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A Comprehensive Yardstick for Residential Thermal Distribution Efficiency

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A Comprehensive Yardstick for Residential Thermal Distribution Efficiency

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1. SYNOPSIS

This paper describes a framework for a figure of merit by which the energy performance of thermal energy distribution systems (e.g., duct systems) in residences could be characterized. The proposed figure of merit is designed to be incorporated into design guides, state energy codes and/or utility DSM programs.

2. ABSTRACT

Thermal Energy Distribution (TED) systems provide the critical link between heating and cooling equipment and the conditioned areas of buildings. TED systems have also been shown to have a large potential for efficiency improvement, particularly in residences. This paper discusses the issues associated with characterizing the performance of TED systems in residential buildings. A possible framework for a universal figure of merit for residential TED systems that takes into account interactions between the TED system and the building envelope, interactions with the heating/cooling equipment, as well as the weather-dependence of TED efficiencies, is proposed. The proposed efficiency characterization framework incorporates the TED/envelope interactions that have been extensively studied in crawlspace and slab-on-grade houses over the past several years, as well as some of the findings of ASHRAE Special Project 43 (SP43), which focused on air distribution systems in basement houses. This framework is designed to allow for compatibility with existing equipment and envelope characterizations (e.g., Annual Fuel Use Efficiency (AFUE), Seasonal Energy Efficiency Ratio (SEER), Heating Seasonal Performance Factor (HSPF), Effective Leakage Area (ELA)), and to allow for comparison of forced-air, hydronic and refrigerant distribution systems, including the impacts of zoning. The proposed backbone for most of the supporting analyses required to develop a practical yardstick is a combined simulation model based upon DOE-2, COMIS (a multi-zone airflow network model) and a combined heat and mass transfer model for duct systems. Efficiency calculations made with this model for a typical attic duct system are included as an example. Two applications identified for this figure of merit are utility DSM programs and building energy codes.

3. INTRODUCTION

Thermal Energy Distribution (TED) systems are the critical link between heating and cooling equipment and the conditioned areas of buildings. Moreover, research over the past two decades in residential buildings has shown that the energy losses and inefficiencies associated with the most common residential distribution system, central forced-air, are often unacceptably large (Cummings and Tooley 1989, Cummings et. al. 1990, Modera 1989, Modera et. al. 1991, Parker 1989, Robison and Lambert 1989). The results of this research, combined with the fact that there aren't any significant technical barriers to installing efficient forced-air distribution systems, suggest that that the reasons for poor performance may be: (1) a lack of widespread knowledge, and (2) a lack of tangible incentives for better performance. Research results obtained in the past five years have received enough dissemination that the energy implications of faulty forced-air distribution systems are becoming fairly widely known. This paper attempts to address the second hypothesized barrier to high-efficiency thermal distribution. It represents a proposed preliminary step towards the development of tangible incentives for improved thermal energy distribution systems for residences. More specifically, we describe a potential framework for characterizing TED efficiency for residential buildings that takes into account interactions between the TED system and the building envelope, interactions with the heating/cooling equipment, as well as the weather dependence of TED efficiencies. Some potential means for implementing the proposed efficiency characterization algorithms are also discussed, and an example efficiency analysis is presented.

4. EFFICIENCY CHARACTERIZATION ISSUES

One of the key impediments to the development of an efficiency characterization for thermal distribution systems has been the degree of interaction between these systems, the heating/cooling equipment to which they are connected, and the building envelope. We shall divide these interactions into three types: (1) interactions with heating/cooling equipment performance, (2) interactions with the building envelope when the fan is on, and (3) interactions with the envelope when the fan is off. In addition to these interactive effects, non-interactive system-location, climate and mixed-fuel issues associated with thermal distribution efficiency also need to be addressed.

4.1. Heating/Cooling Equipment Interactions

One of the key issues in characterizing the efficiency of thermal energy distribution systems is to account for the interactions between the thermal distribution system and the central heating and cooling equipment. These interactions, which are summarized in Table 1, go in both directions: (1) impacts of the heating/cooling equipment characteristics on the performance of the distribution system, and (2) impacts of the distribution system on the efficiency of the heating/cooling equipment.

