Analysis of Attic Radiant Barrier Systems Using Mathematical Models

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ABSTRACT

During the past six years, the Florida Solar Energy Center (FSEC) has conducted extensive experimental research on radiant barrier systems (RBS). This paper presents recent research on the development of mathematical attic models.

Two levels of modeling capability have been developed. A very simplified model [1] based on ASHRAE procedures is used to study the sensitivity of RBS performance parameters, and a very detailed finite element model [2] is used to study highly complex phenomena, including moisture adsorption and desorption in attics. The speed of the simple model allows a large range of attic parameters to be studied quickly, and the finite element model provides a detailed understanding of combined heat and moisture transport in attics.

This paper concentrates on a parametric analysis of attic RBS using the simplified model. The development of the model is described, and results of the parametric analyses are presented and discussed. Preliminary results from the finite element model are also compared with measurements from a test attic to illustrate the effects of moisture adsorption and desorption in common attics.

INTRODUCTION

Development of analytical models to study attic RBS performance has been identified as a major research need in the development of RBS technology [3]. Logically, this capability should develop in steps such that both detailed and simplified models are available to researchers and the design community. A necessary step in the process is the definition of model parameter sensitivities. In most cases, this kind of work can be carried out with reasonable accuracy using relatively simple models. To this end, a simplified, heat balance model has been developed and exercised to study RBS performance parameters with respect to the performance of a standard attic.

In March 1987, the U.S. Department of Energy established the Radiant Barrier Systems Technical Panel to identify research issues associated with RBS technology development. The panel consists of members from the private and public research community, the utilities, trade organizations, and industry (see also Reference 3). The RBS performance parameters chosen for study and reported here are based primarily on the recommendations of this panel and are as follows:

1. Effect of attic ventilation rate
2. Effect of radiant barrier surface emittance
3. Effect of vent air inlet temperature (ambient temperature)
4. Effect of solar radiation (sol-air temperature)
5. Effect of room set-point temperature
6. Effect of ceiling insulation level
7. Effect of radiant barrier placement within the attic.

Because attic ventilation was believed to be a major performance parameter, each of the other parameters was examined as a function of attic ventilation airflow.

SIMPLE HEAT BALANCE MODEL

A simple, steady-state heat-balance model called AEBS (Attic Energy Balance Simulation) was created to perform the parametric analysis. The AEBS model is illustrated in Figure 1.

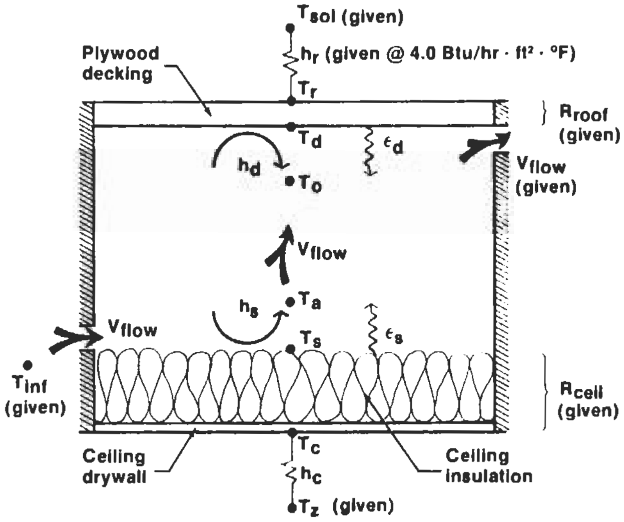

Figure 1. Schematic diagram of two-zone AEBS model.

AEBS uses the following energy balance equations:

$$@T_r: \quad h_r(T_r - T_{sol}) + 1/R_{roof}(T_r - T_d) = 0 \tag{1}$$

$$@T_d: \quad h_d(T_d - T_o) + 1/R_{roof}(T_d - T_r) + E(T_d^4 - T_s^4) = 0 \tag{2}$$

$$@T_o: \quad h_d(T_o - T_d) + V_{flow}(T_o - T_a) = 0 \tag{3}$$

$$@T_a: \quad h_s(T_a - T_s) + V_{flow}(T_a - T_{inf}) = 0 \tag{4}$$

$$@T_s: \quad h_s(T_s - T_a) + 1/R_{ceil}(T_s - T_c) + E(T_s^4 - T_d^4) = 0 \tag{5}$$

$$@T_c: \quad h_c(T_c - T_z) + 1/R_{ceil}(T_c - T_s) = 0 \tag{6}$$

where:

$$E = \frac{1.713 \times 10^{-9}}{\frac{1}{\varepsilon_d} + \frac{1}{\varepsilon_s} - 1} \tag{7}$$

$$h_d = 0.12(T_d - T_o)^{0.25}$$

$$h_s = 0.27(T_s - T_a)^{0.25}$$

$$V_{flow} = \rho V C_p$$

and:

ρ = air density

V = volumetric airflow rate

C_p = specific heat of air

The model uses temperature- and direction-dependent flat-plate convection coefficients from ASHRAE [4]. Cavity radiation is modelled using infinite parallel-plate assumptions and effective surface emittances. Effective surface emittances are used to account for more than one material being on the same plane. For instance, the radiant barrier surface is assumed to occur only between the framing members of the attic. The effective surface emittance of this plane is calculated by adding the area-weighted surface emittance of the framing (0.75 x 0.1) to the area-weighted surface emittance of the radiant barrier (0.05 x 0.9), giving an effective surface emittance of 0.11. The effective surface emittance of a kraft paper barrier plane (0.89) is calculated in a similar fashion.

The AEBS model allows the radiant barrier to be placed either on the top surface of the ceiling insulation with the low emittance surface facing upward toward the attic airspace or on the bottom surface of the roof decking with the low emittance surface facing downward. There is no capability to model multiple attic airspaces that may be created when a radiant barrier is placed elsewhere between the roof undersurface and the top of the ceiling insulation.

The major simplifying assumption used in the model is that airflow between the floor of the attic and the roof of the attic is driven by buoyancy. To accomplish this, the attic airspace is divided into two lumped air zones. The lower zone, represented by T_a, is assumed to communicate with the inlet airflow and interact with the ceiling insulation through natural convection (see Equation 4). The upper air zone, represented by T_o, communicates with the outlet vent airflow and interacts with the underside of the roof decking through natural convection (see Equation 3). No buoyancy calculations are performed, but the energy flow between the lower air zone (T_a) and the upper air zone (T_o) is assumed to occur by convective mass flow at the prescribed ventilation airflow rate (V_{flow}).

Examination of the major assumption. The assumption of buoyancy driven airflow in the attic constitutes a major modeling assumption. The reasoning behind this assumption stems from both experimental results and logic.

Steady-state RBS test results obtained by F.A. Joy in 1958 [5] indicate that RBS performance is significantly better for attic systems in which ventilation airflow is parallel to rather than perpendicular to the attic structure. Joy attributes this performance difference to a high degree of thermal stratification in an attic having ventilation airflow parallel to the attic structure. In an attic with airflow perpendicular to the attic structure, he hypothesizes that the ventilation airflow is much more turbulent, causing a more thorough mixing of the attic air.

Joy's test attics, however, had different geometries. The attic with parallel airflow had a flat roof attic, while the attic with perpendicular airflow had a peaked roof attic with gable venting.

Experimental research conducted by the authors in peaked roof attics with soffit and ridge vents has confirmed the presence of significant thermal stratification in peaked attics with parallel airflow [1]. This research also shows that the presence of a radiant barrier in the attic greatly augments this stratification. Thus, the assumption made in the model is that the cooler ventilation air remains near the attic floor, while the warmer attic air rises to the attic ventilation outlet.

To assess the validity of the thermal stratification and buoyancy assumptions, the model was compared to Joy's experimental data for flat-roofs with airflow parallel to the attic structure. To observe the difference between the assumption of two stratified attic air zones and the more common assumption of one isothermal air zone, a second energy balance was added to the model. The upper air zone (T_o) was eliminated, and energy balance Equations 3 and 4 were combined into a single balance equation on the attic air (T_a):

$$@T_a: \quad h_d(T_a - T_d) + h_s(T_a - T_s) + V_{flow}(T_a - T_{inf}) = 0 \tag{8}$$

No other energy balance equations or model parameters were altered.

