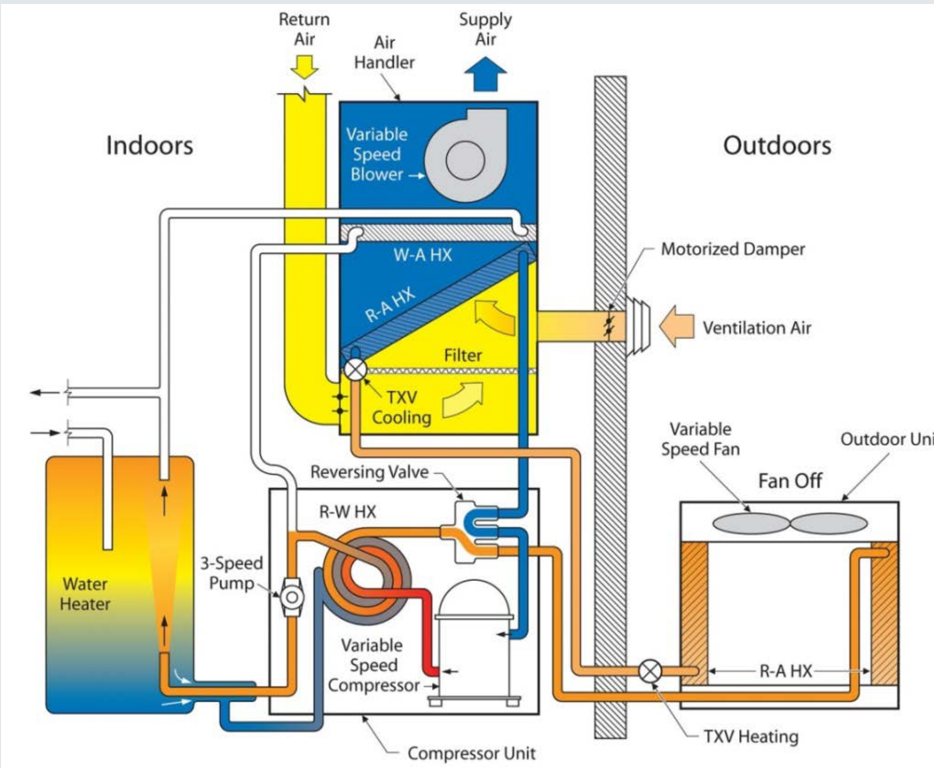

Figure 1. AS-IHP 1 concept schematic.

Figure 2. AS-IHP 1 field test prototype installation; left) indoor sections (hot water storage tank, compressor and water heating module, and indoor fan coil), right) outdoor section.

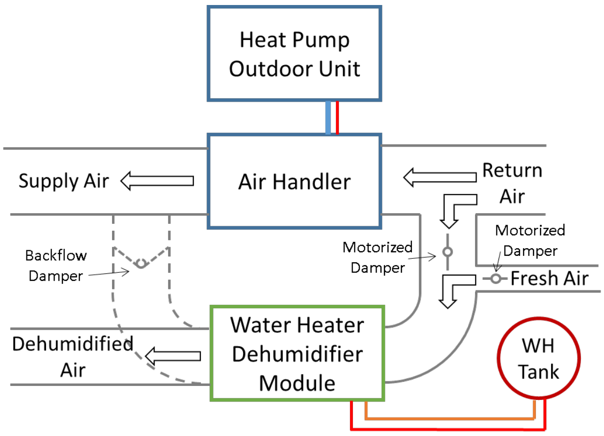

Figure 3. AS-IHP 2 concept schematic.

The second configuration (AS-IHP 2) combines a commercially available high-efficiency air-source heat pump (ASHP) with a separate prototype module for WH, demand DH, and V control - WH/DH module [3], see Figure 3. The major components of the prototype WH/DH are a single-speed compressor and water pump, a VS fan, and separate condensers for WH and DH modes. It included a solid-state microcontroller to manage competing WH and DH demands, with WH having priority. The VS blower uses the same speed for WH and DH but slows down for controlled fresh-air ventilation. As shown in Figure 3, the WH/DH module may be integrated with the ASHP unit via connections to the air handler return and supply duct work. When operating in WH or DH mode, it pulls air from the ASHP return duct and discharges it to either the supply duct or directly to the conditioned space (the configuration used in the field test). It operates in V mode when there is no WH or DH call, to ensure that adequate fresh air is supplied to the home. Figure 4 shows the indoor sections of AS-IHP 2 field test system.

Figure 4. AS-IHP 2 field-test prototype in installation process.

The separate WH/DH module for the AS-IHP 2 system also allows maximum flexibility for retrofit applications. If an existing WH tank is remote from the ASHP system, the WH/DH unit can be co-located with the tank, thus upgrading the WH to a combined WH/DH and V appliance. But integration with the ASHP return duct may not be possible in this case.