Table 1:	Thermal Distribution Interactions with Heating/Cooling Equipment
•	Dependence of TED Efficiency on Equipment Type, Sizing, Operating Mode (Heating/Cooling).
•	System Cycling Interactions
•	Impacts of Fluid Transport Temperature/Medium on Equipment Heat Exchanger and Efficiency
•	Impacts of Variable Capacity Equipment and Fans

The principal impact of the heating/cooling equipment on TED performance is embodied in the temperature (and moisture content for forced-air cooling) of the distribution medium (air, water, refrigerant) entering the supply side of the distribution system. The energy transferred to/from surrounding zones by conduction or leakage on the supply side of the distribution system varies with this temperature (or enthalpy) and therefore with the heating/cooling capacity of the equipment to which it is connected. However, if the thermal efficiency of the distribution system is defined as the ratio of the energy delivered to the conditioned zone divided by the energy supplied to the distribution system by the heating/cooling equipment, the thermal efficiency generally increases as the capacity of the heating/cooling equipment connected to that distribution system is increased. More specifically, for a fixed distribution-medium flowrate, the temperature differential between the distribution system and its surroundings, and therefore the losses, do not increase proportionately with increases in equipment capacity. Although this may seem somewhat counter-intuitive, it can be understood by noting that the supply-side temperature differential to the surroundings is made up of the sum of the temperature differential between the inlet and outlet of the heating/cooling equipment (i.e. the capacity), and the temperature differential between the conditioned zone and the zone through which the distribution system passes, which is independent of the capacity. In addition, the reduction in energy delivered due to conduction or leakage on the return side is essentially independent of the capacity of the equipment. It should be noted however that the integrated off-cycle distribution-system losses will increase with equipment capacity, due to shorter fractional on times (see below).

Another impact of equipment characteristics on TED efficiency is the impact of system capacity and thermostat characteristics on system cycling, and thus on the cycling losses associated with the thermal mass of the distribution system. More specifically, for an air system, the energy lost due to storage within the thermal mass of the ducts depends on the number of cycles per unit time associated with each part-load ratio (normally characterized by the number of cycles at 50% load ratio), on the total thermal mass of the ducts and plenum, and on the fan overrun associated with each cycle. It should be noted that the losses associated with each cycle is not constant, but rather depends on the relationship between the time constant of the duct system, and the length of time between on-cycles. Fan overrun has the effect of recapturing some of the energy stored in ductwork, at the expense of fan power and longer periods of heat exchange between house air and the duct surroundings. A hydronic system has a large thermal mass compared to an air system, and therefore a very different cycling behavior, which must be accounted for in any efficiency characterization.

There are two principal impacts of thermal distribution systems on the performance of standard heating/cooling equipment: (1) they modify equipment efficiency by changing the heat transfer at the heat exchanger, and (2) they modify equipment efficiency as a result of their impact on the effective capacity (i.e., delivered energy capacity) of the equipment and thus the part-load inefficiencies. Concerning the former, better heat transfer at the heat exchanger obviously increases the efficiency of the equipment, however it should be noted that increasing heat transfer by increasing the fan size/speed has fan energy impacts, and may increase leakage due to higher pressure differentials. On the other hand, drawing in cold attic air with a leaky return duct will generally increase heating-equipment efficiency. It should be noted that this is not the case for an electric furnace, whose efficiency is essentially independent of the conditions of the return air. The only impact of return-air conditions on an electric furnace is that without fan overrun, the energy stored in the coil, and therefore the cycling loss, will be greater when the coil runs hotter.

Concerning the second impact of distribution systems on equipment performance, the effective capacity reduction associated with an inefficient distribution system is similar to an increase in load. This effective increase in load translates into higher part-load ratios, and therefore improved equipment performance relative to a 100% efficient distribution system. Thus, for a given house, improvements in distribution efficiency have a similar impact on equipment performance as would load reductions resulting from improvements to the building shell.

Concerning the impacts of variable heating or cooling capacity on distribution-system performance, modulating the capacity of the equipment (i.e., reducing the heating/cooling capacity during part-load conditions) is likely to reduce distribution efficiency (see discussion above). The impacts of modulating fan/pump flow in addition to modulating thermal capacity are more complex. Modulating fan/pump flow will tend to: (1) decrease equipment efficiency due to reduced heat transfer relative to full flow (not applicable to electric resistance elements), (2) decrease fan/pump energy consumption (and leakage in air systems due to reduced pressure differentials), and (3) increase conduction losses. Thus the overall impact of fan/pump flow modulation (or fan/pump flow in general) depends on the leakage/conduction characteristics of duct systems, as well as on the sensitivity of the equipment efficiency to changes in flowrate.

4.2. Envelope Interactions During Operation

Another key issue in characterizing the efficiency of thermal energy distribution systems is to account for the interactions between the thermal distribution system and the envelope of the building. These interactions are summarized in Table 2.

