

INTEGRATED HEAT PUMPS FOR COMBINED SPACE CONDITIONING AND WATER HEATING

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ABSTRACT

The efficiencies of U.S. heat pumps as well as markets for high efficiency heat pumps continue to grow in the U.S. Heat pumps, however, are of much more value when there is a coincident need for the heating and cooling produced by the heat pump. Some opportunities for simultaneous heating and cooling are:

- Combined heat pump space heating, cooling, water heating, and dehumidification
- Cool air from heat-pump water heating used for space cooling
- Exhaust heat from refrigeration and freezing used for space heating and hot water.

With the support of DOE, U.S. manufacturers and state organizations, research is underway on combined or integrated heat pump systems that provide space conditioning and produce domestic hot water efficiently. Integrated systems are targeted to be part of the solution in the development of Zero Energy Housing. This paper discusses current activities, results and findings of sponsored U.S. research to develop an advanced integrated heat pump that provides space heating, cooling, dedicated dehumidification and water heater, and a water-heating dehumidifier for retrofit applications.

Key Words: *integrated heat pumps, dehumidification, cooling, heating, water heating*

1 INTRODUCTION – TRENDS LEADING TO INTEGRATED SYSTEMS

Residential and commercial building energy consumption in the U.S. constitutes about one-third of the total energy consumption of the nation. The U.S. Department of Energy is interested in securing major reductions in the overall energy consumption of buildings through research on affordable equipment for both residential and commercial buildings. This research is focused on reducing building loads as well as on developing heating, ventilating and air conditioning (HVAC) systems that have efficiencies well-above what is currently available in today's market. How far can this process go? Although it is possible for a building to be a net producer of electrical energy on an annual basis, a practical goal, however, is the net-zero energy building (ZEB) where, on average for the year, the primary energy consumption of the building (including all purchased energy) is zero. That is, by using photovoltaics, the building produces as much primary energy as it consumes over a year. To be sure, reaching this goal is not a technical challenge; however, reaching this goal in an affordable fashion is a major challenge.

There are building trends in the U.S. that confound the approach to the ZEB as well as help it. On the plus side, HVAC equipment efficiencies continue to improve. Beginning January 2006, the floor for residential heat pump efficiencies will be raised by approximately 30%. At that time, the minimum cooling efficiency will be SEER 13 (tantamount to a seasonal cooling COP = 3.8), and heating efficiency, HSPF = 7.7 (COP = 2.3). SEER and HSPF are Seasonal Energy Efficiency Ratio and Heating Seasonal

Performance Factor respectively and have units of Btu/W-h. Today's highest efficiency system has a SEER rating of 19.6; however, the market for this system is quite small. Thermal loads normalized to floor areas have become smaller as houses have been made tighter through improved construction practices and products that reduce thermal losses and air infiltration from outside. The advantages of having forced air ducting in the conditioned space where thermal losses drop to zero and any leakage is due only to unbalanced pressures in supply and return ducting have been re-discovered. With ducts fully in the conditioned space, heating and cooling loads are reduced, and many new homes are being constructed with ducts in the conditioned space.

Tighter house construction can reduce uncontrolled infiltration of outside fresh air to the point that mechanical ventilation systems may be required. Although there are variations, many of these systems designed to meet the fresh air requirements as outlined in ASHRAE Standard 62.2, bring ventilation air to space-neutral conditions prior to releasing it into the building, and they require energy. Finally, there is a trend in the U.S. towards larger houses: newly built houses are 26% larger (floor area) than the existing housing stock, and this suggests that the energy needed to heat and cool these buildings will be higher as well.

