A Dynamic Ceiling for Improved Comfort with Evaporative Cooling

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ABSTRACT

In dry climates, evaporative cooling offers significant energy and peak demand reductions compared to compressive air conditioning. One of the main barriers to its greater implementation is a difficulty in maintaining occupant comfort on design days. For this reason, envelope upgrades that reduce peak cooling loads are especially beneficial when evaporative cooling is being considered since sufficient reductions can make it a more viable alternative.

Ceiling heat gains may be eliminated if a portion of the conditioned air normally exhausted through open windows during evaporative cooling is first directed through air permeable "dynamic" attic insulation before finally being expelled to a vented attic. The load reductions associated with integrating evaporative coolers with the buildings that they cool in this manner will be greatest during design conditions. In addition to reducing sensible load during these critical periods, controlled ceiling intake locations distributed in different rooms will aid in the circulation of conditioned air throughout a house that is typically supplied to only one central location by an evaporative cooler.

With co-funding from the California Energy Commission and DOE's Building America Program, Steven Winter Associates has developed a furred ceiling design with a small number of controlled openings that allows conditioned air to be uniformly exhausted through attic insulation. Test chamber results demonstrate that a relatively small airflow rate is necessary to eliminate ceiling gains and that this airflow can be captured with a design that does not significantly depart from standard practice. A prototype dynamic ceiling house will be constructed in 2004.

Introduction

Dynamic envelopes attempt to exploit through design the thermal interaction that occurs between infiltration loads and envelope conduction loads. When a typical residential evaporative cooler operates, one-thousand-plus CFM of conditioned outdoor air must be supplied to and exhausted from a house. A dynamic ceiling design integrated with an evaporative cooler would only require a small fraction of this available exhaust airflow to be directed through attic insulation in order to completely eliminate ceiling heat gain. The great availability of exhaust airflow in this application allows for the possibility of a flexible dynamic ceiling design with a minimal departure from standard construction practice. Such a design has been developed for an assembly similar to a conventional furred ceiling. The main components of this design are a continuous plenum above the ceiling drywall and a small number of controlled intake locations in the ceiling drywall that allow room air to escape into the plenum and relieve the pressurization induced by evaporative cooling. The elimination of ceiling heat gain resulting from the flow of room air through such an assembly would only occur when an evaporative cooler runs for a sufficiently long period of time such as during peak and near peak cooling conditions. However, it is only during these design conditions that an evaporative cooler requires assistance in meeting occupant comfort requirements (Huang et al., 1991). In addition to reducing sensible load during these critical periods, controlled ceiling intake locations distributed in different rooms will aid in the circulation of conditioned air throughout a house that in a typical evaporative cooling system design has air supplied to only one central location.

In a hot climate dynamic ceiling design, exfiltrating air will be warmed as it flows through attic insulation. Thus there is no danger of interstitial condensation within the assembly since the relative humidity of the air being exhausted will decrease during exfiltration. In order to minimize undesirable infiltration, gravity dampers that only open when a house is significantly pressurized due to the operation of an evaporative cooler can be used in the ceiling intakes.

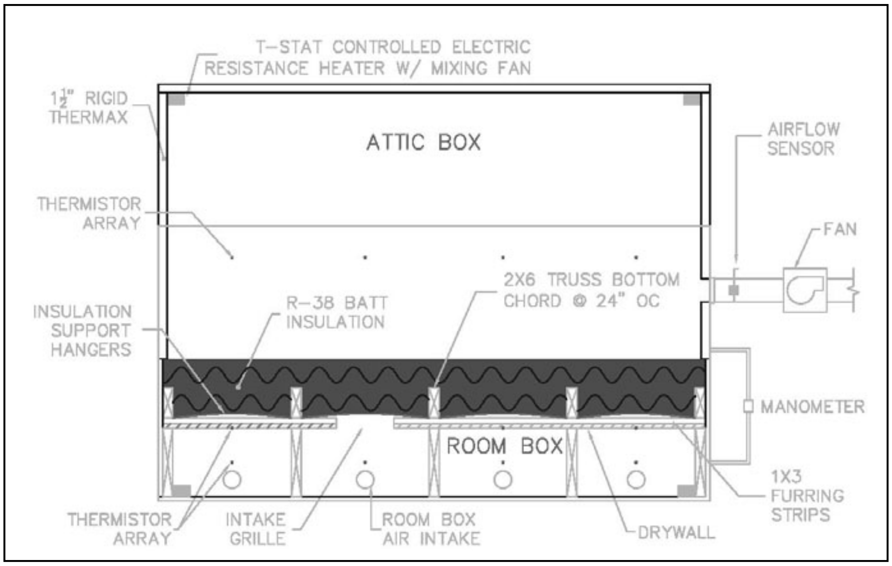
In order to assess the hot climate dynamic ceiling design, a test chamber was constructed that is capable of exposing an eight foot square ceiling assembly to typical peak summer attic temperature conditions. This test chamber demonstrated that the continuous furred plenum constructed between ceiling drywall and attic insulation can uniformly distribute room air from a single intake opening in the ceiling drywall before it is exhausted through attic insulation. In addition to serving as a proof of concept, results from the test chamber confirm that a relatively small airflow rate is necessary to eliminate ceiling gains compared to the airflow supplied by a typical residential evaporative cooler. Hourly building energy simulations of a single-story house with no ceiling heat gains during design conditions indicate that a dynamic ceiling design can reduce afternoon sensible load by 17% - 25% on design cooling days and significantly improve occupant thermal comfort. In order to actually realize these benefits, construction details have been developed to implement a dynamic ceiling design in a prototype house that will be completed this year.

