Application of an ASHRAE 152-2004 Duct Model for Simulating Code-Compliant 2000/2001 IECC Residences

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ABSTRACT

This paper presents the results of the application of the duct model based on ASHRAE 152-2004 - Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems (ASHRAE 2004) to the code-compliant 2001 International Energy Conservation Code (IECC)[1] (ICC 1999, 2001) using DOE-2.1e building energy simulation program[2].

Code compliant DOE-2 simulation model was developed based on IECC and the duct model (Kim and Haberl 2008[3]) was applied to the IECC-code compliant model. Then, the efficiency analyses of the IECC-compliant simulation model were performed on: 1) duct properties, and 2) the different locations of HVAC system and ductwork including the attic space and conditioned space based on the different climate zones.

INTRODUCTION

In 2001, the Texas State Senate passed Senate Bill 5 to reduce ozone levels by encouraging the reduction of emissions of NOx by sources that were not regulated by the TNRCC (Texas Natural Resource Conservation Commission), including point sources (power plants), area sources (residential emissions, etc.), road mobile sources, and non-road mobile sources (TNRCC 2000). For the building energy section, the Texas State Legislature adopted the 2001 International Energy Conservation Code (IECC) as the state's energy code (TNRCC 2000). The 2001 IECC is a comprehensive energy conservation code that establishes a minimum for design and construction parameters such as the thermal properties of insulation on a wall, floor, roof, and the efficiency of the cooling and heating systems through the use of prescriptive and performance-based provisions. Therefore, there was a need to develop an accurate, code-traceable IECC model, which can then be used to simulate residential single-family houses in Texas according to the International Energy Conservation Code (IECC) using the DOE-2.1e building simulation program.

In addition, the duct systems in residential houses, especially in an unconditioned space such as the attic or crawl space can have significant heat loss or gain to the surrounding unconditioned space through the duct systems. Cummings (1991) tested duct leakage using tracer gas tests in 91 homes in Florida. He found, on average, about 12% of the house infiltration occurs in the duct system. Duct repairs were made on 25 homes and cooling energy use was monitored before and after the duct repair. The study showed that the air-conditioning energy use decreased 18% due to the duct repairs. O'Neal et al. (1996) performed a study to quantify the effect of return air leakage and humidity from hot and humid attic spaces on the performance of residential air conditioners. They found that the effective capacity decreased with an increased return air leakage and high humidity in the same temperature condition, and that leakage rates that have high attic humidity caused more reduction of capacity. They concluded that attic conditions, especially attic humidity, were important factors in decreasing the capacity with increased duct air leakage.

However, although there are serious heat losses or gains through duct system in the unconditioned space such as the attic and crawl space especially in the hot and humid climate zone, DOE-2.1e building simulation program cannot calculate those losses without specially written routines. Therefore, this paper focuses on the efficiency analysis of the IECC-compliant simulation model by applying the duct model which was developed and tested by Kim and Haberl (Kim and Haberl 2008).

METHODOLOGY

Base-Case House

The DOE-2 simulation model for this study was adopted from the input file (SNGFAM2ST.INP), developed by the Energy Systems Laboratory (ESL). This input file was developed and used to evaluate amendments of the building energy codes for single-family house, and to quantify the resulting energy savings and emission reductions for the Senate Bill 5. This DOE-2 input file uses DOE-2 PARAMETERS instead of fixed values for various building

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[1] The 2001 IECC notation refers to the 2000 IECC as modified by the 2001 Supplement (ICC 1999; 2000).

[2] DOE-2.1e, Version 119

[3] This paper presents the results of the development of the duct model based on ASHRAE standard 152-2004 (ASHRAE, 2004) using the DOE-2.1e building energy simulation program. To accomplish this, FUNCTION commands for DOE-2 were used to develop the duct model and provide the improved predictions of the duct heat loss or gain from the unconditioned space as well as supply or return duct leakage. After applying the duct model to the DOE-2 base-case simulation model, simulation results were compared with the measurement from the case-study house for verification.

characteristics that include the building geometry, location, building envelope components, HVAC and DHW system, lighting, equipment, and occupancy. Figure 1 presents DrawBDL (Huang & Associates. 2000) views of the base-case house which was 2,500 sq.ft with the delayed construction mode[4], pitched roof, attic space, and duct model.

Figures 2 to 4 show the parameters used to generate a single-family simulation model. The parameters are divided into two major categories: LOADS and SYSTEMS. The LOADS are then further divided into building, construction, space and shading PARAMETERS. In the ESL's input file, the building parameters are used to define the basic dimensions of the building. The current ESL simulation model has a switch between quick (i.e., pre-calculated ASHRAE weighting factors with the floor-weight equal to 11.5 lb/ft^2, as required by Chapter 4 of the 2000 IECC, section 402.1.3.3) and thermal mass (i.e., DOE-2's custom weighting factors) mode. The construction PARAMETERS are divided into two categories: construction I and construction II. The construction I PARAMETERS include the material properties and U-values of the different components for quick construction mode and the glazing properties and the window-to-wall area ratio. The user has the option of changing the window areas for the different orientations. The construction II PARAMETERS include the material properties of the different components for the thermal mass construction mode. The space PARAMETERS are currently fixed at 2 occupants and 3 bedrooms per house. The number of bedrooms is used to calculate the daily domestic hot water consumption, which in turn is used to size the domestic hot water heater according to the section 420.1.3.7 of the 2000 IECC, including the 2001 Supplement. The system PARAMETERS include the type of systems, the system capacity and the efficiencies of the system selected. The user can define the system efficiencies according to the system type that is selected. For the additional analysis for the duct system, PARAMETERS were added such as: 1) supply air (CFM, sy12), 2) supply leakage fraction (sy13), 3) return leakage fraction (sy14), 4) supply duct area (ft^2, sy15), 5) return duct area (ft^2, sy16), 6) R-value for supply duct (sy17), 7) R-value for return duct (sy18), 8) cooling system capacity (Btu/hr, sy19), 9) heating system capacity (Btu/hr, sy20), and 10) duct location (attic or room, sy21).

The size of base-case model for the simulation was an average house as specified by the National Association of Home Builders (NAHB) with HVAC equipment efficiencies meeting the 2001 IECC. The roof side is created using rectangular shape for simplicity because DOE-2 usually considers the area instead of a shape to calculate heat transfer and the area of rectangular shape of the roof side is equivalent to the area of the roof side.

