SIMULATION OF RESIDENTIAL HVAC SYSTEM PERFORMANCE

Iain S. Walker, Jeffrey Siegel and Gwladys Degenetais
Lawrence Berkeley National Laboratory
Berkeley, California
ISWalker@lbl.gov JASiegel@lbl.gov

ABSTRACT

In many parts of North America residential HVAC systems are installed outside conditioned space. This leads to significant energy losses and poor occupant comfort due to conduction and air leakage losses from the air distribution ducts. In addition, cooling equipment performance is sensitive to air flow and refrigerant charge that have been found to be far from manufacturers specifications in most systems. The simulation techniques discussed in this paper were developed in an effort to provide guidance on the savings potentials and comfort gains that can be achieved by improving ducts (sealing air leaks) and equipment (correct air-flow and refrigerant charge). The simulations include the complex air flow and thermal interactions between duct systems, their surroundings and the conditioned space. They also include cooling equipment response to air flow and refrigerant charge effects. Another key aspect of the simulations is that they are dynamic - which accounts for cyclic losses from the HVAC system and the effect of cycle length on energy and comfort performance.

INTRODUCTION

To field test the effect of changes to residential HVAC systems requires extensive measurements to be made for several months for each condition tested. This level of testing is simply impractical due to cost and time limitations. Therefore the Energy Performance of Buildings Group at LBNL has developed a computer simulation tool that models residential HVAC system performance. This simulation tool has been used to answer questions about equipment downsizing, duct improvements and climate variation so that we can make recommendations for changes in residential construction and HVAC installation techniques that would save energy, reduce peak demand and result in more comfortable homes. Although our study focuses on California climates, the simulation tool could easily be applied to other climates.

This paper summarizes the simulation tool and discusses the significant developments that allow the use of this tool to perform detailed residential HVAC system simulations. The simulations have been verified by comparison to measured results in several houses over a wide range of weather conditions and HVAC system performance. After the verification was completed, more than 350 cooling and 450 heating simulations were performed. These simulations covered a range of HVAC system performance parameters and California climate conditions (that range from hot dry deserts to cold mountain regions). The results of the simulations were used to show the large increases in HVAC system efficiency that can be attained by improving the HVAC duct distribution systems and by better sizing of residential HVAC equipment. The simulations demonstrated that improved systems can deliver improved heating or cooling to the conditioned space, maintain equal or better comfort while reducing peak demand and the installed equipment capacity (and therefore capital costs).

This study concentrated on the extreme location for HVAC systems: in the attic (where it is hot during the cooling operation and cold during heating operation). This is the most difficult location to model because the attic has extreme diurnal temperature changes due to solar radiation and is sensitive to other weather conditions because of high ventilation rates. Other more thermally stable duct locations (such as crawlspaces and garages) will be studied in future work.

SIMULATION TOOL OUTLINE

The REGCAP (short for REGister CAPacity) model was developed because existing models of residential HVAC system performance either have too many simplifying assumptions (e.g., proposed ASHRAE Standard 152P, ASHRAE (2000)), or do not adequately model the ventilation, thermal and moisture performance of the ducts and the spaces containing ducts. The attic thermal and air flow elements were developed from existing models outlined previously by Wilson and Walker (1991 and 1992). The attic ventilation and thermal model has been discussed in Forest and Walker (1993a) and (1993b). These models of ventilation and heat transfer, excluding the ducts, were verified with extensive field measurements. A key attribute for the REGCAP simulation tool that makes it unique is that the ventilation air flow rates are calculated from building envelope leakage parameters, weather data and calculations of wind shelter effects, rather than requiring these air flow rates to be known by the user of the simulation. Previous studies discussed in the above references showed how the capability of calculating attic air flow rates is essential in determining the attic air temperatures, which in turn is very important when determining the HVAC system losses.

