MEASURED PERFORMANCE OF CONVENTIONAL AND HIGH-VELOCITY DISTRIBUTION SYSTEMS IN ATTIC AND SPACE LOCATIONS

Edward A. Vineyard, P.E. **Randall L. Linkous** **Evelyn Baskin, PhD**

ABSTRACT

Residential distribution systems are inherently inefficient at delivering heated or cooled air to the conditioned space as the result of poor design and installation practices. Examples of some of the more common problems include heat loss/gain in unconditioned spaces and leakage through supply and return ducts. These defects can result in significantly increased energy consumption, poor thermal comfort, and high peak electricity demand. Efforts to improve distribution systems could result in substantial nationwide energy savings since more than fifty percent of existing homes have ducted systems. In an attempt to quantify the potential energy savings resulting from the elimination of duct losses, a field test was conducted to compare the energy consumption of an attic-ducted system to a no-loss duct system for two types of forced-air distribution systems: conventional and high-velocity. The no-loss system was achieved by locating the entire duct system and air handler in the conditioned space. The results were compared to predicted energy savings using ASHRAE Standard 152P as a means of validating the procedures used for determining distribution efficiency.

The results from the tests indicate that, for the conventional system, placing the ducts in the conditioned space resulted in a measured energy savings of 31% (heating) and 36% (cooling). The predicted savings using ASHRAE Standard 152P were 33% for heating and 15% for cooling. For the high-velocity system, the measured energy savings were 46% (heating) and 35% (cooling). These compare to predicted savings of 51% for heating and 26% for cooling using the standard. Thus, for both types of distribution systems, the standard is a good predictor of heating energy savings but tends to underestimate the cooling energy savings. Additional tests were performed to determine the effects of locating the air handler in the conditioned space. The results of this series of tests indicate measured energy savings of 10% (conventional) and 9% (high-velocity) for heating, whereas Standard 152P predicts savings of 3% (conventional) and 8% (high-velocity). In this instance, the Standard 152P estimate is reasonable for the high-velocity system and low for the conventional system. For cooling, the measured savings were 11% for the high-velocity system compared to 8% as predicted by Standard 152P. Conventional system tests during the cooling season were inconclusive due to errors in the data.

INTRODUCTION

In an effort to provide information for validating the procedures in ASHRAE Standard 152P for determining the efficiency at which the distribution system delivers energy to the conditioned space, a field test was undertaken to measure the energy consumption for two types of forced-air distribution systems: conventional and high-velocity. The information gained from the research effort will also be useful in promoting advanced distribution system designs, such as cornice duct systems, and in evaluating the cost efficiency of such designs.

As outlined in ASHRAE Standard 152P, there are two methods for reporting the efficiency of the distribution system. These are ***delivery effectiveness*** and ***distribution efficiency***. Delivery effectiveness is defined as the ratio of the thermal energy transferred to or from the conditioned space to the thermal energy transferred at the equipment/distribution system heat exchanger.

While this is an important measure, it fails to fully represent the fraction of the supplied energy that reaches the conditioned space to satisfy the building load. Distribution efficiency, defined as the ratio between the energy consumption by the equipment if the distribution system had no losses and the energy consumed by the same equipment connected to the distribution system, takes into account the effects of thermal regain, the interaction of unbalanced duct leakage with natural infiltration, and the impact, if any, of the distribution system on the equipment efficiency (ASHRAE 1997). Thermal regain accounts for energy lost by the ducts to unconditioned space that is effectively recovered by the building through reduction of losses from the unconditioned space to the buffer space due to a temperature change resulting from the duct losses. The interaction of unbalanced duct leakage with natural infiltration changes the building load by either pressurizing or depressurizing the building. This, in turn, results in reducing or increasing the amount of energy that must be supplied by the space conditioning equipment to satisfy the building load (Francisco, et al. 1998).

