SIMPLIFIED MODELING OF TRANSIENT DISTRIBUTION SYSTEM EFFICIENCY FOR DUCTS IN ATTICS

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ABSTRACT

The objective of this work is to develop simplified methods for characterizing the thermal losses in residential air distribution systems. The methods developed here specifically seek to describe the hourly variations in distribution system performance relative to a seasonal average value as might be obtained under ASHRAE Standard 152. The simplified methods are developed using the detailed simulation tool FSEC 3.0 to generate results for a prototypical residence with ducts in the attic. Results indicate that the hourly variations in distribution efficiency can be simply correlated with outdoor weather conditions.

INTRODUCTION

Air distribution systems represent a significant energy loss in residential buildings. These duct systems, typically constructed of sheet metal, are often poorly insulated and leaky. Since the ducts are often located in unconditioned spaces (e.g., attic, crawl space, garage) the thermal losses from the ducts increase energy consumption for heating and cooling the building.

Two different mechanisms contribute to the distribution system losses. First, the conditioned air in the supply ducts is warmer or colder than the unconditioned space in which the ducts are located and drive conduction heat transfer through the duct insulation. Second, the conditioned air in the ducts is at a different pressure than the unconditioned space, causing leakage of air into, and out of, the ducts.

There have recently been efforts to quantify the impact of duct system losses on residential energy use. ASHRAE Standard 152 develops a method to test distribution system performance and calculate system efficiency. The distribution system efficiency determined from the analysis describes the seasonal increase in energy consumption due to the losses. Clearly, these losses change throughout the season depending on influence of outdoor ambient conditions on the unconditioned space and will be greatest at times of peak heating and cooling requirements.

This paper describes an effort to develop a simplified method to account for the hourly variations in distribution system losses. The method is intended to be used in conjunction with a seasonal distribution system efficiency, calculated by ASHRAE Standard 152 or other methods, and is designed as a simple correction based on hourly conditions. For example, the method could be used in a simple spreadsheet to estimate the impact on peak HVAC energy consumption and could be incorporated into building energy codes.

ANALYSIS METHODS

The analysis of distribution efficiency was performed on a prototypical single family detached residence. The 1500 sq. ft. house is meant to be representative of typical construction and was originally developed by the Florida Solar Energy Center (FSEC) for use in ASHRAE Research Project 852-RP (Gu et al., 1996).

The residence is a single story house with no basement and an attached, unconditioned garage. The entire conditioned floor area of the prototype is considered a single thermal zone.

Table 1 shows the general envelope characteristics of the prototypical residence. The thermal characteristics of each house comply with California Title 24 requirements depending on location.

Internal gains from lights, people, and equipment also represent compliance with the standard for California Title 24. The internal loads range from a low of 275 W in the late night to a high of 810 W at 6:00 pm. The load sensible fraction of the internal load is 0.80 and the radiative fraction of the sensible load is 0.30.

The standard residence has a split system air conditioner with an EER of 10 and a rated sensible heat ratio of 0.75. Design airflow is specified at 400 cfm/ton of cooling capacity of the system. The cooling setpoint is constant at 25.6°C (78°F).

Table 1: General Building Characteristics

Characteristic	Description
House Floor Area	139.35 m^2 (1500 ft^2)
Garage Floor Area	42.36 m^2 (456 ft^2)
Roof Surface Area	174.86 m^2 (1882 ft^2)
Exterior Wall Area	83.05 m^2 (894 ft^2)
Window Area	20.90 m^2 (224 ft^2)
House Infiltration	constant at 0.35 ACH
Attic Infiltration	calculated by FSEC 3.0 according to ambient and attic zone conditions

The cooling system was sized for each case to meet the building load with the following tolerances: the load was not met for between 1 and 100 hours of the year and the maximum zone temperature was not allowed to rise more than 2 C above the cooling setpoint. The following system sizes were considered, based on available residential cooling equipment: 2, 2.5, 3, 3.5, 4, and 5 tons. In some cases larger systems were required and system sizes above 5 tons were considered in 1 ton increments.

The standard residence has a natural gas furnace with an AFUE of 80%. The heating setpoint is 20°C (68°F) from 0800 to 2300 with a night setback to 15.6°C (60°F) from 2300 to 0800. The furnace was sized to allow recovery from setback within one hour.

