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Residential Dehumidification Systems Research for Hot-Humid Climates

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Definitions

ECM	electronically commutated motor
ERV	energy recovery ventilation

RESIDENTIAL DEHUMIDIFICATION SYSTEMS RESEARCH FOR HOT-HUMID CLIMATES

ABSTRACT

Twenty homes were tested and monitored in the hot-humid climate of Houston, Texas, U.S.A., to evaluate the humidity control performance and operating cost of six different integrated dehumidification and ventilation systems that could be applied by production homebuilders. Fourteen houses, that also met measured energy efficiency criteria, had one of the six directly- or indirectly-integrated dehumidification and ventilation systems. Three reference houses had the same energy efficiency measures and controlled mechanical ventilation, while three other reference houses met code minimums for energy efficiency and did not have mechanical ventilation. Temperature and relative humidity were monitored at four living-space locations and in the conditioned attic where the space-conditioning equipment and air-distribution ducts were located. Equipment operational time was monitored for heating, cooling, dehumidification, and ventilation. Results showed that energy efficiency measures, combined with controlled mechanical ventilation, change the sensible and latent cooling load fractions such that supplemental dehumidification, in addition to that provided by the central cooling system, is required to maintain indoor relative humidity below 60% throughout the year. The system providing the best overall value, including humidity control, first cost, and operating cost, involved a standard dehumidifier located in a hall closet with a louvered door and central-fan-integrated supply ventilation with fan cycling.

RESIDENTIAL DEHUMIDIFICATION SYSTEMS RESEARCH FOR HOT-HUMID CLIMATES

Background

Like year-around temperature control, year-around humidity control in homes is important to improve indoor air quality, building durability, and owner satisfaction.[1]

In hot-humid climates, thermally efficient building envelopes with controlled mechanical ventilation provide a unique challenge for controlling humidity levels.[2] As the sensible heat load is reduced for a building, primarily through better windows, more insulation, and air-distribution ducts inside conditioned space, the latent load increases in proportion to the total load to the point that conventional cooling systems have difficulty keeping humidity levels within comfortable and healthy limits.[3] Conventional cooling systems are controlled by thermostats that sense temperature and not humidity; hence, during periods of low sensible load and high latent load, high indoor humidity levels can be problematic.

Equipment is available to deal with this challenge in different ways. Ventilating dehumidifiers (both DX and desiccant) are thought to be the best way to control humidity levels separate from the conventional cooling system, but they are often commercial-type systems and are believed to be too expensive to make major inroads with production homebuilders. In addition, integrating dehumidification with ventilation using “off-the-shelf” dehumidifiers may appear to be primitive and energy inefficient – although costs and benefits have remained speculative as a result of lack of data and field research.

The objective of this study was to identify the best performing, most energy-efficient and cost-effective techniques to provide controlled mechanical ventilation and humidity control in hot-humid climates with thermally efficient building envelopes. It was known that these strategies vary widely in first cost. However, the whole-house humidity control performance and operating cost was much less known and was, therefore, measured in this study. This information was expected to provide the basis for definitive recommendations to production homebuilders on the best commercially available methods to provide their customers with superior residential product at the most cost-effective and energy-efficient level.

Research Approach

Twenty occupied homes were included in the study conducted in cooperation with Pulte Home Corporation in Houston, Texas. Six different integrated dehumidification and ventilation systems were evaluated in homes that were at least 30% better than Model Energy Code 1995. These homes were constructed with unvented-cathedralized (conditioned) attics.[4,5] Three reference houses had the same energy efficiency measures and controlled mechanical ventilation, but no dehumidification separate from cooling. Three other reference houses met code minimums for energy efficiency and did not have mechanical ventilation or dehumidification separate from cooling and had conventional vented attics.

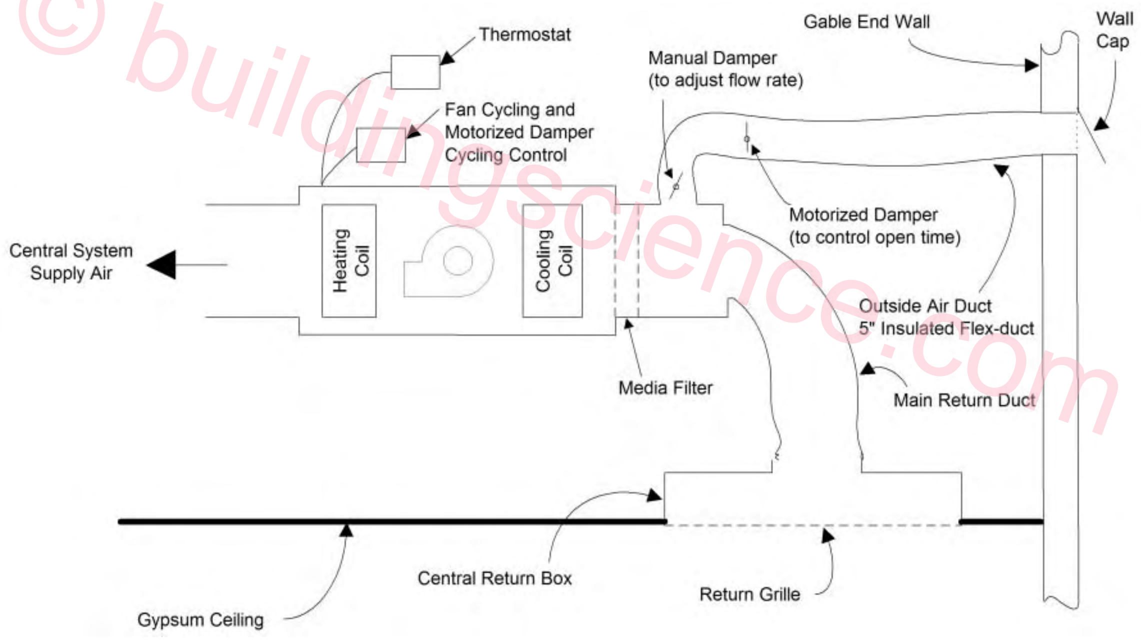

Figure 1. Diagram of central-fan-integrated supply ventilation

A schematic of the central-fan-integrated supply ventilation system used in many of the houses is shown in Figure 1.[6,7] An outside air duct was routed from a fresh air location to the return side of the air handler. A manual damper was installed in the outside air duct to set the flow rate, while a motorized damper was installed to control the air-flow volume as a function of time. Outside air was intermittently drawn in by normal thermostat-driven operation of the central cooling and heating system and, when necessary, by activation of the central air-handler blower via a fan cycling control. Control of the motorized damper limited over-ventilation.

A description of the six dehumidification and ventilation systems follows.

System 1: Stand-alone Dehumidifier in Hall Closet with Central-fan-integrated Supply Ventilation (Two Homes Tested)

The stand-alone dehumidifier system involved installation of an off-the-shelf 50-pint-per-day dehumidifier in an interior closet with a louvered door near the central air return. The dehumidistat built into the dehumidifier energized the dehumidifier whenever the humidity level rose above the user setting. The fan cycling control was set to 33% duty cycle (on for 10 min if it had not been on for 20 min) to intermittently average air conditions throughout the house and distribute ventilation air.

System 2: Stand-alone Dehumidifier in Conditioned Attic with Central-fan-integrated Supply Ventilation (Two Homes Tested)

The stand-alone dehumidifier system involved installation of an off-the-shelf 50-pint-per-day dehumidifier in the conditioned attic with a small return air duct located near the dehumidifier outlet. The dehumidistat built into the dehumidifier energized the dehumidifier whenever the humidity level rose above the user setting. The fan cycling control was set to 33% duty cycle (on for 10 min if it had not been on for 20 min) to intermittently average air conditions throughout the house and distribute ventilation air.

System 3: Ultra-Air Dehumidification and Ventilation System (Three Homes Tested)

The Ultra-Air system involved installation of a ducted high-efficiency ventilating dehumidifier located in the conditioned attic. The Ultra-Air blower operated continuously on low speed, drawing in about 40 cfm of outside air and about 120 cfm of recirculated house air. The mixed air was filtered and supplied to the main supply air trunk of the central air distribution system. A remote dehumidistat located in the living space activated the dehumidifier compressor if the humidity level rose above the user setting. The fan cycling control was set to 17% duty cycle (on for 10 min if it had not been on for 50 min) to intermittently average air conditions throughout the house and distribute ventilation air.

The Ultra-Aire blower was operated continuously because we needed to maintain at least a 3-to-1 ratio of inside recirculated air to outside ventilation air to avoid condensation of humid air in the supply plenum and ducts when the central fan was off. So, the potential for reducing the runtime of the Ultra-Air blower was limited by the mixed air volume requirement. This was also true for System 4. In addition, we avoided the cost and complication of an additional timer control and a motorized outside air damper. The motorized damper would have been required to avoid air leakage to outside through the Ultra-Aire system when the Ultra-Aire was off but the central fan was on.

System 4: Filter-Vent Ventilation with Dehumidifier in Ducted Cabinet (Three Homes Tested)

The Filter-Vent ventilation and dehumidification system involved installation of a blower/filter unit and a stand-alone dehumidifier placed inside a sheetmetal cabinet located in the conditioned attic. The Filter-Vent blower operated continuously on low speed, drawing in about 40 cfm of outside air and about 120 cfm of recirculated house air. The mixed air was filtered and ducted through the dehumidifier cabinet where the dehumidifiers' built-in dehumidistat energized the dehumidifier whenever the humidity level rose above the user setting. The air was then supplied to the main supply trunk of the central air distribution system. The fan cycling control was set to 17% duty cycle (on for 10 min if it had not been on for 50 min) to intermittently average air conditions throughout the house and distribute ventilation air.