Water heating constitutes about 14% of the total energy consumption of homes in the U.S. If water heating efficiencies remain unchanged, and heating, cooling, and lighting loads drop by 50% due to tighter construction, better shell insulation, high-efficiency windows, and use of fluorescent lighting, the fraction of total home energy consumption used by the water heater rises to 21%. This assumes that the efficiency of storage water heaters (by far the most prevalent type of water heater in the U.S.) remains unchanged from the existing stock of water heaters. Although DOE Minimum Efficiency Standards raised the minimum efficiency of storage water heaters available in the market by about 10% starting January 2005, there is clear evidence that the efficiencies of water heaters, particularly electric, have about topped out. The Energy Factor (a measure of water heater efficiency) of today's most efficient electric storage water heater is 0.95, and analyses have shown that the practical efficiency limit for this type of water heater is 0.98 (the remaining 2% is due to thermal losses from the electrical wiring associated with the water heater). A heat pump water heater (HPWH), however, is able to overcome this limit by drawing energy from the ambient air surrounding the HPWH through a vapor compression cycle to heat the stored water. Experiments, field studies and laboratory development over a number of years has shown that the typical delivered efficiency of an HPWH is 2.0+ based on the heat delivered to the homeowner and the electrical energy into the device. Moreover, the HPWH produces cooling and some dehumidification that can be beneficial depending on the location of the HPWH in the house (and the relative duration of the cooling vs. heating season). However, several major barriers to wider use of the HPWH in the U.S. remain including (1) high first cost – typically in the \$1000 range, (2) unfamiliarity with the HPWH both on the part of the distributor/dealer/installer and the ultimate consumer, (3) lack of an infrastructure for marketing, selling and servicing the HPWH, (4) application limitations due to the space and location for the water heater, and (5) an incremental cost that must be justified through energy savings that are highly dependent on hot water consumption which is driven principally by the number occupants in the house. Although significant efforts have been made most recently by manufacturers, state agencies, DOE and others to develop a HPWH that is reliable and efficient, the other barriers remain and are not easily overcome. One way to remove these barriers is to combine the heat pump system used to provide space conditioning with a water-heating function thereby leveraging the efficient heat pumping process to heating water as well as space conditioning. Although an integrated heat pump (heating, cooling and water heating) is not new, advanced buildings under construction today as well as buildings on the path to the ZEB will need the benefits that an IHP of the proper design can deliver, and these include efficient space heating and cooling, efficient water heating, space dehumidification particularly at times when sensible loads are small and latent loads especially from the mechanical ventilation air system, are large.

2 DESIGN OF AN INTEGRATED HEAT PUMP

Based on the need for an integrated heat pump (IHP) that delivers space heating and cooling, water heating and dedicated dehumidification, ORNL selected the design illustrated in Figure 1 for evaluation. A principal difference from prior designs is the capability for continuous ventilation of the house during all seasons including low-load times when the ventilation air would need only to be dehumidified. This concept uses one modulating compressor, two variable-speed (VS) fans, and heat exchangers including two air-to-refrigerant, one water-to-refrigerant, and one air-to-water to meet all the HVAC and water-heating loads. The air-to-water HX uses excess hot water generated in the cooling and the dehumidification modes to temper the ventilation air, as needed, to provide space-neutral conditions. Compressor or indoor fan speed and water pump speed control would be used to control both humidity levels and indoor temperature, when needed. (Note from Figure 1 that both water heating and air tempering can be done at the same time.)