For this study, we are only concerned with the distribution efficiency since it more accurately reflects the actual energy requirements of the equipment in a field application experiment. Standard 152P addresses two measures of distribution efficiency: seasonal and design. The seasonal distribution efficiency is a measure used for energy consumption estimates while the design distribution efficiency is used for system sizing (capacity) (ASHRAE 1997). The estimated savings in energy consumption as the result of eliminating the duct losses were compared to measured savings for a no-loss system. In addition, the energy savings resulting from moving the air handler from the attic to the conditioned space were also determined. Calculations were also made for the expected equipment downsizing that would result from a no-loss distribution system.

BACKGROUND

Previous research efforts related to reducing the energy consumption of residential heating and cooling systems have focused primarily on improving the equipment efficiency. However, as evidenced by the increasing numbers of papers, conferences, and workshops, the focus is shifting to distribution systems as an area of growing concern due to the amount of energy lost from ducts for a variety of reasons, e.g., improperly installed ducts, leaking joints, or ducts located in the unconditioned space.

The distribution efficiency of forced-air heating and cooling systems is greatly affected by the type of distribution system and its location, e.g., attic, crawlspace, or basement. In 1983, forty-nine percent of existing residential heating and cooling systems in U.S. households relied on forced-air ducts to supply conditioned air to the building (Andrews and Modera 1991). However, the percentage of homes with ducts is increasing as indicated by more recent information showing that approximately 96% of new construction uses ducted distribution systems (NAHB 1999). Some of the drawbacks of ducted systems are that they require large amounts of space, tend to be noisy, are extremely prone to leakage, and can result in maldistribution of air and large infiltration losses. In addition, dust collection and the growth of mold and mildew inside ducts can cause indoor air quality problems (Kesselring 1993).

Estimates for energy losses for ducts in unconditioned and partially-conditioned spaces are 35% and 20% respectively (Gupta et al. 1995). Further, losses in ducted distribution systems contribute to high peak electricity demands. Air leakage from ducts may also lead to pressure differences that could cause pollutants such as radon to infiltrate the conditioned space.

METHODOLOGY

The houses used in the field test are 1150 ft^2 (107 m^2), single-story homes with basements, located in Lenoir City, Tennessee (Figure 1). One set of forced-air distribution ducts is located in an insulated, vented attic. A second set of ducts, representing a no-loss distribution system, is located in the conditioned space. A high-velocity, forced-air distribution system was installed in the attic and space in the first test house. In the second house, a conventional forced-air distribution system was installed in the attic and space. This enables a side-by-side comparison of the attic versus space for both types of duct systems. The high-velocity distribution system located in the attic was comprised of a 7 inch (18 cm) diameter main trunk line (R-4.6) in a perimeter loop configuration with twelve 2 inch (5 cm) diameter flexible supply ducts (R-4) and a total surface area of 259.2 ft^2 (24.1 m^2). The return, also located in the attic, was a 12 inch (30 cm) diameter flexible duct with R-4.2 insulation and a total surface area of 28.3 ft^2 (2.6 m^2). The conventional attic distribution system in the second house consisted of a main trunk line down the center of the house with sections of 14 inch (36 cm), 12 inch (30 cm), and 10 inch (25 cm) diameter ducts (R-6.8) and five 6 inch (15 cm) diameter and two 7 inch (18 cm) diameter flexible supply ducts (R-4.2). The total surface area was 239.6 ft^2 (22.3 m^2). The return, partially located in the attic, was a 14 inch (35 cm) diameter flexible duct with R-4.2 insulation and a total surface area of 11 ft^2 (1 m^2).

The two houses were built on adjacent lots and are essentially identical in terms of construction (floor area, insulation levels, window treatment, and orientation). The insulation levels for both houses are as follows: R-20 in the floor, R-40 in the attic, and R-11 in the walls. The heat pump for the conventional system has the following performance: 23,800 Btu/hr (6975 W), 12.3 SEER (cooling) and 23,600 Btu/hr (6916 W), 7.95 HSPF (heating). For the high-velocity system, the heat pump has a capacity of 22,000 Btu/hr (6448 W), 11.0 SEER (cooling) and 23,000 Btu/hr (6741 W), 7.50 HSPF (heating). One of the most significant differences between the two heat pumps is that the high-velocity system operates at a lower evaporating temperature in cooling and higher condensing temperature in heating as the result of the reduced indoor air flow rate. Although this increases energy consumption, comfort is improved relative to conventional heat pump systems as the result of lower relative humidity levels achieved in the house during the summer and higher discharge temperatures at the register in winter.