Test Chamber Methodology

The test chamber, shown in Figure 1, is comprised of a temperature controlled upper box that simulates summer attic temperature conditions and a lower box that is maintained at room temperature. These two boxes are separated by a continuous layer of ceiling drywall. This drywall is an air barrier except for where there is an opening cut for a 10x6 return air grille. In addition to this return air grille, a continuous plenum space between the ceiling drywall and the attic insulation distinguishes the dynamic ceiling design from that of a conventional ceiling. The plenum is created by 1” x 3” wood furring strips attached to the underside of the truss bottom chords and by steel insulation support hangers that are used to slightly raise the R-38 fiberglass batt insulation. A variable speed fan and duct system is used to exhaust air from the attic box. Exhausting air from the attic box induces air from the room box to flow through the ceiling return air grille, fill the plenum space below the attic insulation and then flow through the attic insulation into the attic.

A data logger was used to record the average temperature on the underside of the ceiling drywall with sixteen thermistors, the average attic box temperature with eight thermistors and the average room box temperature with eight thermistors. A rotating vane anemometer especially calibrated for low airflow applications was used to measure the exhaust airflow rate through the system.

Figure 1. Dynamic Ceiling Test Chamber Schematic



During a thermal test for a particular exhaust airflow rate, the attic box is maintained at 130 ^oF, approximately 60 ^oF higher than room temperature. The average temperature on the underside of the ceiling drywall is then compared to the average room box temperature. There are three possible outcomes to such a comparison:

- In the case of zero airflow through the system as in a conventional attic, the average temperature on the underside of the ceiling drywall will be higher than the average room temperature by an amount that corresponds with the level of attic insulation.

$$T_{drywall} - T_{room} = \Delta T_{conventional}$$

- If the air flow rate through the system is high enough to completely offset ceiling heat gains, the average drywall temperature will closely track the average room temperature.

$$T_{drywall} - T_{room} = \Delta T_{dynamic} \approx 0$$

- If the air flow rate through the system is only high enough to partially offset ceiling heat gains, the average temperature difference between the drywall and the room box will be greater than zero but smaller than that of a conventional attic.

$$0 < \Delta T_{dynamic} < \Delta T_{conventional}$$

For a specific attic insulation level, the fraction of heat gain offset by a dynamic ceiling compared to a conventional ceiling (F) may be expressed as:

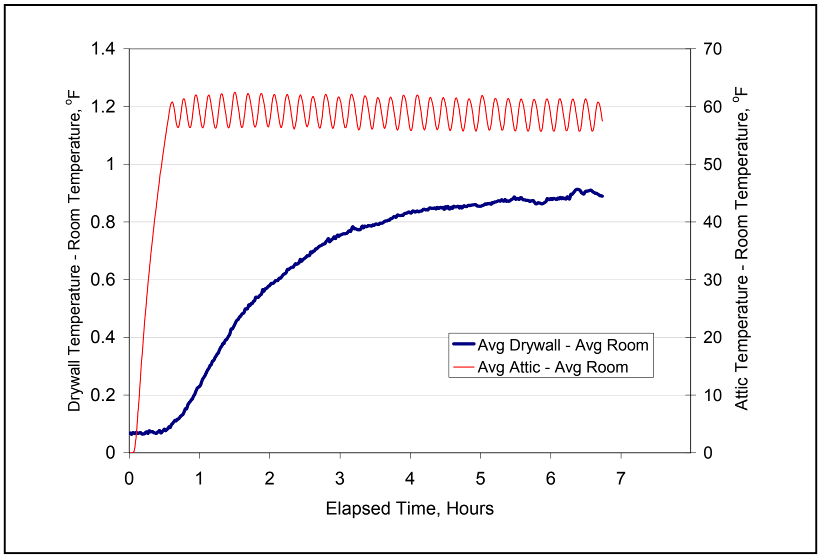
$$F = 1 - \frac{U_{dyn}}{U_{conv}} = 1 - \frac{\Delta T_{dynamic}}{\Delta T_{conventional}}$$

In addition to the thermal performance of the dynamic ceiling, the test chamber is also equipped to measure the relationship between airflow and pressure drop through the dynamic ceiling and its components.