Both versions were then run for all vent rates and compared to Joy's measured parallel airflow (flat roof) data. Figures 2 and 3 give results from the two-zone AEBS model for kraft paper and foil barriers, respectively. Considering the simplicity of the AEBS model, the results agree very well with

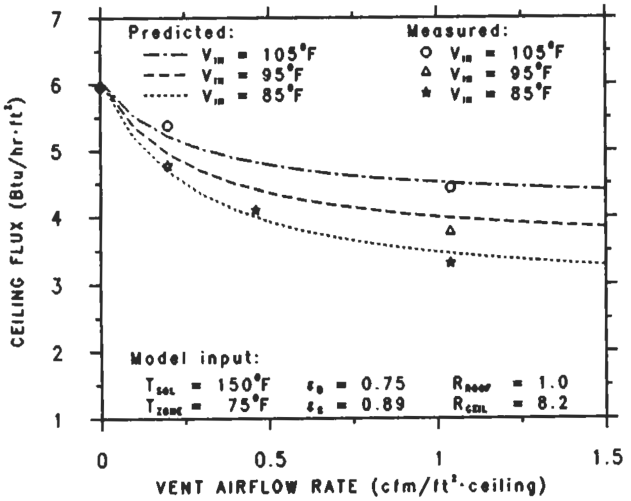

Figure 2. Comparison of two-zone AEBS model predictions with Joy's measurements for parallel airflow attics with kraft paper barriers on the ceiling insulation.

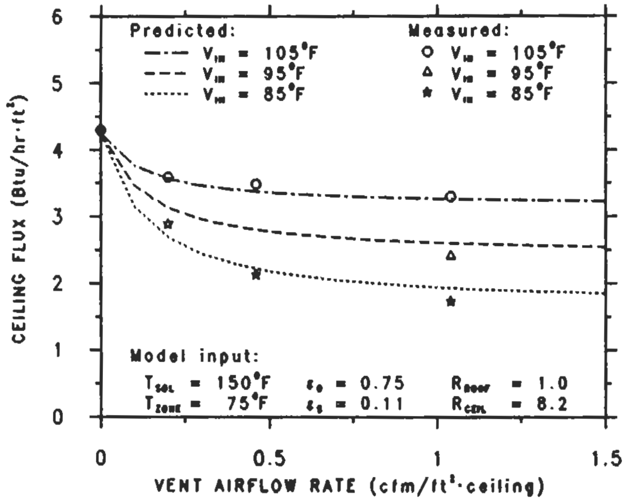

Figure 3. Comparison of two-zone AEBS model predictions with Joy's measurements for parallel airflow attics with foil radiant barriers on the ceiling insulation.

the measured data. Agreement is poorest at high ventilation rates and low vent air temperatures. For both the kraft paper and the foil barrier cases, the model slightly overpredicts heat flow through the ceiling at these conditions.

Figures 4 and 5 give results from the one-zone model. For the most part, the one-zone model does not show good agreement with the data. Agreement for the kraft paper, no-vent case, however, is reasonable for the one-zone model (Figure 4). Both models appear to adequately predict ceiling heat flux if the attic is unvented and radiation transfer across the attic is high. When radiation transfer is inhibited, however, the one-zone model predictions are poor (see Figure 5).

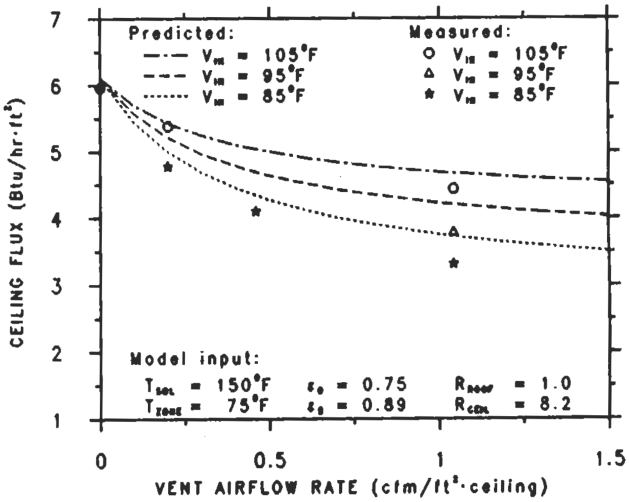

Figure 4. Comparison of one-zone AEBS model predictions with Joy's measurements for parallel airflow attics with kraft paper barriers on the ceiling insulation.

