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CONCEPTUAL FRAMEWORK FOR THE THERMAL DISTRIBUTION METHOD OF TEST

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ABSTRACT

A Standard Method of Test for residential thermal distribution efficiency is being developed under the auspices of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). Thermal distribution systems are the ductwork, piping, or other means used to transport heat or cooling effect from the equipment that produces this thermal energy to the building spaces that need it. Because thermal distribution systems are embedded in and interact with the larger building system as a whole, a new set of parameters has been developed to describe these systems. This paper was written to fill a perceived need for a concise introduction to this terminology.

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INTRODUCTION

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has established Standard Project Committee SPC152P to develop "A Standard Method of Test for Determining the Steady-State and Seasonal Efficiencies of Residential Thermal Distribution Systems." Thermal distribution systems are the ductwork, piping, or other means used to transport heat or cooling effect from the equipment that produces this thermal energy to the building spaces that need it. The test method will provide, for thermal distribution systems, a figure of merit analogous to the ones already in place for heating and cooling equipment, such as Annual Fuel Utilization Efficiency for furnaces and boilers, Heating Seasonal Performance Factor for heat pumps, and Seasonal Energy Efficiency Ratio for air conditioners.

The ASHRAE committee has decided to divide the standard test method into three "pathways," called Research, Diagnostic, and Design. Each pathway is intended for different use. The **design pathway** will be used to reduce or eliminate thermal distribution losses in new construction. The **diagnostic pathway** is intended for use by weatherization practitioners, to enable them to determine whether the thermal distribution system in an existing house is a suitable candidate for retrofit. The **research pathway** is intended for scientific studies that seek to gain new knowledge about energy flows in houses as they are affected by thermal distribution. This knowledge can be used to validate theory (including simulation codes); it can also be used to characterize, on a statistical basis, the existing housing stock within a region or of a specific type. The discussion of testing in this report is based primarily on the research pathway, although the parameters as defined here apply to all three pathways.

The cost of the measurement and calculation procedure must be significantly lower for the design and diagnostic pathways than for the research pathway, although there is strong incentive to keep research costs down as well. The extent of field measurements will increase as one goes from the design pathway (no field measurements) to the diagnostic pathway (minimal field measurements) to the research pathway (extensive field measurements).

Because thermal distribution systems are embedded in and interact with the building system as a whole, a new set of parameters has been developed to characterize these systems. The process of developing this terminology was begun in the 1980's in a government- and industry-sponsored project managed by ASHRAE that is commonly referred to by its ASHRAE designation, SP-43.[Jakob et al. 1986a,b; Herold et al. 1987; Jakob et al. 1987; Locklin et al. 1987] This project developed and validated a computer model of a house with forced-air heating and cooling that included a detailed treatment of the duct system. In the course of this project, parameter definitions closely paralleling the ones in current use by the ASHRAE SPC152P committee were developed. These are used in the chapter on Furnaces of the 1992 ASHRAE Systems and Equipment Handbook.[ASHRAE 1992] Further elaboration on this theme was carried out by Modera et al. (1992). More recently, the SPC152 committee has been developing the details of the test methods to put this terminology to practical use.

This paper was written to fill a perceived need for a concise introduction to this terminology, to facilitate discussion among all technically interested persons. The discussion here has not used language appropriate for final inclusion in the ASHRAE standard. That step is being undertaken by SPC152P as it converges on the content of the test method. Furthermore, no attempt has been made to present the system parameters in the order in which they would be measured in practice. These are described in logical rather than temporal order.

For simplicity, much of the discussion focuses on heating, although it is intended that cooling will be included in the test method. Also, it is couched implicitly in terms of time frames short enough that the system parameters and external conditions can be considered to remain constant. No discussion of how to translate such short-term results into seasonal figures of merit is included here. Finally, to avoid roundabout wording, the thermal distribution system will sometimes be spoken of in terms of "ducts," a word that is taken to include air ducts, water ducts (pipes), or any other engineered fluid-transport mechanism.