Both supply and return ducts for the standard residence are located entirely in the attic. The duct system in the standard residence is the same for all cases with the exception of the leakage and duct insulation. The duct surface area of the standard residence is 45.34 m^2, or 32.5% of the conditioned floor area. The size of the duct system was not changed for different system sizes.

Leakage is concentrated at two points, located close to the fan, in the duct system, one point for the supply and one for the return. The leakage flow rate is calculated by

$$\dot{m} = C\Delta P^n \qquad (1)$$

where n is fixed at 0.65 and C is specified for each case to achieve the desired leakage flow rate.

The analysis of the different test cases was performed using the FSEC 3.0 building simulation software developed at the Florida Solar Energy Center (FSEC 1992). The program is a general building simulation tool for analysis of whole-building systems, including simultaneous evaluation of energy, moisture, multizone airflows, and air distribution systems.

The program consists of three main sections. The first section calculates heat and moisture transfer in the building envelope. The second section calculates overall energy and moisture balances for the building zones. The third section focuses on HVAC systems, including calculations of system airflows and pressures for multiple zones. Air distribution system performance is calculated in the third section.

The attic model used for this analysis was developed by Gu, et al. (1996), under ASHRAE Research Project 852-RP. Four features of the model make it particularly appropriate for our analysis.

- The attic model accounts for the interactions between the attic thermal environment and the air distribution system. Specifically, both duct leakage and surface heat transfer can be modeled.
- The attic can be modeled as two interacting thermal zones. Specifically, the upper portion of the attic can be at a different temperature than the lower portion.
- The model accounts for radiative exchange among surfaces in the attic. Specifically, the model includes radiation among the roof, the upper ceiling surface, and the duct system in the attic.
- The model accounts for natural ventilation of the attic, reflecting the interacting effects of roof and attic temperature on attic ventilation.

The HVAC system model includes both the performance of the heating and cooling equipment and the behavior of the air distribution system. The equipment performance models are based on those in the DOE2 building energy simulation program (Winkleman, et al., 1993). The furnace is modeled with a constant efficiency. Both the capacity and power consumption of the air conditioner are dependent on outdoor conditions and the conditions of the air entering the indoor coil.

The air distribution system interacts with the attic through leakage and thermal exchange. It is assumed that the leakage occurs at the entrance and exit to the HVAC equipment and that heat transfer occurs across the entire area of the duct. The model also accounts for the transient heat transfer in the duct system.

Building Test Set

The models for hourly distribution system efficiency are developed for use in California in the context of compliance with Title 24. As a result, the analysis has been performed specifically for California climates and for building characteristics identified in the Title 24 documentation.

Fourteen test case residences and their associated base cases were developed to simulate the range of duct leakage flow rates, duct insulation levels, and ceiling insulation levels that will be encountered in typical California residences. Cases 1 through 7 do not have a radiant barrier in the attic and Cases 1R through 7R have a radiant barrier in the attic. Specific values for leakage, duct insulation, ceiling insulation, and radiant barrier emissivity are obtained from the Title 24 documentation. The implementation in the fourteen specific test cases are given in Table 2.

For residences with a radiant barrier in the attic the emissivity and absorptivity of the plywood layer in the roof assembly were changed to 0.10 to reflect the addition of a radiant barrier with emissivity of 0.05 to the roof. The assembly emissivity of 0.10 reflects the reduction in emissivity due to framing effects.

The *base case* residence is used to measure the performance of the test cases and quantify the effects of duct leakage and insulation levels. The base case residence models a residence with an ideal duct system; no air leakage losses and no conduction losses through the duct walls. The base case residence used for each comparison has the same ceiling insulation and radiant barriers as the cases against which it is compared. For example, a base case residence with R-19 (IP) ceiling insulation and no radiant barrier is compared against a test case residence with R-19 (IP) ceiling insulation and no radiant barrier. Similarly a base case residence with R-38 (IP) ceiling insulation and a radiant barrier in the attic is compared against a test case residence with R-38 (IP) ceiling insulation and a radiant barrier in the attic. Specifically, there are six separate base buildings used in the analysis of the fourteen test cases, corresponding to three different ceiling insulation levels with and without radiant barrier.