Test Chamber Results

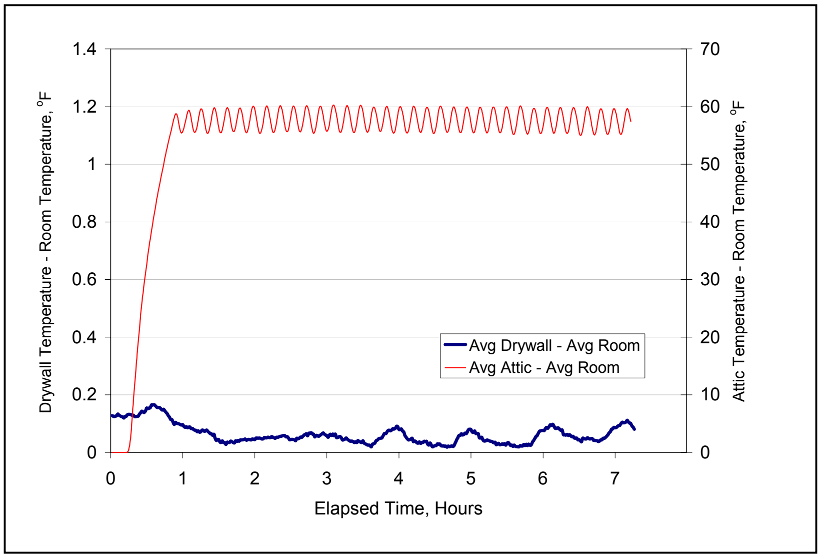
In Figure 2, the difference between the average drywall and room temperature is plotted on the same graph but on a different scale as the difference between the average attic and room temperature for a thermal test with zero airflow through the dynamic ceiling. For this case representing a conventional R-38 insulated ceiling assembly exposed to a typical peak summer attic temperature, the average steady state drywall-room temperature difference is 0.90 °F.

Figure 2. Conventional R-38 Ceiling Performance



In Figure 3, the difference between the average drywall and room temperature and difference between the average attic and room temperature are presented for a thermal test with a constant airflow rate of 11 CFM (0.17 CFM per square foot) through the dynamic ceiling.

Figure 3. Dynamic R-38 Ceiling Performance @ 11 CFM (0.17 CFM per ft^2)



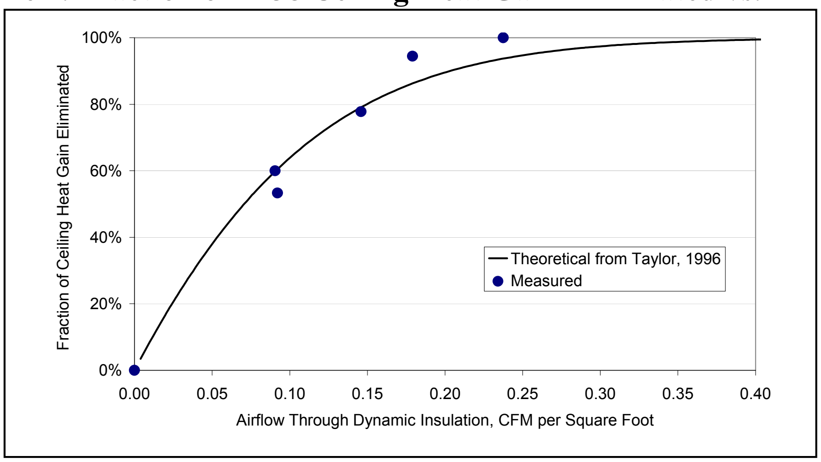
For this case representing an R-38 insulated dynamic ceiling assembly exposed to a typical peak summer attic condition, the average steady state drywall-room temperature difference is 0.05 ^{o}F.

In Figure 4, the fraction of ceiling heat gain eliminated through the R-38 insulation as measured in the test chamber is compared to one-dimensional steady state analytical results developed by Taylor for a range of airflow rates (Taylor, 1996):

$$F = 1 - \frac{U_{dynamic}}{U_{conventional}} = 1 - \frac{V\rho C_p R}{e^{V\rho C_p R} - 1}$$

V → velocity of air	ρ → density of air
C_p → heat capacity of air	R → R-value of conventional assembly

Figure 4. Fraction of R-38 Ceiling Heat Gain Eliminated vs. Airflow



Both experimental and analytic results indicate that approximately 0.25 CFM of airflow per square foot of ceiling area is required to completely eliminate ceiling heat gain through R-38 attic insulation. This minimum airflow rate required by the dynamic ceiling is significantly less than the minimum supplied per square foot by a typical evaporative cooler.