The model does not explicitly include any moisture transport phenomena. This is mainly due to the lack of verified models of moisture performance for buildings in general and specifically, those that can be used based on the simple information available for a house. For example, we could not find a simple verified model for air conditioner moisture performance (particularly one that would include the transient effects required in our modeling). Although the attic model has the capability to determine the moisture content of the attic air based on outdoor, indoor and attic wood conditions (Forest and Walker (1993a) and (1993b)), there is no equivalent model for indoor air moisture, mostly due to large unknowns in the hydroscopic performance of the house furnishings and the large impact occupants have on indoor moisture. In addition, the houses tested for verification purposes were in dry climates.

The air flow modeling in REGCAP combines ventilation models for the house and attic with duct, register, and leakage flows using a mass balance of air flowing in and out of the house, attic and duct system. The thermal modeling uses a lumped heat capacity approach so that transient effects are included. The ventilation and thermal models interact because the house and attic ventilation rates are dependent on house and attic air temperatures. Also, the energy transferred by the duct system depends on the attic and house temperatures.

The equipment model for REGCAP (Proctor (1999)) is based on manufacturers' performance data. The capacity and power consumption change with the outside weather conditions, flow rate across the evaporator coil, and the return air conditions. Additional information regarding air conditioner performance changes due to incorrect system charge and system air flow have been adapted from laboratory data (Rodriguez et al. (1995)). The output from the airflow and thermal models are used together with weather data to determine the air conditioner performance. For example, the capacity of the air conditioner is decreased as the outdoor temperature increases, and refrigerant change and air flow across the evaporator decrease. The temperature change across the cooling coil is determined from the volumetric flow rate through the coil (the system fan flow) and the calculated capacity of the equipment. Due to the limited data available and the possible changes in equipment performance for specific A/C units the equipment performance algorithms are as simple as possible and assume that the various effects combine independently. Field measurements on houses with a range of systems in different climates have been used to verify the predictive ability of the model (Siegel et al. (2000)).

The thermal model uses a lumped heat capacity approach in which the attic, house and HVAC system are split into 16 nodes (plus the outside conditions and the equipment capacity). . These nodes are illustrated in Figure 1. Heat is transferred between the nodes by air motion (for the air nodes), convection (between air and surfaces), radiation (between surfaces in the attic, solar effects and night time exterior surface cooling) and conduction (between nodes in contact with each other). Two attic surfaces form the two pitched roof decks and they are important to allow for differential solar heating depending on roof orientation. The attic gable ends are lumped together in the end walls.

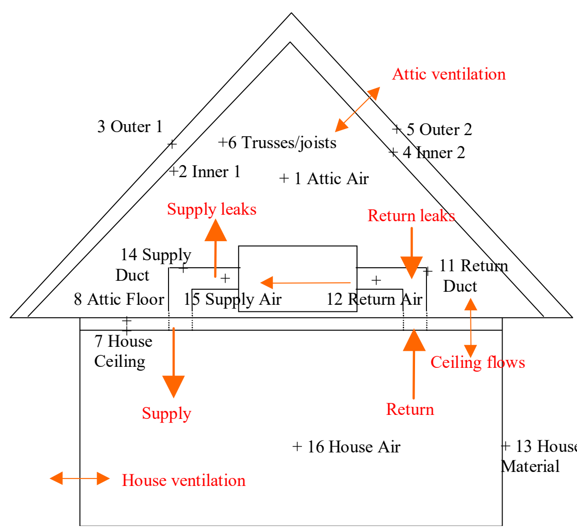

Figure 1. Nodes for thermal model

The model is able to use single nodes for the supply and return duct branches because the all the supply and all the return ducts are in the same space: the attic. If some ducts were in other locations (e.g., a crawlspace) then additional nodes would be required to account for heat transfer to these other spaces. The use of a single node per duct location does is not a large source of uncertainty because the temperature changes within the supply or return ducts are smaller than the other temperature differences active in the heat transfer calculations. As the verification results show, a single modeled supply temperature air temperature is very close to the average of the measured supply temperatures. This single node approach has also been successfully used by many other researchers (e.g., ECOTOPE (1997)) and in a draft ASHRAE Standard for thermal distribution system efficiency (ASHRAE (2000)).