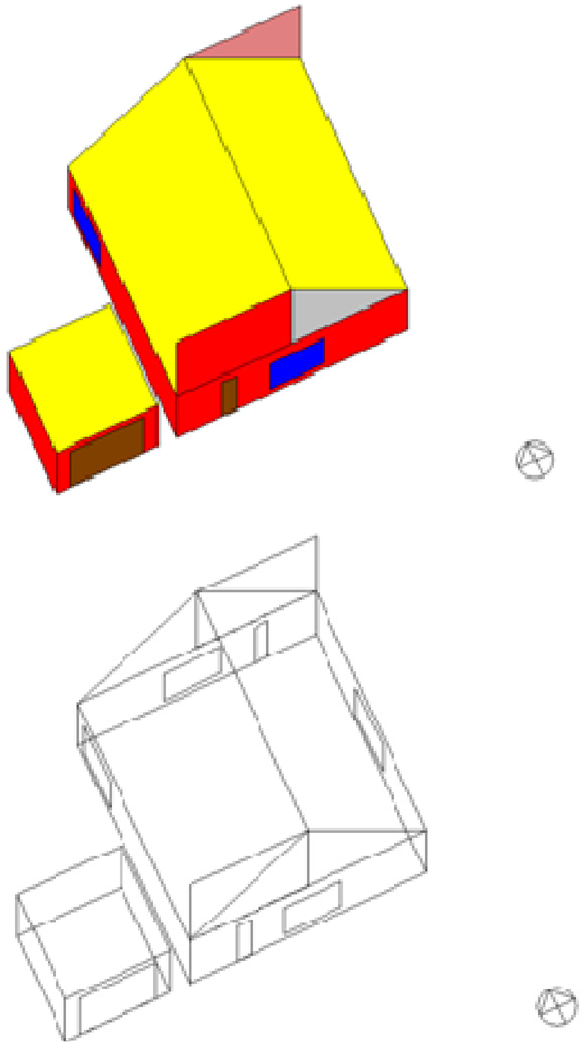

Figure 1. DrawBDL View of Base-Case Model

Incorporating the Duct Model

ASHRAE developed ASHRAE Standard 152-2004 - Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems (ASHRAE 2004) to estimate design and seasonal efficiency for residential building systems. This calculation considers the impacts of duct leakage, location (i.e., attic space, crawl space, etc.), insulation level, climate, etc.

[4] In the DOE-2 program there are two methods to specify wall, roof and floor construction: 1) the "quick" mode option, which uses U-values for the walls and roofs, a lumped thermal mass and pre-calculated ASHRAE weighting factors for the wall's thermal mass components, and 2) the delayed mode option which uses layered walls and roof construction and DOE-2's Custom Weighting Factors (CWFs) to calculate a more accurate heat transfer through the layered building components (LBNL 1993), and includes a proper accounting of buildings's thermal mass elements.

PARAMETER	NO	DESCRIPTION	DEFAULT	STATUS	COMMENTS
BUILDING	b01	Quick or thermal mode (Q or T)	T	User defined	Q simulates the building as massless, T simulates thermal mass
	b02	Location	HAR	User defined	41 Counties, ( ): DOE WEATHER FILE
	b03	Azimuth of building (degree)	0	User defined	Orientation of the building
	b04	Width of building (ft)	49.87	User defined	From NAHB survey (2002)
	b05	Depth of building (ft)	49.87	User defined	From NAHB survey (2002)
	b06	Height of wall (ft)	9	User defined	From NAHB survey (2002)
	b07	Door height (ft)	6.67	Fixed	From survey of manufactured doors
	b08	Door width (ft)	3	Fixed	From survey of manufactured doors
	b09	Run year	2001	Fixed	
	b10	Option of second floor (1 or 2)	1	User defined	Control activation/deactivation of one and two story portions of BDL input
	b11	Activation/ Deactivation of crawl (C or S)	S	User defined	Control activation/deactivation of crawl space and slab on grade floor types for the residence
	b12	Height of crawl space wall above ground(ft)	1.5	User defined	
	b13	Height of crawl space walll under ground(ft)	1	User defined	
	b14	Pitch of roof	23	User defined	Measured from the case study house
CONSTRUCTION I	c01	Roof outside emissivity	0.90	User defined	c01 and c02 are used to define "Roof Color"
	c02	Roof absorptance	0.50	User defined	
	c03	Roof roughness	1	Fixed	This is used to calculate the outside film coefficienct for heat transfer calculations, DOE-2 allows values from 1 to 6 increasing in smoothness
	c04	Roof R-value (Hr-sq.ft-F/Btu)	26	User defined	
	c05	Wall absorptance	0.55	User defined	c05 and c07 are used to define "Wall Color"
	c06	Wall roughness	2	User defined	This is used to calculate the outside film coefficienct for heat transfer calculations, DOE-2 allows values from 1 to 6 increasing in smoothness
	c07	Wall outside emissivity	0.90	User defined	c05 and c07 are used to define "Wall Color"
	c08	Wall R-value (Hr-sq.ft-F/Btu)	13	User defined	
	c09	Ground reflectance	0.24	Fixwd	This defines the fraction of sunlight reflected from the ground
	c10	Window option (S or D)	S (Same)	User defined	S: Same widow ratio for all side, D: Different winow ratio for each side. Activate from c21 to c25
	c11	U-Factor of glazing (Btu/hr-sq.ft-F)	0.75	User defined	
	c12	Solar Heat Gain Coefficient(SHGC)	0.40	User defined	
	c13	Number of panes of glazing	2	Fixed	
	c14	Frame absorptance of glazing	0.7	Fixed	
	c15	Frame type - A,B,C,D,E	A (Aluminum without thermal break)	User defined	5 kinds of window frames
	c16	VOID			
	c17	Floor weight (lb/sq-ft)	11.50	Fixed	Activated if b01 is Q (Quick mode), from IECC2000 p.64 (If T:themal mass mode), Floor weight = 0), DOE Default 30=light; 70 = medium; 130 = heavy
	c18	VOID			
	c19	R-value of concrete slab (hr-sq.ft-F/Btu)	0.44	Fixed	R-value of concrete slab, Now 4" heavy weight concrete(CC03 in DOE Library). For Winkelmann calculation
	c20	Air film resistance (hr-sq.ft-F/Btu)	0.77	Fixed	The average of the air film resistance, Current heat flow up from article by Winkelmann. For Winkelmann calculation
	c21	Percentage of window area (%) for whole area or front side wall	15.00	User defined	If c10 is S, then this percentage is applied to all window area. Or If c21 is D, then this percentage is applied only to front side wall.
	c22	Percentage of window area (%) for back side wall	15.00	User defined	Only when c10 is D, this percentage is applied to back side wall.
	c23	Percentage of window area (%) for right side wall	15.00	User defined	Only when c10 is D, this percentage is applied to right side wall.
	c24	Percentage of window area (%) for left side wall	15.00	User defined	Only when c10 is D, this percentage is applied to left side wall.
	c25	Percentage of window area (%) for 2nd floor left side wall	15.00	User defined	Only when c10 is D, this percentage is applied to 2nd floor left side wall.
	c26	Floor R-Value (hr-sq.ft-F/Btu)	11	User defined	Default from IECC2000, page 81 (Window 15%, R-11). Crawl space only
	c27	Crawl space wall R-value (hr-sq.ft-F/Btu)	F (R-5)	User defined	Option (A, B, C, D, E, F, G, H, I, J, K, L, M, N). Default from IECC2000, page 81 (Window 15%, R-5). Crawl space only
	c28	Slab perimeter R-value and depth	A (R-0)	User defined	Option (A, B, C, D, E, F, G, H, I, J, K). Default from IECC2000, page 81 (Window 15%, R-0). Slab only
CONSTRUCTION II	cc01	Wall type selection	A	User defined	A: Wood frame B: Metal C: Masonary
	cc02	Wall stud type	a	User defined	a: 2 x4" stud dimensions b: 2 x 6" stud dimensions
	cc03	Wall stud position	WSPA	User defined	Fixed at WSPA: Postion of studs at 16" c/c
	cc04	Wall cavity insulation	CIA	User defined	Corresponding insulation values in the DOE-2 material library: CIA: R-11 CIB: R-13 CIC: R-15 CID: R-19 CIE: R-20

Figure2. Single-Family Input Parameters (a)