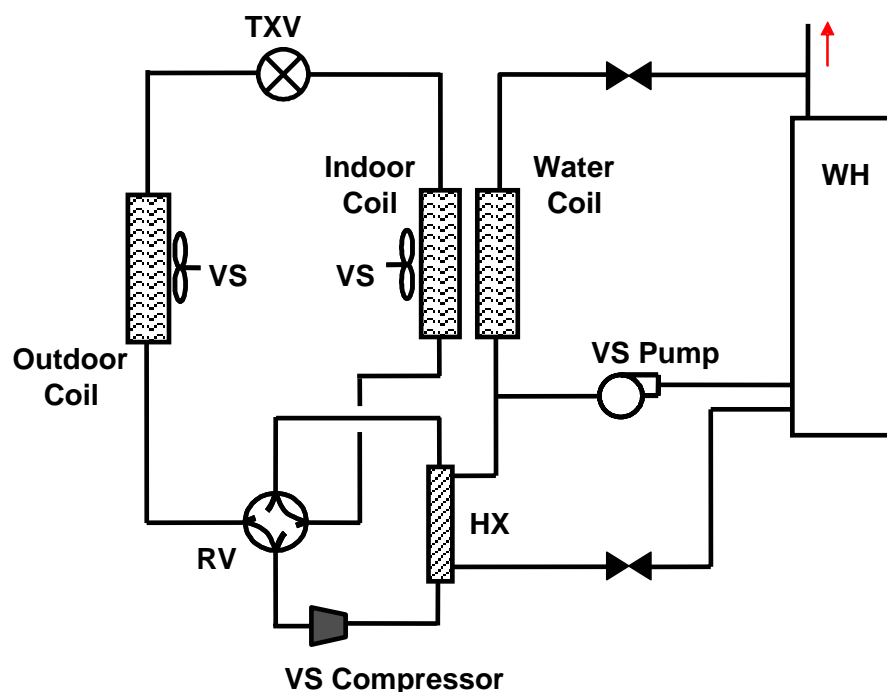


Fig. 1. Conceptual Diagram of Integrated Heat Pump Design.

We chose to design the IHP around a near ZEH, a 177 sq. m (1900 sq. ft.), well-insulated house with ducts in the conditioned space, and tight enough to require 0.35 ACH which is 2.55 cu. m/min (90 CFM) of continuous ventilation air for the selected house. Located in DOE Region IV, the heating, cooling and water heating loads of this house were 9460, 4130 and 4370 kWh (32.3, 14.1 and 14.9 MMBtu) respectively. Our analysis showed that a 4.40 kW [(1.25-ton), (15,000 Btu/h)] heat pump was sufficient to meet the design day cooling load of this house (Andrews 1999). We performed an initial steady-state design analysis of the IHP concept assuming brushless DC (BDC) modulated fans and compressor. From this analysis, we determined the required capacity modulation ranges in space cooling and heating, ventilation air preconditioning, and water heating modes that would meet the required loads of the house. Moreover, we determined the compressor and fan modulation combinations that would give best performance. This was accomplished using the DOE/ORNL Heat Pump Design Model (HPDM) with BDC-drive modeling capability, after various modifications were made to enable the program to handle the outdoor air ventilation modes ranging from mixing ventilation air with return air to 100% outdoor air. Using the model's design parametric capabilities, we optimized the indoor and outdoor fan speeds for a

range of compressor speeds in cooling and heating mode, and found the best levels for condenser subcooling. The results of this optimization (Table 1) show the speed (as a % of full speed) for each of the major components of the IHP for each overall system speed from the lowest (LL for ventilation) to the highest (F). The last column of Table 1 shows the system cooling capacity over a 21.1 – 37.8C (70 – 100F) outdoor temperature range. As shown, the IHP provides a capacity turndown ratio of 4:1 which is needed to accommodate maximum space cooling capacity at high ambient temperatures and the low capacity needed for dehumidification at lower ambients when the sensible cooling load is low and dehumidification is needed.

Table 1. Results of IHP Variable Speed Optimization in the Ventilation and Space Cooling Modes

| Speed | % of nominal | | | mBtu/h |
|-------|--------------|--------|------------|---------|
| | ID Fan | OD Fan | Compressor | |
| LL | 23 | 55-60 | 21-41 | 4 – 6.7 |
| L | 50 | 65 | 45 | 7.7 |
| M | 75 | 73 | 73 | 11.5 |
| F | 100 | 100 | 100 | 15.4 |

Control requirements were determined for the compressor in the ventilation cooling only mode to maintain a constant water removal rate (to meet an assumed approximate constant outdoor humidity ratio) over a range of outdoor temperatures in cooling. Since the ventilation mode airflow is fixed, the moisture removal rate is maintained by increasing the compressor speed and lowering the indoor coil temperature in response to deviations from the indoor RH set point. Any needed supply air tempering is provided by the air-to-water coil using heat-pump-generated hot water. (In ventilation heating, a space neutral supply temperature is maintained by either low speed heating operation or with the hot water coil.)