In addition to measuring the airflow required to completely offset ceiling heat gains, the test chamber was also used to determine the room pressure necessary to force this critical airflow through a dynamic ceiling assembly. The relationship between flow rate and pressure drop is well understood for airflow through return air grilles and porous insulation. Flow through return air grilles such as at the intake of the dynamic ceiling is fully turbulent and is well characterized by a power law relationship for flow through openings (ASHRAE Fundamentals, 2001):

$$Q_{grille} = C_1(P_{room} - P_{plenum})^n$$

C_1 → power law coefficient	n → power law exponent

Pressure drop through porous insulation is directly proportional to flow by a constant known as the airflow permeability of a material (Yarborough, 1992).

$$Q = K \times \frac{A\Delta P}{L\mu}$$

A → area	L → insulation thickness
K → airflow permeability	μ → viscosity of air

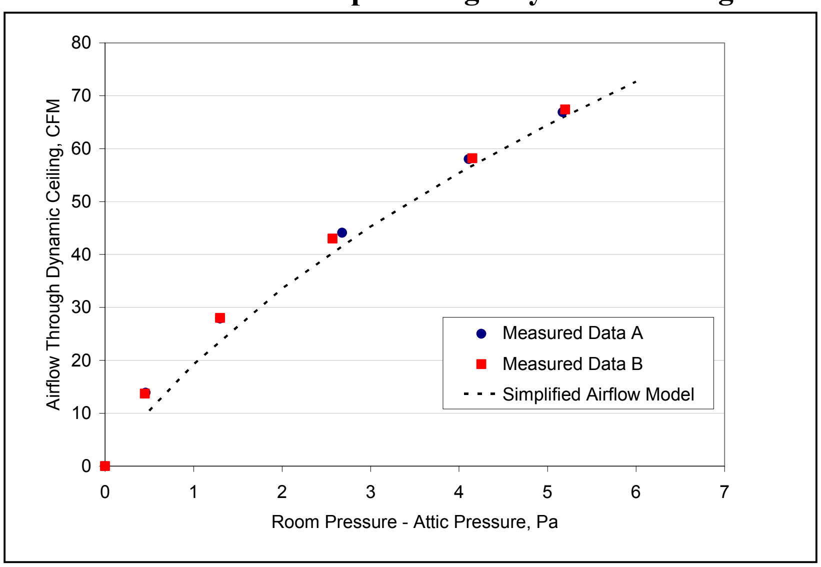
$$\therefore\ Q_{insulation} = C_2(P_{plenum} - P_{attic})\ ;\ C_2 = \frac{KA}{L\mu}$$

The power law coefficient and exponent for airflow through return air grilles are reasonably well available from manufacturers. The airflow permeability of loose fill fiberglass and cellulose at different densities has been measured by other workers (Yarborough, 1992). By combining relationships for airflow through these two primary components, a simplified model for the airflow through a dynamic ceiling system as a whole has been developed. All the airflow that passes through the ceiling grille must pass through the insulation. Setting the two expressions for airflow through a return air grille and porous insulation equal to each other yields a relationship between the plenum pressure and the room pressure:

$$(P_{room} - P_{plenum}) = (C_2 / C_1)^{1/n} (P_{plenum} - P_{attic})^{1/n}$$

The attic pressure may be assumed to be zero (atmospheric) relative to the plenum and room pressures. Then, for a particular combination of ceiling area, intake grille type, insulation airflow permeability and thickness, the plenum pressure may be calculated as a function of room pressure. Once the plenum pressure is known, the airflow through the system may be determined. Modeled results for the airflow through an eight foot square R-38 dynamic ceiling system with a 10” x 6” intake grille are compared to measured test chamber results in Figure 5. The modeled results for the dynamic ceiling as a system are based on the measured airflow characteristics of the 10” x 6” grille and the R-38 insulation. Alternatively, since the measured airflow characteristics for the grille and insulation were found to agree closely with data from manufacturers and other workers, these sources could be used to inform the model in the future.

Figure 5. Airflow vs. Pressure Drop Through Dynamic Ceiling Test Chamber



The excellent agreement between predicted and measured results in Figures 4 and 5 indicates that the dependence of ceiling heat gain on airflow rate and the dependence of airflow rate on room pressure are well predicted by simple analytic equations that can be combined for use in a design tool. For instance, results presented in Figure 4 indicate that an airflow rate of approximately 16 CFM (0.25 CFM per square foot) through the eight foot square, R-38 test chamber will eliminate attic heat gain. At the same time, the simplified airflow model in Figure 5 indicates that a room pressure of only one Pascal greater than attic pressure will be sufficient to ensure that this critical airflow rate passes through the test chamber dynamic ceiling system.