PARAMETER	NO	DESCRIPTION	DEFAULT	STATUS	COMMENTS
CONSTRUCTION II	cc05	Wall exterior Insulation	EIB	User defined	Corresponding Exterior insulation/ sheathing values from DOE-2 material library:
					EIA: R-0
					EIB: R-5
					EIC: R-7.5
					EID: R-10
					EIE: Polyisocyanurate R 3.6
	cc06	Exterior finish	EFA	User defined	Corresponding finishing values from DOE-2 material library:
					EFA: Stucco R 0.2
					EFB: Vinyl Siding R 0.045
					EFC: Brick Siding R 0.33
					EFD: Hardi-Plank R 0.24
					EFE: Wood-Siding R 0.494
	cc07	Void			
	cc08	Void			
	cc09	Void			
	cc10	Roof type selection	WOODFRAME	User defined	WOODFRAME: Custom made frame for both ceiling and roof
					TRUSS: Pre-designed/Engineered truss
	cc11	Roof stud selection	a	User defined	a: 2 x 6" stud dimensions
					b: 2 x 8" stud dimensions
	cc12	Ceiling stud selection	a	User defined	a: 2 x 6" stud dimensions
					b: 2 x 8" stud dimensions
	cc13	Roof truss size	a	User defined	a: 2 x 4" stud dimensions
					b: 2 x 6" stud dimensions
	cc14	Placement of cavity insulation in roof	no	User defined	Roof insulation: No Ceiling insulation: yes
					Roof insulation: No Ceiling insulation: No
	cc15	Placement of cavity insulation in ceiling	yes	User defined	Roof insulation: yes Ceiling insulation: no
					Roof insulation: yes Ceiling insulation: yes
	cc16	Choice of cavity insulation	CCIA	User defined	Corresponding exterior finish values from DOE-2 material library:
					CCIA: R-19
					CCIB: R-26
					CCIC: R-28
					CCID: R-30
	cc17	Stud position for roof and ceiling	RSPA	User defined	Fixed at RSPA: Postion of studs at 16" c/c
	cc18	Choice of exterior insulation for roof			Place holder
	cc19	Choice of exterior finish for roof	Asphalt shingles	User defined	Fixed value obtained from DOE-2 library: Asphalt shingles
	cc20	Ceiling finish	Fixed at GP01	Fixed	Fixed value obtained from DOE-2 library: GP01 (1/2 " thick Gypsum or Plaster Board)
	cc21	Interior floor structure	a	User defined	a: 2 x 10" stud dimensions
					b: 2 x 12" stud dimensions
					TRUSS: Engineered Truss
	cc22	Interior floor stud position	IFSPA	User defined	IFSPA: Postion of studs at 16" o.c.
					IFSPB: Position of studs at 24" o.c.
					IFSPC: Position of studs at 16" o.c.
	cc23	Interior floor finish	FIFA	User defined	Corresponding floor finish values from DOE-2 material library. Activated when second story present:
					FIFA: CP01 (Carpet finish) R 2.08
					FIFB: ST01 (Stone finish) R .08
					FIFC: Hardwood R 0.68
	cc24	Floor slab structure	Fixed at 4" concrete	Fixed	Fixed value obtained from DOE-2 library: CC14
	cc25	Choice of studs for floor over crawl space	a	User defined	a: 2 x 10" stud dimensions
					b: 2 x 12" stud dimensions
					c: 3"x2" chord size wirh 11 7/8" truss
					d: 3"x4" chord size wirh 16" truss
	cc26	Crawl space stud position	FSPA	User defined	FSPA: Postion of studs at 16"
					FSPB: Position of studs at 24"
	cc27	Type of crawlspace	Vented	User defined	Vented
					Unvented
	cc28	Crawl space insulation	FCIA	User defined	Corresponding insulation values from DOE-2 material library:
					FCIA: R-11
					FCIB: R-13
					FCIC: R-15
					FCID: R-19
					FCIE: R-4
					FCIF: R-5
					FCIG: R-6
					FCIH: R-10
					FCII: R-12
	cc29	Crawl space floor finish	FFA	User defined	Corresponding floor finish values from DOE-2 material library:
					FFA: CP01 (Carpet finish) R-2.08
					FFB: ST01 (Stone finish) R-0.08
					FFC: Hard wood R-0.68
	cc30	Crawlspace wall finish	CSWA	User defined	Corresponding floor finish values from DOE-2 material library:
					CSWA: CB31 (Concrete block, 8" medium weight, hollow) R 1.72
					CSWB: CB32 (Concrete block, 8" medium weight, concrete filled) R 1.34
					CSWC: CB33 (Concrete block, 8" medium weight perelite filled) R 5.84

Figure 3. Single-Family Input Parameters (b)

PARAMETER	NO	DESCRIPTION	DEFAULT	STATUS	COMMENTS
SPACE	sp01	Number of people	2		
	sp02	Number of bedroom	3		Default calculated from IECC 2001(402.1.3.7) HOT WATER CONSUMPTION/MIN = ((30*a)+(10*b))/1440, a=living unit, b=# of bedroom
SHADE	s01	Front eave shade (ft)	0	User defined	Front eave shade (ft)
	s02	Back eave shade (ft)	0	User defined	Back eave shade (ft)
	s03	Left eave shade (ft)	0	User defined	Left eave shade (ft)
	s04	Right eave shade (ft)	0	User defined	Right eave shade (ft)
	s05	Tree shade	NO	User defined	NO: No shading
					E: East side of the house
					W: West of the house
					EW: East and west side of house
	s06	Shading type	Liveoak	User defined	Activated only when s05 has shade
					Liveoak
					Deciduous
					Evergreen
SYSTEM	sy01	Mode of system: 1, 2, 3	1	User defined	Allows user to select all-electric, gas/electric or heat pump for HVAC
	sy02	Cooling capacity of cooling system (Btu/hr)	0	User defined	0: Let DOE2 calculate
	sy03	Heating capacity of heating system (Btu/hr)	0	User defined	0: Let DOE2 calculate
	sy04	Seasonal Energy Efficiency Ratio (SEER)	10	User defined	C-EIR: 0.1-1 (3.41/SEER = C-EIR)
	sy05	Annual Fuel Utilization Efficiency (AFUE)	0.78	User defined	F-HIR: 1-1.75 (1/AFUE = F-HIR)
	sy06	Heating Seasonal Performance Factor (HSPF)	6.8	User defined	H-EIR: 0.1-2 (3.41/HSPF = H-EIR) (ResCheck HSPF: 6.6 - 12)
	sy07	The number of pilot lights of DHW	1	User defined	Each pilot light is 500 BTU/HR
	sy08	The number of pilot lights of Furnace	0	User defined	Each pilot light is 500 BTU/HR
	sy09	The number of pilot lights of others	0	User defined	Each pilot light is 500 BTU/HR
	sy10	Switch for Energy Factor for Domestic Hot Water consumption	A	User defined	If "A", then macro in DOE-2 calculates the Energy Factor, if S then the EF is calculated using values input by the user in sys11 parameter.
	sy11	Energy Factor (%) for Domestic Hot Water	0.55	User defined	MIN MAX values available only when sy10 = S. If fuel is Electric, EF(Energy Factor) is calculated by 0.93-0.00132*DHW-SIZE(Gallon), or if fuel is Gas, EF(Energy Factor) is calculated by 0.62-0.0019*DHW-SIZE(Gallon). DHW-SIZE in Gallon = (30*a) + (10*b) (a: Number of living units, b: Number of bedrooms). IECC2000(p.65) 402.1.3.7. The criteria listed in section 504.2.1 decribing the efficiency is overruled as the EF is calculated per DHW heater which is installed per unit.
	sy12	Supply air (CFM)	2487	User defined	1CFM/ft^2
	sy13	Supply leakage fraction	0	User defined	
	sy14	Return leakage fraction	0	User defined	
	sy15	Supply duct area (ft^2)	746.17	User defined	From ASHRAE 152-2004, 30% of Building Area
	sy16	Return duct area(ft^2)	124.36	User defined	From ASHRAE 152-2004, 5% of Building Area
	sy17	R-value for supply duct	8	User defined	From IECC 2000/2001
	sy18	R-value for return duct	4	User defined	From IECC 2000/2002
	sy19	Cooling system capacity (Btu/hr)		User defined	From DOE-2 calculation (SV-A report)
	sy20	Heating system capacity (Btu/hr)		User defined	From DOE-2 calculation (SV-A report)
	sy21	Duct location	Attic	User defined	Attic or Room