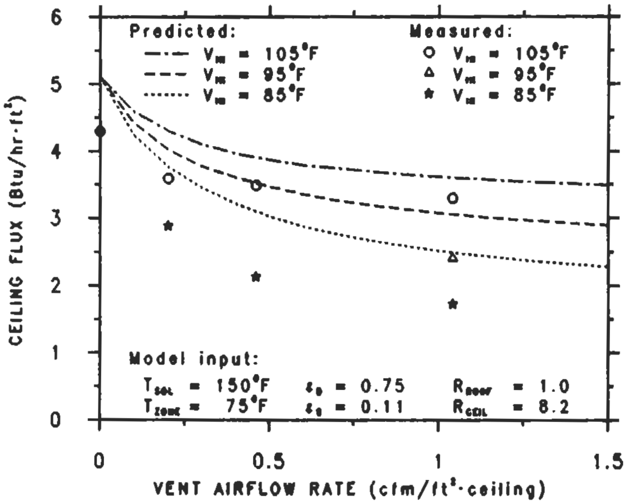

Figure 5. Comparison of one-zone AEBS model predictions with Joy's measurements for parallel airflow attics with foil radiant barriers on the ceiling insulation.

The agreement seen in Figure 4 for the no-vent case is probably due to the fact that there is much less difference in temperature between the roof decking and the insulation surface when radiation transfer is high. There is less opportunity for thermal stratification of the attic air under these conditions and the one-zone assumption errs less. Likewise, the disagreement seen in Figure 5 is caused by the fact that the model cannot account for the thermal stratification that exists in the enclosed attic when radiation across the airspace is severely reduced.

One additional observation can be made from these results. On comparing the results from the two models, one observes that the predictions of the two-zone model have a more distinct point of inflection (knee) than those of the one-zone model. This indicates that there is a qualitative as well as quantitative difference between the models. The difference is especially apparent in the foil barrier case, for which the two-zone model gives good agreement (Figure 3) and the one-zone model gives poor agreement (Figure 5).

The inflection is most prominent for the foil barrier because the lack of radiation across the attic airspace results in insulation temperatures that are much closer to the vent air inlet temperatures. Thus, the effectiveness of attic ventilation approaches its limit at much lower vent airflow rates. For the kraft paper barrier (Figure 2) the knee is not as pronounced because much higher vent airflows are needed to counter the thermal effects of radiation from the roof to the insulation surface.

The one-zone model cannot predict these effects because it does not allow for thermal stratification of the attic air (see Equation 8 as compared to Equations 3 and 4). The attic air temperature (T_a) used in Equation 8 to calculate convection at the surface of the insulation is overpredicted because it is intimately coupled to the attic roof decking. This results in overprediction of the insulation surface temperature and underprediction of the effectiveness of the attic ventilation. Since T_a is not directly coupled to the decking surface temperature in Equation 4, this effect is not seen in the two-zone model.

This effect is much more pronounced for the foil barrier than for the kraft paper barrier. In fact, there is only a small difference between the two models for the no-vent, kraft paper barrier case (see Figures 2 and 4). This is indicative of the overriding effects of radiation transfer in typical attics.

In all aspects, the two-zone AEBS model gives better agreement with data than does the one-zone model. Thus, the two-zone model assumption of buoyancy driven airflow within the attic appear to be supported by both logic and measurement.

Results of the analysis. The simplicity of the model requires that results be interpreted only in a general sense. The model can show trends and parameter sensitivities but cannot describe fully the complex, dynamic phenomena that occur in real attics. The reader should remember that the results presented here apply only to attics exhibiting thermal stratification. Attics with airflows perpendicular to the attic structure may exhibit different trends.

Results from the parametric analysis are expressed as a reduction in ceiling heat transfer with respect to the same attic system without a radiant barrier. Except where specifically noted, results are for radiant barriers located at the underside of the roof in contact with the roof decking, with the low emittance surface facing downward toward the attic airspace.

The analysis indicates that radiant barrier surface emittance and vent air inlet temperature are the strongest of the attic RBS performance parameters. Effectiveness is most sensitive to radiant barrier surface emittance. Figure 6 clearly illustrates the effect of surface emittance on the performance of attic RBS. A rapid degradation in performance occurs with increase in radiant barrier surface emittance. Also note that the inflection of the performance curves diminishes with increasing surface emittance.