Whole Building Energy Modeling Methodology

Building envelope and equipment energy simulations were conducted in order to assess the peak load reduction and comfort benefits of integrating an Indirect-Direct Evaporative Cooler (IDEC) in a house with a dynamic ceiling. A building energy model of a 1600 square foot, single-story Title 24 compliant house developed by the Davis Energy Group with MICROPAS software was used to determine hourly sensible cooling loads for a Sacramento location based on a 78 ^oF thermostat set point. Envelope specifications for this model include un-insulated slab on grade construction with low-e, vinyl windows (U=0.50 Btu/hr/ft^2/^{o}F, SHGC=0.50), 2x4 walls with R-13 cavity insulation and R-38 ceiling insulation (Hoeschele, 2004).

Evaporative cooling systems typically do not employ an elaborate ducted distribution system with a large surface area exposed to attic conditions and many possible air leakage locations. To reflect this fact, no distribution system losses were assumed in the MICROPAS model. Cooling loads were calculated with this model for a Base Case house with conventional heat gains and a Dynamic Ceiling house with no ceiling heat gains. The zero ceiling heat gain assumption is only valid when a Dynamic Ceiling house is pressurized due to the supply airflow of an evaporative cooler. This limitation is not problematic since the primary purpose of this work was to assess the benefits of a dynamic ceiling during peak and near-peak cooling conditions when an evaporative cooler will be operating.

A spreadsheet-based model of an IDEC was created by the authors based on the supply airflow rate and saturation effectiveness of the OASys IDEC developed by the Davis Energy Group and manufactured by Speakman CRS. Saturation effectiveness is defined as the dry bulb temperature depression of an air stream that is forced through a direct or indirect evaporative cooler divided by the difference between the entering dry bulb and wet bulb temperature of that air stream (ASHRAE HVAC Applications, 1999).

Table 1. OASys Performance Characteristics (High Speed, Un-ducted)

Supply Airflow Rate	Direct Stage Saturation Effectiveness	Indirect Stage Saturation Effectiveness
1551 CFM	87.1%	52.2%

Source: OASys Performance Characteristics, 2004

Given a particular ambient air thermodynamic condition, the IDEC model determines the corresponding thermodynamic condition of the supply air. The IDEC supply air dry bulb temperature calculated with this model was combined with the supply airflow rate to yield the sensible cooling capacity of the IDEC at any particular hour. In order to assess occupant thermal comfort, results from the envelope sensible cooling load model were integrated with results from the IDEC sensible cooling capacity model. In the MICROPAS simulations, envelope cooling loads were calculated based on a thermostat set-point of 78 ^oF. The resulting indoor space temperatures determined by the MICROPAS simulations are valid for any hour where the envelope cooling load is less than or equal to the sensible cooling capacity of the IDEC. For any hour that the envelope load was greater than the IDEC sensible cooling capacity, the indoor space temperature was recalculated using the equation presented below:

$$T_{room} = 78\ ^oF + \frac{Q_{envelope\_load}(Btu/hr) - Q_{IDEC\_capacity}(Btu/hr)}{Supply\_Airflow\_Rate(CFM)x60x\rho_{air}(lb/ft^3)xCp_{air}(Btu/lb\cdot^oF)}$$

When an IDEC system is operating, the indoor humidity of a building is dominated by the IDEC supply air humidity and is relatively unaffected by internal moisture generation. Thus the indoor absolute humidity in the simulated house was considered to be equal to the absolute humidity of the supply air from the IDEC. This approximation is valid during the peak and near peak cooling conditions that are the focus of this analysis. It is important to note that the indoor absolute humidity of the Base Case house and the Dynamic Ceiling house are identical since these values depend only on IDEC supply air absolute humidity.

Whole Building Energy Modeling Results

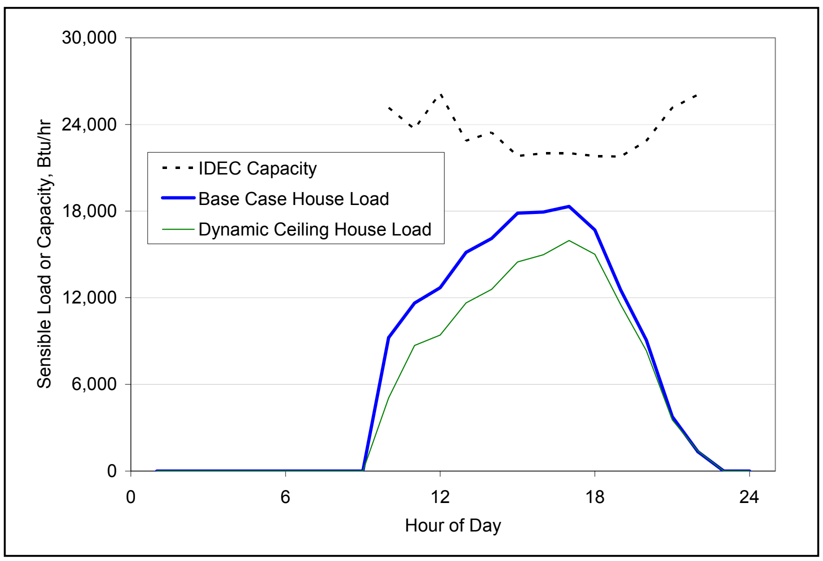
The thermal comfort resulting from integrating an OASys IDEC with the modeled house was analyzed on two different days with peak afternoon conditions presented in Table 2.