The ventilation mode is quite interesting in that while ventilating, the IHP can also accomplish water heater using the desuperheater heat exchanger at the exit of the compressor as shown in Figure 1. Continuing to use the outdoor coil for condensing while desuperheating allows the efficiency of the ventilation cooling mode to remain high while making enough hot water to keep the tank ready for most hot water needs. We examined the ventilation mode of operation to determine the impact of both dehumidification and water heating on the system Energy Efficiency Ratio (EER). Figure 2 shows the

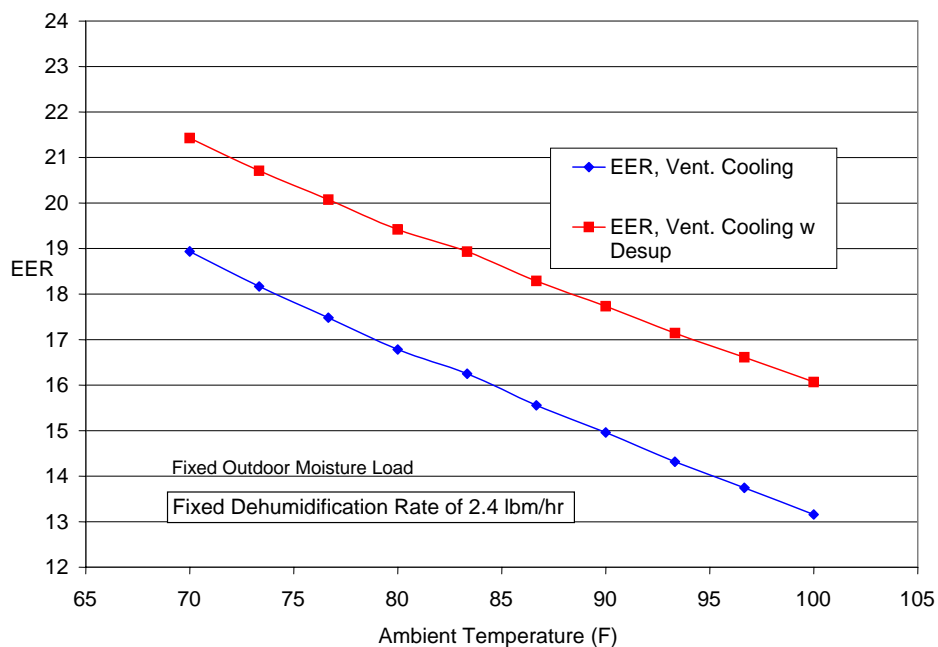


Fig. 2. IHP Ventilation Cooling EER with and without desuperheater output

results of these analyses. If there is no need for water heating, the system efficiency (energy efficiency ratio) is about 19 (Btu/W-h) with an ambient air (outside) temperature of 21C (70F), and at higher ambient temperatures, the EER falls since the IHP does more sensible cooling at higher source/sink temperatures and so the compressor speed and heat exchanger loadings rise. If, at the same time as ventilation is occurring, hot water is produced, the overall EER for delivered services is as shown in the upper curve in Figure 2. EERs of this magnitude would be quite difficult to accomplish were it not for the water heating function. If more hot water is needed, the ventilation mode can be switched to a full condensing water heater with a lower ventilation cooling EER and higher power draw, but with an even higher EER for delivered services.

Figure 3 shows the capability of the IHP to remove moisture from the ventilation air in terms of sensible heat ratio (SHR), especially at low-to-moderate ambient temperatures. As the ambient temperature drops, the SHR of the indoor coil can be lowered in the desired direction by compressor speed control alone. At the 21.1 C (70F) lower temperature limit shown, the SHR of the IHP is smaller as it should be to accomplish significant dehumidification. SHR of this magnitude are typical of desiccant dehumidification systems but can also be attained with the IHP with sufficient compressor speed control.