In order to investigate the effects of system cycling, equipment capacity and alternative thermostat settings, the timestep for the simulations shown here was set to one minute. Shorter timesteps produce too much computational burden for no significant improvement in time response and longer timesteps are too coarse to differentiate the detailed system performance changes (e.g., the changes in cyclic behaviour for reduced capacity systems).

To reduce the input data burden, REGCAP uses simple correlations based on field measurements in attics to correlate the attic floor area and roof pitch to determine the geometry used in the attic heat transfer calculations and the thermal mass of the attic wood.

The attic surfaces experience both natural and forced convection. The forced convection is based on empirical relations developed from standard Nusselt relationships and linearized (Ford (1982)) over the range of temperatures seen in residential buildings. The velocities for exterior surfaces are based on the exterior wind speed at eaves height, and the interior velocities are based on the ventilation air flows and the size of holes through which the ventilation air passes. This assumption is physically more realistic and gives higher velocities for attic interior surfaces than the traditional plug flow assumption used by Ford (1982) and Burch and Luna (1980). Similarly, the natural convection coefficient uses the same length scale and a standard Nusselt relationship (Holman (1981)). Fortunately, changes in the heat transfer coefficient due to surface orientation do not significantly affect the attic heat transfer and a coefficient based on a single orientation can be used. The total heat transfer coefficient is determined from the cube root of the sum of the forced and natural heat transfer coefficients cubed. This makes the larger of the two coefficients most dominant, whilst maintaining a smooth transition from one to the other. For the house the convection heat transfer coefficient is fixed at 7 W/m^2K. This value is based on the correlation given in ASHRAE Fundamentals, Chapter 3 (ASHRAE (1997)) that is not very sensitive to internal air flow velocities.

REGCAP uses a simple single node/zone model for estimating house loads because the model is focussed on HVAC system performance rather than building envelope performance. In addition, without detailed house and site information. a more complex house thermal model was not justifiable.

For air flows, the house and attic are both treated as single zones. Most attic spaces are of open construction and a single zone is a good assumption. Houses tend to be compartmentalized by interior partitions and if doors are closed between rooms the house will have several linked interior zones. If we were interested in predicting heat and air movement for individual rooms, then this would be a concern, but when determining overall values for the whole house the single zone approach is probably adequate. In addition, the extra information on the flow resistance of all the flow pathways between all the rooms of the house is almost impossible to determine - so the required input information for a more complex model is generally unknown. One significant aspect of the single zone assumption is that it ignores heat transfer through the ducts when the air handler is off that is transported by air flow through the ducts from room to room. This is generally not a problem for this study because it is a very small part of the load for the whole house. Some simple calculations show that the room-to-room flows through attic ducts contribute less than 100 W to the house load. Note that REGCAP does include air flows (and the associated heat transfer) between the house and the attic through the duct leaks when the air handler system is off.

FIELD VERIFICATION

To validate the REGCAP simulations, this study used measured data from three different sites: Palm Springs, Sacramento and Las Vegas. These homes have an average floor area of 1500 ft^2 (140 m^2) and have ducts located in the attic. Other houses used to validate REGCAP have ducts brought in to conditioned space and are discussed in Siegel et al. (2000).

The comparisons between measured and predicted results were examined for the house, attic, supply, and return air temperatures. In general, REGCAP gives temperatures close to the measured values (typically within ± 2°C (± 3.6°F)). The equipment model predicts power consumption and capacity very closely for all sites (within 4% of measured values). The differences between measured and predicted values are mainly due to model simplifications and do not significantly change the building load or the predicted HVAC system performance.

House temperature: The average absolute difference between the simulated and the measured data was in the range of 1 to 2 °C (2 to 4°F). Observations of the simulation results and some additional parametric analyses have shown that these differences are mainly due to the simplifications regarding coupling of house thermal mass to the house air, and under-prediction of solar radiation effects.