AS-IHP development and field test summary

AS-IHP 1

We worked with Nortek Global HVAC, Inc. (formerly Nordyne) to develop the design and build two lab test prototypes. The lab test results were used to calibrate a detailed heat pump simulation model [4] for the system to generate performance maps. These maps were input to a TRNSYS [5] simulation to estimate annual energy savings for a high efficiency ~240 m^2 house with a 7 kW design SC load in several locations. Table 1 summarizes the performance predictions for AS-IHP 1 vs. a baseline consisting of a minimum efficiency ASHP ($SCOP_c$ of 3.8 and $SCOP_h$ of 2.3) and an electric WH with rated energy factor (EF) of 0.9. Electric resistance backup energy use for SH was zero in all locations except Chicago where it was ~12 % of the total SH energy use.

A field test prototype based on the final lab test system (design cooling capacity of 10.6 kW) was installed in a 223 m^2 test house and monitored from May 2014 to May 2015. The house was unoccupied but occupancy and domestic hot water loads were simulated as described in [2] and [3].

Two baseline systems were field tested during 2011-2012 in the same area (at a different but similar-size house) achieving an average measured $SCOP_h$ of 1.65 and $SCOP_c$ of 2.29. AS-IHP 1 field test results are compared to the base systems' field performance in Table 2. Since the tank and hot water distribution line losses were not included in the AS-IHP 1 field performance, they are also omitted from the baseline (e.g. baseline WH COP = 1.0). The largest savings come from WH, at 61 % or 1905 kWh. SC and SH energy savings are estimated at 1800 kWh (55 %) and 1461 kWh (20 %), respectively. Estimated total annual savings for AS-IHP 1 vs. baseline at the Knoxville test site were about 38 %. It must be noted that the field test house thermal envelope performance was much poorer than that of the house used in the performance predictions shown in Table 1 [2]. Figure 5 shows the field measured SH

Table 1. Predicted annual energy savings for AS-IHP 1 based on lab tested performance.

CITY	BASELINE SYSTEM	AS-IHP 1	
	Energy use, kWh	Energy use, kWh	Percent savings
Atlanta	7 361	3 433	53.4 %
Houston	6 476	2 960	54.3 %
Phoenix	14 676	3 543	47.1 %
San Francisco	7 351	2 019	61.1 %
Chicago	11 209	6 066	45.9 %

Table 2. AS-IHP 1 2014-2015 performance vs. estimated baseline performance at test site.

	AS-IHP	ESTIMATED BASELINE PERFORMANCE	PERCENT SAVINGS
Space cooling			
Load (kWh)	7 416	7 416	
Energy used (kWh)	1 444	3 244	55 %
Space heating			
Load (kWh)	12 125	12 125	
Energy used (kWh)	5 899	7 360	20 %
Water heating			
Load (kWh)	3 104	3 104	
Energy used (kWh)	1 199	3 104	61%
TOTALS			
Energy used (kWh)	**8 542**	**13 708**	**38 %**

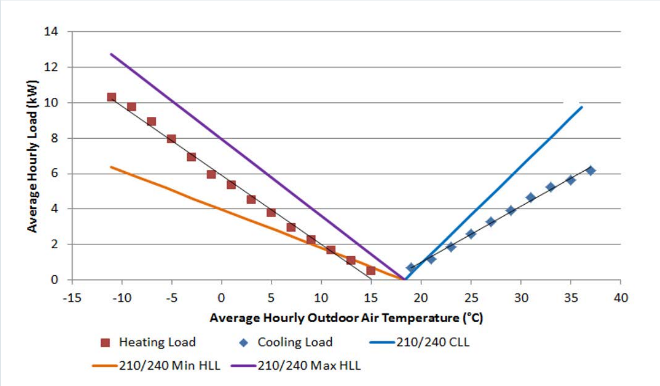

Figure 5. Field-test house 2015–2016 heating and cooling load lines vs. Ref [6] load lines.

and SC load lines (LL) for the test house compared to standard LLs from the U.S. ASHP rating standard [6]. The measured SH LL is seen to be closer to the maximum SH LL, but the house used for the Table 1 analyses had an SH LL closer to the minimum LL from [6]. Thus, back-up SH energy use was higher than expected; ~26 % of the total SH energy use. This and higher indoor blower energy usage (vs. lab measured performance) negatively impacted the SH performance of the field prototype system.

AS-IHP 2

We worked with Lennox Industries, to develop the WH/DH design and build two lab test prototypes. Test results were used to calibrate a WH/DH model [4]. Performance maps for the WH/DH and a high-efficiency, commercially available ASHP were generated for input to TRNSYS to estimate annual energy savings. For these simulations a two-speed ASHP ($SCOP_c$ of 5.4 and $SCOP_h$ of 2.7; design SC capacity of 7 kW) was coupled with the WH/DH module. The simulations were made for

Table 3. Predicted annual energy savings for AS-IHP 2 based on lab tested performance.