Table 2: Description of Alternative Cases

Case	Ceiling R-Value	Duct R-value	Duct Leakage
1	R-10	R-4.2	8%
2	R-10	R-4.2	22%
3	R-19	R-4.2	15%
4	R-38	R-4.2	8%
5	R-38	R-4.2	22%
6	R-38	R-8.0	8%
7	R-38	R-8.0	22%

R suffix includes radiant barrier

Climate Data

There are sixteen identified California climate zones as shown in Figure 1. Hourly weather data for each climate zone were obtained from Berkeley Solar Group and formatted for use with the FSEC 3.0 simulation program. The regressions were developed with a focus on climate zones 13, 15, and 16. Zone 16 represents the mountainous regions of the state, incuding Lake Tahoe, with the greatest heating requirements. Zone 15 represents the desert areas of the state, including Palm Springs, with the highest cooling loads. Zone 13 represents the San Joaquin valley, including Fresno, with both heating and cooling needs.

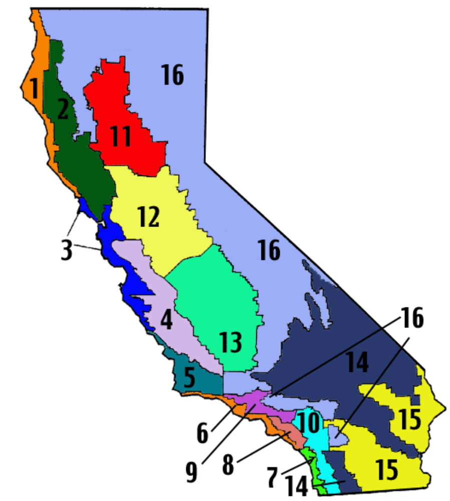

Figure 1 California Climate Zones

MODEL DEVELOPMENT

Detailed simulations of the above test case residences and their associated base cases were performed using the FSEC 3.0 software tool in a several California climate zones, representing the range of cooling climates experienced in California. The detailed simulation results were used to develop a regression-based model of the hourly normalized distribution efficiency. This model can then be used in a spreadsheet to calculate the additional cooling energy consumption due to duct leakage and duct insulation of a given residence with an attic-based duct system.

The model developed here assumes that another primary building simulation program will be used to perform an hourly analysis of the energy consumption of the residence and its HVAC system. This primary simulation program will calculate the hourly energy use assuming an ideal distribution system, i.e., no duct leakage or duct conduction losses.

Considerable previous work has been performed on the evaluation of air distribution systems on seasonal system performance. Specifically, ASHRAE Standard 152, Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems, provides a method to account for seasonal distribution system efficiency for a wide range of system designs. Our approach builds on this previous work by providing a modifier to this average seasonal value to account for hourly variations in the distribution system efficiency.

The following definitions are used for the development of the model and are critical for its correct application.

Seasonal Distribution Efficiency, Cooling: Annual base case cooling energy consumption by the equipment divided by the annual cooling energy consumption for the residence with duct losses. For example, if the base case annual cooling energy consumption by the equipment is 500 kWh and the identical residence with duct losses consumes 750 kWh, the seasonal cooling distribution efficiency is 0.667.

Seasonal Distribution Efficiency, Heating: Annual base case heating energy consumption by the equipment divided by the annual heating energy consumption for the residence with duct losses.

Distribution Efficiency, Hourly: The heating or cooling energy consumption by the equipment of the applicable base case residence for a given hour divided by the heating or cooling energy consumption by the equipment of the residence with duct losses for a given hour. For example, during a given hour the base case residence consumes 1.5 kWh of energy for cooling and the identical residence with duct losses consumes 2.0 kWh of energy for cooling the hourly distribution efficiency is 0.75.

Normalized Distribution Efficiency, Hourly: The seasonal distribution system efficiency divided by the applicable hourly distribution efficiency. For example, using the numbers in the above examples the hourly normalized distribution efficiency would be 0.667/0.75, or 0.889.

Duct Leakage, %: Supply duct leakage plus return duct leakage divided by the design airflow rate.

Regression Model Form

The objective of the regression model is to predict the hourly normalized distribution efficiency for a residence. The model assumes that the primary building simulation program has generated hourly performance for the base case building, and that the hourly results are available for use in the model.