Attic temperature: The simulation results show average differences of about 3°C (5°F) between measured and predicted temperature. This is a reasonable difference given the highly variable attic temperatures. The simulations are good at reproducing the large diurnal fluctuations in attic temperatures, as shown in Figure 2. The main reasons for the differences are poor estimates of exterior radiation effects (solar gains during the day and radiative cooling at night). This hypothesis is confirmed by the study of other sites for which measured data are lower than predicted data in the morning before sunrise and higher after sun-rise. Factors such as cloud cover and the spectral emissivity and absorptivity of the roof material are not well known and this uncertainty in model input contributes to these differences.

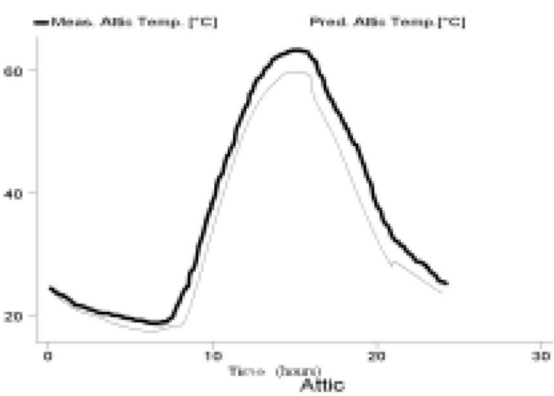

Figure 2. Comparison of measured and predicted attic air temperature

The simulations and measured data show similar variations in attic temperature due to duct system operation. As the system cycles, it cools the attic air when the cooling system is on. The attic air then warms up when the system is off (this can be seen in Figure 4). This cycling shows how the duct losses are conditioning the attic rather than the house. A system with no duct losses would not show this cycling of attic temperature.

Return Duct air: The return duct air temperature agreement is very good when the air handler is on. The return duct air temperature is close to indoor conditions and is dominated by the indoor air flow into the return due to air handler operation. When the air handler is off, the predicted temperatures are higher than the measured results.

Supply duct air: Figure 3 shows that the Supply duct air has the same behavior as return duct air, with good agreement when the air handler is on but not when it is off. The high temperatures for the supply and return duct simulations with the air handler off are due to strong coupling to the hot attic air temperature and radiation exchange with the interior attic surfaces. In addition, any air flows from room-to-room through ducts when the air handler is off will cool the duct air and these multi-zone effects are not taken into account in the simulation. REGCAP only calculates the flow of air passing from the attic to the house or from the house to the attic through duct and ceiling leaks. It should be noted that these errors when the air handler is off do not affect the results when the air handler turns on, and do not have a significant effect on the overall building load or system losses. With the air handler on, the heat transfer is dominated by the air handler flows and equipment operation.

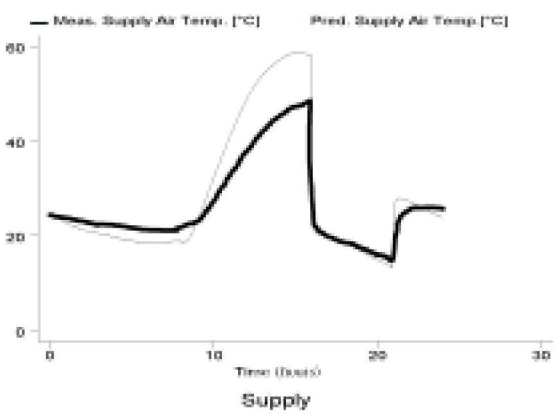

Figure 3. Comparison of measured and predicted supply air temperatures.

SIMULATING IMPROVED HVAC SYSTEMS

REGCAP was designed to answer questions about the effect of heating and cooling system inefficiencies on system performance. Specifically, the goals of this research were to answer the following questions:

1. What are the energy and comfort penalties associated with inefficient heating and cooling systems in California climates?
2. How much does correcting those efficiencies improve system performance?