Table 2:	Thermal Distribution Interactions with the Building Envelope During System Operation
•	Impacts of Duct Leakage on Infiltration Rates and Locations
•	Impacts of Imbalanced Air Flows on Infiltration Rates and Locations
•	Impacts of Leakage/Conduction Losses to Unconditioned Spaces (i.e., basements, attics, crawlspaces, garages)
•	Impacts of Zoning on Envelope and Internal Wall Design
•	Impact of Radiant/Convective Split on Thermostat Setpoints

As has been cited in the literature (Cummings et. al. 1990, Modera 1991), air distribution systems tend to have large impacts on residential air exchange rates, which can be seen as an interaction between the distribution system and the building envelope. The two mechanisms for these exchange-rate impacts are: (1) leakage rates between the ducts and their unconditioned surroundings and any associated pressure differentials across the shell, and (2) the creation of of pressure differentials across the building shell by fan operation when the internal doors are closed. Concerning the former, leakage between ducts and their unconditioned surroundings can be accounted for in the definition of duct efficiency without taking into account the envelope of the building. However, as leakage flows on the return side of the duct system tend to pressurize the house, and leakage flows on the supply side tend to depressurize the house, any difference in magnitude between these two flows creates pressure differentials across the building shell, resulting either in increased exfiltration or infiltration through the envelope. The second air-exchange impact of air distribution systems does not stem from duct leakage, and can occur even when the duct system is located entirely within the conditioned space. As a large fraction of residential duct systems have multiple supply registers but only one or two returns, significant pressure differentials are often created whenever internal doors are closed during fan operation. These pressures result from the fact that for standard system flowrates the undercuts on internal doors cannot practically be made large enough to pass the supply air from one zone to an adjacent zone's return without incurring a significant pressure drop.

Another interaction between distribution systems that pass through buffer zones (e.g., attics, crawlspaces, basements and garages) is the change in building conduction load resulting from partial conditioning of buffer zones by distribution-system energy exchange. The magnitude of this effect depends on the relationship between the thermal resistance between the buffer zone and the house, and the thermal resistance between the buffer zone and the outdoors. The size of this impact is generally small for vented crawl-spaces and attics, but can be substantial for basements.

As the capability for zoning is generally considered an attribute of the distribution system, it should also be noted that the energy effectiveness of zoning is dependent both on the design of the distribution system, and on the design of the building shell and interior passageways. Moreover, the efficiency of a distribution system can be strongly dependent on whether or not it is used for zoning.

Finally, the distribution system can impact the thermostat settings needed to assure thermal comfort. More specifically, the distribution system can affect: (1) the degree of room-air motion, (2) the degree of thermal stratification within rooms and between stories, (3) the uniformity of thermal conditions from room to room, and (4) the differential between the mean radiant temperature and the air temperature. As examples, the location of return and supply grilles affects the degree of thermal stratification, the airflow design and balancing of a duct system affects the temperature variability between zones, and a radiant heating or cooling system affects the differential between mean radiant and air temperature. These effects should probably be included in the load modification components of distribution-system efficiency (however they are not yet incorporated in the figure of merit proposed below).

4.3. Off-Cycle Envelope Interactions

In addition to the interactions between the thermal distribution system and the building envelope during system operation, there are several impacts that the distribution system can have on building loads when it is not in operation, some of which are summarized in Table 3.

Table 3:	Thermal Distribution Interactions with Building Envelope During Off-Cycle Periods
•	Impacts of Duct Leakage on Infiltration Rate (including changes in neutral level)
•	Impacts of Continuous Fan Operation on Infiltration and Conduction Losses
•	Thermal Bridge/Thermal Siphon Effects Poorly Insulated Ducts in Unconditioned Spaces
•	Hydronic-System Losses During Off-Cycle Periods

Duct system leaks have an important impact on the building envelope even when the conditioning equipment and fan are not operating. A number of studies have shown that duct leaks in attics and crawlspaces represent roughly 10-20% of the overall leakage of the envelope, which implies that roughly 10-20% of the infiltration load of the building should be attributed to the distribution system, even when it is not in operation (Modera 1986, Cummings et. al. 1990, Modera et. al. 1991). These figures might be somewhat on the conservative side, as ducts tend to be located at one or both of the height extremes of the conditioned zone, which implies a larger than proportional impact on infiltration.

Some duct-system fans are run continuously when the heating and cooling equipment are not in use. This type of operation results in significant heat exchange through both conduction and leakage when ducts pass through unconditioned spaces, and potential infiltration rate increases when internal doors are closed (whether or not the ducts pass through unconditioned spaces).

Even if a duct system is completely air-tight, bouyancy-induced air flows can create a thermal bridge between the conditioned zones of the building and the buffer zones. The magnitude of this effect depends on the system geometry, as well as on the degree of insulation of the duct system.

Due to their substantial time constants, hydronic distribution systems continue to exchange energy with their surroundings even when the heating/cooling equipment is not in operation. These losses can change the building conduction load as a result of partial conditioning of buffer zones by distribution-system energy exchange, particularly for basement installations.