EXPERIMENTAL PLAN

The distribution system, heat pump, and house were instrumented to determine energy consumption, room-by-room temperature distribution, and indoor and outdoor ambient conditions. The distribution system efficiency (seasonal and design) was calculated using techniques outlined in ASHRAE Standard 152P. Temperature measurements, as shown in Figure 2, were made in each room at three different heights to evaluate the temperature distribution throughout the house and to ensure that uniform temperatures were achieved. In addition, relative humidity was measured in three locations (at two ends of the house and in the middle) to determine the relative humidity levels throughout the house. The results from the temperature and humidity measurements are not reported but will be the subject of a later report on the comfort and room-by-room temperature distribution for both types of distribution systems. Outdoor temperature and humidity were measured using a weather station located on the back porch. Relative humidities and temperatures for the basement and attic were also recorded. Energy consumption of the outdoor unit (compressor and outdoor fan) and indoor air handler (indoor fan) were determined using watt transducers. All data were measured on 15 second scan intervals, averaged for one minute periods, and recorded on a daily (twenty-four hour) basis.

Each distribution system/air handler configuration was tested over a three to four week period and a range of outdoor temperatures to determine the effects of the duct/air handler location on energy consumption. The one minute energy consumption data was binned for different outdoor to indoor temperature differentials and averaged to arrive at a single data point for each temperature interval. This method aided in reducing the scatter and resulted in high R^2 values for the plotted data.

EXPERIMENTAL RESULTS

The field test is designed to assess the energy consumption of the space conditioning equipment/distribution system over a range of outside ambient temperatures. The testing occurred over a period from December to August. Three modes of operation were tested: 1) air handler and ducts in the attic, 2) air handler and ducts in the conditioned space, and 3) air handler in the space and ducts in the attic.

Distribution Efficiency – Winter Tests

The energy consumption for winter operation of the conventional and high-velocity distribution systems is plotted in Figures 3 and 4, respectively, for all three configurations (attic/attic, space/space, and space/attic) as a function of the difference between the outdoor and indoor air temperatures. The average indoor temperature for the winter tests was 70^0F (21^0C). At high outdoor winter ambient temperatures (greater than 50^0F (10^0C)), corresponding to approximately a -20^0F (-11^0C) temperature differential on Figures 3 and 4, there is minimal difference in the energy consumption between all three configurations. However, as the temperature differential begins to increase, i.e., the outdoor temperature drops below 50^0F (10^0C), the energy consumption of the attic-attic and space-attic configurations begins to dramatically increase relative to the space-space configuration. This is the result of increased conduction losses from the ductwork to the attic space as the attic temperature becomes colder.

One of the most significant accomplishments from eliminating the duct losses, in addition to the energy savings, is the reduction in peak power. Since some utilities are more interested in shaving the peak load than saving energy, the results from this study indicate that benefits from no-loss distribution systems, either from reduced energy consumption or peak requirements, appeal to a wider range of utilities.

Conventional distribution system tests

The seasonal distribution efficiency is determined from ASHRAE Standard 152P at a temperature of 39^0F (4^0C), which is the ***heating seasonal*** temperature for Knoxville, Tennessee, the closest location to the testing. The seasonal distribution efficiency for the conventional attic-attic system arrangement using Standard 152P measurement techniques is 67%. This indicates that a 33% savings could be realized by eliminating all the duct losses. The actual energy savings from eliminating the losses for the system located in the attic can be determined by comparing its energy consumption to that for the system located entirely in the space at a temperature difference of –31^0F (-17^0C), which represents the temperature differential between the outdoor temperature at the heating seasonal temperature (39^0F (4^0C)) and the indoor temperature (70^0F (21^0C)). Comparing the measured energy consumption for the attic-attic configuration (1013 W-min/min) to the space-space system (700 W-min/min) indicates an energy savings of 31% (Table 1). Thus, ASHRAE Standard 152p is an excellent predictor of energy savings in this test.