The development of the model is guided by the following principles:

- The model should be mathematically simple. The model is expected to be applied in a spreadsheet as a simple correction to hourly energy consumption.
- The model should be general and robust. Specifically, it is more important that the model give *reasonable* results over a broad range of conditions than that the model give *accurate* results under specific conditions.
- The model should only use variables that are readily available from weather data or typical hourly building simulation results.
- The results of the hourly model for distribution efficiency should be consistent with the seasonal distribution efficiencies obtained with ASHRAE Standard 152. That is, the sum of the hourly energy use over a season predicted by the hourly model should match the seasonal energy consumption using the single seasonal value of distribution system efficiency.

Our preliminary studies also showed a strong relationship between cooling distribution efficiency and attic dry-bulb temperature. In both studies the cooling distribution efficiency decreased with an increase in either outdoor dry-bulb or attic dry-bulb temperature. The attic temperature is strongly influenced by incident solar radiation and indoor zone temperature in addition to outdoor dry-bulb temperature. After comparing several regression models, it was seen that using the difference between the indoor and outdoor temperature in conjunction with global horizontal insolation proved superior to simply using the outdoor dry-bulb temperature and global horizontal insolation. Because the model must only use weather file data or base case simulation results, the indoor – outdoor temperature difference used must be the outdoor dry-bulb temperature minus the *base case* indoor zone temperature. This temperature difference characterizes the cooling load on the base case building, which is assumed to be in proportion to the cooling load on the actual building with duct losses. The addition of the global horizontal insolation accounts for increases of the attic temperature due to solar gains of the roofing.

In an effort to simplify the regression model, the effect of solar radiation was combined with the outdoor temperature in the form of the *sol-air* temperature. The sol-air temperature is defined as the effective outdoor temperature that would give the same heat transfer by convection to the outdoor air alone as the actual scenario of combined heat transfer by convection and radiation. Specifically, the model uses the sol-air temperature on a horizontal surface to characterize the effect of radiation on attic heat transfer.

$$T_{sol} = T_{amb} + \left(\frac{\alpha}{h_o} \right) I_{hor} - \Delta T_{sky} \quad (2)$$

where

T_{sol}	sol-air temperature, °C
T_{amb}	outdoor air dry-bulb temperature, °C
ΔT_{sky}	reduction of sol-air temperature due to sky radiation, = 3.6°C
I_{hor}	global solar radiation on horizontal surface, W/m^2
α	solar absorptivity of roof = 0.50
h_o	outside surface convection coefficient, = 20 W/m^2°C

Note that the values of $\alpha = 0.50$ and $h_o = 20$ W/m^2°C are representative values for absorptivity and surface coefficient.

The model uses the difference between the sol-air temperature and the indoor air dry-bulb temperature as a single independent variable to describe the variation in distribution system efficiency.

$$\Delta T_{sol} = T_{solair} - T_{in} \quad (3)$$

where

T_{in}	indoor air dry-bulb temperature, °C

Perhaps the greatest challenge in the model development is the desire to maintain consistency between the hourly and seasonal calculations. ASHRAE Standard 152 provides a method to calculate the seasonal effect of the distribution system on energy consumption using the seasonal distribution efficiency

$$DE_{season} = \frac{E_{ideal,season}}{E_{season}} \quad (4)$$

where

DE_{season}	seasonal average distribution system efficiency
E_{season}	seasonal HVAC system energy use
$E_{ideal,season}$	seasonal HVAC system energy use for ideal duct system with no losses

In our approach, we calculate the seasonal energy use by summing the hourly energy use as calculated by adjustments to the hourly energy consumptions using hourly distribution system efficiencies. For consistency, the sum of the corrected hourly values should equal the corrected seasonal value.

$$E_{season} = \frac{E_{ideal,season}}{DE_{season}} = \frac{1}{DE_{season}} \sum_{season} E_{ideal,hr} \left(\frac{DE_{season}}{DE_{hr}} \right) \quad (5)$$

In our approach, we develop a model for the bracketed correction factor that is the ratio of the seasonal distribution efficiency to the hourly distribution efficiency. This correction factor is a function of the sol-air temperature difference defined above. For consistency, the energy-weighted sum of the correction factor must equal unity.