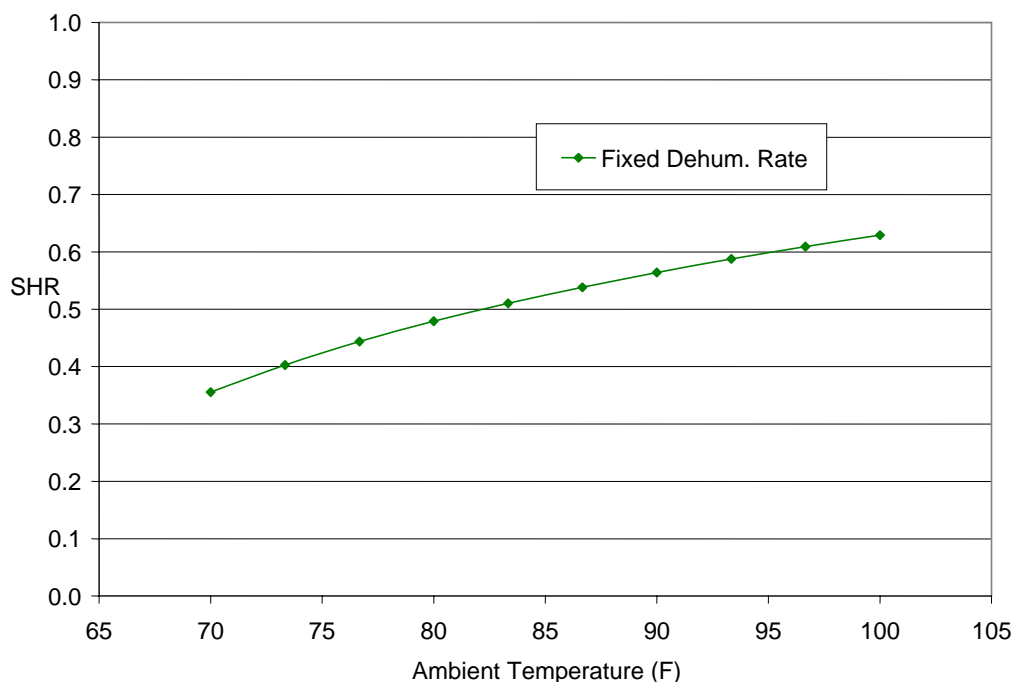


Fig. 3. HP Ventilation Mode, Sensible Heat Ratio

We also examined the energy savings potential of the IHP over a conventional heat pump with electric resistance water heating. Figure 4 shows this comparison. The baseline is a SEER 13, HSPF 7.7 heat pump and an electric resistance water heater with an EF=0.88. The baseline system is at the origin of the plot. The bottom curve shows the energy savings by moving towards higher efficiency heat pumps keeping electric resistance as the water heating option. The performance improvement of the IHP is shown by the upper curve where the heat pump not only provides space conditioning but water heating as well. A baseline HPWH EF of 2.2 was estimated. (The HP and HPWH performance was related to increasing SEER levels, for example, giving an estimated HSPF of 8.6 and EF of 2.4 at SEER=16.) Increasing the efficiency (SEER) of the heat pump provides increasing energy savings as shown. The

relationship in this figure indicates that an IHP with an SEER of 16 produces savings of about 37% - far more than is possible with a 19.6-SEER, non-IHP system. The 19.6 SEER system is the highest performing heat pump on the U.S. market today, and if that technology were applied as an IHP, the