Figure4. Single-Family Input Parameters (c)

The following equations show the procedure for the calculation of the delivery efficiency of the heating and cooling systems considering duct conduction loss and air leakage in the supply and return ducts (ASHRAE 2004).

$$DE_{heating} = a_s B_s - a_s B_s (1 - B_r a_r)\frac{\Delta t_r}{\Delta t_e} - a_s (1 - B_s)\frac{\Delta t_s}{\Delta t_e} \qquad \text{Eq. 1}$$

$$DE_{cooling} = \frac{a_s Q_e \rho_{in}}{E_{cap}}\left(\frac{E_{cap}}{60 Q_e \rho_{in}} + (1 - a_r)(h_{amb,r} - h_{in}) + a_r C_p (B_r - 1)\Delta t_r + C_p (B_s - 1)(t_{sp} - t_{amb,s})\right) \qquad \text{Eq. 2}$$

where,

B_s = conduction efficiency of supply duct $= \exp\left(\frac{-A_s}{60 Q_e \rho_{in} C_p R_s}\right)$, Eq. 3

B_r = conduction efficiency of return duct $= \exp\left(\frac{-A_r}{60 Q_e \rho_{in} C_p R_r}\right)$, Eq. 4

a_s = air leakage efficiency of the duct of supply duct $= \left(\frac{Q_e - Q_s}{Q_e}\right)$, Eq. 5

a_r = air leakage efficiency of the duct of return duct = $\left(\frac{Q_e - Q_r}{Q_e}\right)$, Eq. 6

E_{cap} = capacity of the equipment (Btu/hr),

Q_e = system air flow (CFM),

C_p = specific heat (Btu/(lb$_m$·ºF)),

Δt_e = temperature rise across the equipment (ºF) = $\frac{E_{cap}}{60 Q_e \rho_{in} C_p}$, Eq. 7

Δt_s = temperature difference between the building and the ambient temperature surrounding the supply (ºF)

Δt_r = temperature difference between the building and the ambient temperature surrounding the return (ºF) $= t_{in} - t_{amb,r}$, Eq. 8

t_{in} = temperature of indoor air (ºF),

t_{sp} = supply plenum air temperature (ºF),

$t_{amb,s}$ = ambient temperature for supply ducts (ºF),

$t_{amb,r}$ = ambient temperature for return ducts (ºF),

$h_{amb,r}$ = enthalpy of ambient air for return (Btu/hr),
h_{in} = enthalpy of air inside conditioned space (Btu/hr),
A_s = supply duct area (ft^2),
A_r = return duct area (ft^2),
ρ_{in} = density of air (lb/ft^3),
R_s = thermal resistance of supply duct (hr-ft^2-°F /Btu),
R_r = thermal resistance of return duct (hr-ft^2-°F /Btu).

Figures 6 and 7 show the procedures of the FUNCTION developed for DOE-2 to apply the duct model using the equations of ASHRAE Standard 152-2004. In this procedure three FUNCTIONS are used (SAVETEMP, DUCT, and DUCT 2). 1) The SAVETEMP function saves the calculated buffer zone temperature and conditioned space temperature to send these temperatures to the next function. 2) The DUCT function calculates the delivery efficiency using the saved temperatures, data from the hourly report and user inputs, and it modifies the Energy Input Ratio (EIR) to the air conditioner every hour in proportion to the losses. 3) The DUCT2 function changes the modified EIR back to the original value for the next hour calculation. After tests and verification (Kim and Haberl 2008), the duct model was applied to IECC-compliant simulation model.

Analysis of an IECC-Compliant Simulation Model

Duct efficiency analysis of an IECC-compliant residence was performed using TMY2 weather data for Amarillo, Fort Worth, Houston, and Brownsville, Texas (Figure 5). Table 1 presents the primary input model information about the building envelope, fenestration, duct properties, HVAC systems, etc. HVAC and duct systems were located at the attic space where it was unconditioned. The 2001 IECC provides the different levels of insulation for the wall and ceiling, and fenestration properties according to the climate zones. The wall insulation level is R-13 and the ceiling insulation level is R-38 for the climate zone 9, while the wall insulation level is R-11 and the ceiling insulation level is R-19 for the climate zone 2. Because of the different levels of insulation, the insulation levels of the wall and ceiling were adjusted using the thickness variable in the DOE-2 input to perform the simulations. The walls of the base-case house were constructed with 2x4 studs placed 24 inches on center. These walls had insulation in the cavity between the studs. The exterior of the house was vinyl sheathing over plywood and the interior of the walls was ½ inch gypsum board. The roof construction consisted of composite shingles on 5/8" plywood deck placed on 2x6" trusses set at 24" on centers. The ceilings were made of 5/8" gypsum boards on 2 x 6" trusses set at 24" on centers with insulation.

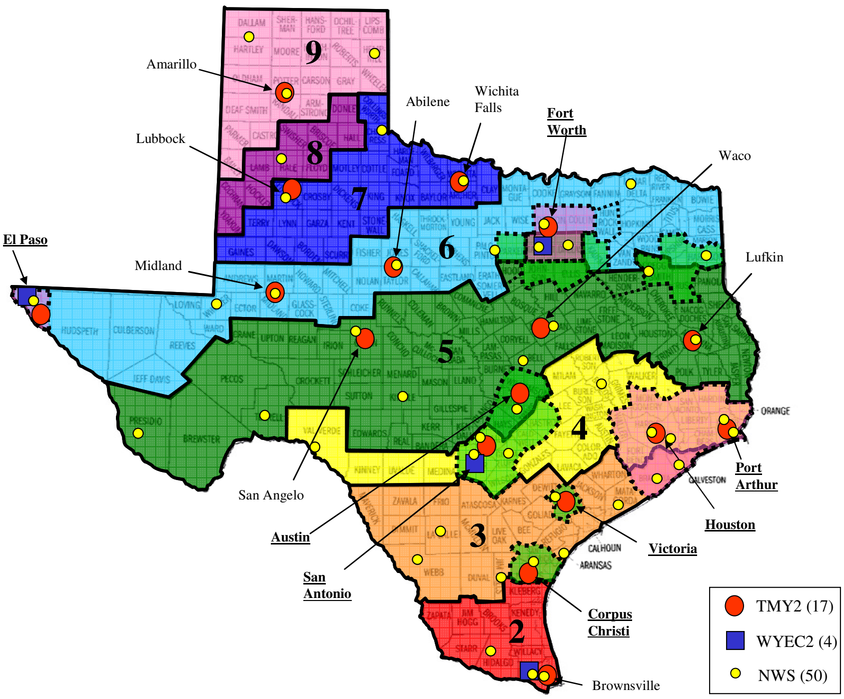

Figure 5. Map of Climate Zone (Haberl el al. 2004)