System 5: Energy Recovery Ventilator (ERV) System (Three Homes Tested)

The Energy Recovery Ventilator (ERV) system included a desiccant wheel energy exchanger installed in the conditioned attic. The ERV blower operated continuously, drawing in about 40 cfm of outside air and exhausting about 40 cfm of inside air. In the energy exchanger, heat and moisture were exchanged between the incoming outside air and the outgoing inside air, such that much of the heat and moisture stayed on the side that it came from. In this way, during the cooling season, the introduction of heat and moisture from ventilation air is lessened. This system will not dehumidify house air, but will lessen the need for dehumidification. The house exhaust air stream exited through the roof, and the tempered ventilation air was supplied to the main return air trunk of the central air distribution system. The fan cycling control was set to 17% duty cycle (on for 10 min if it had not been on for 50 min) to intermittently average air conditions throughout the house and distribute ventilation air.

System 6: Enhanced Dehumidification with Two-stage Cooling and ECM Fan with central-fan-integrated Supply Ventilation

The enhanced dehumidification with cooling system included the installation of a Carrier cooling system with a two-stage compressor, an electronically commutated motor (ECM) indoor fan unit, and a Thermidistat controller. The system was designed to allow better matching of the load to the cooling system capacity to avoid poor humidity control inherent with short-cycling of over-sized systems. The ECM fan allowed lowering the air-flow rate over the cooling coil for enhanced moisture removal. The Thermidistat control was both a temperature and humidity controller that coordinated the two-stage compressor and ECM fan features to achieve enhanced humidity control, especially at start-up and part-load conditions. The fan cycling control was set to 33% duty cycle (on for 10 min if it had not been on for 20 min) to intermittently average air conditions throughout the house and distribute ventilation air. System 6 was considered to be representative of the best, mass-market cooling system available to control indoor humidity.

TEST PLAN

The test plan was designed to evaluate the humidity control performance, energy consumption, and cost effectiveness of the different integrated dehumidification and ventilation strategies.

All of the houses were commissioned for the study, including setting the appropriate controls and setting the ventilation air flow rate according to the number of bedrooms and house size (either 40 cfm continuous or 60-80 cfm at 33% duty cycle depending on the house size). Proper air filtration and condensate drainage was verified. The 17 houses with improved energy efficiency measures were inspected for insulation quality and high-performance window characteristics. These houses were also tested to be certain they met or exceeded criteria for building envelope leakage, duct leakage, and room pressurization shown in Table 1. Relative to Table 1, the standard reference houses were found to have as much as 40% more building air leakage and 150% more duct air leakage to outside than the high-performance homes. Closed-room pressurization for the reference houses generally ranged from 5 to 10 Pascal as a result of lack of return air path.

Monitoring Instrumentation

All of the houses were instrumented for hourly monitoring of temperature and relative humidity at four interior locations (master bedroom, two other bedrooms, and near the thermostat) and one location in the attic. Outdoor temperature and relative humidity was monitored under the shaded north-east soffit of one of the houses.

The mechanical equipment was instrumented for monitoring of operational time for heating, cooling, central air handler fan, ventilation fan, and dehumidification. Hourly electrical energy consumption was calculated by multiplying the measured power draw for each device by the measured on-time per hour.

Data collection periods are shown for each house in Table 2. As shown, the monitoring period was not always the same for the environmental conditions and the equipment runtime because of differences in construction completion and occupancy. The house floor area and number of stories is also noted in Table 2.

Table 1. Criteria for Air Leakage and Pressure Relationships

Item	Test Criteria
Building envelope leakage	Not more than 0.25 cfm/ft^2 surface area at 50 Pa pressure differential
Air distribution system leakage	Not more than 5% of high speed flow to outside
Room pressurization	Not more than 3 Pa between rooms or between rooms and outside

Table 2. Monitoring Periods and Size for Each House

		Environmental Monitoring Period	Total Days	Equipment Monitoring Period	Total Days
STAND-ALONE IN CLOSET					
19803 Ash	2 story, 2386 ft^2	Oct-01 to Jul-02	286	Oct-01 to Jul-02	301
19902 Ash	2 story, 2397 ft^2	Oct-01 to Jul-02	300	Oct-01 to Jul-02	300
STAND-ALONE IN ATTIC					
19950 Ash	2 story, 2397 ft^2	Jul-01 to Aug-02	366	Jun-01 to Aug-02	398
2731 Sun	2 story, 2448 ft^2	Jan-02 to Aug-02	189	Oct-01 to Aug-02	303
ULTRA-AIR					
19915 Ash	1 story, 2100 ft^2	Oct-01 to Aug-02	288	Oct-01 to Aug-02	288
19938 Ash	2 story, 2448 ft^2	Jul-01 to Jul-02	365	Jul-01 to Jul-02	365
19923 Ash	2 story, 2397 ft^2	Oct-01 to Aug-02	288	Oct-01 to Aug-02	288
FILTER-VENT + STAND-ALONE					
19934 Ash	1 story, 1830 ft^2	Oct-01 to Jul-02	300	Oct-01 to Jul-02	300
19922 Ash	1 story, 2100 ft^2	Oct-01 to Aug-02	288	Oct-01 to Aug-02	288
19954 Ash	2 story, 2386 ft^2	Oct-01 to Jul-02	300	Oct-01 to Jul-02	300
ERV					
19926 Ash	1 story, 1830 ft^2	Jul-01 to Jul-02	365	Aug-01 to Jul-02	364
19942 Ash	1 story, 2197 ft^2	Oct-01 to Jul-02	287	Oct-01 to Jul-02	301
19930 Ash	2 story, 2448 ft^2	Nov-01 to Jul-02	272	Oct-01 to Jul-02	301
2-STAGE + ECM AHU					
19422 Col	1 story, 2197 ft^2	Oct-01 to Aug-02	274	Oct-01 to Jul-02	274
ENERGY EFFICIENT REFERENCE					
2802 Sun	2 story, 2386 ft^2	01-Jun-01 to 02-Aug-02	427	23-Mar-01 to 02-Aug-02	497
2814 Sun	1 story, 2197 ft^2	01-Nov-01 to 01-Aug-02	273	23-Mar-01 to 01-Aug-02	496
19906 Ash	2 story, 2386 ft^2	31-Jul-01 to 01-Aug-02	366	31-May-01 to 01-Aug-02	427
STANDARD REFERENCE					
19622 Her	2 story, 2448 ft^2	02-Jun-01 to 01-Aug-02	425	Jun-01 to Aug-02 (parts)	320
4818 Cot	1 story, 2197 ft^2	30-Jun-01 to 01-Aug-02	397	30-Jul-01 to 01-Aug-02	367
6263 Clear UP	2 story, 3300 ft^2	02-Jun-01 to 01-Aug-02	357	21-Jul-01 to 01-Aug-02	386
DN				11-Jul-01 to 01-Aug-02	376

RESULTS

The incremental first-cost of each system compared to the Standard Reference house is given in Figure 2, broken down by material and installation. As with any research project of this type, the actual production costs may vary from those gathered to perform the study. However, we worked with the suppliers, builder, and HVAC contractor to make appropriate judgments relative to production homebuilding.

Figure 3 shows a frequency plot of outdoor environmental conditions during the testing for drybulb temperature, dewpoint temperature, and relative humidity. Drybulb temperature peaked at 107°F and went as low as 27°F, but the bin with the most hours was between 75°F and 80°F. Dewpoint temperature peaked at 82°F and went as low as 4°F; the largest bin, by a large margin, was between 70°F and 75°F. Forty percent of the time, outdoor relative humidity was above 85%.

Figures 4 through 9 provide a partial example of the analysis procedure conducted for each house. This analysis was then summarized in order to compare the houses in each group.

Figure 4 shows an hourly time trace of relative humidity measured in five locations of a house with the Ultra-Aire system. As shown, the dehumidification separate from cooling effectively limited the indoor relative humidity to predominantly below 60%. It can also be seen how mild outdoor dewpoint temperatures in Houston reduces interior humidity between November and March.

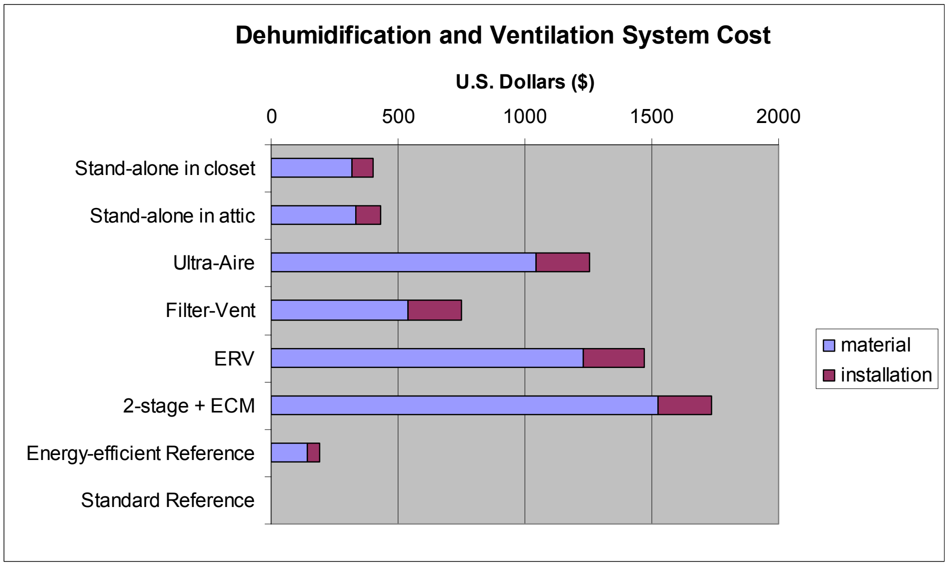

Figure 2. Incremental first-cost (initial cost) of each ventilation and dehumidification system compared to the Standard Reference house