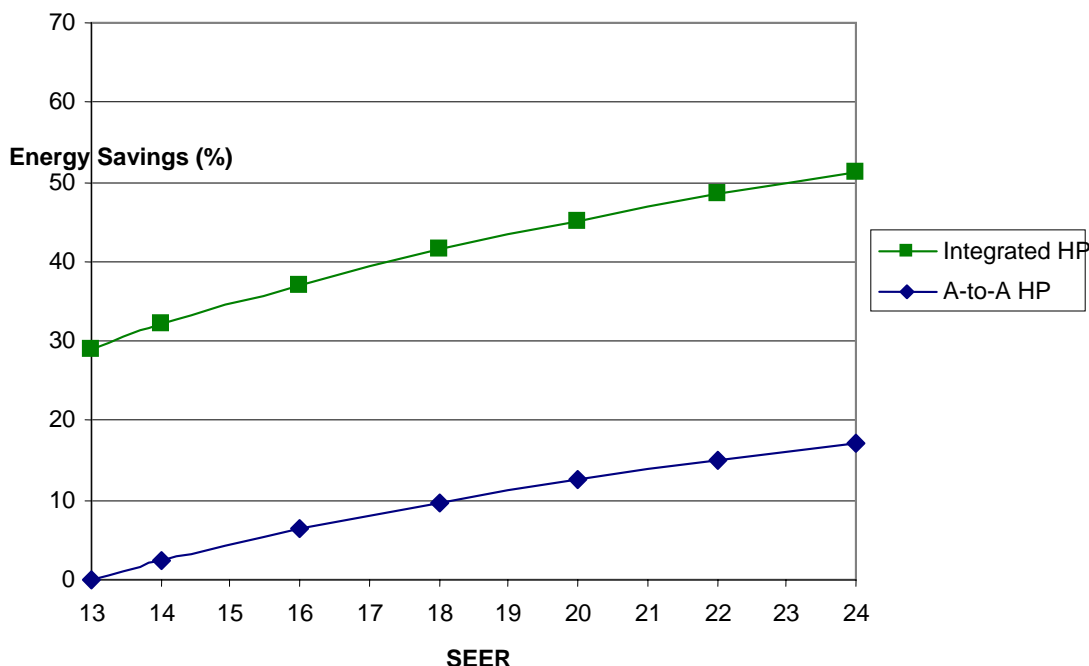


Fig. 4. Estimated heating/cooling energy savings for IHP; baseline is EF=0.88 electric resistance water heater and IHP with water heater COP = 2.2

energy savings would be about 44% over the baseline system.

ORNL is working to develop a laboratory prototype of the IHP. As part of this effort, TRNSYS, a widely-accepted transient simulation code is being used to model the performance of the IHP in high-efficiency homes being studied and constructed through the DOE Building America Program.

Comprehensive spreadsheet plots were made of the IHP performance in all the various operational modes and performance equations generated for use in the TRNSYS-based model to simulate the annual performance of the IHP on an hourly basis. We found from the steady-state analysis that a BDC-driven rotary compressor could provide a sufficient range of modulation for all functions with high operating efficiency. Overspeeding the compressor in the heating season so that the IHP accomplishes space and water heating is also being examined. We determined that overspeed operation in the water heating mode would be limited to about 50% over nominal, due to the high torque requirements. Further, overspeed operation would be possible in space heating mode however, as the torque requirements here are reduced since the condensing temperatures are lower.

We determined, after contacting a number of manufacturers of candidate equipment for the IHP, that the required size of a standalone efficient BDC-modulating compressor cannot presently be obtained in the U.S. There are, however, some units that could be obtained from abroad that would likely meet the IHP requirements. In lieu of obtaining a suitable single BDC compressor, we are currently investigating other options including dual compressor approaches to provide the flexibility needed for the IHP. Based on the modulation requirements found from the initial steady-state design analysis, we determined that two high-efficiency single-phase rotary compressors (from the room-AC market), one with 38% and the

other with 62% of nominal cooling capacity may be a sufficiently close approximation to the space cooling modulation needs while still providing efficient system operation. This would provide three discrete capacity levels. This combination would not suffer from inverter losses but would have lower motor efficiency than a BDC, so at design conditions the net drive efficiency should be about the same. With discrete compressor sizes, humidity control would require more tempering heat due to the overcooling of the ventilation air and/or need some mixed return airflow. The control logic is also expected to be more involved. The cyclic operation of the discrete compressors would also provide less continuous moisture control of the indoor air. The limitations of a two compressor design could be minimized by use of a lower-cost add-on inverter for the smaller compressor to provide further continuous capacity modulation over a more limited 2:1 turndown ratio. Both compressors would operate simultaneously to meet the design space cooling and heating loads and the maximum water heating loads. This configuration would not have the maximum space heating or water heating capacity of the oversped BDC unless a third compressor or a second dual-stroke compressor were employed. A lower cost option to this could be the use of an extra water storage tank to provide extra heating capacity that could be charged up during the winter daytime for help in meeting peak space and water heating needs. (It could also be used to store excess hot water in the space cooling mode to ensure 100% of the WH and space tempering needs.)