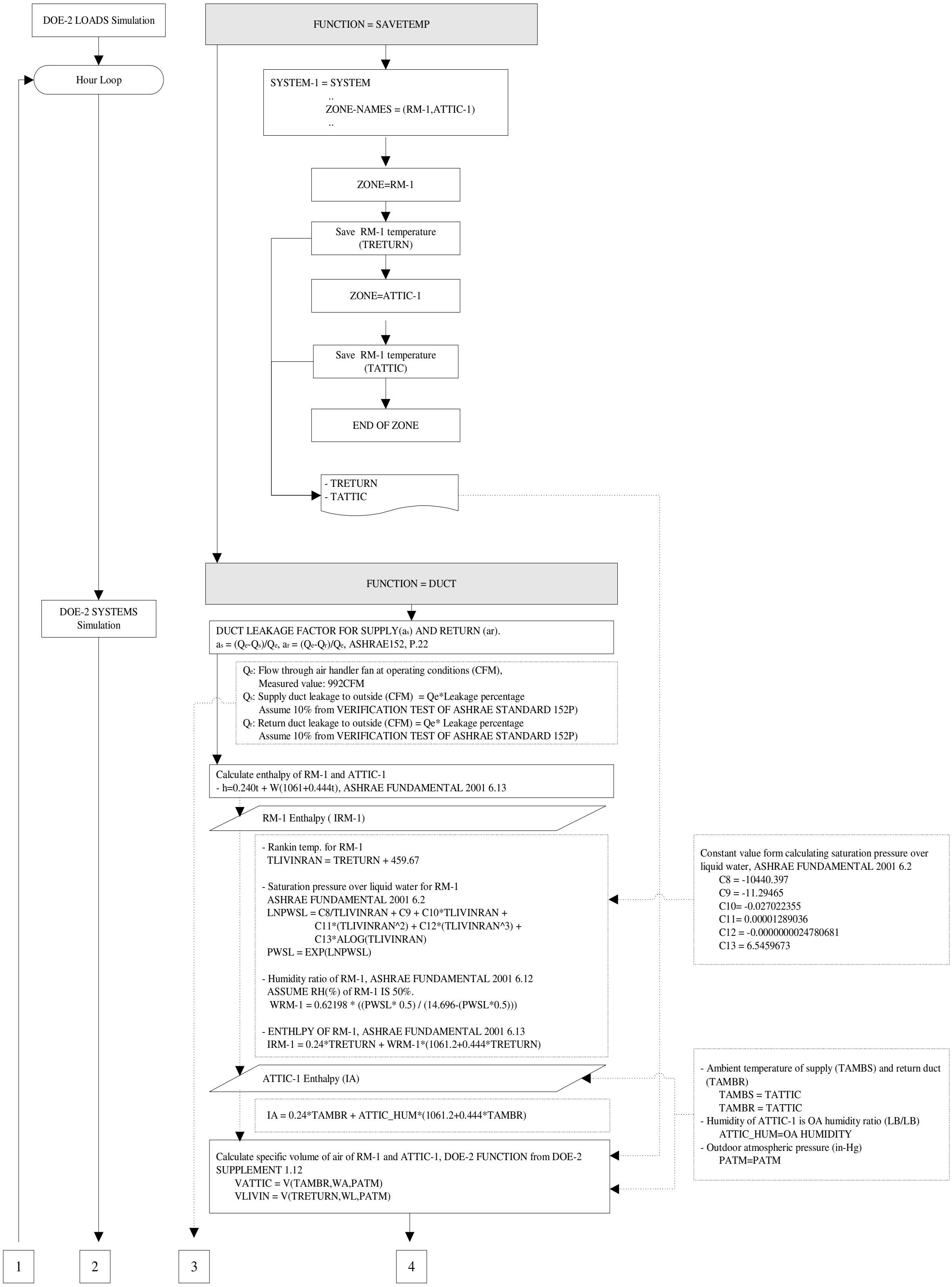

Figure 6. Diagram of DOE-2 FUNCTION Command for ASHRAE 152-2004 Duct Loss Model (a).

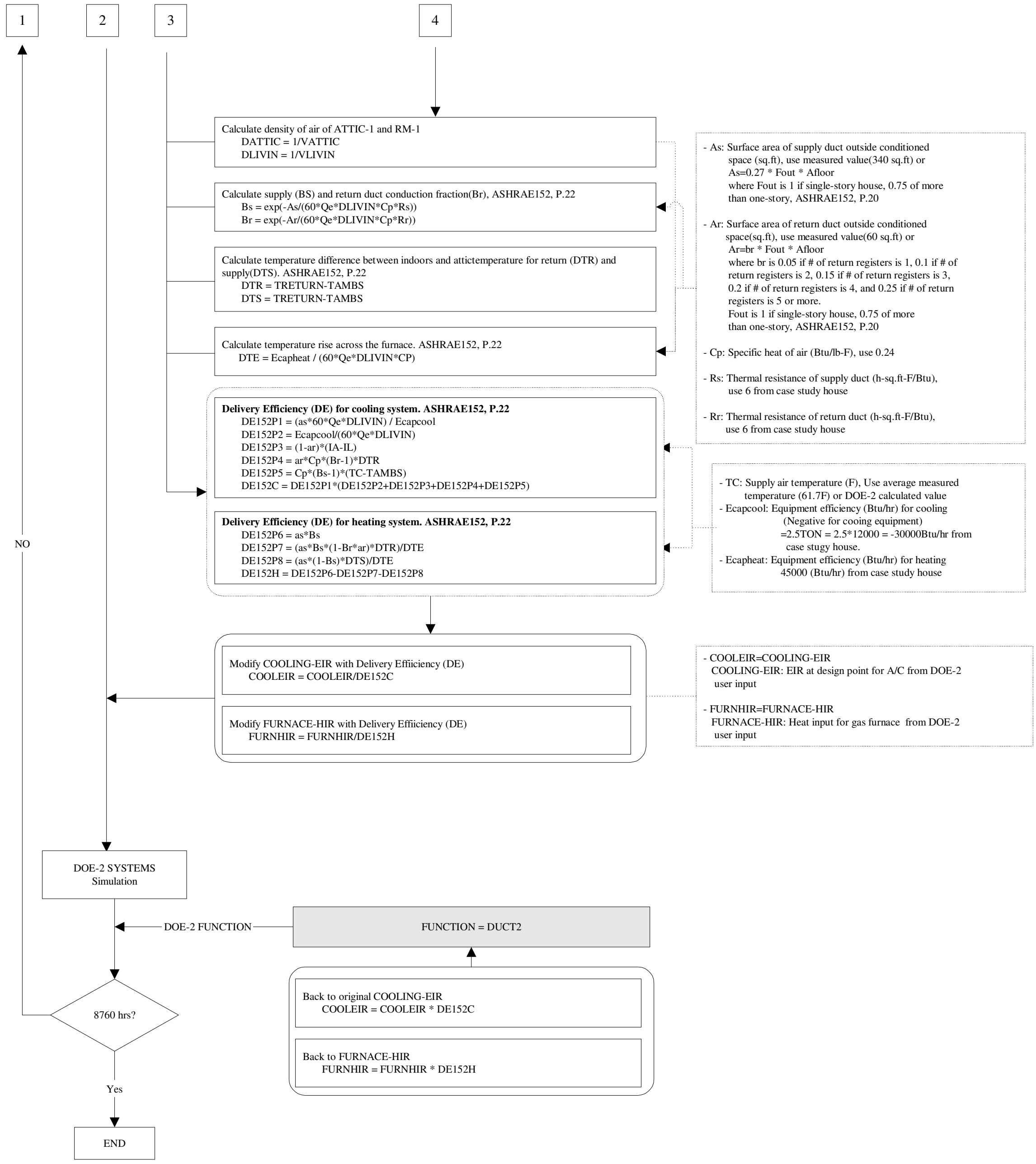

Figure 7. Diagram of DOE-2 FUNCTION Command for ASHRAE 152-2004 Duct Loss Model (b).