SYSTEM DESCRIPTIONS

In order to gain a clear perspective on the philosophy of the test method, it is necessary to define three separate space-conditioning systems. These are:

1. The system that is to be tested, namely the in-place equipment and distribution system coupled to the actual building. This will be referred to as the **System Under Evaluation (SUE)**.

2. A hypothetical system utilizing the same equipment as SUE, but with a "perfect distribution system" that has no thermal losses and has no impact on either the space-conditioning load of the building or on the efficiency of the heating or cooling equipment. This will be referred to as the **No Energy Loss or Impact** system **(NELI)**.

3. A system that substitutes a direct supply of heating or cooling energy to the building spaces, without losses, bypassing both the equipment and the distribution system. Whereas NELI has a perfect distribution system but imperfect equipment, this system can be thought of as having perfect equipment and distribution. In the heating mode, this system would most commonly be implemented with electric **co-heaters**. By definition, co-heating utilizes 100% of the energy input that crosses the system boundary (so that there are no equipment losses), and delivers 100% of this energy to meet the heating load (so that there are no distribution losses). **Co-cooling** could be accomplished via a chilled-water loop supplied from outside the building. This system will be referred to as the **Co-Heating (or Air-conditioning) System (CHAS)**.

These acronyms were chosen in part to serve as mnemonics by similarity to human names: i.e. "Sue," "Nellie," and "Charles."

It is to be noted that SUE and CHAS can be physically embodied in the test building, whereas to do this with NELI would be costly and difficult. The definition of thermal distribution efficiency, however, will involve a comparison of SUE and NELI in which only the ducts are changed but everything else remains the same. CHAS will come to the aid of NELI in this respect.

The System Under Evaluation (SUE) is depicted schematically in Figure 1. This figure divides the universe into two mutually exclusive regions, the conditioned space (inside the dotted line) and its environment (outside the dotted line). The broad arrows represent energy flows, while the dashed lines represent secondary effects.

The conditioned space includes only the portion of the building that is intentionally heated. If the thermal distribution system passes through a zone of the building that is not intentionally heated (e.g. a crawlspace, attic, or unheated basement) this is called a **buffer space**. Such a buffer space is considered part of the "environment."

In Figure 1, a supply of input energy to the equipment enters the boundary on the left. Some energy may be lost from the equipment directly to the outside. (For a heat pump these equipment losses will be negative.) In any case, the difference between the input energy and the equipment losses is passed on to the thermal distribution system. The distribution system may lose additional energy to the outside, and then the remainder of the heat is delivered to the building envelope, from which it eventually is lost to the outside through the usual mechanisms of thermal conduction and air infiltration.

Besides losing energy directly, the thermal distribution system may affect the operation of the equipment and the heating or cooling energy requirement of the building. Equipment efficiency is affected because the presence of distribution losses increases the fractional on-time of the equipment; pressure drops in ductwork can also affect the efficiency of a furnace, heat pump, or air conditioner.

The distribution system can affect the building load in several significant ways. First, if the system utilizes forced air, the operation of the air handler can increase the air infiltration rate of the house. Second, air leaks in a duct system can produce increased air infiltration even when the air handler is off, because of stack and wind effect. Third, regardless of the distribution system type, if it is located in a buffer zone that can retain heat to any extent, heat lost from the distribution system can raise the temperature of the buffer zone, which can in turn reduce the heat-loss rate from the conditioned space to that buffer zone. Other effects have also been observed. In one of these, ducts can provide pathways for convective loops that extract heated air from the house into the duct system, exposing it to conductive and leakage losses. This effect is usually referred to as thermosyphoning.

Thus, correct treatment of thermal distribution efficiency requires consideration of the following four factors:

- Direct heat losses via **conduction** through duct or pipe walls.
- Direct heat losses via mass-transfer (**duct leakage**). We note that this mechanism should not exist for hydronic systems.
- Impact (positive or negative) of the thermal distribution system on the **efficiency of the equipment**.
- Impact (positive or negative) of the thermal distribution system on the **heating or cooling load** of the building.

The first two loss mechanisms can be lumped together under the heading "direct thermal losses." The other two effects can be considered together as "system impacts."