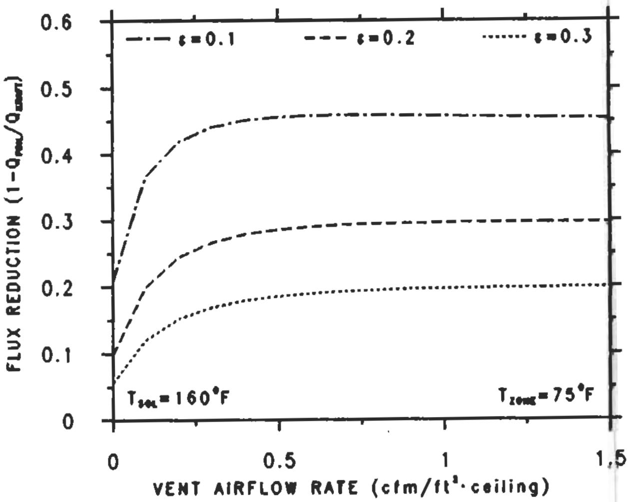

Figure 6. Predicted effect of surface emittance for roof mounted RBS in attics with R-19 ceiling insulation and 85°F vent air inlet temperature.

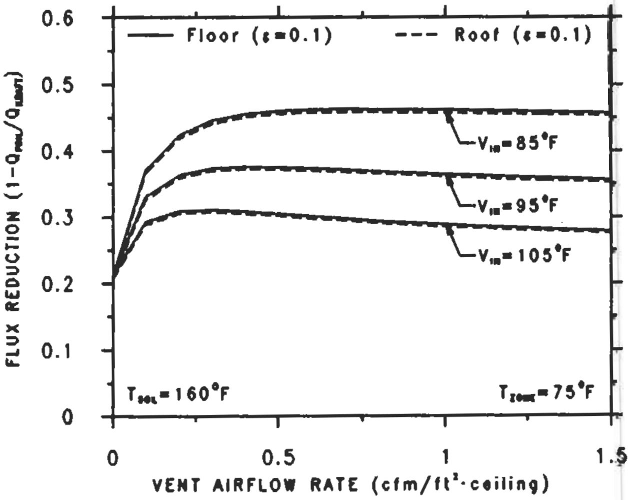

Figure 7. Predicted effect of barrier placement for three vent air inlet temperatures in attics with R-19 ceilings and foil barriers at the attic roof and floor.

The effect of radiant barrier placement and vent air inlet temperature are shown in Figure 7. While the effectiveness of the RBS is a strong function of the vent air inlet temperature, the model shows no sensitivity to radiant barrier placement (attic roof versus attic floor).

Measured attic RBS data, obtained in parallel-airflow attics with low-emittance gable end walls and vent air temperatures near 85°F, are in close agreement with these predictions. Ceiling heat flux reductions of 0.18 and 0.19 were measured in sealed attics for floor and roof mounted RBS, respectively [6]. For attics vented at 0.25 cfm/ft^2·ceiling, measured ceiling heat flux reductions for floor and roof mounted RBS were 0.51

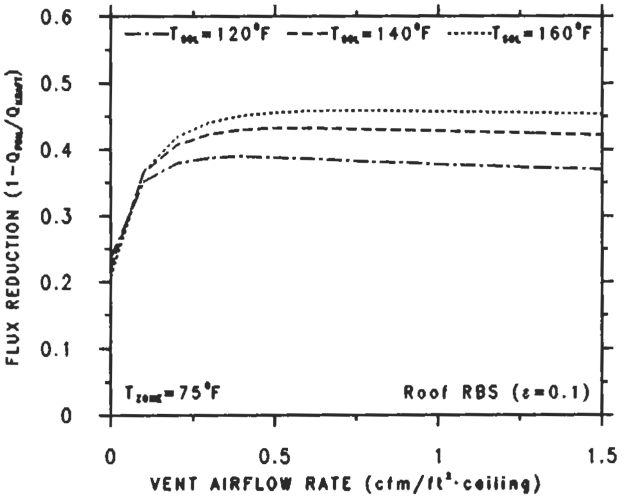

Figure 8. Predicted effect of sol-air temperature for attics with R-19 ceilings and 85°F vent air inlet temperature.