CITY	BASELINE SYSTEM	AS-IHP 2	
	Energy use, kWh	Energy use, kWh	Percent savings
Atlanta	7 941	5 071	36.0 %
Houston	8 187	5 264	35.7 %
Chicago	11 514	7 762	32.6 %

Table 4. AS-IHP 2 2015-2016 performance vs. estimated baseline performance at test site.

	AS-IHP	ESTIMATED BASELINE PERFORMANCE	PERCENT SAVINGS
Space cooling + DH			
Load (kWh)	9 189	9 189	
Energy used (kWh)	2 201	4 013	45 %
Space heating			
Load (kWh)	11 561	11 561	
Energy used (kWh)	5 225	7 061	26 %
Water heating			
Load (kWh)	2 739	2 739	
Energy used (kWh)	1 146	2 739	58 %
TOTALS			
Energy used (kWh)	**8 572**	**13 813**	**38 %**

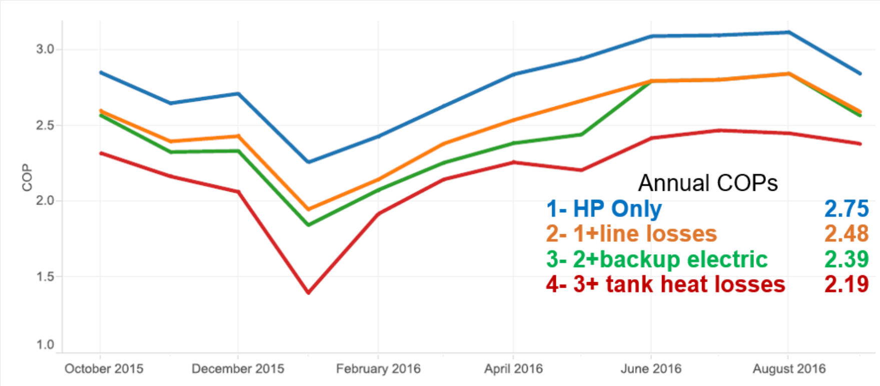

Figure 6. Monthly average WH mode COPs of the WH/DH module. Note: HP – heat pump.

the same house model as used for AS-IHP 1 but only in locations having significant year-round DH loads. Table 3 summarizes the performance predictions. In this case backup SH energy was ~1.5 % of total SH in Atlanta and ~14 % in Chicago. Since AS-IHP 2 includes the demand DH and V functions, the baseline system included a standalone dehumidifier (with rated energy factor (EF) of 1.4 litre/kWh) and V fan in addition to the minimum efficiency ASHP and electric WH.

A field test prototype based on the final WH/DH lab prototype coupled with a variable speed ASHP ($SCOP_c$ of 6.3 and $SCOP_h$ of 2.9; design SC capacity of 10.1 kW) was installed in the same house as AS-IHP 1 and tested from Oct. 2015 to Oct. 2016.

AS-IHP 2 field results are compared to its base systems in Table 4, with SC and demand DH combined. The base system ASHP is assumed to meet the same total SC and DH loads as the AS-IHP 2 prototype. The table shows that the largest savings come from WH, at 58 % (1593 kWh). SC+DH and SH energy savings are estimated at 1812 kWh (45 %) and 1836 kWh (26 %), respectively. Estimated total annual energy savings vs. the baseline at the Knoxville test site were about 38 %. Again, the relatively poor SH performance of the house envelope resulted in higher back up energy use than expected; ~24 % of the total SH energy use.

Figure 6 summarizes WH mode COPs for the WH/DH (heat pump) only, heat pump with tank-to-WH/DH connecting line losses (~10 %), with backup resistance use (~5 % of total WH energy use), and entire WH/DH system including WH tank heat losses. There were no hot water draws for 20 days in January causing the dip in efficiency that month.

The WH/DH did an excellent job of maintaining the house RH <55 % year-round, with an average annual efficiency of 1.7 L/kWh. Re-evaporation of evaporator coil condensate during V mode degraded DH mode efficiency. Adjustment of the controls to minimize V air flow significantly reduced the re-evaporation and led to reduced DH mode runtime.

Conclusions

Integrated heat pumps have the potential to reduce space conditioning, water heating, dehumidification, and ventilation energy use by 40-60 % over minimum efficiency equipment. Two different system designs were presented and field tested by ORNL and its partners with promising results. Field performance would have shown better results if the test house had better thermal envelope performance (e.g., near-zero-energy ready). Additional work on equipment packaging and optimizing controls is needed to further advance the designs toward commercial products.

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