Based on the analyses of duct system performance and the requirements of the model, we have identified the following form for a correction factor to account for hourly variations in distribution system efficiency.

$$\frac{DE_{season}}{DE_{hr}} = 1 + C_{DT} \cdot \left(\frac{\Delta T_{sol,hr}}{\Delta T_{sol,season}} - 1 \right) \quad (6)$$

The hourly correction factor is a function of the hourly difference between the sol-air temperature and the indoor temperature and uses a single regression coefficient, C_{DT}. The hourly sol-air temperature difference has been normalized with respect to the effective seasonal sol-air temperature difference, which is calculated as the energy-weighted sum of the hourly sol-air temperature difference.

$$\Delta T_{sol,season} = \frac{\sum_{season} \Delta T_{sol,hr} E_{hr}}{\sum_{season} E_{hr}} \quad (7)$$

The regression of Eqn. 6 has the following features:

- The regression is simple, using a single regression coefficient.
- The model is relatively robust. While it may not recognize many subtle effects of building and

HVAC system design and operation, it is unlikely to yield absurd results for any circumstance.

- The model has the desirable feature that the hourly distribution efficiency is always equal to the seasonal distribution efficiency when the independent variable, ΔT_{sol}, is at its seasonal average value.

The weighted average sol-air temperature difference can be obtained in one of two ways. First, if the complete results of the primary building energy simulation are available, the value can be directly calculated from the results. Alternately, representative values can be calculated for generic applications and tabulated for general use. This second approach would be valuable in cases when the hourly correction for distribution system efficiency are integrated with the primary building energy simulation. In theory, the weighted average sol-air temperature difference will be a function of both location and the specific building design and operation. For example, in heating, a building with high internal gains will have a larger portion of the heating load at lower outdoor temperatures. However, it is expected that the primary factor will be climate – the effective cooling temperature difference in Palm Springs will be much greater than that in Oakland. Table 3 gives values for the seasonal sol-air temperature difference, $\Delta T_{sol,season}$, for the sixteen California climate zones.

Table 3: Seasonal Sol-Air Temperature Difference, °C

Climate Zone	Cooling	Heating
1	12.78	-11.12
2	17.61	-13.13
3	13.14	-10.50
4	14.61	-11.74
5	14.46	-11.25
6	13.22	-9.51
7	13.98	-9.53
8	17.16	-10.81
9	18.18	-10.47
10	18.52	-11.96
11	19.02	-13.54
12	19.25	-12.95
13	19.18	-12.73
14	19.61	-14.24
15	18.52	-11.29
16	16.35	-16.59

The regression coefficient, C_{DT}, will be a function of the system characteristics. For example, a duct with little insulation or large leakage could be expected to be more sensitive to attic temperature, and by association, to outdoor conditions. Similarly, attic construction could also influence its value. An attic with a radiant barrier or large ventilation rates will have a lower attic temperature during cooling season, reflecting a smaller impact of sol-air temperature on distribution system efficiency. The nature of these effects will be discussed later.

A preliminary analysis of simulation results indicated that the ceiling insulation level had relatively little impact on the hourly variation of distribution system efficiency. As a result, the results presented here are focused on Test Cases 4, 5, 6, and 7, both with and without radiant barriers. Separate analyses have been performed for heating and cooling seasons.

The coefficients for the regression model of Eqn. 6 were developed in two steps. First, individual regressions were performed to obtain regressed values for C_{DT} for the individual test cases. That is, eight separate values of C_{DT} were obtained for Test Cases 4, 5, 6, 7, 4R, 5R, 6R, and 7R. Second, the individual values of C_{DT} were regressed with the values of duct insulation level, leakage rate, and radiant barrier emissivity to obtain the final combined regression.

RESULTS AND ANALYSIS

Figure 1 gives the relationship between the hourly normalized distribution efficiency and the normalized sol-air temperature difference for the four test cases without a radiant barrier. Recall that Cases 4 and 6 are at low duct leakage with two different duct insulation values, while Cases 5 and 7 are at high leakage with the two different duct insulation values. The results indicate that there is a strong relationship between the distribution efficiency and the sol-air temperature difference. There is relatively little sensitivity to duct insulation, but significant sensitivity to duct leakage. There is also more scatter at higher leakage rates.