Figure 2 characterizes NELI, the hypothetical "perfect distribution" system with which SUE is to be compared. It differs from Figure 1 in that there are, by definition, no direct distribution losses and no distribution impacts on either the building envelope or the heating equipment (although the heating equipment may still suffer losses of its own). Because the distribution impacts have been removed, the heating load and the equipment efficiency will in general be different in NELI than they are in SUE.

Figure 3 illustrates the co-heating implementation of CHAS. Note the 100% utilization of heat that enters the system boundary.

Figures 4-6 show the corresponding elements for the cooling mode. Heat flows are generally reversed from Figures 1-3, though the air conditioner still requires an input of mechanical or electrical energy. The co-cooling equipment referred to in Figure 6 could embody an external source of chilled water. This is labeled as an energy takeout, because the co-cooling system extracts heat from the building.

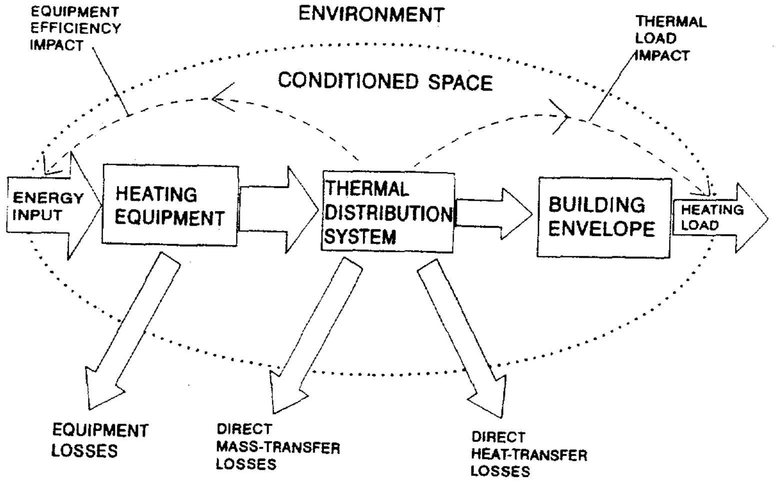

Figure 1. Energy Flows and System Impacts for Thermal Distribution System Under Evaluation (SUE)--Heating Mode.

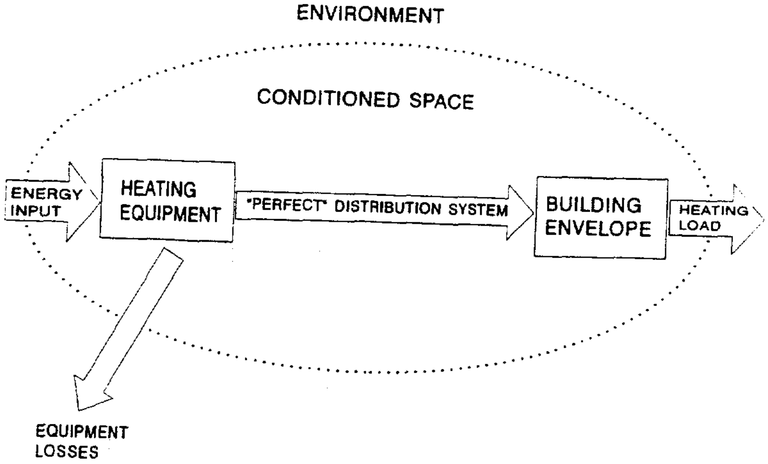

Figure 2. Hypothetical No Energy Loss or Impact (NELI) System to Be Compared with SUE--Heating Mode.

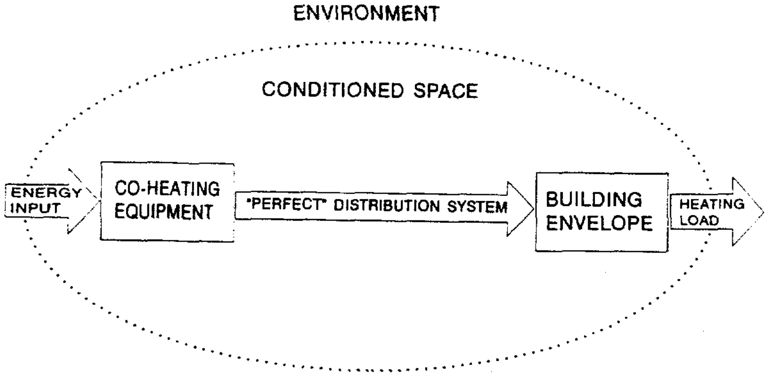

Figure 3. Co-Heating (or Air-Conditioning) System (CHAS) in the Heating Mode.