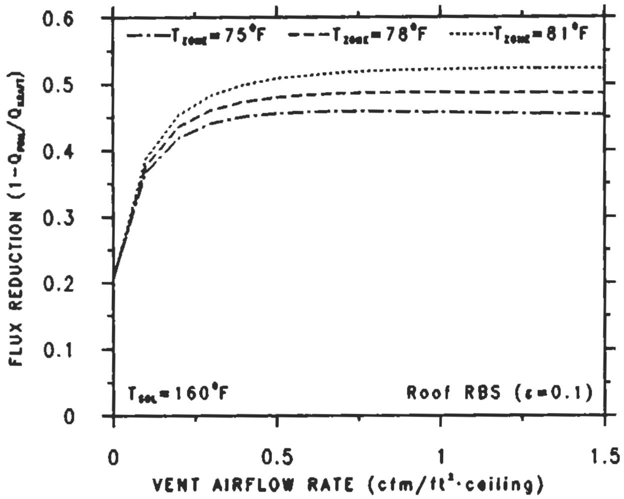

Figure 9. Predicted effect of room thermostat setting for attics with R-19 ceilings and 85°F vent air inlet temperature.

and 0.48, respectively [1]. Results obtained at attic vent rates of 0.5 cfm/ft²·ceiling, showed a ceiling heat flux reduction of 0.43 for roof mounted RBS [6], indicating, as does the AEBS model, that heat flux reductions reach limiting values at fairly low attic vent rates.

These model results, however, agree poorly with performance measurements obtained by Levins and Karnitz [7] in the Karns houses. The Karns house results compare air conditioning consumption in identical residences in Karns, Tennessee, and show the performance of floor-mounted RBS to be substantially better than that of roof-mounted RBS.

One can only conclude that the substantial performance difference observed in the Karns houses (21% versus 13% cooling load savings) is due to a phenomenon that the AEBS model does not simulate. The Karns houses have high-emittance gable end walls and perpendicular vent airflow. The AEBS model uses parallel airflow assumptions and does not account for radiating end walls. Each of these factors may account for some of the observed differences.

Recent research by Cummings [8] provides another interesting example of potential side effects of floor mounted RBS. From field monitoring studies, Cummings has noted that the operation of the fan coil units of central air conditioning systems often induce air leakage from the attic directly to the house near the return side of the air handler unit. In such cases, an air barrier placed directly on top of the ceiling insulation should result in significantly less air leakage and, therefore, a significant reduction in air conditioning energy consumption. This air conditioner load savings should occur regardless of the surface emittance of the air barrier.

The remaining performance parameters show less sensitivity to changes. Performance is somewhat sensitive to both the sol-air temperature and the conditioned space temperature. As the roof temperature (sol-air) is decreased, the performance of the attic RBS also decreases (Figure 8). This result is due to the fact that the radiation transfer potential across the attic has been reduced but the base ceiling heat flux has not changed. There is a base ceiling flux that is driven by the difference between the conditioned space temperature and the vent air inlet (ambient) temperature that cannot be overcome by an attic RBS. Since the radiation potential across the attic has been reduced and this base heat flux has not changed, there is a decrease in the relative performance of the attic RBS. In the limiting case, when the roof temperature is reduced to the vent air inlet (ambient) temperature, no reduction in ceiling heat flux occurs.

For variations in the conditioned space temperature (Figure 9) the base case ceiling flux is changed. Raising the conditioned space temperature causes the base ceiling flux to fall. Thus, the RBS is able to make greater comparative reductions in ceiling heat flux when the temperature of the conditioned space is increased.

The model indicates that changes in ceiling insulation level also have little effect on the relative effectiveness of the attic RBS (Figure 10). This result is also in conflict with other research reported in the literature [9]. Results from a combination of measurements and modeling for the Karns houses have indicated that ceiling insulation levels have a significant effect on the relative performance of attic RBS. Reference 9 reports cooling load savings of 16%, 21%, and -2% for houses with R-11, R-19 and R-30 ceiling insulation, respectively. It is true that cooling load savings for RBS are significantly less than relative ceiling heat flux reductions, but the increase in cooling load savings between the R-11 and R-19 attics, followed by a 2% increase in cooling load for R-30 attics, cannot be explained by the modeling results reported here.