4.4. Non-Interactive Characterization Issues

In addition to the interactions with building equipment and envelopes, a number of other basic issues need to be addressed in the development of a figure of merit for thermal distribution efficiency. Some of the key issues a summarized in Table 4.

Table 4:	Non-Interactive TED Efficiency Characterization Issues
•	Algorithm for Combining Thermal and Fan/Pump Energy
•	TED System Location Impacts
•	Temporal (e.g. Weather) Variations in Efficiency
•	Climate Impacts

Although it is a much more significant factor in commercial buildings, the fan or pump energy required to transport the thermal energy cannot be ignored, even in residential systems. In general, the study of frictional losses and flow design in both air and water systems has received considerable attention, and will not be treated in any significant detail in what follows. However, as there are trade-offs between transport energy requirements and thermal performance, and the costs and primary energy implications of electricity are significantly different than those for gas, transport energy needs to be incorporated into the distribution efficiency equation.

Another issue that has been made evident by various measurement and modeling studies of air distribution systems is that their location has a dramatic impact on their efficiency (Modera 1991). Perhaps the most obvious instance is the location of the return duct in crawlspace houses during the summer. As a disproportionately large fraction of duct leakage is typically found on the return side, and returns are depressurized, they often draw in large quantities of air from the unconditioned zones in which they are located. Thus, as the temperature differential between the crawlspace and the house is in many instances very small during cooling periods, whereas the attic is typically 10-20°C hotter than the house during those periods, simulations have shown average distribution-efficiency differentials between the two locations to be on the order of 15-20 percentage points.

As was noted relative to location effects on distribution efficiency, it is clear that the temperatures in the zones through which the system passes should have a significant impact on the distribution efficiency. Thus, as the conditions in those zones are often closely tied to outdoor weather conditions, it is clear that the efficiency of a given distribution system in a given house will change over the course of the year. The degree of variability has been demonstrated to be large with simulations, as has the fact that these efficiencies are typically lowest under the highest energy load conditions (Modera 1991). These results make it clear that the seasonal efficiency of a distribution system is also climate dependent.

5. PROPOSED CHARACTERIZATION FRAMEWORK

The proposed efficiency characterization framework attempts to incorporate the TED/envelope interactions that have been extensively studied in crawlspace and slab-on-grade houses over the past several years, as well as a number of TED/equipment interactions, into a universal figure of merit for comparing alternative thermal distribution systems in residences. The chosen formalism is similar in many ways to that incorporated into Chapter 24 of the ASHRAE Equipment Handbook (ASHRAE 1988). The handbook chapter is based principally upon the results of the ASHRAE SP43 project, which focused on the interactions between forced-air systems and furnaces in basement houses (Jakob et. al. 1986, Locklin et. al. 1986). There are however a number of key differences between the proposed figure of merit and the existing ASHRAE model which are worth pointing out in advance. The figure of merit proposed in this paper:

- Focuses specifically on the thermal distribution system and its different applications, including forced-air air-conditioning and heat-pump systems, boilers/hydronic distribution, and refrigerant distribution, as well as forced-air furnace systems.
- Should be able to interface directly with existing yardsticks for heating and cooling equipment (e.g., steady state efficiency or Annual Fuel Use Efficiency (AFUE) for furnaces, Energy Efficiency Ratio (EER) or Seasonal Energy Efficiency Ratio (SEER) for air conditioners, Coefficient of Performance (COP) or Heating Seasonal Performance Factor (HSPF) for heat pumps),
- Includes more building-envelope interactions, such as infiltration due to external duct leakage and thermal siphon effects during off-cycle periods, as well as the impact of variability in envelope leakage.
- Includes more detail and flexibility in the treatment of return ducting, such as directly taking into account the enthalpy of leaks into return ducts, envelope pressurization and depressurization due to inadequate return-air pathways (i.e., single returns with closed internal doors), and envelope pressurization or depressurization due to imbalanced supply and return leakage.

The proposed figure of merit does not require the use of a specific program to evaluate distribution-system performance, but rather focuses on characterizing performance by means of simplified algorithms and a specified set of descriptive parameters. These descriptive parameters can be obtained from established system properties, from measurements, or from default values based upon the literature.

The proposed distribution efficiency characterization process can be divided into five steps:

(1) Definition of the overall, nominal and thermal distribution system efficiencies,

(2) Incorporation of equipment and envelope interactions,

(3) Specification of base-case building/equipment/distribution systems,

(4) Incorporation of climate and weather variability into seasonal average figures of merit, and

(5) Compilation of alternative techniques for making efficiency calculations for any given distribution system.

This paper addresses the first two steps, and briefly discusses the remaining three steps.