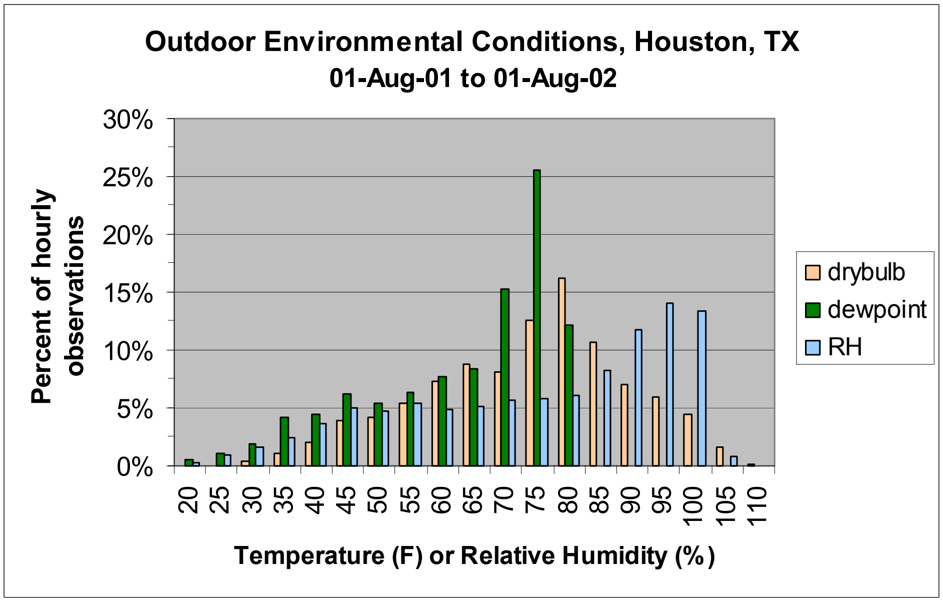

Figure 3. Outdoor environmental conditions from August 2001 to August 2002

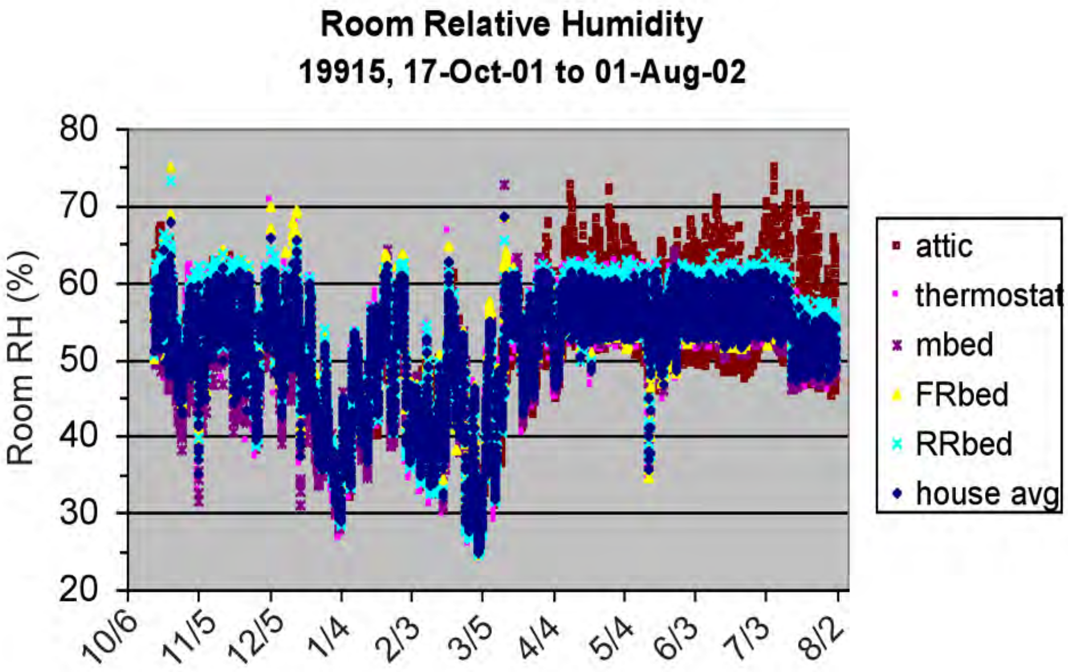

Figure 4. Hourly time trace of indoor relative humidity for a house with the Ultra-Aire system

The individual room relative humidity plotted against the house average relative humidity in Figure 5 shows that the spread in relative humidity between locations was usually within 10%. Typically, master bedroom relative humidity was higher because of higher occupancy density and moisture generation. Comparing Figure 5 to the same plot of a Standard Reference house in Figure 6 provides an example of how fan cycling for whole-house mixing can even out relative humidity conditions throughout the house. This was a general trend in all of the houses and was true for temperature uniformity as well. The highest daily variation in relative humidity was generally found in the master bedroom. Without fan cycling, the highest relative humidity difference was usually found between the master bedroom and the thermostat location.

The hourly equipment on-time fraction plot shown in Figure 7 illustrates the infrequent use of heating in energy-efficient homes in Houston and shows how the cooling and dehumidification systems sometimes operate for entire hours. The average on-time fractions shown at the bottom of the plot are for the entire monitoring period.

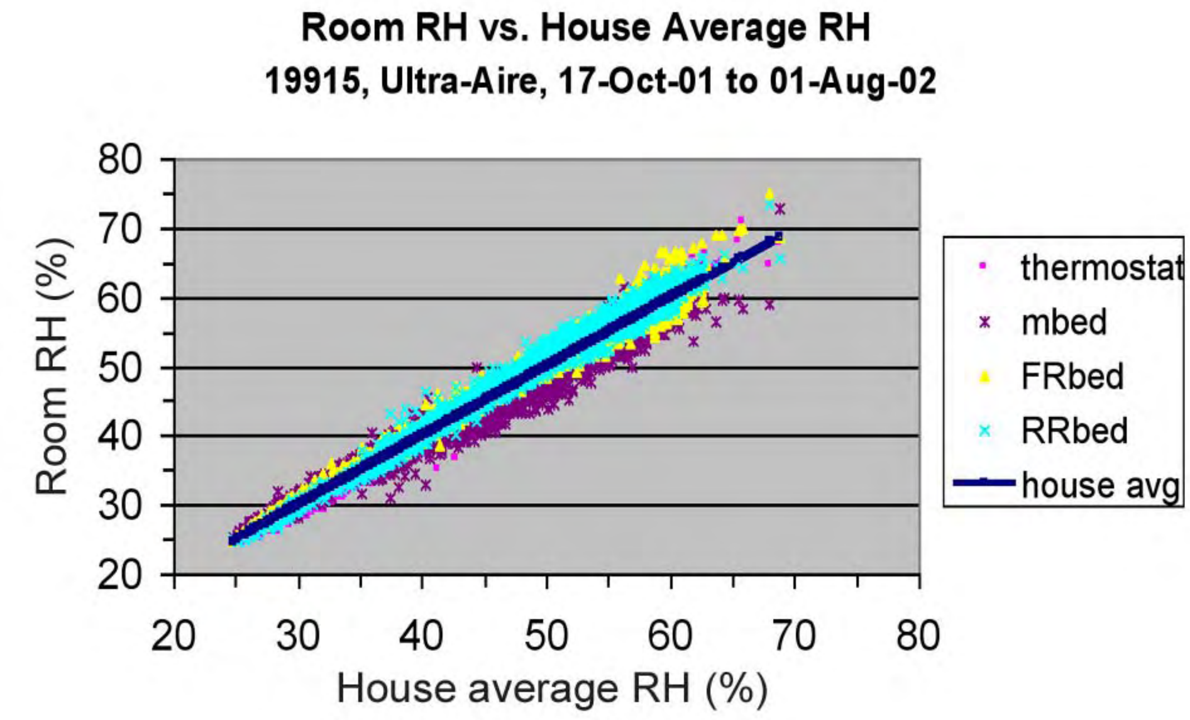

Figure 5. Plot of individual room relative humidity versus house average relative humidity, showing the tight control of relative humidity throughout the house with the Ultra-Aire and fan-cycling system

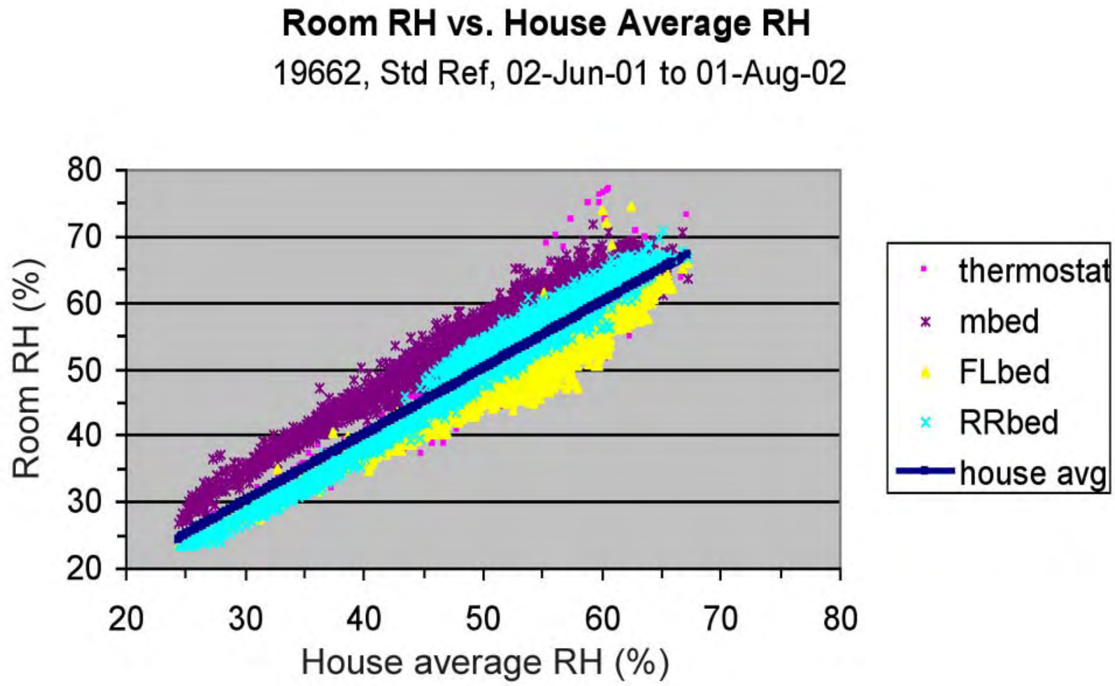

Figure 6. Plot of individual room relative humidity versus house average relative humidity for a Standard Reference house, showing a 20% variance compared to half that for the energy-efficient house in Figure 5 with mechanical ventilation, supplemental dehumidification, and central fan cycling