Table 2. Peak Ambient Conditions on Simulated Design Days

	Peak Dry-Bulb Temperature	Peak Wet-Bulb Temperature
Day 1 (0.4% DB condition for Sacramento)	101 °F	68 °F
Day 2 (0.4% WB condition for Sacramento)	97 °F	72 °F

The sensible cooling loads of the base case and dynamic ceiling house along with IDEC capacity in response to the design DB day conditions are presented in Figure 6.

Figure 6. Sensible Cooling Load & IDEC Capacity on a Design DB Day

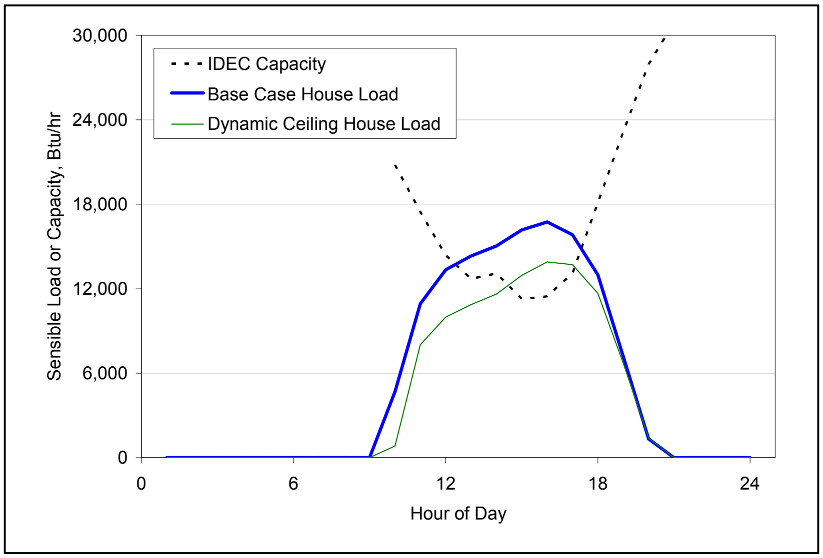


The fraction of the Base Case house total sensible cooling load offset by the dynamic ceiling ranges from 25 percent at 12 PM to 17 percent at 4 PM. Even when the IDEC capacity is lowest during peak afternoon conditions, it is still high enough to meet the sensible cooling load in both the Base Case and Dynamic Ceiling houses. Since the sensible cooling capacity of the IDEC is greater than the sensible cooling load in the Base Case house and Dynamic Ceiling house at all hours, the thermostat set-point of 78 °F is maintained in both cases. As was previously noted, the indoor absolute humidity calculated for the Base Case house is equal to that of the Dynamic Ceiling house. Because the indoor dry bulb temperature of these two houses is also identical on the design dry bulb day, the calculated indoor wet bulb temperatures are equal.

The calculated indoor wet bulb temperatures were less than 67 °F for every hour of the design dry bulb day. ASHRAE summer thermal comfort guidelines for people "during primarily sedentary activity" indicate that room wet bulb temperature should not exceed 68 °F. (ASHRAE Fundamentals, 2001). By this standard, simulations indicate that an IDEC can maintain occupant thermal comfort during a representative Sacramento 0.4% ASHRAE design dry bulb temperature day in both the Base Case house and a Dynamic Ceiling house.

The sensible cooling loads of both houses and IDEC capacity in response to Sacramento 0.4% ASHRAE design wet bulb conditions are presented in Figure 7. The sensible load reduction due to the dynamic ceiling coincides with the critical afternoon hours when IDEC capacity is lowest. Thus, while the sensible load is not met in the Base Case house for five hours of the day the Dynamic Ceiling house experiences only three such hours.

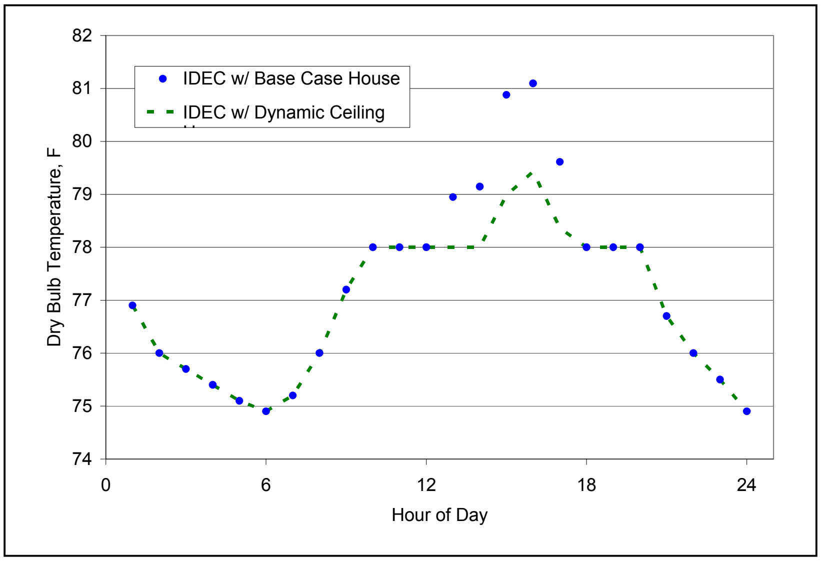
Figure 7. Sensible Cooling Load & IDEC Capacity on a Design WB Day