The design distribution efficiency, which was calculated at a ***heating design*** temperature of 19^0F (-7^0C), is 72%. This indicates that a 39% increase in capacity, 23600 Btu/hr versus 16992 Btu/hr (6916W versus 4980 W), could be realized by eliminating all the duct losses for the conventional distribution system. Thus, for a typical 3.5 ton system, the capacity could be reduced to approximately 2.5 tons, resulting in a significant cost savings to the consumer.

High-velocity distribution system tests

The seasonal distribution efficiency for the high-velocity attic-attic system arrangement is 49%, indicating a potential energy savings of 51% for a no-loss distribution system. The measured energy consumption at a -31^{0}F (-17^{0}C) temperature differential (Figure 4) indicates a 46% savings (1220 W-min/min versus 661 W-min/min) (Table 2) as the result of eliminating the losses by placing the ducts in the conditioned space. Again, Standard 152P is a reasonable predictor of the potential energy savings. It should be mentioned that the poor seasonal distribution efficiency for the high-velocity system was the result of a large leak on the return side of the air handler located in the attic. The leak was caused by a retrofit box that was added to the air handler to enable insertion of a flow plate for airflow measurements. Thus, distribution efficiencies should be much higher with correct installation.

The design distribution efficiency is 56%. This indicates that a 79% increase in capacity, 23000 Btu/hr versus 12880 Btu/hr (6741 W versus 3775 W), could be realized by eliminating all the duct losses for the high-velocity distribution system.

Air handler location tests

Additional tests were performed by disconnecting the duct from the attic air handler and reconnecting it to the air handler located in the space. The results for the space-attic configuration indicate that a 10% (1013 W-min/min versus 913 W-min/min) (Table 1) and 9% (1220 W-min/min versus 1112 W-min/min) (Table 2) savings for the conventional and high-velocity distribution systems is realized by moving the air handler from the attic to the conditioned space. The results for the seasonal distribution efficiency using ASHRAE standard 152P indicate efficiencies of 70% for the conventional space-attic system and 57% for the high-velocity space-attic system. Comparing the efficiencies determined from Standard 152P techniques for the attic-attic arrangement yields a predicted savings of 3% (70% versus 67%) for the conventional distribution system and 8% (57% versus 49%) for the high-velocity distribution system. Thus, Standard 152P underestimates the potential energy savings from locating the air handler in the conditioned space by approximately 7% for the conventional distribution system and only 1% for the high-velocity system.

Distribution Efficiency – Summer Tests

The energy consumption during summer operation of the conventional and high-velocity distribution systems is plotted in Figures 5 and 6, respectively, for all three configurations (attic/attic, space/space, and space/attic) as a function of the difference between the outdoor and indoor air temperatures. The average indoor temperature for the summer tests was 72^{0}F (22^{0}C). As the temperature change begins to increase, i.e., as the outdoor temperature goes above 72^{0}F (22^{0}C), corresponding to a 0^{0}F (0^{0}C) temperature differential on the chart, the energy consumption of the attic-attic and space-attic configurations begins to dramatically increase relative to the space-space configuration. This is the result of increased conduction losses from the attic space to the ductwork as the attic temperature becomes warmer.

Conventional distribution system tests

For summer operation, the seasonal distribution efficiency is determined at a temperature of 81^{0}F (27^{0}C), which is the ***cooling seasonal*** temperature for Knoxville, Tennessee. Using Standard 152P techniques, the seasonal distribution efficiency for the conventional attic-attic system arrangement is 85%, indicating that only 15% savings could be realized by eliminating all the duct losses. At the cooling seasonal temperature, the temperature differential between the outdoor temperature and indoor temperature is 9^0F (5^0C). Comparing the measured energy consumption at this temperature differential (Figure 5) for the attic-attic configuration (915 W-min/min) to the space-space system (587 W-min/min), the energy savings is 36% (Table 1). For this series of tests, Standard 152P underestimates the energy savings by a large amount.