Table 1. Primary Input Model for the Efficiency Analysis

Climate Zone	Weather file (TMY2)	Floor Area (sq.ft)	Wall Height (ft)	Wall R-Value	Ceiling R-value	Window Area (%)	Glazing U-value	SHGC
		NAHB	NAHB	IECC 2000	IECC 2000	IECC 2000	IECC 2000	IECC 2000
9	Amarillo	2487.22	9	13	38	15	0.45	0.66
5	Fort Worth	2487.22	9	13	30	15	0.65	0.40
4	Houston	2487.22	9	13	26	15	0.75	0.40
2	Brownsville	2487.22	9	11	19	15	0.90	0.40

Duct Insulation	ACH	SEER	AFUE(%)	DHW PILOT LIGHT (500 BTU/HR)	AC Size (TON)	Heating Size (Bru/hr)	Supply Duct Area (sq.ft), 30%	Return Duct Area (sq.ft), 5%
	ASHRAE 136-1993	IECC 2000	IECC 2000		Manual	Manual	ASHRAE 152-2004	ASHRAE 152-2004
SR-8, RR-4	0.65	10	78	Y	5.0	75000	746.17	124.36
SR-8, RR-4	0.51	10	78	Y	5.0	75000	746.17	124.36
SR-8, RR-4	0.46	10	78	Y	5.0	75000	746.17	124.36
SR-8, RR-4	0.51	10	78	Y	5.0	75000	746.17	124.36

Duct Insulation Level and Leakage Rate

In order to investigate the energy impact of varying duct insulation levels and leakage rates, simulations were performed for different insulation R-values and duct leakage rate. For this analysis, the duct R-values of the supply and return side were changed from R-8 for the supply duct and R-4 for the return duct (which is the base case) to R-12 for the supply duct and the return duct in increments of 2 for 4 different climate zones. For the simulations, the different levels of the duct R-value and duct leakages were simulated from 0 % to 20 % in increments of 5%. Since the 2001 IECC does not define the duct leakages, the duct leakage for the base-case house was set at 0%. Duct systems were located in the attic space where it was unconditioned. Table 2 shows the simulation plan of variations in the duct insulation levels and duct leakages of the different climate zones for the analysis.

Table 2. Simulation Plans for Duct Insulation Level and Leakage

Location	Duct R-value		Duct Leakage (%)				
	Supply	Return					
Climate zone 9	**8**	**4**	**0**	5	10	15	20
	6	6	**0**	5	10	15	20
	8	8	**0**	5	10	15	20
	10	10	**0**	5	10	15	20
	12	12	**0**	5	10	15	20
Climate zone 5	**8**	**4**	**0**	5	10	15	20
	6	6	**0**	5	10	15	20
	10	10	**0**	5	10	15	20
	8	8	**0**	5	10	15	20
	12	12	**0**	5	10	15	20
Climate zone 4	**8**	**4**	**0**	5	10	15	20
	6	6	**0**	5	10	15	20
	10	10	**0**	5	10	15	20
	8	8	**0**	5	10	15	20
	12	12	**0**	5	10	15	20
Climate zone 2	**8**	**4**	**0**	5	10	15	20
	6	6	**0**	5	10	15	20
	8	8	**0**	5	10	15	20
	10	10	**0**	5	10	15	20
	12	12	**0**	5	10	15	20

*Base case simulations (Bold and Underline) is R-8 for supply duct, R-4 for return duct and 0% duct leakage.

The Locations of the HVAC Systems

Table 3 shows the simulation plans for the analysis of the locations of the HVAC system. Simulations were performed for the different locations (i.e., the attic space (unconditioned space) and the conditioned space) of the HVAC systems which were provided by the current simulation input file. Duct leakage rates were changed from 0% to 20% in increments of 5% for both locations, including the attic and conditioned space. For the system efficiency, a 10 SEER air conditioner and a 78% AFUE for the gas furnace (base case) were used for the simulation.

Table 3. Simulation Plan for the Location of the HVAC System

Location	Air conditioner	Gas furnace	Duct leakage (%)					Location
	SEER	AFUE (%)						
Climate zone 9	**10** (Base case)	**78** (Base case)	**0**	5	10	15	20	**Attic space**
			0	5	10	15	20	Conditioned space
Climate zone 5			**0**	5	10	15	20	**Attic space**
			0	5	10	15	20	Conditioned space
Climate zone 4			**0**	5	10	15	20	**Attic space**
			0	5	10	15	20	Conditioned space
Climate zone 2			**0**	5	10	15	20	**Attic space**
			0	5	10	15	20	Conditioned space

*Base case simulations (Bold and Underline) is SEER 10 for air conditioner, 78% for gar furnace, 10% duct leakage and HVAC systems in the attic space.

RESULTS

The simulation conditions of the base-case house were altered individually in combination with other factors. For this analysis, different values were assigned to the parameters of the DOE-2 input that represent the characteristics of the building systems and components. The simulations were performed in four different climate zones (climate zones 9, 5, 4 and 2). In order to investigate the impacts of the annual energy use, the Building Energy Performance Summary (BEPS) of the DOE-2 output was used to determine the values of those parameters that resulted in energy savings, when applied individually and in combination. The annual energy results consisted of four categories: 1) an annual other category which included lighting, equipment, etc., 2) the annual DHW (Domestic Hot Water) energy use, 3) the annual heating use and 4) the annual cooling use. Using DOE-2's BEPS output, the heating, cooling and total energy differences were calculated and plotted according to each climate zone.

The results are shown as annual energy use plots and energy savings plots, according to the different climate zones. In order to present the results of the simulations, stacked bar charts were used to plot the annual energy use for the different values of the parameters and the climate zones (Figures 8 to 12).

Analysis of the Duct Properties

In order to find the savings achieved from the duct properties, the annual energy use was plotted by changing the R-value for the supply and return side, and the duct leakage rate. The other properties were the same as in the base-case house. For the base-case house, the insulation level for the supply duct was R-8 and the return duct was R-4. Furthermore, since the 2001 IECC does not define the duct leakage rate, the duct leakage rate for the base-case house was set at 0%, and the duct systems were located in the attic space where it was unconditioned. From these simulation results, the following traits were observed:

1) The duct leakage rate affected the cooling and heating energy savings more than different levels of duct insulation did.
2) There were more variations in cooling energy in hot climate zones, while more heating energy variations were detected in cold climate zones.
3) Changes for the duct insulation levels from R-8 for the supply side and R-4 for the return side to R-6 for the supply and return sides with the same duct leakage rates produced negative effects for the total, heating, and cooling energy consumptions. Other improvements in duct insulation (from R-8 for the supply and R-4 for the return to R-8 for both the supply and return, R-10 for the supply and return and R-12 for the supply and return) produced total, heating, and cooling energy savings for ducts located in the attic. Table 4 shows the summary of the simulation results of the duct properties (mBtu/year) from Figures 8 to 12.