The maximum unmet sensible cooling load is 5300 Btu per hour in the base case house and 2400 Btu per hour in the dynamic ceiling house. Thus, the unmet sensible cooling load in the Dynamic Ceiling house would be significantly easier to eliminate with other envelope upgrades (such as better performing windows) than the unmet sensible cooling load in the Base Case house. As was also the case on the design dry bulb temperature day, the fraction of the Base Case house total sensible cooling load offset by the dynamic ceiling on the design wet bulb temperature day ranges from 25% at 12 PM to 17% at 4 PM.

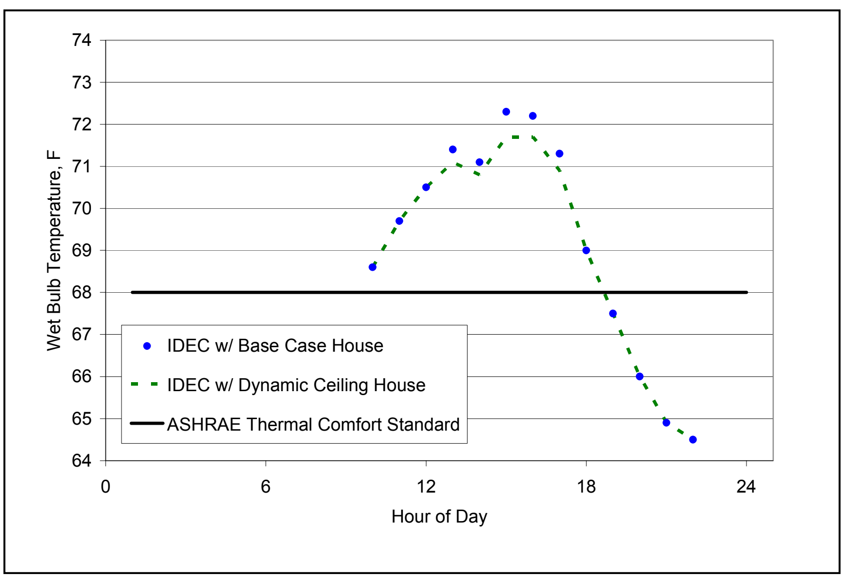
Since the sensible cooling capacity of the IDEC equipment is less than the sensible cooling load at several hours in the Base Case house and Dynamic Ceiling house, the thermostat set-point of 78 °F is not maintained in either case. However while the peak indoor temperature in the Base Case house is 81.1 °F, the temperature in the dynamic ceiling house does not exceed 79.4 °F. Also, it is important to note that specified attic loose fill insulation R-values are often not realized in practice. In a comprehensive study of 30 new California homes, Hoeschele et al. found blown-in ceiling insulation to be "installed uniformly and to required thickness" only 40% to 60% of the time (Hoeschele, 2003). In these cases, the performance difference between a Dynamic Ceiling house (with no ceiling heat gain regardless of attic insulation level) and a conventional house will be even greater than predicted by the MICROPAS modeling results.

Figure 8. Indoor Dry Bulb Temperature on a Design WB Day



The corresponding indoor wet bulb temperature calculated for peak conditions is presented in Figure 12. According to the ASHRAE summer comfort guidelines, the indoor wet bulb temperature resulting from the operation of the IDEC is too high between 10:00 AM and 6:00 PM in both the Base Case house and the Dynamic Ceiling house.