The design distribution efficiency, which was calculated at a ***cooling design*** temperature of 90^0F (32^0C), is 73%. This indicates that a 37% increase in capacity, 23800 Btu/hr versus 17374 Btu/hr (6975 W versus 5092 W), could be realized by eliminating all the duct losses for the conventional distribution system.

High-velocity distribution system tests

The seasonal distribution efficiency for the high-velocity attic-attic system arrangement is 74%, indicating a 26% savings as the result of placing the ducts in the conditioned space. The energy savings at a 9^0F (5^0C) temperature differential (Figure 6) indicate a 35% savings (1319 W-min/min versus 854 W-min/min) (Table 2) from eliminating all the duct losses. Again, Standard 152P underestimates the energy savings, although the difference is not as large as it was for the conventional system tests.

The design distribution efficiency is 55%. This indicates that an 82% increase in capacity, 22000 Btu/hr versus 12100 Btu/hr (6448 W versus 3546 W), could be realized by eliminating all the duct losses for the high-velocity distribution system.

Air handler location tests

The results for the space-attic configuration indicate that an 11% savings (1319 W-min/min versus 1180 W-min/min) (Table 2) for the high-velocity distribution system is realized from moving the air handler to the conditioned space, compared to the entire system located in the attic. This result is comparable to that achieved in the winter tests (9%). The predicted energy savings for a no-loss high-velocity distribution system as determined by Standard 152P is 8% (82% versus 74%). Again, Standard 152P yields a reasonable prediction. The tests for the air handler in the space for the conventional system were omitted due to errors in the data during the testing period. By the time the error was caught, it was too late to perform the tests a second time. A comparison using Standard 152P would indicate an efficiency improvement of 2%. However, it should be noted that the actual savings were much higher than Standard 152P predicted for the winter testing.

CONCLUSIONS

Several significant findings were concluded from the field test. The seasonal distribution efficiency of the conventional system was determined to range from 67% (heating) to 85% (cooling), indicating that the system was representative of a well-installed distribution system. Typical distribution system efficiencies for residential construction are in the range of 60% - 70% (Modera 1993). The seasonal distribution efficiency of the high-velocity system ranged from 49% (heating) to 74% (cooling), indicating a poor installation. The lower efficiencies, compared to the conventional system, were the result of a large air leak on the return side.

From the seasonal distribution efficiencies calculated using ASHRAE Standard 152P methods, the potential energy savings from eliminating all the losses are estimated to be 33% (heating) and 15%

(cooling) for the conventional system. The potential energy savings for the high-velocity system are higher, 51% (heating) and 26% (cooling). The actual energy savings for both systems compared favorably in heating to the predicted energy savings. However, in cooling, the actual energy savings were considerably higher. For the series of test with the air handler in the conditioned space and the ducts in the attic, the standard was a reasonable predictor for the high-velocity distribution system. However, for the conventional system, the predicted savings were quite low.

One finding of particular interest is that the heat pump capacity could be substantially reduced as the result of eliminating the duct losses. For the conventional system, the improvement in capacity ranged from 37% (cooling) to 39% (heating). For the high-velocity system, which had a sizeable leak in the return duct, the capacity improvement was even more significant, 82% for cooling and 79% for heating. Improvements of this magnitude would result in cost reductions for the heat pump that could be applied towards improved distribution systems.

FUTURE PLANS

The next series of tests will focus on evaluating the performance of a variable-speed system to determine if the duct losses are higher due to the reduced airflow when the heat pump is operating at lower capacities. Tests will be conducted using two levels of duct insulation, one with R- 4.2, and the second series at a higher R-value to determine the impact on the overall system efficiency.