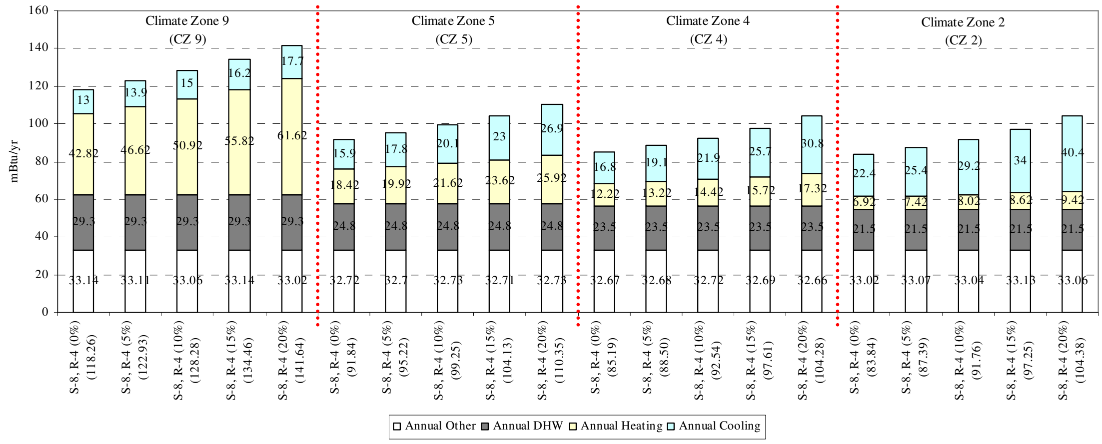

Figure 8. Annual Energy Use of SR (Supply Duct R-value)-8 and RR (Return Duct R-value)-4 According to the Duct Leakage Rate

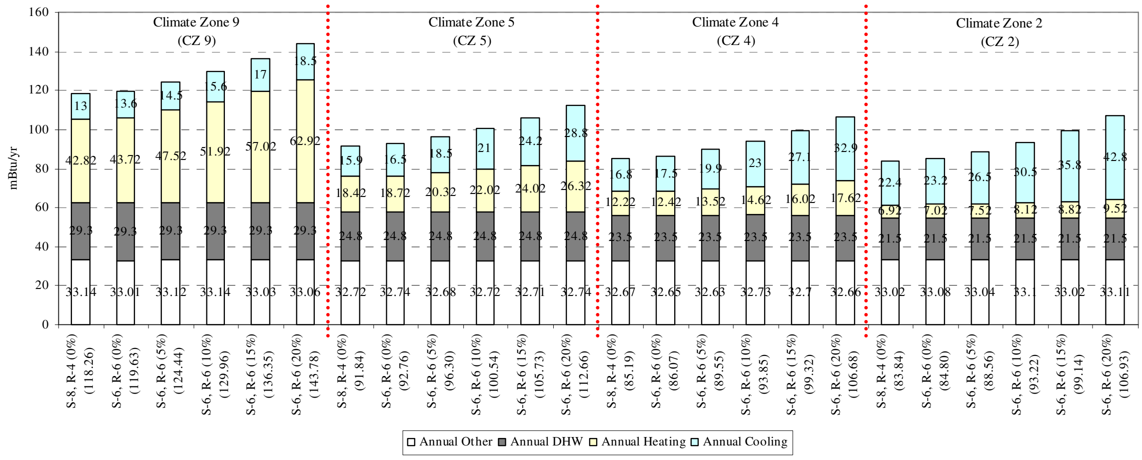

Figure 9. Annual Energy Use of SR-6 and RR-6 vs. SR-8 and RR-4 According to the Duct Leakage Rate

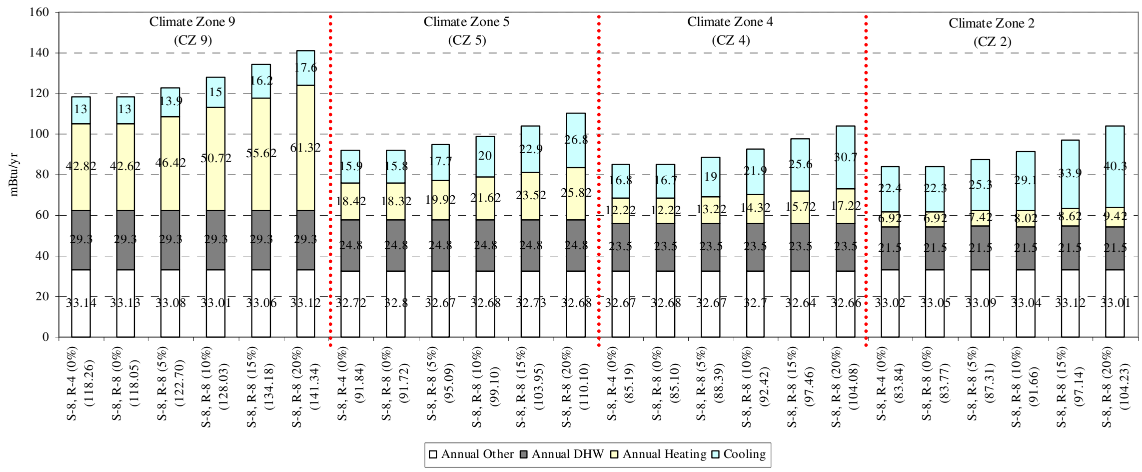

Figure 10. Annual Energy Use of SR-8 and RR-8 vs. SR-8 and RR-4 According to the Duct Leakage Rate

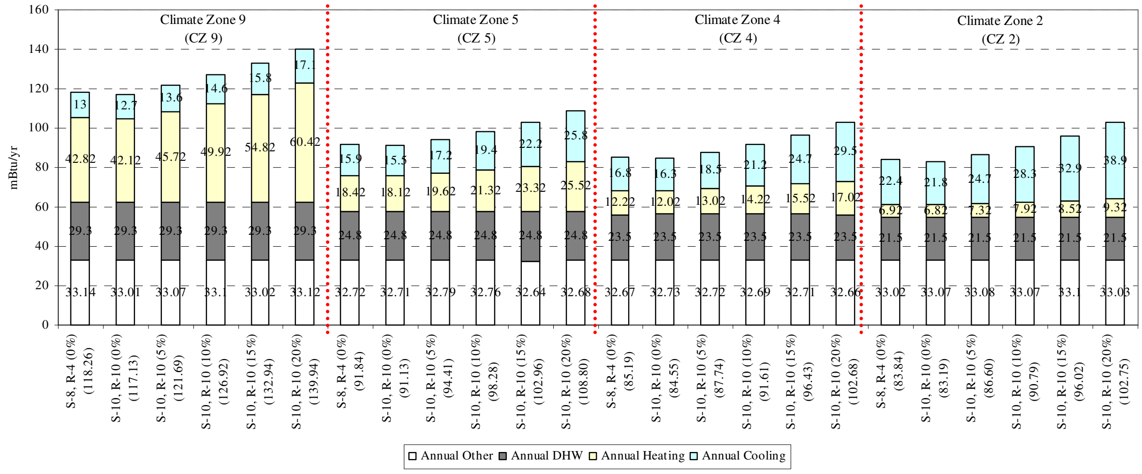

Figure 11. Annual Energy Use of SR-10 and RR-10 vs. SR-8 and RR-4 According to the Duct Leakage rate