Figure 9. Indoor Wet Bulb Temperature on a Design WB Day

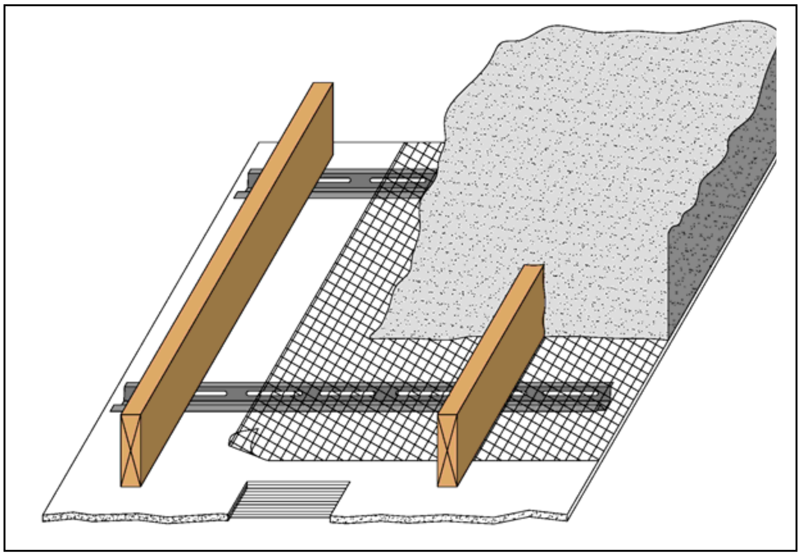


Since the supply air absolute humidity of a particular IDEC is unaffected by sensible cooling load, a dynamic ceiling will not reduce supply air humidity and therefore has a less significant effect on house wet bulb temperature than dry bulb temperature. However along with other envelope upgrades, a dynamic ceiling could be part of a whole house strategy to reduce sensible loads enough that they could be met by an IDEC with warmer but less humid supply air.

Prototype House Design

As a result of the beneficial impact of a dynamic ceiling on occupant thermal comfort indicated by the building energy modeling results, construction details have been developed to implement a dynamic ceiling design in a prototype two-story house outside of Salt Lake City that will be completed in 2004. For this application, the dynamic ceiling plenum design has been refined to incorporate steel resilient ("hat") channels typically used in dropped ceilings and an insulation support mesh like the type used in for blowing loose fill fiberglass in wall cavities.

Figure 10. Refined Dynamic Ceiling Design



During construction of the original dynamic ceiling assembly in the test chamber, the insulation support hangers were judged to require too much quality control to be successfully implemented in a house. In the new design, the insulation support mesh allows the system to be compatible with either loose fill or batt insulation while the slots in the resilient channels allow for continuity in the plenum space in two directions. Due to its greater permeability to airflow, loose fill fiberglass will be used instead of cellulose to insulate the attic.

There will be no vapor compression equipment in the prototype home and all cooling will be provided by an OASys IDEC in a first floor thru-the wall application. The OASys unit itself will be located in a first floor mechanical closet and be ducted via a short run to one supply register in the kitchen and one in the living room. When the OASys unit is operating, fresh supply air will be drawn upstairs by intakes in the second floor dynamic ceiling. Since second floor interior partition walls will interrupt the continuity of the dynamic ceiling plenum, a dynamic ceiling intake grille will be installed in each bedroom and the upstairs hallway. Over-the-door transfer grilles installed as part of the forced air heating system will also allow fresh air from the OASys unit to reach bedrooms and bedroom dynamic ceiling intakes even when doors are closed. To prevent moisture problems, no dynamic ceiling intake grilles will be installed in the second floor bathroom. In the prototype house, a novel dynamic ceiling intake design will be evaluated that will include a fire damper and spring-loaded gravity damper that only opens when the house is significantly pressurized due to evaporative cooling.

Conclusions

A dynamic ceiling design has been developed to improve comfort in evaporative cooled houses by enhancing the circulation of conditioned air and eliminating ceiling heat gain during peak conditions. Test chamber results for an eight foot square ceiling indicate that a continuous furred plenum constructed between ceiling drywall and R-38 attic insulation can uniformly distribute room air from a single intake opening in the ceiling drywall before it is exhausted through attic insulation. The minimum airflow rate required to completely eliminate ceiling heat gain through this configuration is 0.25 CFM per square foot – significantly less than supply airflow of typical residential evaporative coolers. Measurements indicate that the dependence of ceiling heat gain on airflow rate and the dependence of airflow rate on room pressure are well predicted by simple analytic equations that are useful as preliminary design tools.

Whole building energy modeling results indicate that eliminating ceiling heat gain in a minimally Title 24 compliant 1600 square foot single story house can reduce sensible cooling load by 17 percent to 25 percent during peak afternoon hours when the sensible cooling capacity of an evaporative cooling system is lowest. In both the Base Case house and Dynamic Ceiling house modeled, the ASHRAE standard for thermal comfort was maintained by the OASys IDEC on a Sacramento 0.4% ASHRAE design dry bulb temperature day. On a Sacramento 0.4% ASHRAE design wet bulb temperature day, modeled indoor dry bulb temperature and wet bulb temperature were too high in both houses. However, the dynamic ceiling reduced the number of hours that indoor dry bulb temperature was greater than 78 ^{o}F from five to three and slightly reduced indoor wet bulb temperature during peak afternoon hours.

Finally, a refined dynamic ceiling design has been developed with a continuous plenum created using insulation support mesh and steel resilient channels. This plenum construction will be implemented along with a novel dynamic ceiling intake design in a prototype house in 2004.

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