In contrast to the Karns house results, the AEBS model predicts relative ceiling heat flux reductions that are higher for the lower ceiling resistances (see Figure 10). This difference is explained by the fact that the ceiling heat flux

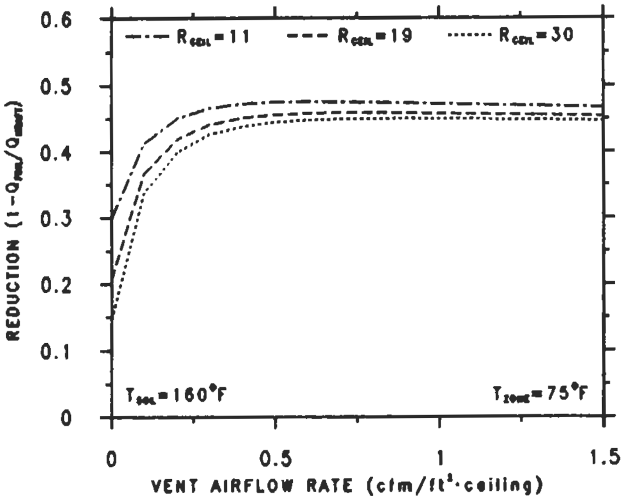

Figure 10. Predicted effect of ceiling insulation level for attics with 85°F vent air inlet temperatures and roof mounted RBS.

for the no-RBS case increases more than the ceiling heat flux for the RBS case when the ceiling insulation level is reduced.

In summary, results from the AEBS model indicate that the major parameters affecting attic RBS performance are the emittance of the radiant barrier surface and the attic vent air inlet (ambient) temperature. It should be possible to combine the effects of the sol-air temperature and the vent air temperature by subtracting one from the other and developing an effectiveness ratio based on the result. The ventilation airflow rate also affects performance but, in most cases, this effect appears to approach a limit at attic ventilation rates that are expected in naturally vented field attics (0.25 cfm/ft^2).

DETAILED FINITE ELEMENT MODEL

A preliminary finite element analysis of a test attic without a radiant barrier also has been conducted to examine the effects of moisture sorption and transport in attics (also see References 1 and 2).

During the past few years FSEC has developed the analytical capabilities to model combined heat and mass transfer. The result of this effort is FEMALP, an in-house software capable of modeling simultaneous heat, mass and momentum transport. Reference 2 presents a comprehensive discussion of combined heat and mass transport theory, the FEMALP program, mathematical moisture transport algorithms and available material moisture property data.

The detailed modeling analysis consisted of two cases: 1) a thermal only simulation of the attic and 2) a coupled heat and mass transport simulation of the attic. In both cases, the finite element approach was used to solve the governing equations for the solid components of the attic, and a lumped approach was used to model the attic air.

The selected geometry simulated attic Cell 2 of the FSEC Passive Cooling Laboratory (PCL). Detailed measurements of temperatures, airflows, dew points and heat fluxes were obtained at 15-minute intervals. Reference 1 contains a complete description of the model, the attic geometry, the attic and ambient instrumentation, and the nature of the experiments.

The attic air space is divided along the ventilation airflow path into seven lumped air zones for the simulation. These zones are coupled by interzone airflow such that all air entering the attic is transported from zone to zone until it exits the attic from zone seven. No recirculation of air between zones was considered, and no thermal stratification within air zones is modeled. Although a single temperature defines the thermal state of a given zone, the multizone model allows the air conditions to vary from one zone to the next. Seven zones were used to represent the division used in the PCL measurements.

Measured thermal data were used as boundary conditions at the bottom of the ceiling drywall and the top of the plywood roof decking. Temperature- and direction-dependent coupling (convection) coefficients between the attic air and solid surfaces were taken from ASHRAE [4]. Values for thermal conductivity, density and specific heat were also taken from ASHRAE [4]. Moisture properties were taken from Reference 2. The measured attic vent air inlet temperature, dewpoint temperature and airflow rate served as inputs for the simulation.

Thermal only simulation. The first simulation considered only thermal transport through the attic. Although moisture effects were not modeled, the measured data match reasonably well with the results of the simulation.

Figure 11 compares the measured and simulated temperatures at the top surface of the ceiling insulation. The figure also shows the measured vent air moisture removal rate of the attic. Disparities between measured and predicted temperatures are expected when the effects of moisture are ignored. The model underpredicts during the cooling period (nighttime) when moisture adsorption is occurring, and overpredicts during the heating period (daytime) when moisture desorption is occurring. Most of the disparity observed in Figure 11 is believed to be due to these moisture sorption effects.