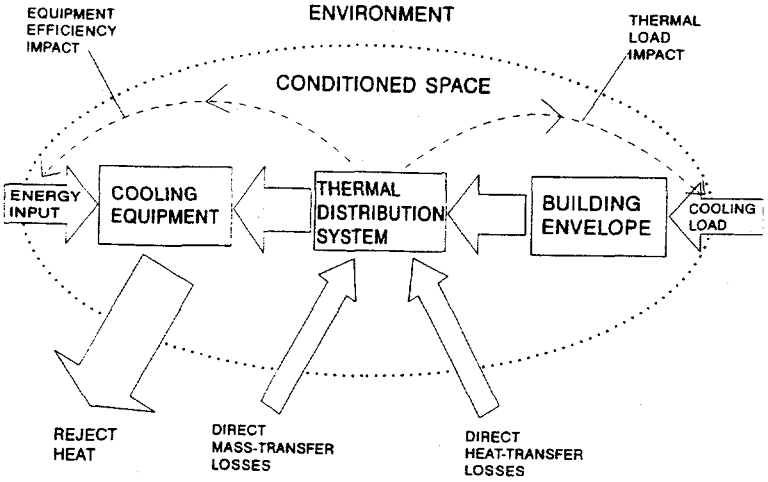

Figure 4. Energy Flows and System Impacts for Thermal Distribution System Under Evaluation (SUE)--Cooling Mode.

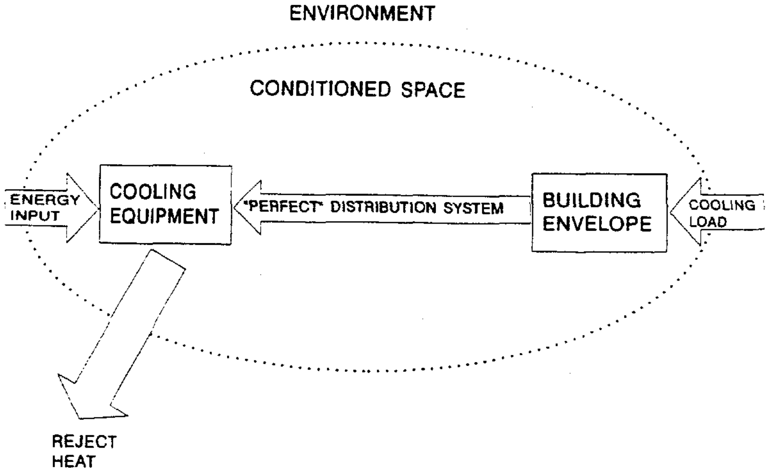

Figure 5. Hypothetical No Energy Loss Impact (NELI) System to Be Compared with SUE--Cooling Mode.

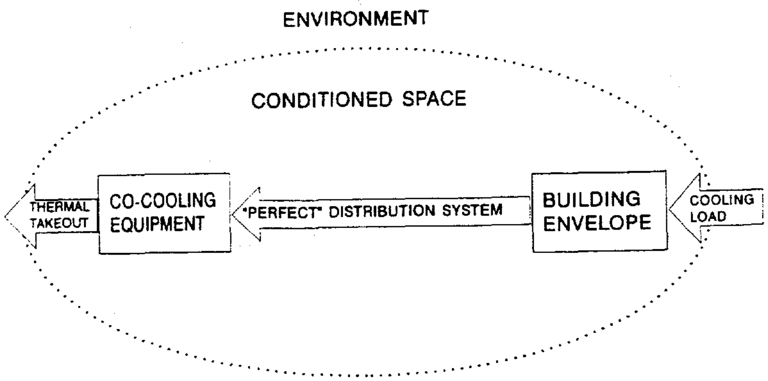

Figure 6. Cooling-Mode Energy Flows in CHAS.