The results indicate that there is a slight curvature to the relationship. However, for the sake of simplicity, we have elected to use a linear regression rather than a polynomial regression. The linear regression lines are shown in Figure 1. Table 4 shows the statistical characteristics of the regression. Note that each regression has an adjusted correlation coefficient R^2 of approximately 0.85. The standard error, σ, is less than 2% for the 8% leakage cases and less than 3% for the 22% leakage cases. Note that 95% of the data points are within $\pm 2\sigma$.

Table 5 shows the statistical characteristics of the regressions for the analogous cases with the radiant barrier. The standard errors of the regressions are slightly higher, though no regression has a standard error greater than 3.8%.

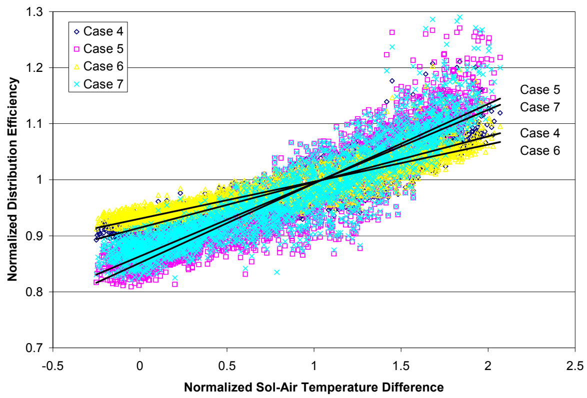

Figure 1 Distribution Efficiency Without Radiant Barrier, Cooling

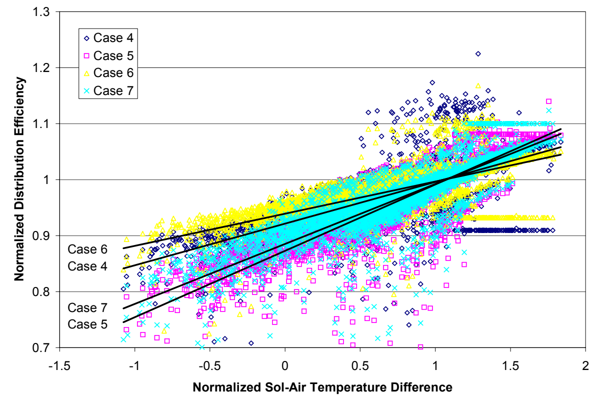

Figure 2 Distribution Efficiency Without Radiant Barrier, Heating

Table 4: Individual Regressions: Cooling, No Radiant Barrier

Duct Insulation	R-4.2	R-4.2	R-8.0	R-8.0
Leakage	8%	22%	8%	22%
C_{DT}	0.0660	0.0989	0.0540	0.0911
Multiple R	0.9011	0.9018	0.8927	0.8954
R Square	0.8121	0.8132	0.7970	0.8018
Standard Error	0.0194	0.0291	0.0166	0.0278

Table 5: Individual Regressions: Cooling, Radiant Barrier

Duct Insulation	R-4.2	R-4.2	R-8.0	R-8.0
Leakage	8%	22%	8%	22%
C_{DT}	0.0846	0.1465	0.0686	0.1349
Multiple R	0.9257	0.9232	0.9195	0.9188
R Square	0.8570	0.8523	0.8454	0.8443
Standard Error	0.0212	0.0376	0.0180	0.0357

Table 6: Individual Regressions: Heating, No Radiant Barrier

Duct Insulation	R-4.2	R-4.2	R-8.0	R-8.0
Leakage	8%	22%	8%	22%
C_{DT}	0.0684	0.1121	0.0523	0.1010
Multiple R	0.7216	0.9014	0.7311	0.8974
R Square	0.5208	0.8125	0.5346	0.8053
Standard Error	0.0287	0.0232	0.0213	0.0213

Table 7: Individual Regressions: Heating, Radiant Barrier

Duct Insulation	R-4.2	R-4.2	R-8.0	R-8.0
Leakage	8%	22%	8%	22%
C_{DT}	0.0600	0.0699	0.0485	0.0634
Multiple R	0.7591	0.7541	0.7711	0.7516
R Square	0.5762	0.5686	0.5947	0.5649
Standard Error	0.0232	0.0244	0.0181	0.0221

Figure 2 gives the relationship between the hourly normalized distribution efficiency and the normalized sol-air temperature difference for the heating season for the four test cases without a radiant barrier. The results indicate that there is again a strong relationship between the distribution efficiency and the sol-air temperature difference. There is relatively little sensitivity to duct insulation, but significant sensitivity to duct leakage.