3. Are there performance penalties associated with downsizing (or, more accurately, rightsizing, equipment)?

In order to answer these questions, some performance parameters need to be defined.

The two **comfort** related issues studied are: **pulldown time** and **Tons At the Register**. A common operating strategy used to reduce energy consumption is to turn off the air conditioning system during the day when the house is unoccupied. The **pulldown time** is the time required to cool the house after it has heated up during the day. A short pulldown time means that the house is comfortable sooner, which is desirable for the occupants. The power delivered to the conditioned space via the register is called **Tons At the Register (TAR)** (although this is a misnomer for heating systems, it is retained for convenience). Higher TAR implies more energy delivered to the conditioned space. TAR is used as a comfort parameter because it changes the occupants perception of cooling system performance and also effects consumer expectations of how much heating or cooling the system should provide (as discussed further in Walker et al. 1998).

This study evaluates the energy related issues of **system performance** by evaluating **duct efficiency**, **equipment efficiency**, **total HVAC efficiency**, **peak power** and **total energy**. The **total energy** represents the energy consumed during the 24-hour period simulation. The three efficiencies are defined as follows:

Equipment efficiency = Equipment Output Capacity / Power Consumption

Duct efficiency = TAR / Equipment Output Capacity

Total HVAC efficiency = TAR / Power Consumption

Cooling simulations were run minute-by-minute for 24 hour periods corresponding to a design day. Weather data for a whole year were searched for a day that represented a design day (99%/1% design conditions from ASHRAE Fundamentals (1997)). The heating simulations were run for 36 hours. The additional 12 hours allow a full night of simulations (when heating loads are highest). The input weather data were the hourly weather data developed by the California Energy Commission for use in residential energy calculations (CEC (1998)). These weather data include all 16 climate Zones for the state of California. The cooling system simulations were performed for climate zones from 8 to 15 because other zones do not require residential cooling. The heating system simulations were performed for all of the 16 climate zones. The hourly weather data include the solar radiation, outdoor temperature, outdoor humidity ratio, wind speed, wind direction and the atmospheric pressure. The one-hour data were linearly interpolated down to one minute for the simulations.

The input data for the house and attic were based on a typical California house defined by the California state energy code for new residential buildings (CEC 1999) and field observations of residential attics by the authors. The house is a 164 m^2 two-storey house with the system in the attic. The characteristics of the house, attic and system are given in more detail in Degenetais et al. (2001). Four systems were simulated:

- **Base case** - This case describes an average new house in California, with duct leakage of 22% of air handler flow (split evenly between supply and return ducts), 85% of correct refrigerant charge and air handler flow, duct surface area of 27% of floor area, nominal R4 duct insulation, and a 4 ton air conditioner.
- **Poor case** - this case describes a below-average house in California. Duct leakage is increased to 28% and charge reduced to 70%,
- **Best case** - this case describes an average new house in California that has been improved by duct sealing (to 12%), refrigerant charge addition (to 100%), and correction of air handler flow.
- **Best resized** – this is the best case with a properly sized air conditioner according to *Manual J* and *Manual S* (ACCA (1986, 1992)). For cooling, this system has one ton less capacity and for heating the capacity reduction is also 25%. The air flow and duct surface area are also reduced by 25%.

RESULTS

An example of the temperatures generated by the simulations are shown in Figure 4. This figure clearly shows the effect of solar gains on daytime heating of the attic. The cycling behavior of the cooling system can be seen in the large temperature variations for supply air and smaller variations for house air. In addition, the cooling losses from the duct system are illustrated by the cyclic fluctuations in attic temperature. These detailed simulation results have been analyzed in order to determine answers to focus on comfort and energy related issues.