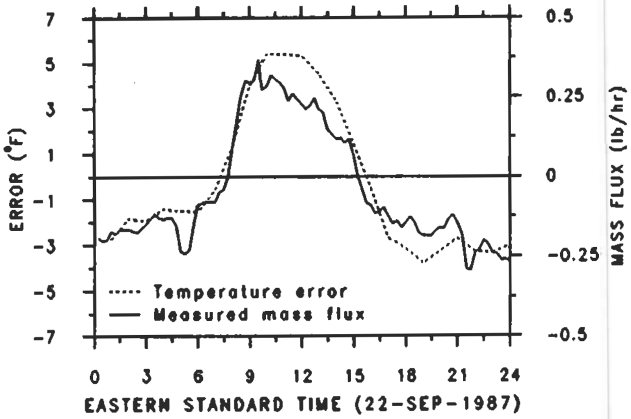

Figure 11. Comparison of insulation top surface temperature prediction errors with measured vent air moisture removal rate.

Combined heat and moisture transfer simulation. To examine this hypothesis more closely, coupled thermal and moisture transport in the attic was also simulated. Only inlet and outlet vent air moisture contents are measured; material moisture contents are not available. Therefore, the simulation was run for a 10-day period to allow initial material moisture conditions to decay beyond any significance.

Predictions from the coupled model are significantly closer to the measured values than they are for the previous simulation. The measured data, however, show a smaller temperature gradient between inlet and outlet air zones than does the model. This is believed to be due to recirculation and buoyancy effects occurring in the attic air. These effects have not yet been included in the model.

Figure 12 compares the thermal prediction errors at the top surface of the ceiling insulation with and without the effects of moisture included in the model. As originally anticipated, the prediction error is considerably reduced when moisture effects are simulated. The maximum prediction error when moisture is ignored is about 5.5°F compared with 1°F when moisture effects are included. Inclusion of moisture transport in the model has substantially reduced discrepancies between prediction and measurement. Uncertainties in moisture material property data and attic airflow patterns are believed to cause the major remaining disparities.

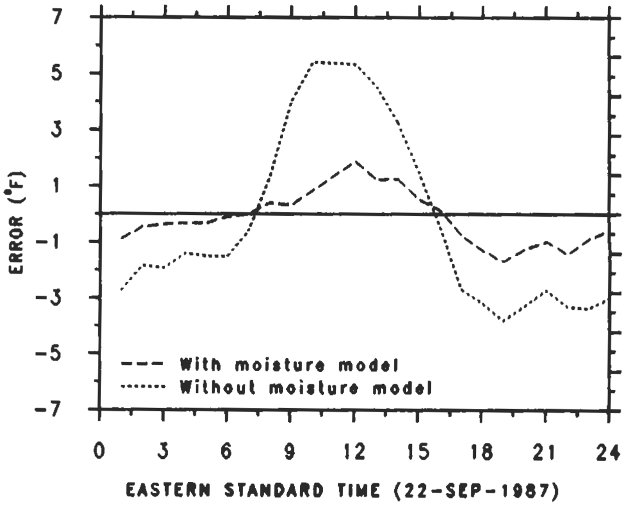

Figure 12. Comparison of insulation top surface temperature prediction errors for models with and without moisture transport simulation.

CONCLUSIONS

A very simple, steady-state attic energy balance model called AEBS has been developed. The reasonableness of the model has been verified using measured steady-state data reported by Joy [5] for flat-roof, parallel-airflow attics. The results indicate that thermal stratification and buoyancy driven airflow are significant considerations in attic models, particularly when radiant barriers are present. A parametric analysis conducted using the AEBS model showed the radiant barrier surface emittance and the vent air inlet temperature to be the strongest determinants of attic RBS performance. Changes in sol-air temperature, room thermostat setting, and ceiling insulation level showed second-order effects. The model, and some performance measurements [1,6], showed practically no sensitivity to the placement (attic roof versus attic floor) of the radiant barrier.

A detailed finite element model also has been developed. This model is used to study moisture effects in buildings. Preliminary results from this model show significant improvements in ceiling insulation surface temperature predictions when the effects of moisture transport and sorption are included in the model.

ACKNOWLEDGEMENTS

The work reported here is part of a cooperative research project, funded in part by Florida Power & Light Company and the U.S. Department of Energy. The authors wish to thank the sponsors for their continued support of this work.

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