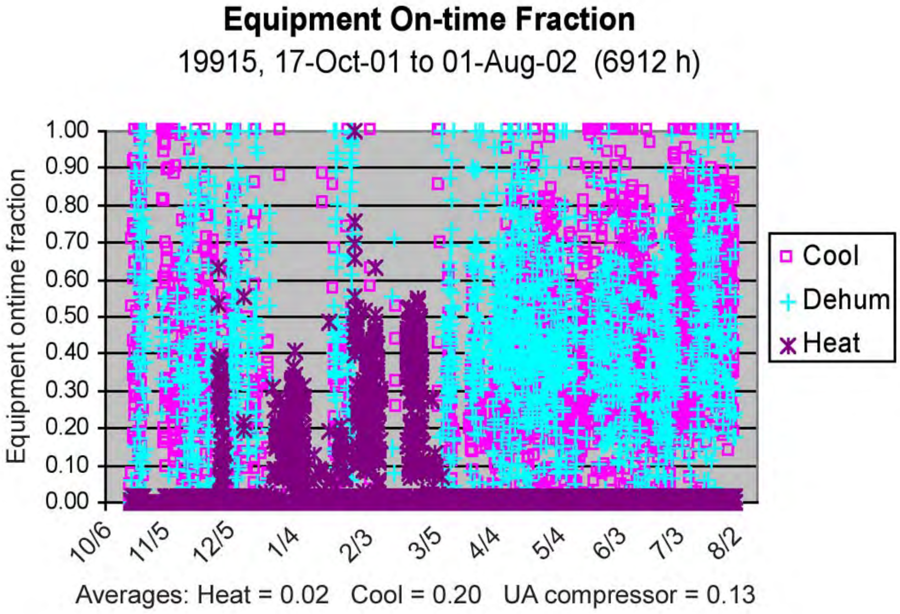

Figure 7. Cooling, dehumidification, and heating equipment hourly on-time fractions for a house with the Ultra-Aire system

Mechanical equipment on-time fraction as a percentage of the total hourly observations is shown in Figure 8. The Ultra-Aire blower was on continuously, while, for most of the time, the Ultra-Aire compressor was on less than 10% of any given hour. Hourly cooling system on-time was predominantly in the range of 0.25 to 0.70, showing that the cooling system size was an appropriate balance between capacity and long cycles for good moisture removal and efficiency. Heating is rarely used in the Houston climate.

Mechanical equipment electrical energy consumption in kW-h/h is shown in Figure 9 for a house with the Ultra-Aire system. In addition to giving a summation of the kilowatt-hours consumed over the monitoring period, this plot shows the electrical demand and the demand profile for each piece of equipment in the space conditioning and ventilation system.

Humidity Control Performance

Figure 10 shows the percentage of hours that the house-average relative humidity was more than 60% for each house in the study.

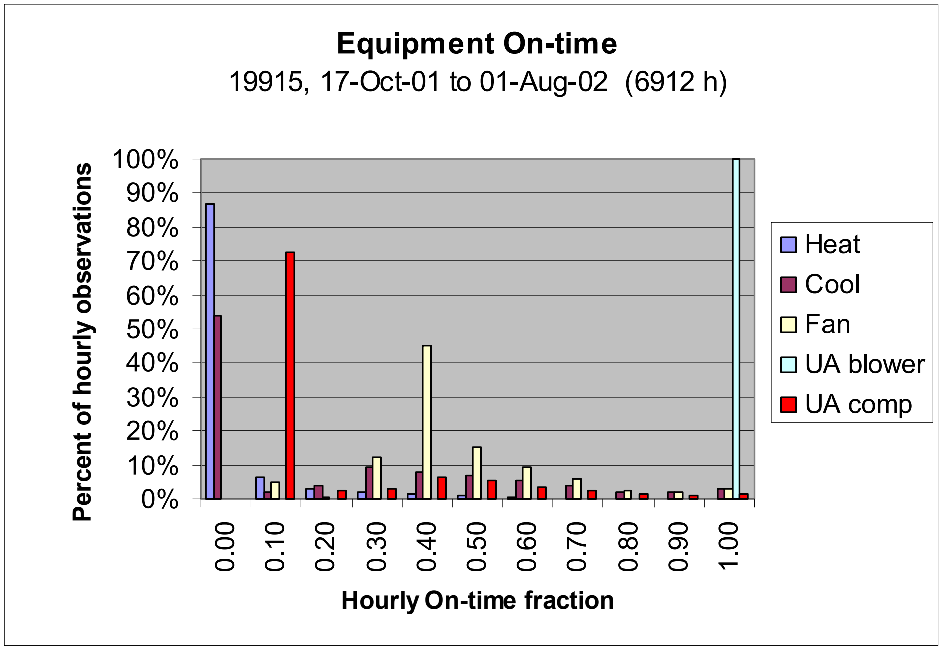

Figure 8. Mechanical equipment on-time fraction as a percentage of the total hourly observations

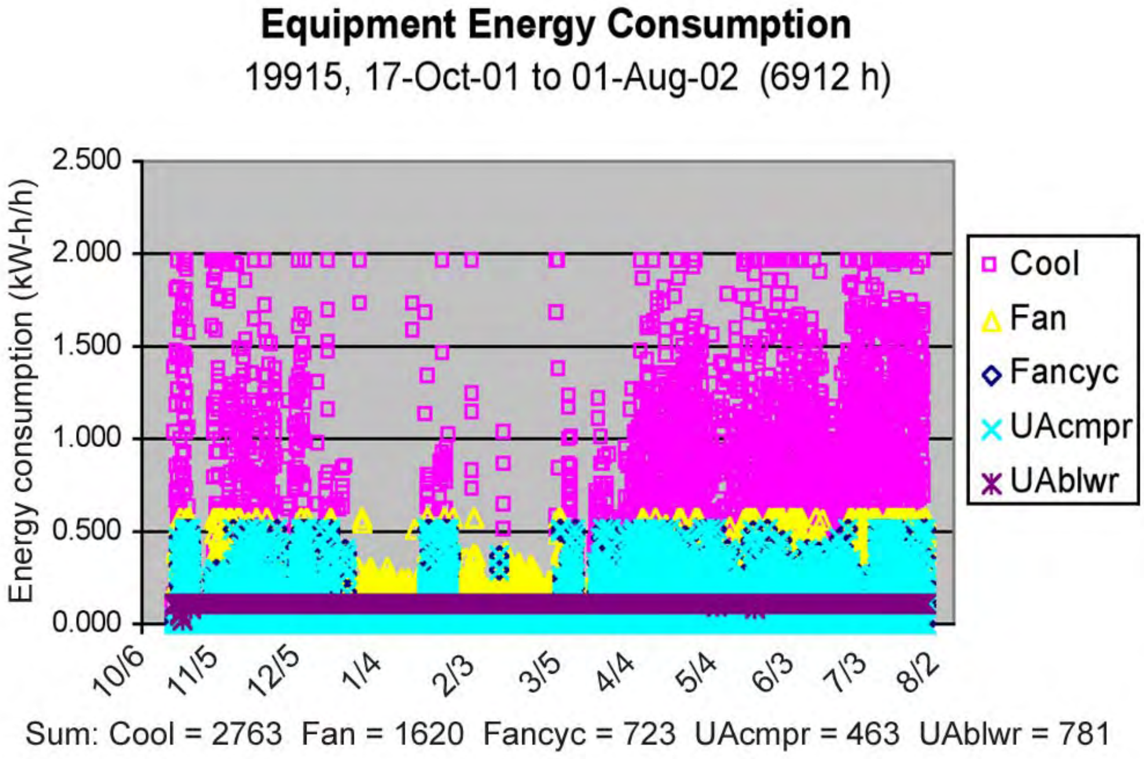

Figure 9. Mechanical equipment electrical energy consumption (kW-h) and demand (kW) for a house with the Ultra-Aire system