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Table 1
Energy Savings – Conventional System

HVAC/Duct System	Energy Consumption (W-min/min)		Energy Savings (%)	
	Winter	Summer	Winter	Summer
Attic-Attic	1013	915	-------	-------
Space-Space	700	587	31	36
Space-Attic	913	-------	10	-------

Table 2
Energy Savings – High-Velocity System

HVAC/Duct System	Energy Consumption (W-min/min)		Energy Savings (%)	
	Winter	Summer	Winter	Summer
Attic-Attic	1220	1319	-------	-------
Space-Space	661	854	46	35
Space-Attic	1112	1180	9	11

Figure 1. Test house

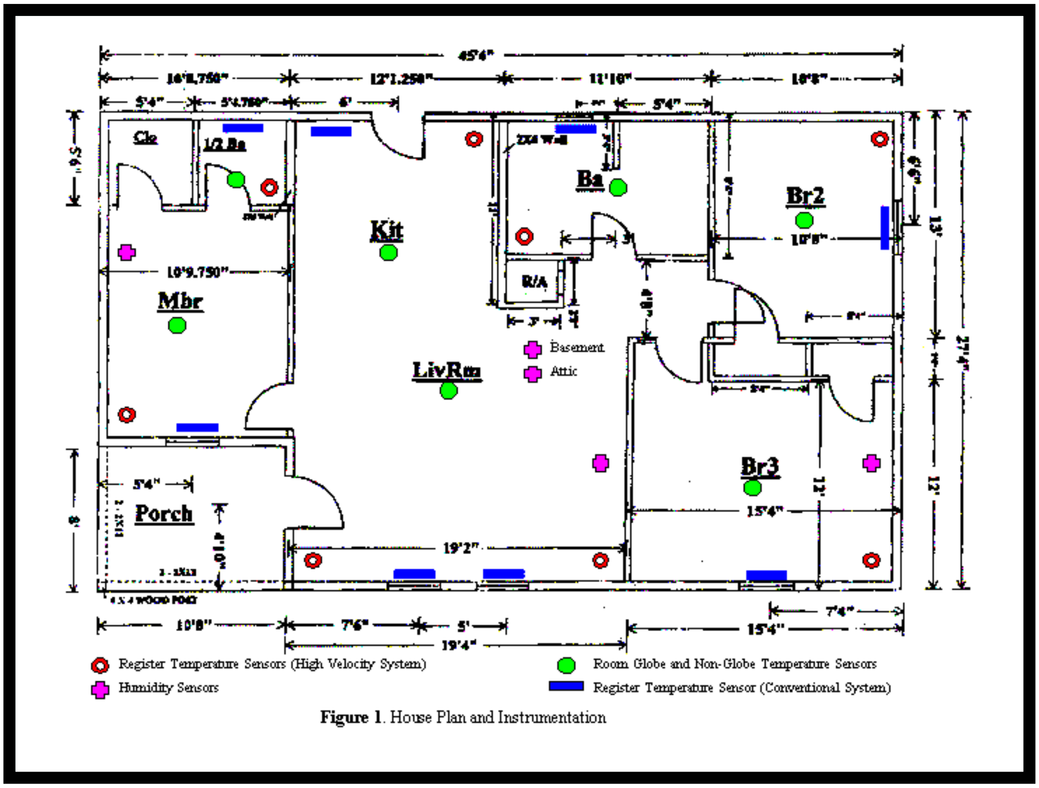

Figure 1. House Plan and Instrumentation

Figure 2. Instrumentation