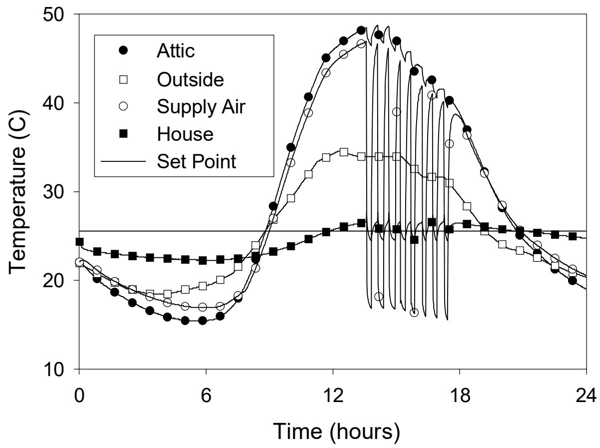

Figure 4. Example of predicted REGCAP temperatures for a base case system in Climate Zone 8.

In the discussion of the cooling simulations, the results are shown for climate zone (CZ) 8 and climate zone 15, which are respectively the mildest (32°C design temperature) and hottest (43°C design temperature) cooling climates. Other climate zones give results between these two extremes. Because the focus of this study was on potential reductions in electricity consumption for residential cooling and for brevity, the heating system results are only discussed briefly.

Figure 5. Climate and system dependence of the time required to cool a house (pulldown time)

Climate strongly affects pulldown time, as shown in Figure 5, with less than an hour required to control the indoor temperature in mild climates, but more than five hours required in the hottest climate. Because of the short pulldown times in CZ 8, the 15 to 30 minute differences between the systems are not important to most homeowners. However, in CZ 15 the **good** system takes two hours less to achieve a comfortable indoor temperature than the **base** and **poor** systems. The **good resized** system requires a longer pulldown time then the **good** system, but is still better than the **base** system.

For systems with a long pulldown time, a homeowner is likely to operate the system such that the air conditioning is turned on at an appropriate time to have a comfortable house temperature at 5 p.m. or at 6 p.m. Additional REGCAP simulations were performed to determine the turn on times required for CZ 12 and for the **base** and **good resized** systems only. This procedure is iterative because we cannot know in advance when to turn a system on to achieve the desired temperature at a fixed time. The good resized system can be turned on half an hour later (at 3:15 rather than 2:45) to achieve the same indoor conditions at 5:00 p.m. This causes reduced electricity use during the afternoon peak period.

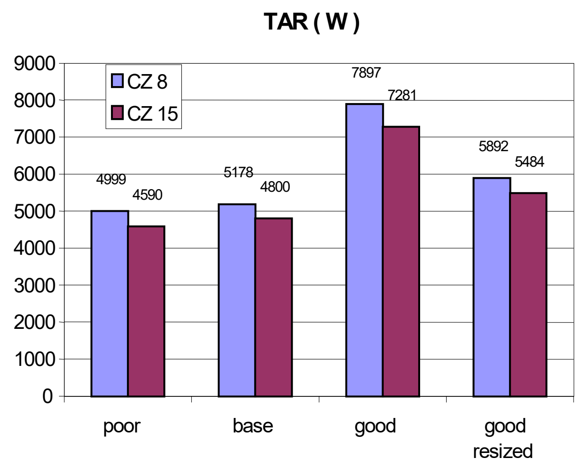

Figure 6. Changes in TAR with climate and system performance

Figure 6 illustrates the range of TAR calculated in the simulations. The **poor** system delivers only 60% of the TAR of the **good** system - the rest being lost because of poor ducts and equipment. The **good resized** system is able to deliver more TAR than the larger **base** system. The difference between the climates is due to the increased ambient temperatures in CZ 15 that increase duct losses and reduce air conditioner capacity. In all cases the TAR is substantially less than the nameplate capacity of the equipment that is four tons or about 14 kW (or 3 tons (10.5 kW) for the **good resized** system). Even the **good** system only delivers about half the nameplate capacity. This is due to the combination of duct losses, poor equipment performance at elevated ambient temperatures and overstating of equipment capacity by manufacturers. For the base and poor systems, the capacity is further reduced by low air handler flows and low refrigerant charge. The discrepancy between TAR and nameplate capacity is also discussed in Siegel et al. (2000)

The duct efficiency increases as the systems are improved, from about 50% for a poor system to 70% for good systems. The remaining 30% of duct losses can be reduced if the HVAC equipment and ducts are brought inside conditioned space (see Siegel et al. (2000)). The higher duct efficiency implies reduced losses and more of the equipment output going into the conditioned space.