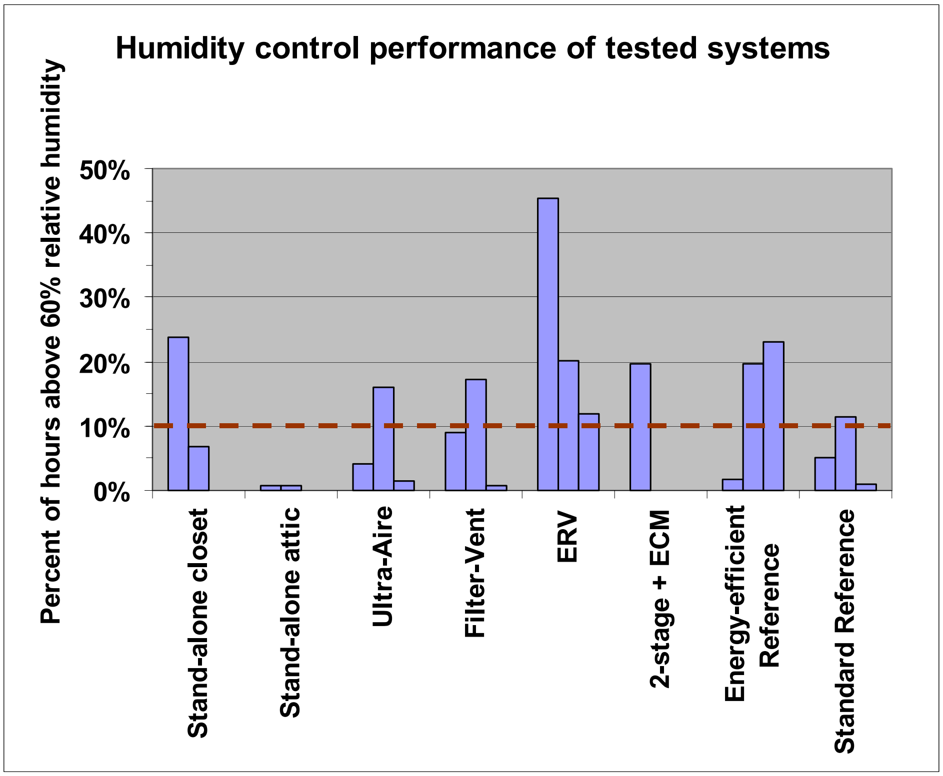

Figure 10. Humidity control performance of all homes in each category

As seen in Figure 10, there was some inconsistency in humidity control performance between houses in each group. Most of that can be explained because of known occupancy effects and known mechanical equipment problems. The most significant occupancy effects were the thermostat and dehumidistat settings chosen by the occupants based on their own comfort level. Because of limitations in our ability and desire to influence the homeowners' choices, these were not factors that we tried to control in the study, however, we did recommend that they not cool the houses below 75°F and that they maintain a relative humidity setting around 55%. For example, the owners of the first house in the Stand-alone in hall closet category preferred a high cooling setpoint (near 80°F) and chose to set the dehumidistat to a high setting. This caused this house to be an outlier in the humidity control and operating cost analysis. The dehumidifier blower was also put on low speed at this house in order to lower the sound level.

Another important occupancy effect was the amount of interior moisture generation as a result of the number of occupants, the time they spent in the house, the activity level, and use of exhaust fans for spot ventilation. For example, some of the homes were occupied by one or two people who were not home during the day while other houses were occupied by families with children and with people home much of the time. Bathroom, kitchen, and laundry exhaust fan usage was generally minimal in these homes based on individual interviews with the homeowners. The master bathroom exhaust fan was located in the toilet closet and rarely got used to exhaust shower moisture. If dryer venting is restricted or poorly connected, a significant amount of moisture can be exhausted through use of the laundry exhaust fan. However, most owners didn't use the laundry exhaust when using the laundry equipment. Undesirable noise was one reason given.

Mechanical equipment problems that sometimes played a role in affecting the humidity control performance and/or energy consumption of some homes included:

1. Hot water thermosiphoning that effectively allowed hot water from the water heater to fight the cooling system as a result of a failed check valve; and
2. AirCycler® combo-STAT (thermostat for combination space and domestic hot water heating systems) control problems that sometimes caused heating and cooling to operate at the same time and sometimes operated the central fan constantly for many hours at a time.

Therefore, in order to allow a more direct comparison of the results between categories, a home from each category was selected to be representative of that category based on our knowledge of adherence to the recommended temperature and humidity control setpoints, occupancy effects, and equipment problems, combined with observation of the measured data. The humidity control performance of these selected homes is shown in Figure 11.

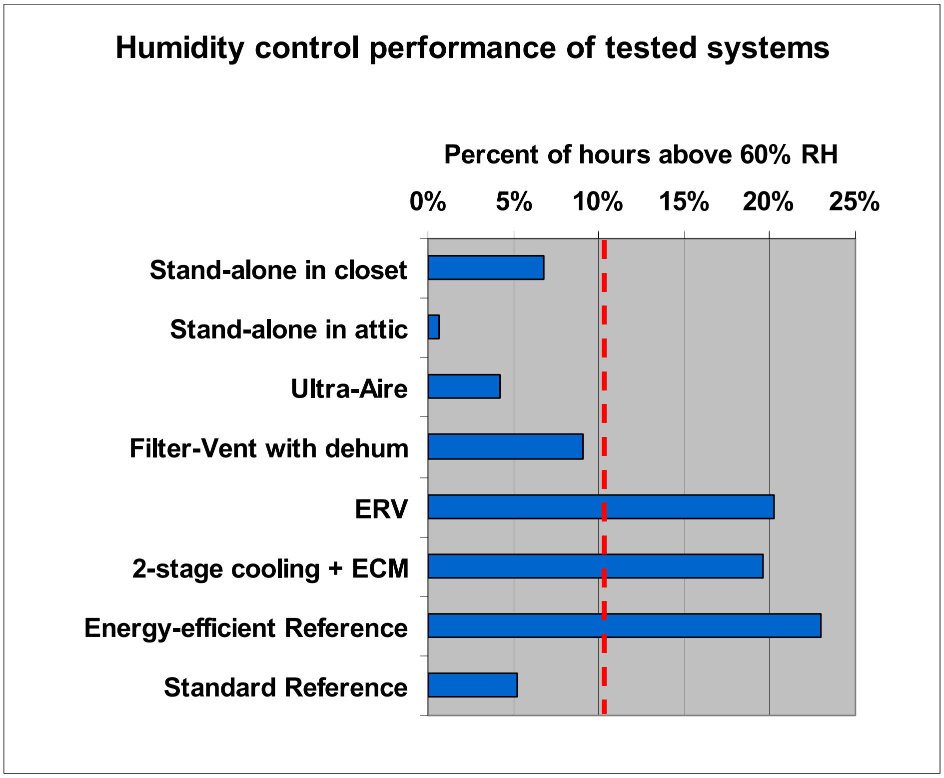

Figure 11. Humidity control performance of the representative house in each system category

As shown in Figure 11, all of the homes with dehumidification separate from cooling and the energy-efficient reference house had fewer than 10% of the monitored hours with relative humidity higher than 60%. In comparison, all of the homes without dehumidification separate from cooling had relative humidity greater than 60% about 20% of the monitored hours. The two-times factor between these groups supports a need for additional humidity control means in energy-efficient homes in hot-humid climates.

Interviews with homeowners showed a high level of satisfaction with the additional humidity control provided by the dehumidification systems. Even while some concern was raised by three homeowners regarding the additional electrical energy consumption, none of them wanted to go without the benefits of the dehumidification system.

Energy Consumption Performance

Average daily electrical energy consumption is shown in Figure 12 for the ventilation and dehumidification systems for each house tested. Note that the Energy-efficient Reference houses did not have dehumidification separate from the cooling system, and the Standard Reference houses did not have dehumidification or mechanical ventilation. Also note that the Ultra-Aire, Filter-Vent, and ERV systems had central fan cycling at 17% duty cycle, used as a whole-house mixing tool only, while the two Stand-alone systems, the two-stage with ECM system, and the Energy-efficienct Reference houses had fan cycling at 33% duty cycle because the central fan was used for drawing in ventilation air in addition to mixing.

There was consistency between the houses in each category except for one house in the Filter-Vent system category, which had a number of mechanical equipment problems that didn't get resolved until late in the study.

The representative houses used in Figure 11 are again listed in Figure 13, showing the average daily electrical energy consumption for ventilation and dehumidification. The energy consumed for central fan cycling was about 2 kilowatt-hours per day for the non-ECM fan systems with 33% duty cycle and was about half that for the systems with 17% duty cycle. Fan cycling energy consumption for the ECM fan system was about one-third as much as the standard fan systems with permanent split capacitor motors. Constant ventilation fan operation for the Ultra-Aire, Filter-Vent, and ERV systems was about 3 kilowatt hours per day. Energy consumption for dehumidification was low for the Stand-alone dehumidifier in the hall closet system and the Ultra-Aire system. For the two-stage cooling system, dehumidification energy was considered to be that of first-stage cooling alone, which was active 16% of the time. Energy consumption for dehumidification was high for the Stand-alone dehumidifier in the attic system and the Filter-Vent system because of the location of the dehumidistat as discussed in detail further on.

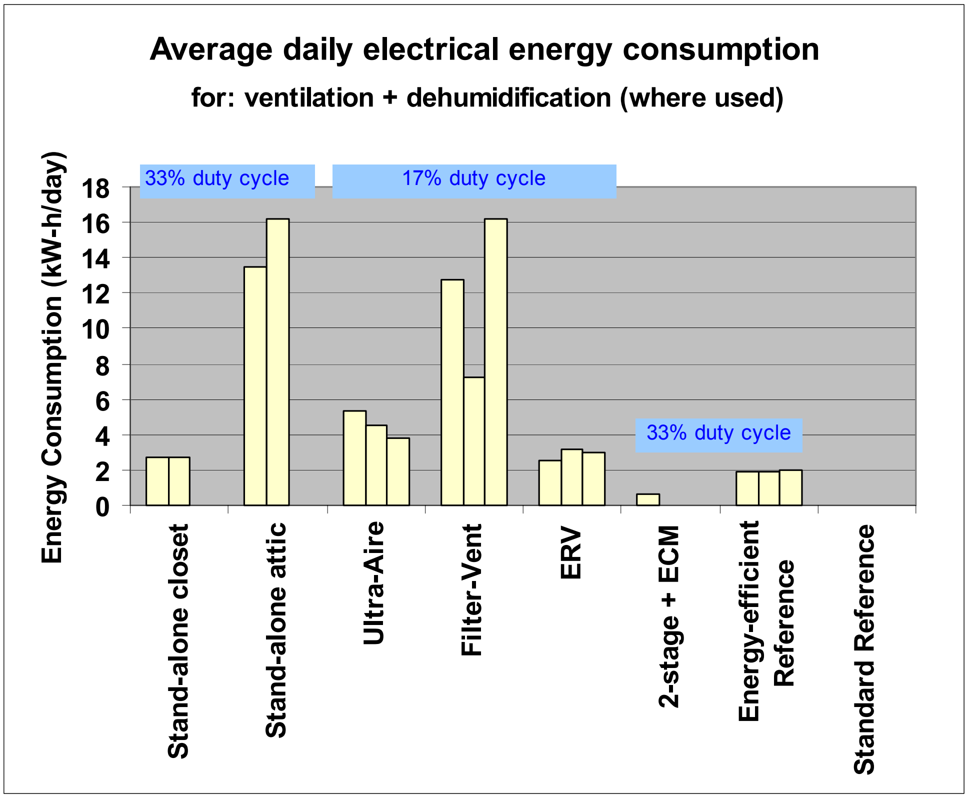

Figure 12. Average daily electrical energy consumption for ventilation and dehumidification for each house, by system category