3 OTHER APPROACHES TO INTEGRATED WATER HEATING TECHNOLOGY

Other approaches to integrated water heating systems have been examined by ORNL and other researchers, and they range from the simple ideas to more complex systems. The efficiency of an HPWH depends on a number of factors, and one of them is evaporator temperature. Locating the HPWH near a heat source raises the evaporator temperature and the efficiency of the HPWH. This method of installing the HPWH in favorable locations has been applied in many commercial building settings such as commercial or coin-operated laundries where the HPWH is located near the dryer to capture waste heat and in commercial restaurant kitchens near the dishwasher to again, capture the heat and humidity present. In homes with HPWHs, it may be possible to locate the HPWH evaporator near the refrigerator closet so that condenser heat from the refrigerator can be used by the HPWH. The duty cycle of a typical refrigerator is around 45% and the duty cycle of the HPWH can be 50% or more for small-capacity HPWHs, so there is a reasonable opportunity for coincident operation of the two appliances. Locating the HPWH evaporator near the refrigerator not only raises the efficiency of the HPWH, but the efficiency of the refrigerator as well by lowering its condensing temperature. This “soft-integrating” of two appliances has been tested with measurable results in a small Habitat-for-Humanity house near ORNL. Others including Davis Energy Group in Davis, California are working to develop a domestic refrigerator that also heats water using condenser heat from the refrigerator. A modification to this approach is the HPWH refrigerator in which a second air-source evaporator is used to allow the refrigerator’s vapor compression cycle to continue to operate even after the refrigeration load is satisfied. Although more complicated than the refrigerator condenser heat recovery system, the HPWH refrigerator can meet the water-heating needs of a typical family and helps to cool and dehumidify the kitchen. Clearly, the benefit is great in the summer and swing seasons where dehumidification and space cooling are desired and smaller during the winter where the source heat to the HPWH refrigerator comes ultimately from the space heating system used in the home.

Efforts are also underway “redesign” the conventional HPWH so that it is better suited for the needs of the tighter, near ZEBs described earlier. This redesign is intended to maximize the performance of the HPWH as a dehumidifier. Conventional dehumidifiers both room and whole-house are available and can be used effectively as a single function device. Surprisingly, the U.S. market for dehumidifiers is strong: 2003 sales of residential dehumidifiers totaled more than 1.3 million units, and in 2003, the installed base of dehumidifiers was more than 11.3 million units. On average, the dehumidifier market has seen a 12% annual growth over the past five years. The performance of dehumidifiers (an Energy Factor) is characterized as the ratio of the volume of water condensed from moisture in air under standard testing

conditions, and the total electrical energy required by the humidifier. Data on EnergyStar dehumidifiers provided in Figure 5 show that on average, larger dehumidifiers are more efficient than smaller ones.