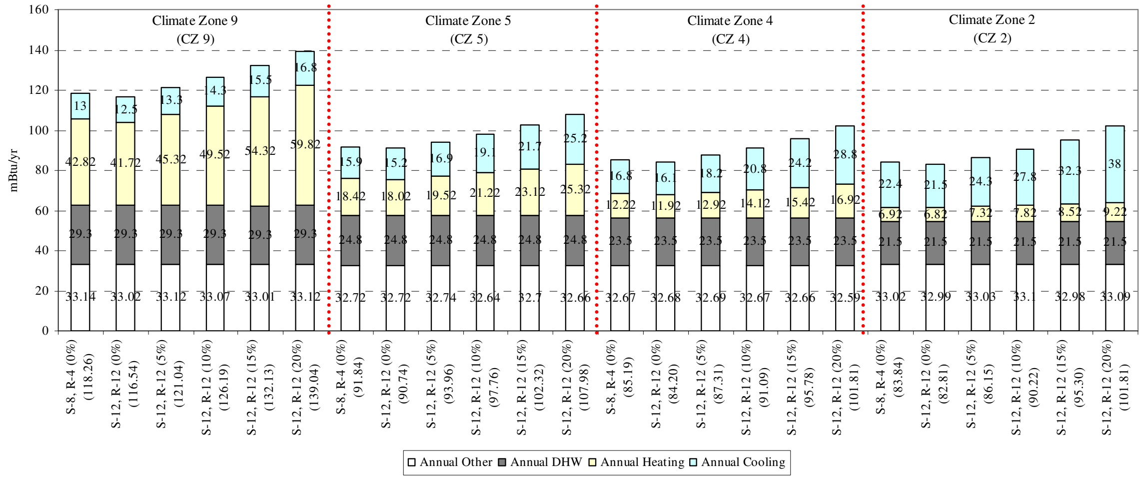

Figure 12. Annual Energy Use of SR-12 and RR-12 vs. SR-8 and RR-4 According to the Duct Leakage Rate

Table 4. Summary of the Simulation Results of the Duct Properties (mBtu/year)

	Climate Zone 9					Climate Zone 5				
	0%	5%	10%	15%	20%	0%	5%	10%	15%	20%
SR-8, RR-4	118.26	122.93	128.28	134.46	141.64	91.84	95.22	99.25	104.13	110.35
SR-6, RR-6	119.63	124.44	129.66	136.35	143.78	92.76	96.30	100.54	105.73	112.66
SR-8, RR-8	118.05	122.70	128.03	134.18	141.34	91.72	95.09	99.10	103.95	110.10
SR-10, RR-10	117.13	121.69	126.92	132.94	139.94	91.13	94.41	98.28	102.96	108.80
SR-12, RR-12	116.54	121.04	126.19	132.13	139.04	90.74	93.96	97.76	102.32	107.98

	Climate Zone 4					Climate Zone 2				
	0%	5%	10%	15%	20%	0%	5%	10%	15%	20%
SR-8, RR-4	85.19	88.50	92.54	97.61	104.28	83.84	87.39	91.76	97.25	104.38
SR-6, RR-6	86.07	89.55	93.85	99.32	106.68	84.80	88.56	93.22	99.14	106.93
SR-8, RR-8	85.10	88.39	92.42	97.46	104.08	83.77	87.31	91.66	97.14	104.23
SR-10, RR-10	84.55	87.74	91.61	96.43	102.68	83.19	86.60	90.79	96.02	102.75
SR-12, RR-12	84.20	87.31	91.09	95.78	101.81	82.81	86.15	90.22	95.30	101.81

Analysis of the Location of the HVAC Systems

In an attempt to evaluate the effects of placing the ducts in the conditioned space as opposed to the attic space, the duct leakage rates varied from 0% to 20% for those HVAC systems located in the attic space and as well as in the conditioned space.

The following show the annual total, heating, and cooling energy use by placing the duct in the unconditioned and conditioned space and by changing the duct leakage rate from 0% to 20% in increments of 5%. The other properties remained the same as in the base-case house. Both energy uses in the attic space and the conditioned space with the same duct leakage rate were compared in order to investigate the energy use difference between the attic space and the conditioned space. Figure 13 shows the results based on the location of the HVAC systems

The following are detailed explanations of the results obtained according to the duct locations and the duct leakage rate in each of the simulations. It was found that climate zone 9 produced the highest total energy savings and heating energy savings, and climate zone 5 produced the highest cooling energy savings. According to the IECC Chapter 402.1.3.9, the heating/cooling system efficiency should be proportionately adjusted for portions of the ductwork located outside or inside the conditioned space. Also, if the duct system was relocated from unconditioned space to conditioned space, there could be 20% savings for the heating and cooling energy. From this analysis, it was found that there were savings variations from 1.54% to 18.59% for the cooling system, and from 1.45% to 15.90% for the heating system depending on the amount of the duct leakage rates and the climate zones.

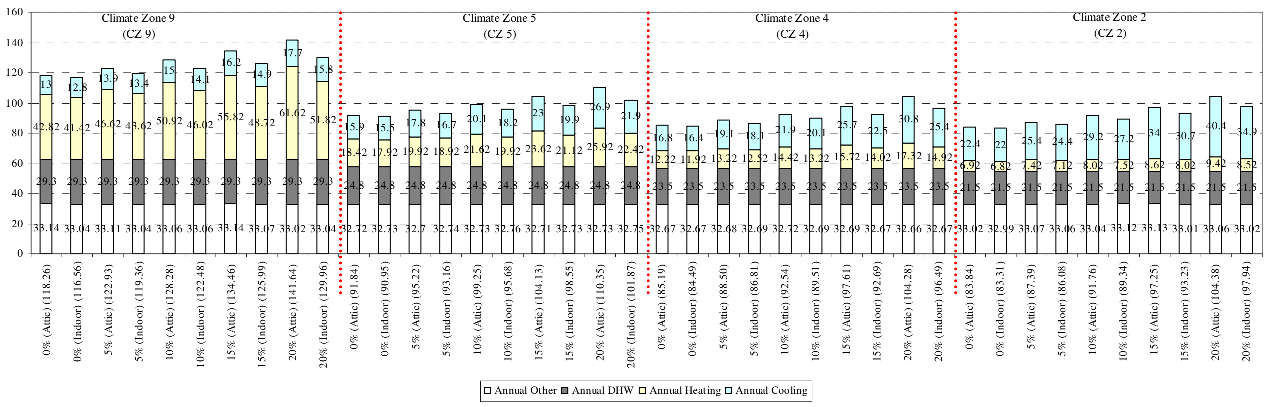

Figure 13. Annual Energy Use According to the Locations of the HVAC Systems

DISCUSSION

Duct leakage rates were found to be a significantly important factor in increasing energy consumption in unconditioned space. Thus, sealing or repairing leaky ducts could immensely reduce energy consumption in all climate zones. Changing the locations of duct systems from unconditioned spaces to conditioned spaces also has a significant effect on energy savings. Currently, most of the duct systems in Texas are located in unconditioned spaces (i.e., the attic space). Therefore, relocating these duct systems to conditioned spaces needs to be considered for possible energy savings when designing residential houses.

Furthermore, the results from the different duct locations (conditioned space vs. unconditioned space) and varying duct leakage rates showed that

there could be a difference from 1.54% to 18.59% in saving varying by climate zone and duct leakage rates when changing the duct location from unconditioned space to conditioned space. Therefore, it is recommended that the new version of the IECC considers various system adjustment factors when changing duct locations according to climate zone and duct leakage rate.

ACKNOWLEDGEMENT

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