For utilities, the reduced power consumption for resized systems reduces peak demand (currently a key issue in California's power crisis). In addition, the improved efficiency of the **good** systems leads to increased diversity and reduced utility system peak load. The cost to the homeowner for these systems depends on the overall energy consumption. The energy consumed for the design day is shown in Figure 7. The **poor** and **base** systems use about 35% more energy compared to a **good** system. There is no significant difference in energy consumption between the **good** and the **good resized** system.

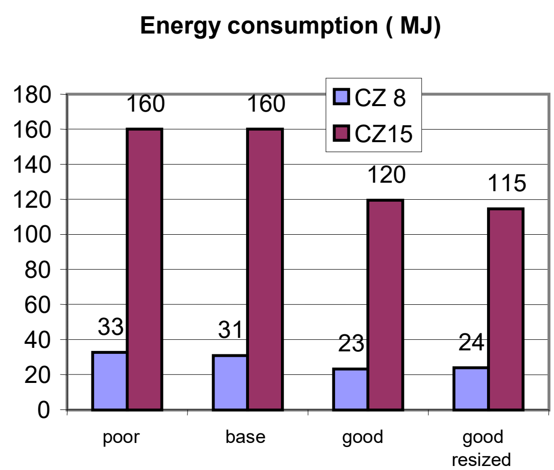

Figure 7. Energy consumption changes with climate and system performance

The results for heating systems are similar to those for cooling, although performance gains are more moderate. Correct air handler flow and less leakage (a **good** system) results in a 10 % improvement in register capacity and a 10 % increase in duct efficiency. It also decreases the energy consumption by 6% in comparison with the **base** system. A **poor** system loses 5% of the register capacity and duct efficiency in comparison with the **base** system. Its energy consumption is about the same as the **base** system energy consumption. In addition to the 25% power (peak) consumption reduction due to resizing, a **good resized** system consumes between 10 % and 12 % less energy than a **base** system for almost all climates and duct locations.

CONCLUSIONS

The REGCAP simulation was developed to examine the performance of residential HVAC systems. REGCAP was developed to be able to use readily available data for a house rather than requiring the user to supply generally unknown input parameters (e.g. attic ventilation rates and temperatures). Comparison to field measurements shows that REGCAP is a good predictor of house and duct system performance, during heating or cooling system operation. When the systems are not operating, the simulations do not match the measured data as well for HVAC system air temperatures, but the errors do not contribute significantly to the energy consumption or system performance results.

Simulations were performed for a typical California house in 16 California climate zones. The typical (**base**) California system used about 35% more energy than a **good** or **good resized** system on a design day for cooling, and about 10% more for heating.

The **good** and **good resized** systems also have significant improvements in thermal comfort. They are able to reach a comfortable indoor temperature hours before typical systems in hot climates. The **good** system is able to deliver more than twice as much cooling to the conditioned space as a base system and still delivers more cooling with a 25% smaller air conditioner.

A properly sized system (about 25% capacity reduction) reduces the power consumption and therefore peak demand. Even though these correctly sized systems have a smaller capacity, they can still provide better or equal comfort than an oversized system. Better comfort is achieved by supplying a higher register capacity and having a shorter pulldown time. For houses operating in pulldown mode (where the house heats up during the day), these correctly sized air-conditioning systems can be turned on later in the day and still achieve the setpoint temperature by the time occupants return to the house in the evening.

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