FIGURES OF MERIT

The performance of a thermal distribution system is characterized by several key parameters. The most important of these are **system efficiency** and **distribution efficiency**. Other factors are equipment efficiency, delivery efficiency, building load factor, and equipment efficiency factor. Their definitions and use in the test method are now described.

System Efficiency

The fundamental quantity measured in the test method (particularly in the research pathway) is the **system efficiency** η_{system}, which is defined as:

$$\eta_{system} = \frac{Energy\ Input\ to\ CHAS}{Energy\ Input\ to\ SUE} \qquad (1)$$

This definition is motivated by the fact that CHAS requires an energy input that is equal to the "basic" heating load of the building, while SUE's energy input is the actual energy required by the system under evaluation. The ratio of the two is thus a reasonable definition of overall system efficiency.

The system is now considered in terms of its three components: the equipment, the ducts, and the building load. **Equipment efficiency** η_{equip} and **delivery efficiency** η_{del} are defined in terms of inputs and outputs in SUE:

$$\eta_{equip} = \frac{Energy\ Output\ from\ Equipment\ in\ SUE}{Energy\ Input\ to\ Equipment\ in\ SUE} \qquad (2)$$

$$\eta_{del} = \frac{Energy\ Output\ from\ Ducts\ in\ SUE}{Energy\ Input\ to\ Ducts\ in\ SUE} \qquad (3)$$

The building load impact is characterized by a **building load factor** $\mathbf{F}_{load}$ defined as the ratio of building loads in NELI and SUE:

$$F_{load} = \frac{Heating\ Load\ in\ NELI}{Heating\ Load\ in\ SUE} \qquad (4)$$

It is also necessary to note some equivalences that are recognized in what follows. Three of these are: 1) the heating loads in NELI and CHAS are the same; 2) the heating load and the energy input to the ducts in NELI are the same; and 3) the energy input to CHAS equals its heating load. Together these can be written:

Energy Input to CHAS = Heating Load in CHAS
= Heating Load in NELI (5*a*)
= Energy Input to Ducts in NELI (5*b*)

Another equivalence states that all the energy a system uses comes in through the equipment:

Energy Input to Any System = Energy Input to Its Equipment (6)

A fifth relation says that no energy is lost on the way from the equipment to the ducts:

Energy Output from Equipment = Energy Input to Ducts (7)

A similar identity relates the output from the ducts to the heating load of the building:

Energy Output from Ducts = Heating Load of Building (8)

This last relation raises an important methodological point. This treatment equates "ducts" with whatever means are used to deliver heat directly to the conditioned space. These may include:

- Heat delivered directly from ducts to the conditioned space as designed, through registers or heat exchangers.
- Heat delivered directly from the ducts to the conditioned space through "unauthorized flow paths" such as thermal conduction or air leakage directly to the conditioned space through cracks that are contiguous to the conditioned space or as a result of a portion of the duct system being in the conditioned space.
- Heat delivered directly to the conditioned space from the equipment, for example because of a vent pipe or the furnace itself being in the conditioned space.

In the ASHRAE SP-43 project (Jakob et al. 1986b), the second and third of these possibilities were lumped into a "miscellaneous gain factor." In designing the present terminology, it was decided to eliminate this factor because it is often very close to 1.00, and instead include these secondary transport mechanisms to be part of the thermal distribution system itself. Thus, a warm vent pipe running through the living space is part of the "duct system" in this treatment. So too would be the furnace jacket, if the furnace were installed in an intentionally heated zone.

It should be noted that the test method which emerges from the SPC152P process may take a different view of what constitutes delivered heat. The result of that would be to move some thermal transport effects (such as leakage from ducts in the conditioned space) from the delivery efficiency to the load factor. The product of η_{del} and F_{load}, however, would remain unaffected by any such "accounting provision." Inspection of Equation 11, below, shows why this is so. The product of η_{del} and F_{load} is equal to the ratio of η_{system} to η_{equip}; and neither of these latter quantities depends, in its definition, on knowledge of precisely what happens to the heat after it leaves the equipment.