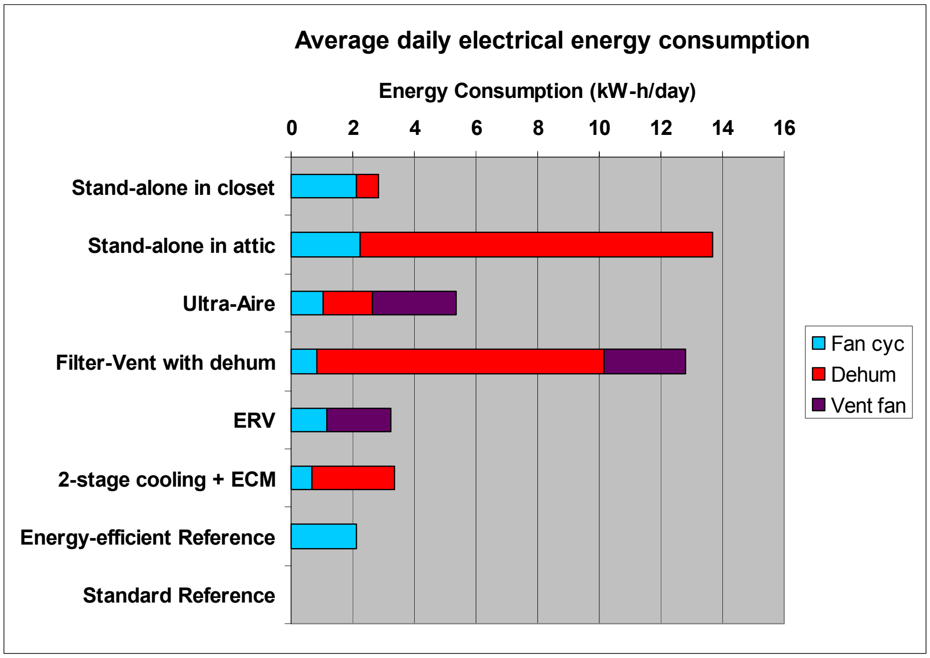

Figure 13. Average daily electrical energy consumption for ventilation and dehumidification for a representative house in each system category

The stacked bar chart in Figure 14 gives a detailed, yet big, picture view of the electrical energy consumed by each piece of space conditioning and ventilation equipment.

While both houses were similar in size, total energy consumed for the Energy-efficient Reference house was less than half that of the Standard Reference house. However, because of the reduced sensible heat gain, and the resultant reduction in cooling system operation, humidity control performance in the energy-efficient house was inferior.

Cooling energy consumption was predictably more for the stand-alone system houses and the energy-efficient reference house, which were larger two-story houses, compared to the Ultra-Aire, Filter-Vent, ERV, and two-stage with ECM system houses, which were smaller one-story houses.

Fan cycling was about one-third of the total air-handler energy consumption for the systems with 33% duty cycle, except for the ECM system where fan energy consumption was almost negligible. Fan cycling was about one-fourth of the total air handler energy consumption for the systems with 17% central fan duty cycle, and fan cycling was about one-third the energy consumed by the continuous ventilation fan.

Dehumidification energy consumption was a small fraction of the total energy except for the stand-alone in attic system and the Filter-Vent system where dehumidification was 50% and 100% of the cooling, respectively.

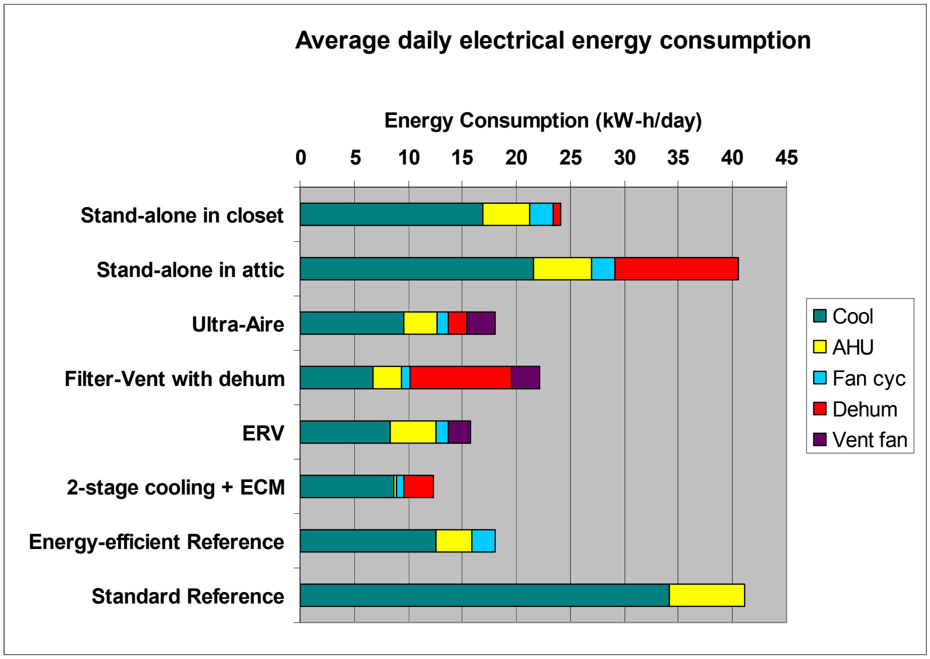

Figure 14. Average daily electrical energy consumption for all mechanical equipment monitored for each representative house in each system category

DISCUSSION

Standard Reference Houses

Monitoring data from all three Standard Reference Houses was analyzed to quantify the humidity control performance of homes that just met code requirements for energy-efficiency and had no whole-house mechanical ventilation system nor dehumidification separate from the central cooling system.

While the cooling system runtimes were predictably short as a result of cooling system over-sizing, there was little correlation between cooling system short-cycling and uncomfortably high relative humidity. Humidity control performance was good in these houses, but cooling energy consumption was high.

Energy-efficient Reference Houses

For the energy-efficient houses with low sensible heat gain, a stronger relationship between indoor humidity and outdoor dewpoint was observed compared to the Standard Reference houses. This indicates that the energy-efficient houses were more affected by outdoor air exchange, but as demonstrated by the Energy Recovery Ventilation system houses, which rejected more than half of the latent load from ventilation air, the dominant factors were lower sensible heat gain and interior moisture generation with little source control by exhaust fan usage. Lower sensible heat gain, causing longer system "off" times and possibly shorter system "on" times, caused the cooling system to operate less, therefore removing less moisture and resulting in poorer humidity control performance.

An inverse relationship was observed between indoor relative humidity and cooling system on-time fraction. Indoor humidity was generally higher with low cooling system on-time fraction.

Stand-alone Dehumidifier in Hall Closet System

The stand-alone dehumidifier in an interior hall closet system, with central-fan-integrated supply ventilation and fan cycling, had the lowest initial cost and operating cost while providing good humidity control. This system is recommended. It requires loss of a lower closet shelf, and some occupants may be sensitive to the new noise.

Stand-alone Dehumidifier in Conditioned Attic System

The stand-alone dehumidifier in the attic system also had low initial cost and very good humidity control; however, the dehumidifier operating cost was high because the attic was kept very dry, even though the dehumidistat setting was the same for all systems with that type of dehumidifier. It is suspected that that type of dehumidistat is very sensitive to the warmer daytime temperatures experienced in the conditioned attics. More testing with the dehumidistat remoted in the living space is warranted.

Both owners with the stand-alone dehumidifier in the attic had complaints about high energy consumption. Neither owner, however, wanted to forego their comfortably dry house conditions for lower energy consumption. Measured data showed that the conditioned attics were maintained to between 30% to 40% relative humidity, and the dehumidifiers operated almost constantly, even though the dehumidistat setting was the same or higher humidity than the stand-alone systems in interior closets. Because the only difference was that, during the daytime, the attic location was generally about 5°F to 10°F warmer than the living space, this indicates that the dehumidistats were sensitive to temperature as well as relative humidity.

Ultra-Aire System

The Ultra-Aire ventilating dehumidifier system was made a part of this study to fill the "best-you-can-do" slot. The system integrates supply ventilation and air filtration with energy efficient dehumidification.

The Ultra-Aire system showed good humidity control, but had the highest first cost and higher operating cost as a result of the continuously operating ventilation fan. It is a relatively costly system that may provide more quality than is needed to do the job in the production homebuilding environment.

In two of the three systems in this category, the living space relative humidity was greater than 60% for less than 5% of the time. For one system, the relative humidity was greater than 60% for 16% of the time, however, that owner was satisfied with a higher dehumidistat setting.

Filter-Vent with Dehumidifier in Ducted Cabinet System

The Filter-Vent with ducted dehumidifier system showed generally good humidity control but had higher first cost and much higher operating cost. The higher operating cost was a result of the high runtime fraction of the dehumidifier and the continuously operating ventilation fan. The dehumidifier operated about 75% of the time because of the dehumidistat being located inside the metal cabinet instead of in the living space. We suspect that the nylon strap-type dehumidistat is sensitive to both relative humidity and temperature, making it difficult to arrive at an even setting if the unit is exposed to temperature swings. The space inside the metal cabinet was generally warmer than the living space for the following reasons:

1. Air moving through the cabinet was a 1/3 fraction of outside air, which was generally warmer than inside air
2. The cabinet was located in the conditioned attic, which, in the daytime, was warmer than the living space by as much as 10°F
3. Heat was generated by operation of the dehumidifier.

More testing with the dehumidistat remoted in the living space is warranted.

One owner of the Filter-Vent system complained of high energy consumption; however, he did not want to forgo the comfortably dry house conditions for lower energy consumption.

One of the three houses in this category had a number of mechanical system problems that were not resolved until late in the test period causing it to be an outlier in the humidity control and operating cost analysis.