The linear regression lines are shown in Figure 2 and Table 6 shows the statistical characteristics of the regression. Note that the correlation coefficient for the heating cases are significantly lower than for the cooling cases. However, the standard error, σ, is less than 3% for all cases. Table 7 shows the statistical characteristics of the regressions for the analogous cases with the radiant barrier.

Combined Regressions

The regression coefficient of Eqn. 3.5, C_{DT}, is different for various values of duct insulation, duct leakage, and radiant barrier emissivity. An analysis of this variation indicates that it is possible to combine the effects of duct insulation and duct leakage using the following relationship.

$$C_{DT} = C_0 + {C_R}/{R_{duct}} + C_L L_{duct} \qquad (1)$$

where

R_{duct} duct insulation R-value, hr ft^2°F/Btu
L_{duct} duct leakage as fraction of supply airflow, dimensionless

Separate regressions have been performed for heating and cooling with and without a radiant barrier. The values of the coefficients are given in Table 8

Table 8: Combined Regression Coefficients

	Cooling Radiant Barrier	Cooling No Radiant Barrier	Heating Radiant Barrier	Heating No Radiant Barrier
C_0	0.0078	0.0186	0.0350	0.0205
C_R	0.1222	0.0877	0.0794	0.1202
C_L	0.5480	0.2995	0.0714	0.2655

Comparison with ASHRAE Standard 152

The models developed here are designed to adjust the seasonal distribution efficiency to account for hourly variations throughout the heating and cooling seasons in California location. The model described here does not explicitly calculate the seasonal distribution efficiency, but rather uses the seasonal value obtained from other sources, such as ASHRAE Standard 152. However, the FSEC 3.0 simulations used to develop the model could also be used to calculate the seasonal efficiencies. It is illustrative to compare the values of the distribution efficiency obtained from FSEC 3.0 to those calculated by the procedures of Standard 152. The comparison can be used as a check for errors in the simulation, but also to highlight some of the very detailed factors that influence distribution system efficiency.

Table 9 shows the comparison between ASHRAE Standard 152 and the FSEC 3.0 program for Climate Zone 13. The results indicate that the FSEC 3.0 program generally predicts a higher value of the seasonal distribution system efficiency than that tabulated in Standard 152.

Table 9: Comparison of Seasonal Distribution Efficiencies

	Heating		Cooling	
Case	Std 152	FSEC 3.0	Std 152	FSEC 3.0
4	0.815	0.920	0.812	0.862
4R	0.815	0.942	0.833	0.891
5	0.743	0.867	0.721	0.765
5R	0.743	0.910	0.694	0.815
6	0.864	0.938	0.793	0.886
6R	0.864	0.955	0.872	0.907
7	0.788	0.880	0.704	0.782

CONCLUSIONS

A simplified model has been developed to account for the hourly variation in distribution system efficiency relative to the seasonal value. The model is based on regression to hourly simulation results. The regression has been developed to be simple and robust, relying only on the normalized difference between the sol-air temperature and the indoor dry-bulb temperature.

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REFERENCES

ASHRAE. 2004. ANSI/ASHRAE Standard 152 *Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

CEC. 2001 Building Energy Efficiency Standards: Energy Efficiency Standards for Residential and Nonresidential Buildings (Title 24). California Energy Commission Publication No. P 400-01-024

FSEC. 1992. FSEC 3.0: Florida Software for Environmental Computation, Version 3.0, Technical Report FSEC-GP-47-92, Florida Solar Energy Center, Cocoa, FL.

Gu, L., J.E. Cummings, M.V. Swami, P.W. Fairey, S. Awwad. 1996. Comparison of Duct System Computer Models That Could Provide Input to the Thermal Distribution Standard Method of Test (SPC152P). Final report for ASHRAE 852-RP, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

Winkelman, F.C., et al. 1993. DOE-2 Version 2.1E, LBNL Report 34946, Lawrence Berkeley National Laboratory, Berkeley, CA.