We now can use Equations 5a and 6 to modify the appearance of Equation 1, the definition of system efficiency:

$$\eta_{system} = \frac{\textit{Heating Load in NELI}}{\textit{Energy Input to Equipment in SUE}} \qquad (9)$$

Equations 7 and 8 can be used to construct ratios that are numerically equal to one; these can then be multiplied by the right-hand-side of Equation 9 without changing its validity:

$$\begin{aligned}\eta_{system} = {} & \frac{\textit{Heating Load in NELI}}{\textit{Energy Input to Equipment in SUE}}\ X \\ & X\ \frac{\textit{Energy Output from Equipment in SUE}}{\textit{Energy Input to Ducts in SUE}}\ X \\ & X\ \frac{\textit{Energy Output from Ducts in SUE}}{\textit{Heating Load in SUE}} \qquad (10)\end{aligned}$$

Equations 2, 3, and 4 can now be brought in to write the fundamental relationship among the major variables:

$$\boxed{\eta_{system} = \eta_{equip}\,\eta_{del}\,F_{load} \qquad (11)}$$

Distribution Efficiency

Although we have discussed system efficiency, we have yet to define **distribution efficiency**. System efficiency relates the bare heating load of the house to the overall energy required to provide this heat. It is the ratio of the energy used by CHAS to that used by SUE. Distribution efficiency is defined as the ratio of the energy used by a system with a perfect distribution system to that used by one with the distribution system under evaluation--in other words, NELI to SUE:

$$\eta_{dist} = \frac{Energy\ Input\ to\ NELI}{Energy\ Input\ to\ SUE} \qquad (12)$$

Equation 1 lets us write this somewhat differently:

$$\eta_{dist} = \eta_{system} \frac{Energy\ Input\ to\ NELI}{Energy\ Input\ to\ CHS} \qquad (13)$$

And then Equation 6 applied to the numerator of the fraction and Equation 5b applied to the denominator lets us transform this to:

$$\eta_{dist} = \eta_{system} \frac{Energy\ Input\ to\ Equipment\ in\ NELI}{Energy\ Input\ to\ Ducts\ in\ NELI} \qquad (14)$$

The ratio to the right of η_{system} in this equation is just the inverse of the equipment efficiency in NELI, which we will write as $\eta_{\text{equip-NELI}}$ to distinguish it from η_{equip}, which without the system identifier is understood as always to refer to SUE. That is,

$$\eta_{dist} = \frac{\eta_{system}}{\eta_{equip\text{-}NELI}} \qquad (15)$$

Finally, since η_{equip} is relatively easy to measure whereas $\eta_{\text{equip-NELI}}$ is difficult or impossible to measure, we find it convenient to rework Equation 15 slightly to:

$$\eta_{dist} = \frac{\eta_{system}}{\eta_{equip}} \left(\frac{\eta_{equip}}{\eta_{equip\text{-}NELI}}\right) \qquad (16)$$

The quantity in parentheses is the ratio of the equipment efficiency with the as-found thermal distribution system to that with a "perfect" one, or the "equipment factor" F_{equip}. That is,

$$F_{equip} = \frac{\eta_{equip}}{\eta_{equip\text{-}NELI}} \qquad (17)$$

The question of how to measure F_{equip} may be a thorny one, since one of the factors in its definition refers to a system that normally can't be realized experimentally. Work on how to address this problem is underway. It is also possible that for large classes of equipment, such as fuel-fired furnaces, F_{equip} may be calculated from other measured parameters to acceptable accuracy. Data from the SP-43 project [ASHRAE 1992] suggest that for furnaces, F_{equip} is generally within a few percent of 1.00.

However that may turn out, we are now in a position to write the second critical relation among the variables:

$$\boxed{\eta_{dist} = \frac{\eta_{system}}{\eta_{equip}} F_{equip} \qquad (18)}$$

Equations 11 and 18 can be said to form the fundamental set describing thermal distribution system performance.

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