Energy Recovery Ventilator System

The ERV system did not show good humidity control performance. Its first cost was high, but operating cost was low. The lack of humidity control resulted because, while this system has the capability to lessen the latent load of ventilation air, it cannot dehumidify the conditioned space. This can be thought of as dehumidification in “ventilation mode” as opposed to dehumidification in “recirculation mode.” This system exhibited less control over indoor relative humidity than the systems with recirculation mode dehumidification capability.

There was a relatively wide spread in humidity control performance between the three houses in this group. In one house, the relative humidity was above 60% for 45% of the time. The ERV was not operational in this house between August 1, 2001, and October 3, 2001, but in the following cooling season, the relative humidity was still elevated. For the other two houses in this category, the relative humidity was greater than 60% for 20% and 12% of the time. It is expected that differences in internal moisture generation contributed to these varying results because the cooling setpoints were not very different.

Two-stage Cooling and ECM Fan System

The two-stage compressor with ECM air handler and Thermidistat system did not show good humidity control performance. Its first cost was the highest but operating cost was low. We believe that the humidity control performance could be improved if the fan speed could be lower during first-stage cooling to keep the evaporator coil temperature colder and if the fan was stopped at the end of cooling calls.

Despite the two-stage compressor and variable-speed ECM indoor blower, a trend of higher indoor relative humidity and low cooling system on-time fraction during part load conditions was observed. It also appears that the low-stage cooling was not effectively matched with a low-enough blower speed to maintain a low evaporator temperature. The lower the evaporator temperature, the more moisture is removed. Because ECM blowers are usually limited by manufacturers to about 50% of high-speed flow, it may be better to use a single-stage compressor and low speed on the ECM blower to maintain a low evaporator temperature.

CONCLUSIONS

All of the systems with dehumidification of recirculated air, separate from the cooling system, exhibited much better humidity control than those with dehumidification of ventilation air only (ERV system) and those with dehumidification only as part of the cooling system. Therefore, the problem of high humidity probably does not lie with mechanical ventilation, and the solution probably does not lie with the cooling system. The problem of elevated humidity in energy-efficient homes in hot-humid climates is likely a result of lowered sensible heat gain and undiminished interior moisture generation. High-performance windows and insulation and locating air distribution ducts inside conditioned space reduces sensible heat gain to the extent that the fraction of latent cooling load to total load is often outside the capacity range of even the best currently available mass-market cooling equipment (such as System 6). The apparent solution is to employ dehumidification separate from cooling in hot-humid locations.

For energy-efficient houses with controlled mechanical ventilation, the reduction of sensible heat gain and interior moisture generation were the dominant factors in increasing indoor relative humidity above 60%. As shown by the relatively high number of hours of relative humidity above 60% for the houses with the Energy Recovery Ventilator systems, controlled introduction of outside air was a smaller factor. The ERV systems were rated to reject about 60% of the latent load from ventilation air and would have shown more improvement in humidity control if ventilation air was a dominant factor.

The houses without energy efficiency improvements and without mechanical ventilation had much fewer hours of high relative humidity than those built to the Building America metrics. Based on analysis of the standard reference houses, it appears that dehumidification separate from cooling may not be necessary to maintain relative humidity predominantly below 60% in homes where

a) clear windows and code minimum insulation are installed,

b) relatively low cooling setpoints are maintained such that the cooling system operates often,

c) the occupant density is low and relatively little interior moisture is generated in comparison to the size of the house.

It should also be noted that fall, winter, and spring weather patterns tend to bring drier air from the north to Texas compared to the Gulf States east of Texas. Therefore, a standard house that seems to have acceptable humidity control in Houston, Texas, may have unacceptable humidity control in central and southern Florida.

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Appendix A:

Photographs And Schematics Of The Various Integrated Dehumidification And Ventilation Systems

Figure A-1a. Photograph of stand-alone dehumidifier in hall closet with louvered door system

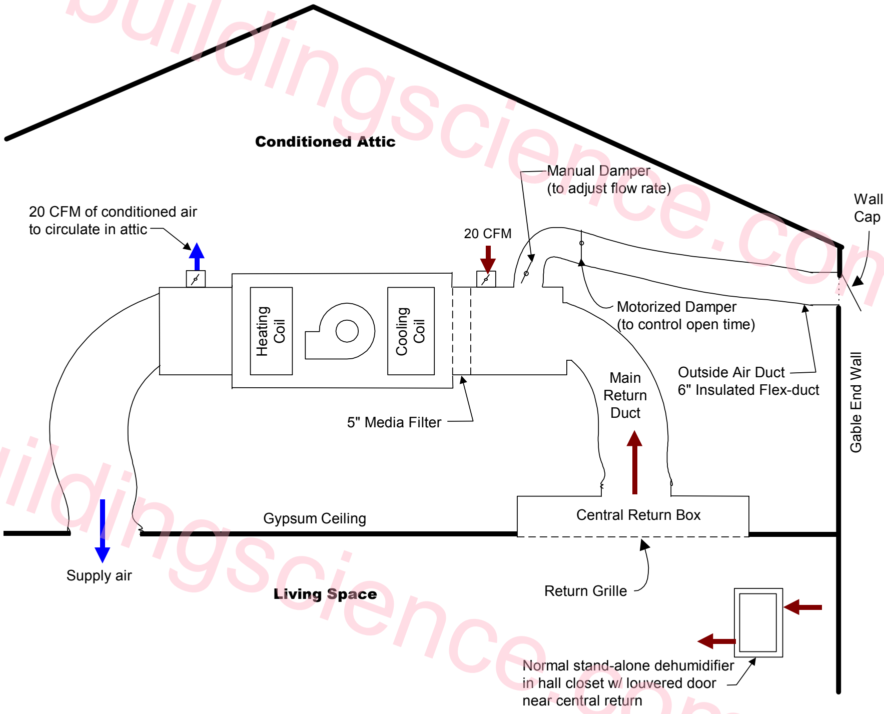

Figure A-1b. Schematic of stand-alone dehumidifier in hall closet system; dry air is mixed throughout the house via central fan cycling that is part of the standard Building America central-fan-integrated supply ventilation system; note the small supply and return air flow circulating in the unvented-cathedralized conditioned attic, this helped remove construction moisture and water vapor diffused through the asphalt shingle roof

Figure A-2a. Stand-alone dehumidifier in conditioned attic

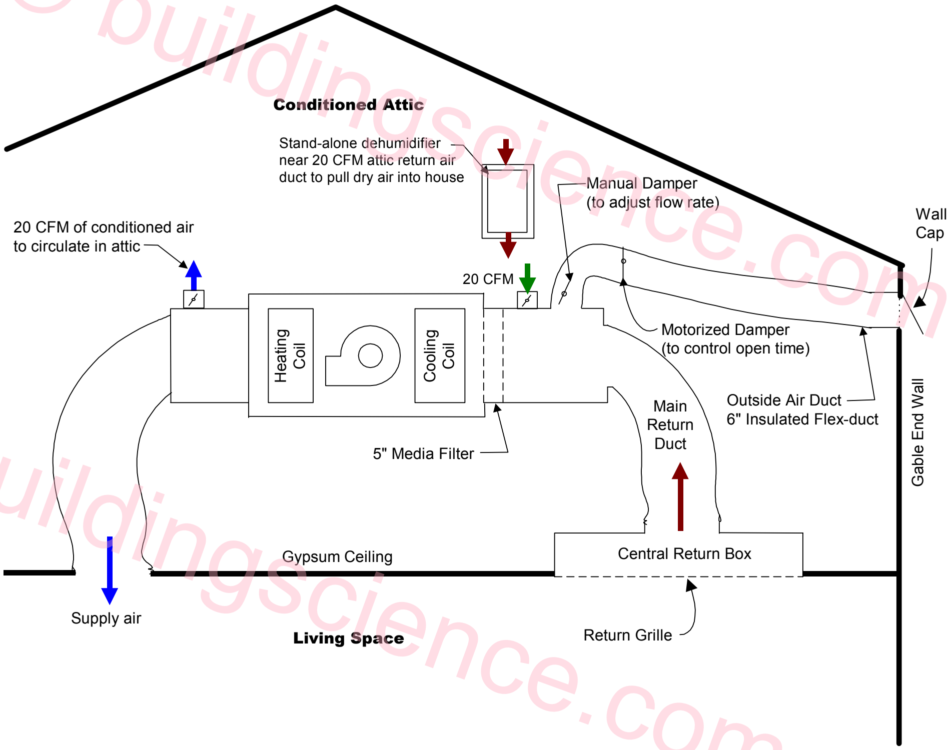

Figure A-2b. Schematic of stand-alone dehumidifier in conditioned attic system; dry air is delivered to the house via a small attic return duct placed near dehumidifier; ventilation is by central-fan-integrated supply as in all the standard Building America houses