5.1. Overall Distribution System Efficiency

The basic definition proposed for thermal distribution system efficiency is the ratio of the energy that would be consumed by a house using a given piece of heating or cooling equipment, to the energy consumed by that house when that heating/cooling equipment is connected to the thermal distribution system in question:

$$\eta_{dist} = \frac{E_{no-dist}}{E_{dist}} \tag{1}$$

Using Equation (1) as the definition for distribution-system efficiency has several ramifications: (1) all interactions are implicitly included, implying that some means would have to be devised for quantifying and/or separating those interactions, (2) characteristics such as zoning could be included either in the numerator and denominator, or in the numerator only, and (3) the energy consumption quoted could be an instantaneous value during system operation, or a seasonal value. In practice, the ratio in Equation (1) could be obtained by simulating the house with and without the system installed. However, such a simulation would have to take into account all of the interactions. As there are very few such simulation tools available, and those available are geared strictly towards researchers, requiring detailed simulations to characterize distribution efficiency is not practical. The suggested characterization scheme is to separate out several factors contributing to the final ratio in Equation (1). If the energy use terms in Equation (1) are defined as:

$$E = \frac{L}{\eta_{nominal}\eta_{equip}} \tag{2}$$

where:

L is the heating or cooling load (where cooling loads are defined to be negative),

$\eta_{nominal}$ is the nominal distribution system efficiency, defined as the thermal efficiency of the distribution system corrected for energy consumed and delivered by the transport motor (fan or pump), and

η_{equip} is the efficiency of the heating or cooling equipment (where cooling efficiency is a negative number, as energy input to the cooling equipment serves to remove energy from the house).

then the overall distribution system efficiency becomes:

$$\eta_{dist} = \eta_{nominal}\left(\frac{\eta_{equip_{dist}}}{\eta_{equip_{no-dist}}}\right)\left(\frac{L_{no-dist}}{L_{dist}}\right) \tag{3}$$

as the nominal distribution efficiency is by definition equal to 1.0 when no distribution system is connected.

Equation (3) separates the distribution-system impacts into three parts: (1) the nominal distribution-system efficiency, (2) an equipment-efficiency correction factor, which accounts for any changes in the heating/cooling equipment efficiency due to the addition of the particular distribution system, and (3) a load modification factor, which takes into account any changes in the building heating or cooling load due to the addition of the distribution system (similar to the combination of the Miscellaneous Gain Factor, F_{MG}, and Load Modification Factor, F_{LM}, in Chapter 24 of the 1988 ASHRAE Handbook of

Fundamentals).

The nominal distribution efficiency depends on the thermal efficiency of the distribution system, and on the energy consumed to transport the distribution medium (i.e., fluid). The conceptual definition for the distribution-system thermal efficiency is the intuitive definition of distribution-system efficiency, and is analogous to that for Duct Efficiency, E_D, in the ASHRAE Handbook - the ratio of the heating/cooling provided to the conditioned space, to the heating/cooling supplied to the distribution medium. The simplified equation associated with our definition of thermal efficiency explicitly disaggregates four causes of inefficiency, includes the recovered fan or pump energy, and includes the energy lost due to distribution system cycling. The four inefficiencies taken into account are: (1) supply leakage, (2) return leakage, (3) supply conduction, and (4) return conduction. The resulting definition for distribution-system thermal efficiency is:

$$\eta_{thermal} = 1 - \frac{UA_{sup}(\overline{T}_{sup} - T_{sup\text{-}sur}) - \dot{m}_{sup\text{-}leak}(h_{house} - h_{sup})}{E_{equip} + E_{trans}R_{recovery}}$$

$$- \frac{UA_{ret}(\overline{T}_{ret} - T_{ret-sur}) + \dot{\overline{m}}_{ret-leak}(h_{house} - h_{ret-sur})}{E_{equip} + E_{trans}R_{recovery}}$$

$$- \frac{nQ_{storage}}{E_{equip} + E_{trans}R_{recovery}} \qquad (4)$$

where:

$\eta_{thermal}$ is the ratio of the heating/cooling delivered to the space, divided by that delivered to the distribution system,

E_{equip} is the energy delivered to the distribution medium by the heating/cooling equipment (negative for cooling), excluding any fan or pump heating,

E_{trans} is the energy consumed to transport the distribution medium,

$R_{recovery}$ is the fraction of the transport energy that is recovered by the distribution medium,

UA is the overall distribution-system conductance to its surroundings,

T is the spatially averaged distribution-medium or surrounding-zone temperature,

$\dot{m}$ is the mass flow of air,

h is air enthalpy,

n is the number of heating/cooling cycles within the period under consideration, and

$Q_{storage}$ is the energy stored in the distribution system that is not recovered over the course of a cycle and is not accounted for in supply and return conduction terms (may decrease at higher cycling rates).