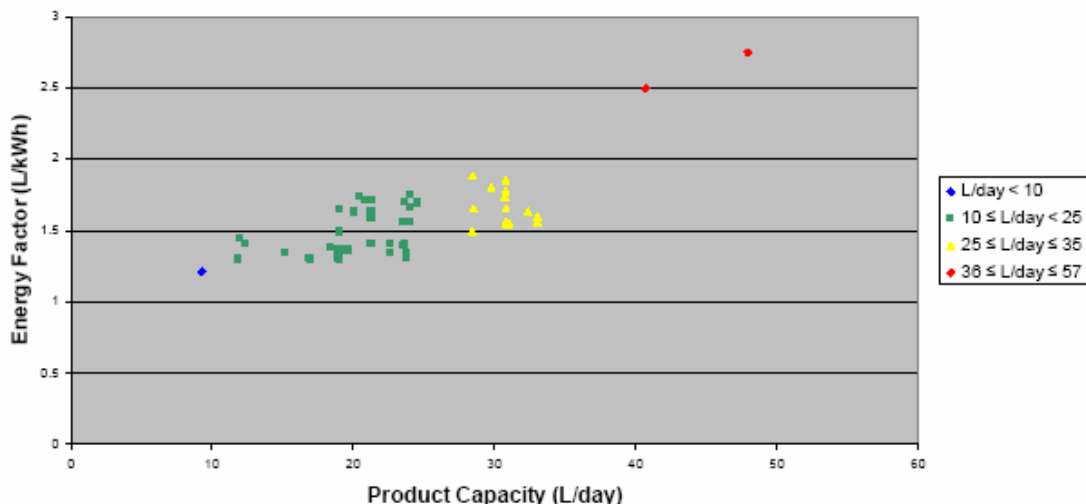


Fig. 5. Efficiency Trend for EnergyStar Dehumidifiers

Although dehumidifiers remove moisture from indoor air, they provide sensible heating to the space at all times including the summertime when cooling is needed. During the summertime especially, it would be more efficient for the condenser heat from the humidifier to be used for domestic water heating rather than space heating. Based on the need for dehumidification and for efficient water heating, an integrated appliance for accomplishing these tasks is being developed with ORNL participation. The water-heating dehumidifier (WHD) is essentially an HPWH designed to dehumidify the surrounding air as it heats water, and to continue providing humidity control in a dedicated dehumidification mode when the need for hot water production is satisfied. In addition to the components used in a conventional HPWH, the WHD employs a second condenser – one that is air-cooled and external from the water tank – as well as special controls that sense the need for dehumidification as well as the need for hot water production. When these two needs are satisfied, the WHD turns off. Operation of the WHD is similar to an HPWH with the added feature of deep dehumidification especially during the dedicated dehumidification mode.

There are several options for the condenser design for a WHD. Perhaps the simplest is to use an external, water-cooled condenser in which water is circulated from the storage tank through the condenser using a small pump. This configuration allows the storage tank to be located away from the WHD and facilitates tank replacement. The drawbacks to this design are (1) lack of a straightforward means to sense tank temperatures since the mechanical components are remote from the tank, and (2) heat losses from the water lines between the two components. Water line heat losses can be appreciable due to the long duty cycles of the WHD as it operates to restore the tank's temperature.

An integrated design where the WHD is affixed to the water tank provides a number of condenser options. They include (1) an external condenser that is wrapped around the bare steel tank before the tank is insulated, (2) an external, surface-mounted condenser that may be applied in other ways including on the bottom of the tank or against the inside of the vent tube of a gas water heater tank that has been suitably converted by removing its burner, (3) condenser technologies that are internal to the tank itself. By using enough condenser surface, all of these condenser options can be designed to provide good performance. A recent ORNL discovery is a method for installing a bayonet-style, linear condenser of large area through the existing small, threaded opening of a conventional hot water storage tank. This allows use of a low-cost, readily-available insulated conventional water heater as a HPWH or as a WHD.

Work is continuing on this development with a goal of effecting a substantial reduction in the cost of heat pumping systems that provide water heating.

4 SUMMARY

Integrated approaches to heat pump water heating are important as a means for reducing the first costs and improving the performance of space conditioning and water heating systems. Experience is showing that well-insulated, tight buildings can require mechanical fresh air ventilation systems, and these systems can exacerbate humidify problems particularly during swing and cooling seasons. The need for humidity control in these buildings coupled with the thermodynamic limit of conventional electric resistance water heaters suggest that integrated approaches that accomplish efficient water heating in addition to space conditioning and dehumidification will become increasingly important in an overall plan to reduce energy consumption in new, residential buildings. An IHP of low capacity and dedicated dehumidification modes that also provides year-round space conditioning is part of the plan as are other integrated water heating system such as the WHD and possibly a water-heating refrigerator. These options are under investigation, and other approaches to integrated water-heating system may become viable as well in the future.

5 REFERENCES

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