Figure A-3a. Photograph of UltraAire system located in conditioned attic

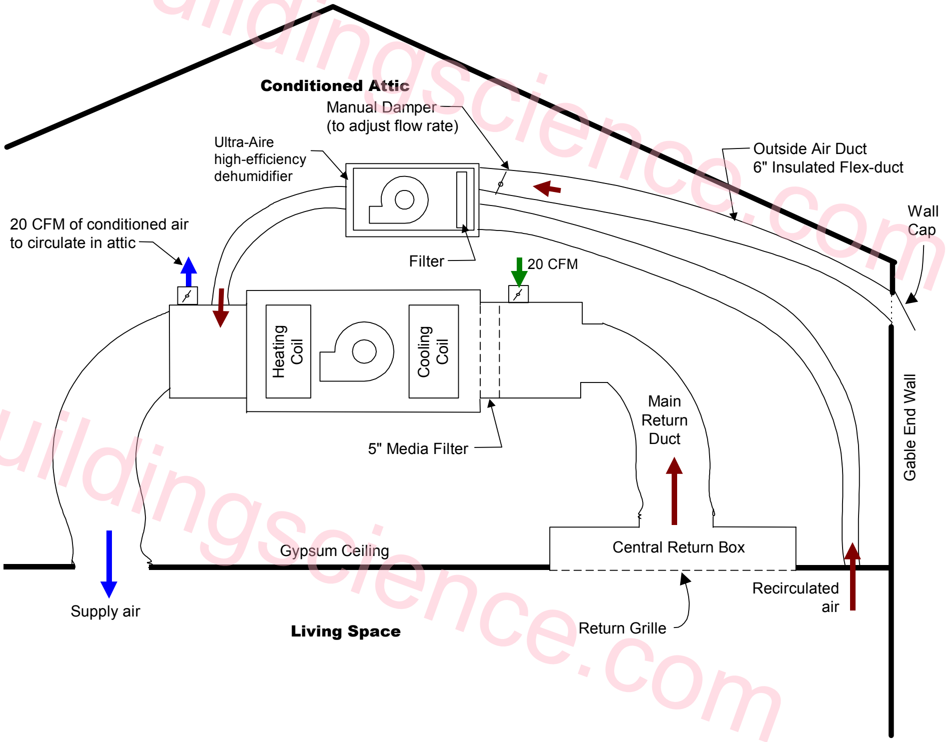

Figure A-3b. Schematic of Ultra-Aire system; outside air is mixed with inside air then filtered and dehumidified as necessary; a remote controller with dehumidistat is located in the house

Figure A-4a. Photograph of Filter-Vent system with ducted dehumidifier in conditioned attic

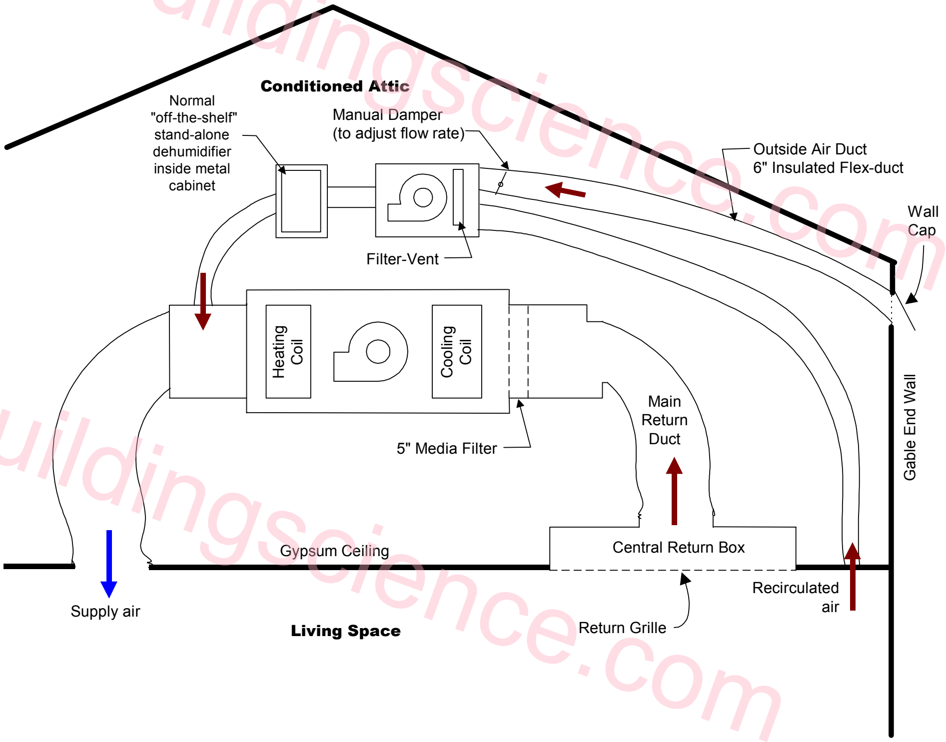

Figure A-4b. Schematic of Filter-Vent with ducted dehumidifier system; outside air is mixed with inside air then filtered and delivered to the main supply duct of the central air distribution system

Figure A-5a. Photograph of ERV system located in conditioned attic

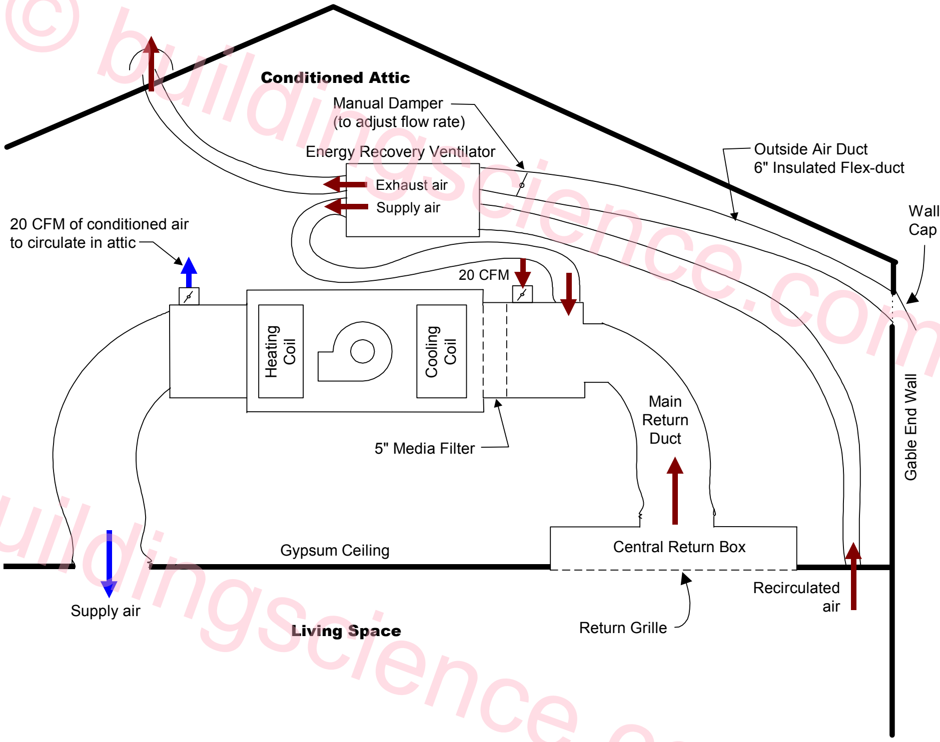

Figure A-5b. Schematic of Energy Recovery Ventilator (ERV) system; outside air is filtered and delivered to the main return duct of the central air distribution system; the ventilation air has reduced moisture and temperature as a result of energy exchange with exhaust air

Figure A-6a. Photograph of air handler unit of two-stage compressor with ECM fan and Thermidistat system

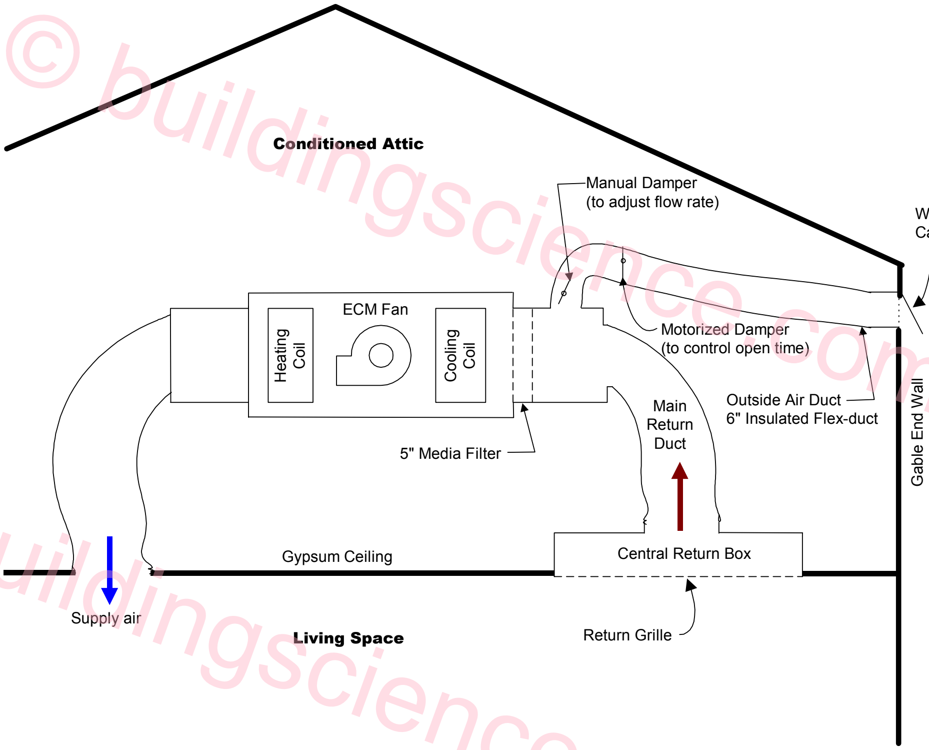

Figure A-6b. Schematic of two-stage compressor with ECM fan and Thermidistat system; evaporator section located in conditioned attic; ventilation is by central-fan-integrated supply; enhanced dehumidification was expected by long runtime with first stage compressor, slower fan speeds, and cooling below the setpoint as orchestrated by the Thermidisat control

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Twenty homes were tested and monitored in the hot-humid climate of Houston, Texas, U.S.A., to evaluate the humidity control performance and operating cost of six different integrated dehumidification and ventilation systems that could be applied by production homebuilders. Temperature and relative humidity were monitored at four living-space locations and in the conditioned attic where the space-conditioning equipment and air-distribution ducts were located. Equipment operational time was monitored for heating, cooling, dehumidification, and ventilation. Results showed that energy efficiency measures, combined with controlled mechanical ventilation, change the sensible and latent cooling load fractions such that dehumidification separate from the cooling system is required to maintain indoor relative humidity below 60% throughout the year. The system providing the best overall value, including humidity control, first cost, and operating cost, involved a standard dehumidifier located in a hall closet with a louvered door and central-fan-integrated supply ventilation with fan cycling.

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