The distribution-system thermal efficiency, as defined by Equation (4), is a function of: (1) physical parameters describing the distribution system (leakage rates, UA values, recovery of transport energy consumption), (2) the capacity of the equipment to which is is connected, and (3) the house and climate in which it is installed (which affect the surrounding zone temperatures). The means by which one can obtain these parameters depends upon the particular situation to which the equation is applied, one example of which will be described below. For the simplest application, steady-state operation under specified surrounding-zone temperature conditions, the storage effects can be ignored, and default or measured air leakage rates can be combined with calculated thermal conductances, the rated output of the heating/cooling equipment and the rated input to the transport equipment to calculate an instantaneous steady-state thermal efficiency.

The thermal efficiency can also be computed for a cycle or a season, however this is a more complex procedure. In both these cases the energy output of the heating/cooling cooling equipment would be based on the fractional on-time, and care must be taken in the specification of the transport medium temperatures and integration periods, as well as in accounting for the cycling effects. In general, off-cycle effects that do not depend on the operation of the system, such as the impact of duct leakage on natural infiltration rates, would not be included in the nominal distribution efficiency, whereas effects such as the fan or pump energy recovered and the thermal losses associated with fan over-run would be included. Similarly, the conduction losses of the pipes and the energy consumed by the pump during off-cycle periods would be included in the nominal efficiency for a hydronic distribution system.

The nominal distribution-system efficiency is designed to account for the energy consumption of the fan or pump, so as reflect the complete non-interactive impact of the distribution system.

$$\eta_{nominal} = \frac{\eta_{thermal}\, L}{L - E_{trans}\,\eta_{thermal}\,(R_{recovery} - \eta_{equip})} \tag{5}$$

where:

η_{equip} is the efficiency of the heating or cooling equipment.

Several points merit some discussion relative to Equation (5). First, it should be noted that most of the standard efficiency yardsticks for air conditioners and heat pumps already include fan energy consumption and heat addition, however the standard yardsticks for furnaces typically do not. Second, in the case of heating, increasing the heat recovery from the fan or pump tends to increase the nominal efficiency, whereas the opposite is true for cooling. Third, increasing heating or cooling equipment efficiency tends to increase nominal efficiency, because higher equipment efficiencies imply that a larger fraction of the input energy is going to the fan or pump.

5.2. Equipment and Envelope Factors

The impacts of the thermal distribution system on the heating/cooling equipment are incorporated into the overall distribution efficiency by means of a multiplicative factor. This factor takes into account changes in the efficiency of the heating/cooling equipment due to: (1) changes in the temperature of the entering distribution medium relative to the rated value, (2) heat exchange efficiency modifications due to changes of the distribution medium flowrate relative to the rated value, and (3) changes in the fractional on-time and therefore part-load efficiency of the equipment due to improvements in distribution efficiency. The third factor essentially accounts for the effective increase in capacity associated with improving distribution efficiency, and therefore its use depends on the application. In new-construction applications, it should probably be assumed that the heating/cooling equipment sizing takes into account the distribution efficiency, and therefore the third factor could be neglected. On the other hand, adjustment of oversizing is usually not possible in retrofit applications and therefore the effective increase in capacity associated with improved distribution will tend to reduce overall energy savings.

For steady-state applications, equipment efficiency corrections could be based upon default curves or manufacturers data for COP variations with input wet-bulb temperature for air conditioners, and by several different techniques for furnaces, boilers or heat pumps. On the other hand, when the equipment-efficiency yardstick is a seasonal value (e.g., AFUE or SEER), the cycling characteristics assumed for the distribution-efficiency characterization should be the same as those used for the equipment-efficiency determinations, and the portions of the equipment efficiencies that do not pertain to the energy delivered to the distribution system would need to be properly taken into account. Finally, although it is clearly an equipment/distribution interaction, the cycling issue is also important in the calculation of the nominal distribution efficiency.

The interactions between the thermal distribution system and the building envelope are also incorporated into the overall distribution efficiency by means of a multiplicative factor. This factor, the ratio of the building load with the distribution system installed to that without the system incorporates six effects: (1) any changes in envelope infiltration rate due to the operation of the system, (2) any changes in natural infiltration when the system is not in operation, (3) any changes in the thermal exchange with the buffer zones due to the operation of the system, (4) any changes in the thermal exchange with buffer zones when the system is not in operation, (5) any heating or cooling recovery of losses from the ducts to the conditioned space, and (6) any changes in the required thermostat setting due to the distribution system. A single expression for this factor as a function of the fractional on-time of the heating/cooling equipment is:

$$\left[\frac{L_{no-dist}}{L_{dist}}\right] = \left[\frac{L_{no-dist}}{XL_{dist_{on}} + (1-X)L_{dist_{off}}}\right] \tag{6}$$

where:

$$L_{dist} = L_{no-dist} + \Delta\dot{m}_{inf}(h_{house} - h_{ambient}) + \dot{m}_{thermo\text{-}siphon}(T_{house} - T_{buffer}) + UA_{house}(T_{setpoint_{dist}} - T_{setpoint_{no-dist}})$$

$$- UA_{house\text{-}buffer}(T_{buffer_{dist}} - T_{buffer_{no-dist}}) - Q_{duct-house_{dist}}$$

X is the fractional on-time of the heating/cooling equipment.