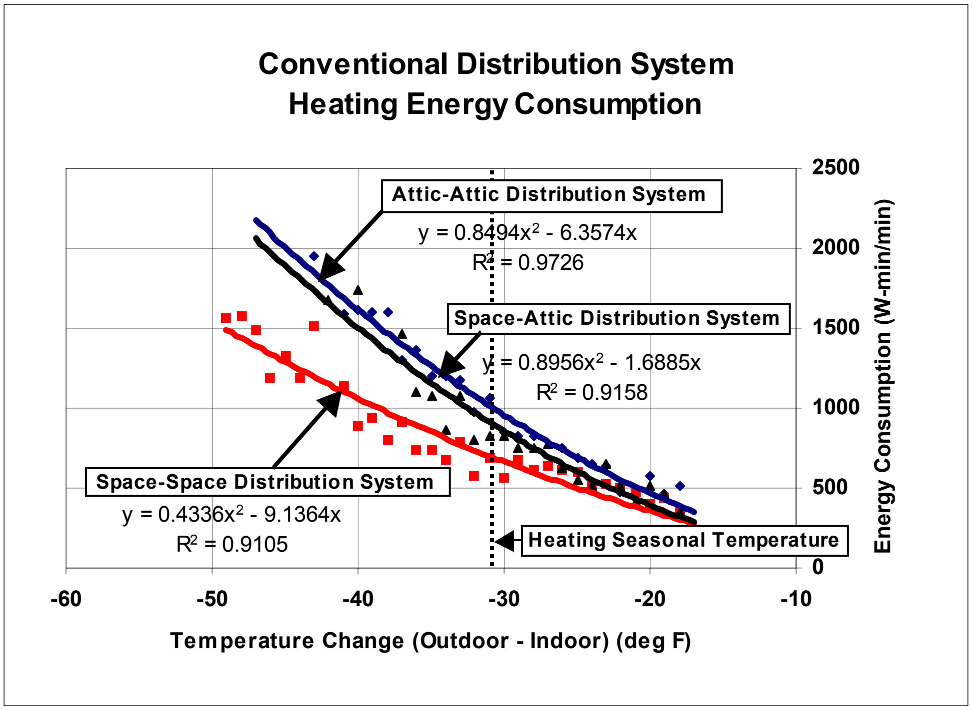

Figure 3. Winter Data – Conventional System

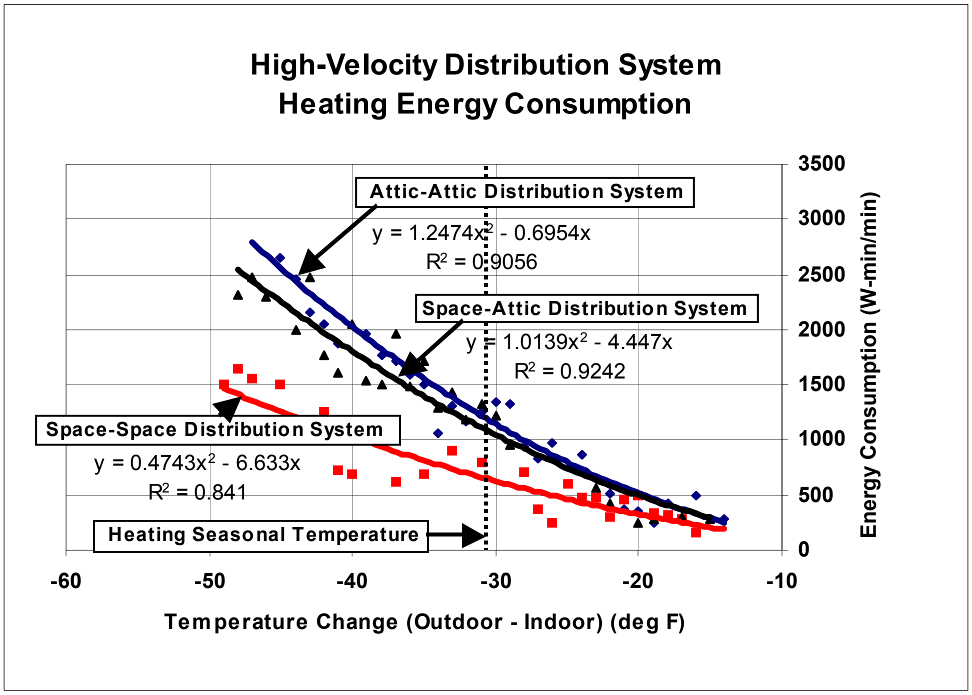

Figure 4. Winter Data – High-Velocity System

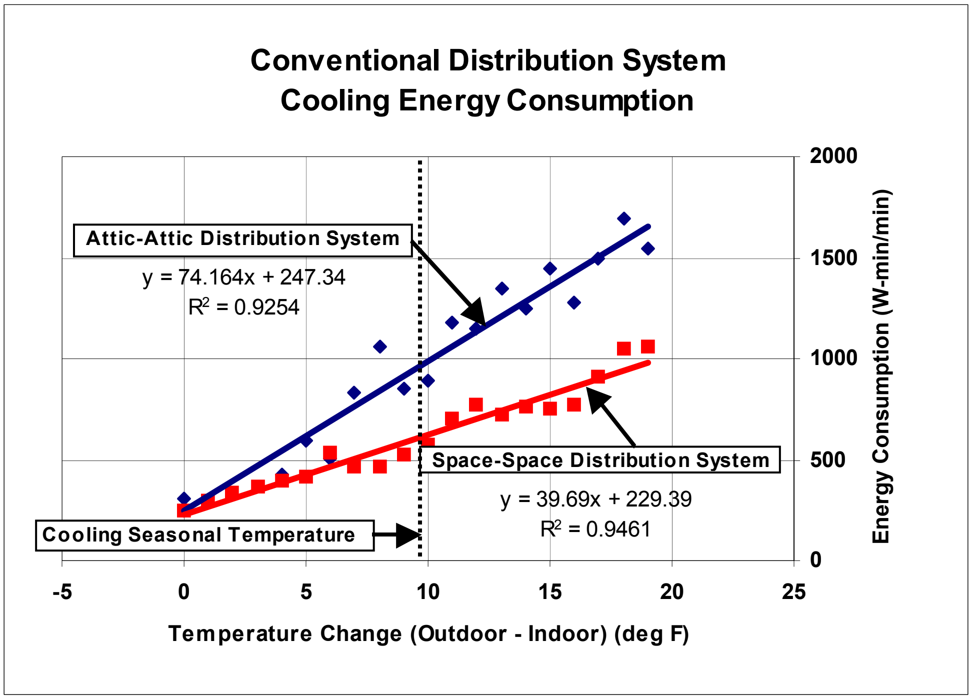

Figure 5. Summer Data – Conventional System

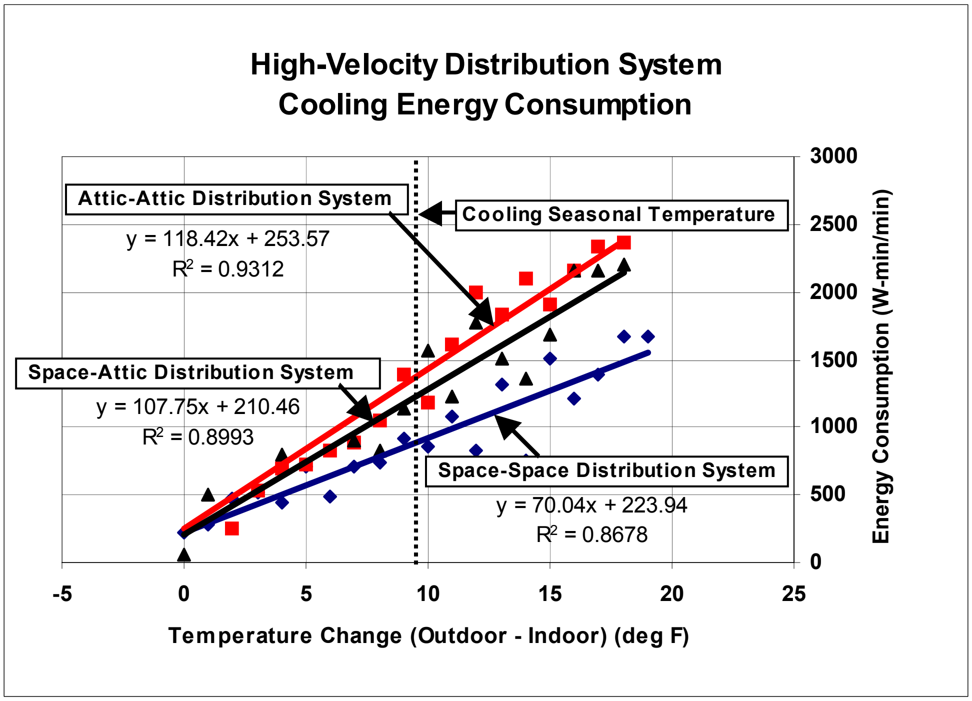

Figure 6. Summer Data – High-Velocity System