Equation (6) is geared towards single-zone conditioning, however the capability for zoning can clearly be treated as a distribution-system attribute. Some public discussion is probably warranted to determine whether $L_{no-dist}$ should be the zoned or unzoned value in Equation (6) when considering multi-zone residential systems.

5.3. Base-Case Building/Equipment/Distribution-System

It should be evident from the text above that the implied base case for evaluating distribution-system alternatives is a house without a distribution system. However, it is also clear that it would be desirable to have some reference efficiencies for typical building/equipment/distribution combinations. Such reference cases can then be used as a baseline for comparing alternative systems, as well as for sensitivity analyses. It is proposed to use existing data on the housing and HVAC stock, new construction sales figures, as well as the results of the field research from the past five years to develop these baseline combinations. Some of the parameters that need to be specified are: (1) return and supply leakage areas (including air handler leakage) and operating pressures, (2) return and supply insulation values (including air handler insulation), (3) attic and crawlspace venting, (4) insulation and leakage levels between the conditioned space and buffer-zone duct locations, (5) the degree of oversizing of the heating/cooling equipment, and (6) the cycling characteristics of the thermostat. It is proposed to use the integrated simulation tool developed by Modera and Jansky (Modera and Jansky 1992), together with representative field data, to simulate baseline distribution-system efficiencies for several house/equipment/system combinations. That simulation tool is based upon DOE-2 (Birdsall et. al. 1990), the COMIS multi-zone airflow network model (Feustel and Raynor-Hoosen 1990), and a combined heat and mass transfer model for the duct system (Modera and Jansky 1992). Input parameters for the simulation tool will be obtained from field studies around the country, and a comparison will be made between the integrated simulation tool and the SP43 model results. Some of the obvious combinations are: (1) attic supply and return ducts with R-4 insulation (plastic flexduct), a single return register, 80 cm^2 of supply leakage and 80 cm^2 of return leakage, connected to a furnace, a heat-pump and an air conditioner, (2) uninsulated sheet-metal supply and return ducts with plenums in an unconditioned basement and half the ducts rising through exterior walls, including two return registers, 80 cm^2 of supply leakage and 80 cm^2 of return leakage, connected to a furnace, a heat-pump and an air conditioner, (3) uninsulated sheet-metal supply and return ducts installed in the space between floors in a two-story house, with specified air and thermal connections between the duct space and the attic/outside, including two return registers, 80 cm^2 of supply leakage and 80 cm^2 of return leakage, connected to a furnace, a heat-pump and an air conditioner, and (4) a hydronic distribution system installed in an unconditioned basement without pipe insulation. [1] For all baseline combinations, the default for the sizing of the heating/cooling equipment and the cycling characteristics of the thermostat should be those values used for the standard equipment efficiency yardsticks (e.g., AFUE, SEER, and HSPF).

5.4. Seasonal Distribution Efficiency for Different Climates

From the equations defining thermal distribution efficiency it is clear that even if all of the physical characteristics of a system are kept constant, the efficiency of that system can be a strong function of the weather (Modera 1991). It is also clear that the efficiency will depend on the characteristics of the house and the heating/cooling equipment. Thus, in order to define a seasonal distribution-system efficiency, the climate, house characteristics and equipment characteristics need to be taken into account.

The basic method proposed for dealing with this variability is to use simplified algorithms such as those presented in Equations (3) through (6) as much as possible, and to perform simulations of the baseline combinations along with suitable perturbations to obtain representative surrounding zone temperatures as well as physically-rigorous mathematical relationships for the interactions between terms. The impact of the weather might then be treated in a bin-like fashion, simply by developing functional relationships between the weather and the buffer-zone conditions for different combinations, and then characterizing each climate by its weather bins. [2] Well-designed simulation-based sensitivity analyses that take into account the interactions of various effects could be used to treat such issues as the impacts of house construction, duct leakage levels and location, insulation levels, duct thermal mass, thermostat characteristics, etc., on each of the three terms making up the distribution-system efficiency. The results of these analyses should provide a simplified procedure for determining the efficiency of any given distribution system from readily available parameters. The simulations could then be used to check the overall performance of the simplified algorithms. In essence, more detailed versions of Equations (3) through (6) would be developed based on first principles, and the simulations would be used: (1) to check for interactions that are not already explicit, (2) to provide temperature boundary conditions as a function of weather and building type, and (3) to generally verify the range of applicability of the simple algorithms.

The integrated simulation tool developed by Modera and Jansky (Modera and Jansky 1992), together with representative field data, is proposed for developing these functional relationships and interaction factors for the three factors contributing to the overall distribution efficiency as for various distribution-system locations and equipment characteristics. It is also clear that a comparison between this model and the SP43 simulation model should be made, and that field and laboratory measurements would ultimately be needed for verification.

6. CHARACTERIZATION EXAMPLE

The most common type of residential distribution system is a forced-air distribution system connected to a furnace/air-conditioner combination. This system, installed in a crawlspace house according to the first baseline building/equipment/distribution combination described above will be used as an example of how the efficiency characterization process could proceed. The prototype combination is a one-story ranch house with a floor area of 144 m^2 (1540 ft^2), an attic with a gable height of 0.8 m (2.6 ft) and a roof angle of 12°, and a crawlspace of 0.8 m (2.6 ft) height, located in Sacramento California. The central plant consists of a furnace/air conditioner unit, ten supply ducts and one return duct. The furnace/ac unit, as well as the supply plenum and one third of the return duct, are located in the garage. Both the return and supply ducts and plenums are assumed to be insulated to U-values of 1.42 W/m^2K (R-4 English). The supply ducts have a diameter of 0.15 m, and the return duct 0.45 m. The furnace has a heating output capacity of 80,000 Btu/h (23.4 kW) and a nominal heating efficiency heating of 80%. The air conditioner capacity is 36000 Btu/h (10.6 kW), and the cooling coefficient of performance (COP) is 2.93. The insulation values for the building envelope were chosen to describe pre-Title-24 California construction. The exterior walls and the floor are assumed to be uninsulated, and the ceilings are assumed to have a U-value of 0.52 W/m^2K (R-11 English). All windows are single pane, and the total window area is 12% of the floor area, all with a shading coefficient of 0.66. The results of the simulations of this house are summarized in Table 5.

Table 5: Annual Simulation Results for a Ranch House with Attic Ducts in Sacramento

Parameter	Heating	Cooling
$\overline{\eta_{dist}}$	0.73	0.66
$\overline{\eta_{nominal}}$	0.70	0.53
$\eta_{nominal_{min}}$	0.61	0.33
$\eta_{nominal_{max}}$	0.80	0.78
$\left(\frac{\overline{L_{no-dist}}}{\overline{L_{dist}}}\right)$	1.04	1.05
$\left(\frac{\overline{\eta_{equip_{dist}}}}{\overline{\eta_{equip_{no-dist}}}}\right)$	1.02	1.17

The results in Table 5 indicate that at least for this distribution system, the average nominal distribution efficiency is somewhat higher for heating compared to cooling. Perhaps more importantly, the range of variability is significantly larger for cooling. This can be explained by the fact that the capacity of the heating equipment is significantly larger than that for the cooling equipment, which implies that the overall losses are much more weather dependent for cooling, as weather-dependent losses represent a larger fraction of the total losses for lower capacity systems.

As an example of how the proposed characterization scheme or figure of merit could be implemented, efficiency ratings based on variations of the baseline combination simulated could be treated as follows. Efficiency credits could be given for reduced leakage based upon: (1) agreement to meet the claimed tightness levels by commissioning after installation, or (2) statistically demonstrated proof that the designed system has less leakage than the population mean (e.g., by employment of positive connection seals such as snap-into-place O-ring seals). Efficiency credits could also be given for including low-resistance return-air pathways for when interior doors are closed, for increased duct and plenum insulation, for reduced thermal mass in the ducts and plenum. Efficiency penalties could be given for placing the return filter at the register (which significantly increases the pressures across the return leaks), or for using more massive supply and return plenums. The magnitudes of these credits or penalties would be determined by substituting the changes into the modified (and verified) versions of Equations (3) through (6).

7. CONCLUSIONS

The principal conclusion to be drawn from the analyses presented in this paper is that the development of a universal figure of merit for thermal distribution systems in residences is not an insurmountable task. Despite the numerous interactions involved, fairly direct means for accounting for those interactions can be developed. Moreover, it seems that such a figure of merit could be designed to fit comfortably into the present frameworks for state energy codes and utility Demand-Side Management incentive programs, as well as into design guides. Finally, such a figure of merit might also be used to help evaluate the peak-demand implications of various distribution-system alternatives.

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9. ENDNOTES

1. The 80 cm^2 leakage values are based upon the results of several field studies, principally from the sunbelt.

2. Attention will have to be paid to long-time-constant effects, particularly for hydronic systems.

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